KEMENTERIAN TENAGA, SAINS, TEKNOLOGI, ALAM SEKITAR DAN PERUBAHAN IKLIM

AKADEMI SAINS MALAYSIA

Think Science, Celebrate Technology, Inspire Innovation

ASM Science JOURNAL

Vol. 12, Special Issue 2, 2019 • ISSN : 1823-6782

WWW.AKADEMISAINS.GOV.MY

Malaysia in Space

Space Law
Space Communication
Space Engineering
Remote Sensing
Space Science
Space Education

Malaysia IAU100

Annular Solar Eclipse 2019

25 Years Planetarium

Photo Courtesy of Karzaman@Langkawi National Observatory

ASM Science Journal
Malaysia in Space

GUEST EDITORIAL BOARD

ASM Science Journal, Volume 12, Special Issue 2, 2019 for Malaysia in Space

ASM Science Journal is listed and indexed in Scopus.

Academy of Sciences Malaysia
Level 20, West Wing, MATRADE Tower
Jalan Sultan Haji Ahmad Shah off Jalan Tuanku Abdul Halim
50480 Kuala Lumpur, Malaysia

ISSN 1823-6782

Editorial: Malaysia in Space

It has been almost two decades since the Malaysian government, through the then newly established National Space Agency, last commissioned a satellite. RazakSAT was officially named by the then Prime Minister, just months before his retirement in 2003. Malaysia's second remote sensing satellite was launched to the Near Equatorial Low Earth Orbit, the first in the world, in 2009 and since that year there has been no significant milestone in the country's Space programme. A National Space Policy was reportedly approved at the National Science Council meeting chaired by the then Prime Minister in February 2017, but it was never officially launched by the Ministry of Science, Technology and Innovation. The absence of an official launch could be the reason the Policy did not result in new funding for any major Space projects.

Despite this apparent lack of development in the Space sector, individuals and groups at Malaysian universities have been continuously carrying out research in space engineering, science, applications, education and law. The intent of this special publication of the ASM Journal is to bring to the fore these research accomplishments. The Review papers on the various themes, in particular, highlight the fact that there have been considerable achievements in the past and interest in Space remains high in the country.

In March 2019, the Ministry of Energy, Science, Technology, Environment and Climate Change, who has purview over Space matters, announced the merger of the Malaysian Remote Sensing Agency with the National Space Agency. The amalgamated entity has been named the Malaysian Space Agency. It is naturally implied that such a merger was conceived because it would bring about better synergies and efficiencies and more impactful outcomes. And so it should. Together with the Policy, this merger should bring about a new phase of the country's Space activities, one that is in line with the New Space global landscape (What is New Space? The Changing Ecosystem of Global Space Activity. https://www.liebertpub.com /doi/full/10.1089/space.2016.0027). This is an exciting period of the Space age, where the private sector is leading the charge, particularly in the field of Space Tourism; established Space faring nations are rolling out ambitious programmes to land humans on the Moon and Mars; while a growing number of emerging Space nations are taking advantage of the lowered barrier to entry to Space.

Malaysia was once ahead of many countries in terms of its accomplishments in Space and was well respected for its vision. It is a shame if, given that a merged Agency and a National Space Policy have been put in place, Malaysia does not take the mantle again and capitalize on what Space has to offer. The authors of the articles in this publication, and many others, are the human capital needed for the venture. The subjects they cover show the depth and breadth of the country's capability. Let us not waste this precious resource.

Mazlan Othman
Guest Editor-in-Chief

Review of Space Law and Policy in Malaysia

Tunku Intan Mainura[1]*

[1]Faculty of Law, Universiti Teknologi MARA, 40450 Shah Alam, Selangor

I. INTRODUCTION

One common similarity that Malaysia has between itself and the international space programme[1] is the year 1957. For Malaysia it was the year of Independence[2] and for the international space programme, the first satellite, Sputnik 1, was launched to outer space by the Soviet Union (USSR)[3]. That was 61 years ago. Today outer space is familiar territory to States at large and Malaysia is one of the players in this arena[4]. Although it has been commented by some writers that 'Malaysia can be considered as new in space activities, since its first satellite was only launched into orbit in 1997'[5], nevertheless, it should be highlighted here that its space activities have grown very rapidly since then because in a time span of ten years, in 2007 it sent its first astronaut to the International Space Station[6].

In general, Malaysia's space activities can be divided into three main programmes. They are the space science and technology programme, the astronaut programme and the space education programme[7]. In order for Malaysia to ensure that its activities under the programme of space science and technology can be effectively undertaken, Malaysia has built space infrastructures, which includes the national observatory and remote sensing centres[8]. Also included under the programme of space science and technology is the satellite activities. Under this activity, Malaysia has participated in it by having four satellites in orbit. Nevertheless, these satellites were not launched from Malaysia's territory, as Malaysia does not have a launching facility[9]. They were all launched as payloads from other countries. For example, MeaSAT 1 and MeaSAT 2 which are the first Malaysian privately owned satellites were launched aboard an Ariane rocket in 1996 from Kourou, French Guiana[10]. TiungSAT which was launched in 2000 and MeaSAT 3 which was launched in 2006 were both launched from Baikanor, Kazakhstan[11]. A fifth satellite, RazakSAT, was launched in 2010 from

---

[1] Gibson, R 2007, 'The history of international space programmes', *Space Policy*, vol. 23, no. 3, p. 155.
[2] Mahathir, M, & Irwan, F 2007, 'Malaysia's role in Asian regional cooperation: A look at foreign policy themes', *Asia-Pacific Review*, vol.v14, no. 2, p. 97.
[3] Jackson, NM 2005, 'The military ascent into space: From playground to battleground - The new uncertain game in the Heavens', *Netherlands International Law Review* , LII, no. 3, p. 461.
[4] Brown, F 2007, 'The changing face of space', *Space Policy*, vol. 23, no. 2, p. 69.
[5] Allaudin, MF, Peter, N, Md Said, MA & Nor, K 2005, 'Capacity building for the space sector: Microsatellite as a way forward. The example of the University of Sains Malaysia', *Acta* Astronautica, vol. 57, no. 2–8), p. 554.
[6] Luo, G, (ed.) 2007, 'Malaysian astronaut blasts into space', *Asia-Pacific Space Outlook,* vol. 3, no. 14, p. 8.
[7] Malaysia Space Agency's official web site

*Corresponding author's e-mail: tunkuintan@yahoo.co.uk

[8] These national observatory and remote sensing centres have the purpose of supervising and monitoring space network frequencies and coordinating space networking, providing a platform for Malaysian scientists and international astronomers to do research on space science, and controlling and maintaining the satellite operations. Malaysia Space Agency's official web site.
[9] Since Malaysia actively participates in satellite activities, a proposal has been made by the Malaysian government to build its own rocket-launching site in the near future. BBC Online, <http://news.bbc.co.uk/1/hi/world/asia-pacific/810057.stm>, 'Malaysia seeks place in space'. Reported on 28 June 2000.
[10] The MeaSAT system is the first Malaysian privately owned satellite, operated by Binariang. The MeaSAT system provides the first direct-to-user (DTU) service in Malaysia, as well as general communications services in an area reaching from India to Hawaii and from Japan to East Australia. Both MeaSAT spacecrafts were built by Hughes Space and Communications Company (HSC) in El Segundo, California. MEASAT Satellite Systems Sdn. Bhd.'s official web site, <http://www.measat.com.my/>.
[11] TiungSAT 1 is Malaysia's first national micro satellite which was built by Astronautic Technology (M) Sdn Bhd (ATSB) and Surrey Satellite Technology Limited. The purposes of this satellite are earth observations, scientific Cosmic-Ray Energy Deposition Experiment (CEDEX) and simple communications applications. Amateur Satellite Organisation's official web page, <http://www.amsat.org/amsat/sats/n7hpr/tiungsat1.html>, accessed 30 January 2008. As for MeaSAT 3 the information can be found at MEASAT Satellite Systems Sdn. Bhd.'s official web site, <http://www.measat.com.my/>

Omelek Island in the Republic of the Marshal Islands[12] as a payload using the Falcon 1 rocket owned by the USA[13]. As for the second type of programme available in Malaysia, that is the astronaut programme, on the 10 October 2007, Malaysia witnessed the departure of its first astronaut, Sheikh Muszaphar Shukor Al Masree, to the International Space Station[14]. As for the programme of space education, Malaysia has activities to encourage the public to be interested in learning about space, by organizing many events suitable for the public[15].

Recently, the Faculty of Electrical Engineering of Universiti Teknologi MARA (UiTM), Malaysia, has collaborated with Kyushu Institute of Technology, Japan, together with the states of the Philippine and Bhutan in a Nano-Sat program named BIRDS-2. UiTM's Center for Satellite Communication, together with the above-mentioned states, constructed a satellite known as UiTMSAT-1 which was deployed to space from the International Space Station in August 2018[16]. This satellite is the first Nanosatellite to be constructed by a public university in Malaysia[17]. Initially, the satellite was launched to the International Space Station in June from the Cape Canaveral Air Force Station Launch Complex in Florida, the United States through the SpaceX Falcon 9 rocket[18].

Due to these rapid expansions of Malaysia's space programme into a wide range of activities, they require a set of regulations in order to ensure that they are undertaken lawfully with proper legal procedures and rules[19]. As was highlighted above, at present Malaysia has a draft legal framework, the Draft Malaysian Outer Space Act 2005, which attempts to regulate the space-related activities of its subjects[20]. Nevertheless, as was also

[12] RazakSAT is medium-sized aperture camera satellite, which was developed jointly by Astronautic Technology (M) Sdn Bhd (ATSB) and SaTReCi (SaTReCi Initiative Co Ltd) of Daejeon, Korea. RazakSAT functions include electro-optical earth observation, telecommunications and space science. The information for RazakSAT can be found at Amateur Satellite Organisation's official web page, <http://www.amsat.org/amsat/sats/n7hpr/tiungsat1.html>

[13] New Straits Times Online, 31 December 2007, <http://www.nst.com.my/Monday/National/212077/Article/index_html>

[14] Luo, G., (ed.) 2007, 'Malaysian astronaut blasts into space', *Asia-Pacific Space Outlook, vol.* 3, no. 14, p. 8. This astronaut programme however, has been criticised by some of the Malaysian public as unnecessary and a waste of public money. See 'Comments by Malaysian public about space programme of Malaysia', <http://www.malaysiakini.com/news/73524>, 'Is he an astronaut or space tourist?', reported 12 October 2007. In reply, Malaysia's government has stated that this astronaut programme does not utilise public funds as the financial burden of this programme is borne by the Russian government. This is due to the fact that this programme is a project that is the result of an offset agreement between Malaysia and Russia, when Malaysia purchased the Sukhoi-30MKM fighter jets from Russia. As such, under this agreement the Russian government is responsible for the cost of training and sending of two Malaysian astronauts to the International Space Station. See New Straits Times Online, 29 September 2007, <http://www.nst.com.my/Current_News/NST/Sunday/Focus/20070929194127/Article>.
Malaysia's government also states that the Malaysian people and the country will gain benefits from this programme because the scientific research done in the International Space Station will contribute greatly in the fields of space medicine, aviation medicine, life science, environmental science and physics. See Malaysian Space Agency's official web site.

[15] Under the programme of space education, they include astronaut fashion design and drawing competitions, carnivals, planetarium shows, and a rocket launching technology challenge. See Malaysian Space Agency's official web site. Space education is also being taught at schools and universities, whereby they include the teaching of space law in some universities in Malaysia. See Space Law Update, Volume 2, Issue 2, September 2005, United Nations Office of Outer Space Affairs official website. As regards to the space education programme, it should be mentioned that although the activities under the theme of space education do not require an actual legal framework, nevertheless the purpose of mentioning it here in this chapter is for the purpose of acknowledging Malaysia's involvement in its space activities. The fact should also be highlighted here that the subject of space is relatively new for the general public of Malaysia because before the programme of space education was introduced by the Malaysian government, the public knew very little about space and its benefits. However, since the introduction of the space education programme, many Malaysians are now aware and alert about matters or activities concerning space. See Berita Harian Online's official web site, 'Interview with Professor Datuk Dr. Mazlan Othman, Director General of Malaysian National Space Agency', reported on 29 December 2007. Should also be highlighted here the fact that for the European countries, it has been suggested that in order for the benefits and potential of space activities to be understood clearly, space policy teaching should be introduced to students in the universities or even high school. This approach is considered important because it is very important to communicate the benefits that space activities have brought and as such the information can educate the society to further supporting the space activities. See Reibaldi, G. G., 'The importance of space policy teaching in communicating space activities to society', (2003) 53 (12) *Acta Astronautica* 997.

[16] https://www.bharian.com.my/berita/nasional/2018/08/460476/uitmsat-1-berjaya-dilancarkan-ke-orbit

[17] Website of BIRDS project, Kyushu Institute of Technology <http://birds.ele.kyutech.ac.jp/newsletter.html>

[18] https://www.nst.com.my/education/2018/07/391936/uitmsat-1-puts-malaysia-final-frontier

[19] For detailed discussion on the legal issues on the launching and operating satellites, see Bender, R., *Launching and Operating Satellites: Legal Issues,* (Netherlands: Martinus Nijhoff, 1998) 43.

[20] 'Subjects' here mean those persons who are regulated and bound by the provisions of the Draft Act. Its Section 3

argued above, having a draft legal framework is not sufficient for Malaysia and what this research intends to examine is not whether Malaysia needs to have a legal framework or otherwise but whether its draft legal framework is 'ideal' in the sense defined above [21]. Furthermore, due to the sheer amount of money going into the programme, there is a need for Malaysia to be able to show results and careful regulation. At present Malaysia's approach to space regulation has been largely mediated through an institutional infrastructure. For example, the issuance of licence and matters concerning memoranda of understanding between Malaysia and the foreign company that launches Malaysian satellites are dealt with by the Ministry of Science, Technology and Innovations, the administration of space-related activities are dealt with by its national space agency, the Malaysian National Space Agency (ANGKASA), and the remote-sensing centres are controlled by the Malaysian Space Centre[22].

With regards to ANGKASA, it was established in 2002 with the purpose of leading and observing the development of space science in Malaysia through three efforts, namely, providing leadership in the educational aspect and the research of space science, assisting the government in formulating and executing the National Space Policy and providing quality service to customers to help achieve the above-mentioned goals. In order for it to be effective, the management of ANGKASA is divided into four divisions. They are the Operations and Space System Division, the Technology Development & Applications Division, the Space Science & Education Division and the Administration & Human Resource Division[23]. Whilst the Operations and Space System Division, and the Technology Development & Applications Division are both based at the National Space Centre, the Space Science & Education Division is based at the National Planetarium, and the Administration & Human Resource Division is based at the Putrajaya Headquarters[24]. With the establishment of ANGKASA, it can be observed that there is in existence in Malaysia an institution that is responsible for managing and administering the space activities of Malaysia. Furthermore, it has also been commented that 'as ANGKASA also holds extensive consultations with other governmental agencies to ensure that there is maximum alignment of the national efforts in terms of education, capacity building, applications, technology acquisition and development, regulations and advancement of knowledge, the establishment of ANGKASA is seen to be the most crucial move for the Malaysian space program'[25].

II. SPACE POLICY

Malaysia is still in the process of developing its own Space Policy. According to Agensi Angkasa Negara, the process of developing "Malaysian Space Policy" is among others, to firstly, set out the vision and goals of Malaysian space activities for the new century; secondly, to provide strategic context for investments in space exploration and exploitation by the Government and industry in order that they contribute effectively towards the socio-economic well-being of the nation; thirdly, to mobilize and organize the resources (financial, manpower & institutional) to make such investments work for the nation in terms of enhancing the productivity and skill-levels of the key economic sectors as well as the generation of high value added products, processes and services; and fourthly, to establish the framework for the effective performance of the various actors involved in the exploration and exploitation of space including the engagement with external parties[26].

The need to have the space policy by 2030 is further emphasised during the National Space Policy 2030 [27]

has a provision that indicates the persons who are affected by this Draft Act as well as the area/territory in which the Draft Act will be applicable. By having this provision, it is clear as to when this Draft Act can be referred to or otherwise.

[21] *Prima facie* a legal framework will ensure transparency of the rules and regulations, whereby when the procedures and rules are clear, they will assist in the efficiency in conducting outer space activities. On the other hand, without a legal framework, inconsistency will also be created among those who want to participate in outer space activities. Moreover, a legal framework is also necessary as it can clearly identify the body that is in charge of administering the space-related activities as well as clearly providing for criminal liabilities and civil penalties for compensation purposes. See Forkosch, M. D., *Outer Space and Legal Liability,* (The Hague: Martinus Nijhoff Publishers, 1982) 37.

[22] Malaysian Space Agency's official web site.

[23] Malaysian Space Agency's official web site.

[24] Malaysian Space Agency's official web site.

[25] Allaudin, M. F., Peter, N., Md Said, M. A. and Nor, K., 'Capacity building for the space sector: Microsatellite as a way forward. The example of the University of Sains Malaysia', (2005) 57 (2-8) *Acta Astronautica* 555.

[26] Malaysia National Space Agency website, http://www.angkasa.gov.my/?q=en/node/109

[27] Malaysian National Space Policy 2030: Driving the Space Sector in Malaysia.

forum, where its current Director, Dr. Noordin Ahmad emphasised the need of a space policy in order to assist Malaysia to coordinate space issues domestically and internationally. He mentioned on the reasons for Malaysia to have the space policy, namely on harnessing the potential of space capabilities as a strategic step towards nation sovereignty, security and economy, to act as a basis to draft Malaysian Outer Space Act and ratify the international treaties, and to compliment other national existing policies. There is a provision in the policy of the need to ensure an adequate qualified, talented and competent workforce to develop and sustain the space sector in Malaysia[28].

III. RATIFICATION STATUS OF THE UNITED NATIONS TREATIES AND AGREEMENTS ON OUTER SPACE

As have been discussed above, there are five treaties that regulate the conduct of States concerning their space-related activities and there are five sets of resolutions adopted by the United Nations General Assembly that lay down the legal principles pertaining to the peaceful uses of outer space[29]. These five treaties are open for signature and ratification by member States and under international law; their provisions are binding upon States that have ratified them[30]. This principle of *pacta sunt servanda* can be clearly seen under Article 26 of the Vienna Convention on the Law of Treaties 1969, whereby it is provided that 'every treaty in force is binding upon the parties to it and must be performed by them in good faith'. Thus, if a treaty creates legally binding obligations, then a breach of a treaty by one of its parties is a breach of international law[31]. In practice, this means that if for example Malaysia signed and ratified the five treaties, therefore, Malaysia would be a party[32] to them, and thus bound by their provisions. As such, Malaysia would be responsible if Malaysia were to breach any provisions provided by them.

On the other hand, if Malaysia did not sign nor ratify the treaties, Malaysia would not become a party to them, and as a third party[33] to these treaties, it would not be bound by their provisions, and technically therefore would not be responsible if it did not comply with any provisions provided by them. Thus, since rights and responsibility go hand in hand together, if Malaysia does not have a responsibility under these treaties, it will also mean that Malaysia does not have any right under these treaties as well.

Be that as it may, although Malaysia does not have a right or responsibility under these treaties, Malaysia still has the right and responsibility under the principles of Public International Law in general.

Nevertheless, many States have considered the 1967 Outer Space Treaty as international customary law, and this means that the principles in the treaty effectively bind all States irrespective whether the States have ratified it or otherwise[34]. This is because according to Article 38 of the 1969 Vienna Convention on the Law of Treaties, it is provided that a treaty rule can be binding upon non-parties if it becomes customary rule of international law[35].

IV. LEGAL FRAMEWORK

Based on the similarities and differences, strengths and weaknesses of the national space legislations of the UK, USA, Australia and Japan, the key components or

http://mycoordinates.org/national-space-policy-2030-driving-the-space-sector-in-malaysia/

[28] National Space Policy 2030: Driving the Space Sector in Malaysia. http://mycoordinates.org/national-space-policy-2030-driving-the-space-sector-in-malaysia/

[29] For detailed discussion on the law made by the United Nations, see Jasentuliyana, N., *United Nations Conference on the Exploration and Peaceful Uses of Outer Space: International Space Law and the United Nations,* (Netherlands: Kluwer Law International 1999) 57. For more detailed discussion on the space treaties and resolutions, see Fawcett, J. E. S., *Outer Space: New Challenges to Law and Policy,* (Oxford: Clarendon Press, 1984) 163.

[30] Brownlie, I., *Principles of Public International Law,* 5th edition, (Oxford: Oxford University Press, 1999) 288.

[31] D'Amato, AA 1971, *The Concept of Custom in International Law*, New York: Cornell University Press, p. 105.

[32] According to Article 2(g) of the Vienna Convention on the Law of Treaties 1969, 'party' means a State which has consented to be bound by the treaty and for which the treaty is in force.

[33] According to Article 2(h) of the Vienna Convention on the Law of Treaties 1969, 'third State' means a State not a party to the treaty.

[34] Cheng, B 1997, *Studies in International Space Law*, UK: Oxford University Press, p. 127.

[35] 1969 Vienna Convention on the Law of Treaties, Article 38.

elements and the best features and design of effective outer space legislation for space activities have been identified. Thus, an ideal framework should contain the followings:

4.1 A legal framework that contains all four key provisions that reflect the key obligations that States must fulfil under international space law and compulsory provisions that are recommended by experts in space law.

4.2 Provisions that allow States to authorise and supervise space activities that those under States' jurisdiction wish to undertake and to continue supervising the space activities that have been undertaken until they end (Authorisation and Supervision).

4.3 Provisions that require States' entities to be responsible towards the consequences of their activities (Responsibility and Liability).

4.4 Provisions that require States to their register space objects within their national registry (Registration of Space Objects).

4.5 Provisions that encourage international cooperation when States entities participate in space-related activities (International Cooperation).

V. CONCLUSION

As a conclusion, the Draft Malaysian Outer Space Act 2005 conforms to the key obligations under international law as prescribed by the UN outer space treaties. This is because the Draft Act contains all the provisions that are obligated upon Malaysia through the operation of international customary law that the 1967 Outer Space Treaty is now taken to represent. Those key international obligations require States to control the type of activity that those under the States' jurisdiction wish to undertake and to continue supervising the space activities that have been undertaken until they end [36], require States to be internationally responsible and liable for all space activities carried out both by their governmental agencies and non-governmental entities[37], require States to register its space objects within its national registry [38] and require States to encourage international cooperation when States' entities participate in space-related activities[39]. In particular, there should be provisions in Malaysian law that allow Malaysia to authorise and supervise the activities that those under Malaysia's jurisdiction wish to undertake and to continue supervising the space activities that have been undertaken until they end (authorisation and supervision), provisions that require Malaysia's entities to be responsible towards the consequences of their space activities (responsibility and liability), provisions that require Malaysia to register space objects within Malaysia's national registry (registration of space objects) and provisions that require Malaysia to encourage international cooperation when Malaysia's entities participate in space-related activities (international cooperation). In Malaysia's situation, the Draft Malaysian Outer Space Act 2005 contains all the provisions needed to fulfil Malaysia's key international obligations. As such, it may be concluded that the Draft Act is in conformity with its key obligations under international space law and therefore sufficient to meet Malaysia's key obligations under international space law.

The Draft Malaysian Outer Space Act 2005, whilst conforming to the obligations and requirements under international law, also contains all the compulsory provisions and characteristics that have been identified by space law experts as compulsory and desirable, the answer is only partly affirmative. This is because the Draft Act has the recommended provisions that national space legislations should contain, that is, provisions on the authorisation and supervision of space activities, provisions on indemnification and provisions on the registration of space objects.

However, from the examination of the Draft Act it is observed, firstly, that it is not comprehensive in scope because it does not comprise the regulation of all its space activities. This is because the Draft Act has no provision that regulates the licensing of its telecommunication services as the telecommunications activities in Malaysia are governed by the Communications and Multimedia Act. However, what is important in national space legislation is not for the national legislation to comprise the regulation of all space activities but to be comprehensive in the sense of being detailed when regulating what it does regulate. To

[36]1967 Outer Space Treaty, Article I, II, IV. VI.VIII.IX.
[37] 1967 Outer Space Treaty, Article VI and VII
[38] 1967 Outer Space Treaty, Article VIII.
[39] 1967 Outer Space Treaty, Article I and V.

this effect, the Draft Malaysian Outer Space Act 2005 is comprehensive on the account of being detailed about all matters that it does regulate. Secondly, the Draft Act does not clearly identify its space policy objectives which conform to key international obligations. Thirdly, due to the fact that some of the provisions of the Draft Act are not arranged systematically and not according to the sub-headings, the legislation is confusing and thus not easy to understand. Therefore, to this effect, the Draft Malaysian Outer Space Act 2005 does not provide for a straightforward licensing regime.

VI. WHAT ARE THE RECOMMENDATIONS FOR MALAYSIA?

6.1 It is recommended that Malaysia should expedite the drafting and adoption process of its Draft Malaysian Outer Space Act 2005 so as to provide for the regulation of its space-related activities. For the legal reasons, it is crucial for Malaysia to have enforced national space legislation because the existence of national space legislation will indicate that it conforms to the requirements placed upon it under international space law. A practical reason is that since Malaysia is an active player in the arena of outer space activities, national space legislation will ensure transparency of the rules and regulations pertaining to its space-related activities. When the procedure and rules are clear it will assist in the efficiency of conducting its space-related activities; otherwise it will create inconsistency among those who want to participate in them. Moreover, national space legislation is also necessary as it can clearly identify the administering body that is in charge of administering the space-related activities as well as clearly providing for criminal liabilities and civil penalties for compensation purposes[40]. As such, the initiative of the Attorney General's Chambers to finalise the Draft Malaysian Outer Space Act 2005 to regulate the space activities is very much awaited.

6.2 It is recommended that Malaysia should expedite the process of developing its space policy, so that it can be explicitly incorporated into the Draft Malaysian Outer Space Act 2005 thus conforming to the best characteristic of national space legislation that requires national space legislation to clearly identify its space policy objectives which conform to international obligations.

6.3 Except for the principles contained in the 1967 Outer Space Treaty that are binding upon Malaysia due to the treaty's status as customary international law, it is recommended that Malaysia ratify other UN treaties. Although it may seem that it would be better for Malaysia not to ratify the treaties which would mean that Malaysia would have fewer obligations, if we examine the intention of the 1967 Outer Space Treaty through its Preamble, we can appreciate that one of the reasons why the 1967 Outer Space Treaty was introduced was, and still is, to ensure that all States participating in space-related activities can do so in a peaceful and systematic environment. Due to this intention, since Malaysia is already bound by the principles of the 1967 Outer Space Treaty, through international customary law, Malaysia should be encouraged to seriously consider the need to ratify them and become bound by their exact procedures and systems. This is because, although the 1967 Outer Space Treaty contains the basic provisions, the four remaining treaties clearly give systematic and clear procedures of how a State should act or react in any given situation. If Malaysia is still reluctant to ratify these treaties, in my opinion, Malaysia should at least ratify the Agreement on Rescue of Astronauts, the Return of Astronauts and of Objects Launched into Outer Space 1968[41]. This is due to the fact that, since

[40] As one commentator has observed, 'since the international space conventions only deal with the rights and obligations of States, national space legislation offers States the opportunity to regulate internally the relationship between the State and private enterprise involved in space activities and proportionate liabilities between them'. In Hanneke L. V. T. E., 'Commercialization of space activities, legal requirements constituting a basic incentive for private enterprise involvement', (1996) 12 (2) *Space Policy* 119.

[41] 672 UNTS 119, adopted by the General Assembly in its resolution 2345 (XXII) on 19 December 1967, opened for

Malaysia has the activity of sending astronauts to outer space, it would be as an advantage for Malaysia and its astronauts because, although the 1967 Outer Space Treaty has already stated that States must protect the interest of all astronauts irrespective of their nationalities[42], the 1968 Rescue agreement clearly and articulately provides for the procedure that needs to be followed in the event that a Malaysian astronaut were to face misfortune.

6.4 The Malaysian government should consider the Draft Malaysian Outer Space Act 2005 with a view to ensuring proper implementation of the powers available to it. This is because having legislation is one thing while implementing it is another. There is no point in having legislation if it cannot be properly implemented. Thus, in order for any space-related activities to be effectively conducted, it is recommended that the Malaysian Space Agency be fully effective in order to oversee that the activities are conducted as prescribed or intended by the Government of Malaysia. Thus, Malaysia should ensure that it is equipped with suitable manpower and human resources who are knowledgeable in the area of outer space law. In this regard the government of Malaysia should encourage more nationals to pursue study in this field.

It is hoped that Malaysia would benefit from these recommendations to develop the best management of its space-related activities and thus turn its dream 'to provide the legal and administrative infrastructure that will optimise the exploitation of benefits derived from space activities'[43] into reality. Similarly, it is also hoped that other States that have a similar economic background to Malaysia and which are active or want to be active in space would equally benefit from these recommendations. As this thesis has been able to identify an ideal legal framework not only for Malaysia but also for these other States, these recommendations can thus now be used as an example for both Malaysia and those States as to how to develop an affective outer space regulatory framework which best implements the provisions of international law.

signature on 22 April 1968, entered into force on 3 December 1968.

[42] 1967 Outer Space Treaty, Article V.

[43] Othman, M. (Datuk Professor Dr), 'The National Space Programme of Malaysia National Space Agency', Proceedings of the United Nations' Workshop entitled 'United Nations Treaties on Outer Space: Actions at the National Level', held at Daejeon, Republic of Korea, 3-6 November 2003, p 73. This statement was made when she was the Director General to the Malaysian National Space Agency. She is presently the Director to the United Nations Office of Outer Space Affairs, Austria.

Satellite Orbits and Spectrum Usage and Management: Challenges for Malaysia

Nafizah G. Khan[1*]

[1]*University of Nottingham Malaysia,*
Jalan Broga, Semenyih 43500,
Selangor, Malaysia

Satellite orbits and spectrum are exhaustible commodities that get scarce with increased deployments of satellites, growth in data traffic and the introduction of new applications. For space services to remain relevant, these diminishing resources require proper management. The International Telecommunication Union Radiocommunication(ITU-R) Sector has been at the forefront of the global management of the radio-frequency spectrum and satellite orbits. ITU-R together with other regional and national regulators manage these space-based assets taking into consideration technical, legal, regulatory, and procedural process involving multiple governmental and industrial players. Although it is the sovereign right of every country to manage their telecommunication, radio waves are not bounded by boundaries. Hence, many telecommunication services require regional harmonisation and some global harmonisation too.

This paper discussed the situation, and future challenges faced by the international communities and Malaysia specifically with regards to these two space-based assets: satellite orbits and spectrum.

Keywords: ITU-R; Spectrum Management; Non-GSO; GSO; Planned Services; Non-Planned Services; First-come, First-served; Equitable Access; Malaysia; Small Satellites; Constellation

I. INTRODUCTION

Today satellites form an integral part of our life. Satellite services such as navigation, earth exploration, and communications are ingrained in many aspects of our everyday lives. Although some of the satellite services are affordable to the general masses, building, launching and operating a satellite is still dauntingly costly. This high cost has hampered the participation of some ITU Member States in space-related activities. The ITU membership is opened only to the Member States of the United Nations, and currently, ITU has 193 Member States.

The 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, preamble states, "Believing that the exploration and use of outer space should be carried on for the benefit of all peoples irrespective of the degree of their economic or scientific development".[1] In 1971, the World Administrative Radio Conference for Space Telecommunications adopted a resolution that declared frequencies and orbits were to be classified as a limited resource, endowing all countries with equal use rights to space radio communication services and the geostationary satellite orbit regardless of their economic status. [2]

II. ORBITAL AND SPECTRUM RESOURCES

The types of satellite orbits are: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geostationary Satellite Orbit (GEO) and Highly Elliptical Orbit (HEO). Among these orbits, the most priced is the GEO, a circular orbit, 35,

*Corresponding author's e-mail: nafizah.khan@nottingham.edu.my

850km above the Earth's equator. A satellite place at GEO appears stationary to the ground because it has the same orbital period as the Earth's rotation. The satellite appearing "stationary" coupled with its large footprint area makes GEO highly attractive for communication satellites.

With regards to the ITU-R, the nomenclature for GEO satellites are referred to as geostationary (GSO) satellites and satellites occupying LEO, MEO, HEO and others as non-geostationary (Non-GSO) satellites. The ITU-R adopts two approaches to manage orbit, and spectrum resource: (i) first-come, first-served; and (ii) distribution of orbit and spectrum resources to each ITU Member States. It is the latter that ensures equitable access to space resources are meted out to all member states regardless of the size of the country, economic status, technology and knowledge capabilities.

A. First Come, First Served

Pertains to "Non-Planned services" where the space networks rights are subject to coordination procedures (under Articles 9 and 11 of the Radio Regulations (RR)) required by the RR. The coordination procedure aims to ensure efficient use of orbit and spectrum, whilst maintaining an interference-free operation environment. The "Non-Planned services" include GSO satellite networks in all services and frequency bands except those concerning the "Planned services"; non-GSO satellite networks in certain frequency bands governed by the No.9.11A procedure, which are subject to advance publication and coordination procedures and where only advance publication procedure is required before notification. Under this approach, orbital and spectrum resources are allotted to early users who have completed advance publication information (API); request for coordination; notification and have brought the notified space network into use within the stipulated timeframe which is no later than seven years from the date of receipt of the API by the ITU.[3]

Granting the space network rights to an operator for a notified orbital slot alienates any possibility for new entrants or those who are technologically and economically lagging to that notified GSO orbital slot. These new entrants/"latecomers" will be perpetually stuck in a non-moving queue for the simple reason that satellites launched to GSO have an average lifespan of 18-20 years. This long time frame essentially blocks others from accessing the slot for that duration of time. This situation is further exacerbated by the fact that the operators of the GSO satellite networks are only required to refile with the ITU-R and launches replacement satellites to extend their occupancy of the orbital and spectrum resources. Another alternative to launching replacement satellites would be to reassign an operational satellite to a slot that is under suspension with the intent of bringing the satellite network assignments back into use. Indirectly, the orbital and spectrum resources under the "first come, first served" allows operators to own this priced resource indefinitely. This is indeed the current scenario of the Non-Planned GSO space networks.

B. Equitable Access

Pertains to "Planned Services" that sets out the provisions for all services and associated plans and list in certain bands under: Appendix 30 for the Broadcasting Satellite Services (BSS); Appendix 30A for feeder links for the BSS; and Appendix 30B for the Fixed-Satellite Service (FSS). In the planned bands, equitable access to spectrum is guaranteed by a priori planning (for example, by way of an allotment plan identifying a particularity of channels, an orbital location, a set of technical characteristics and a given service area for each administration). An ITU Member State converts an allotment to an allocation without coordination when an unmodified assignment in a planned band is brought into use.

The ITU Member States may seek to modify the plans by changing the characteristics of an assignment, or by making an additional use. In either of these cases, there are specific procedures in the relevant Appendix for coordination and notification of these changes to the plan. The procedures for making changes to the plan in Appendix 30B are different from the procedures for making changes to the plans in Appendix 30 and Appendix 30A.

Although the Planned bands provide equitable access to space-based assets, it is not attractive for implementation as the planned technical parameters are antiquated, hence inefficient and not economically viable for operations and rollout. Although modification serves as a possibility to address the inefficiencies of the planned parameters, the process itself is extraordinarily daunting and does not guarantee success. [4]

III. SMALL SATELLITES AND LEO

LEO is described as an orbit around Earth where the lower limit altitude is 400km, and the upper limit altitude is 2,000km. These limits are not strict boundary values but widely accepted. The lower and upper limit boundary is caused by the rapid orbital decay due to atmospheric drag and the inner Van Allen radiation belt respectively. Selecting specific inclination will further classify the LEO orbits as sun-synchronous orbit, polar orbit, dawn-dusk orbit and near-Equatorial orbit. LEO orbital and spectrum management fall under Non-GSO space networks and adopt the “first-come, first-served” filing procedures. This specific orbit has for decades been a non-contentious orbit due to the availability of the orbit resources, unlike the GSO.

LEO has a unique vantage point as the orbit is closer to the Earth’s surface granting its orbit superior for surveillance and reconnaissance and earth observation activities. Satellites equipped with imaging sensors either active or passive provides high spatial resolution images that are used for applications such as mapping, infrastructure planning, agriculture monitoring, disaster management and many more. Earth observation missions are usually planned out and designed in a way to make available long time series observation from various sensors and data continuity. There are two approaches to launching earth observation satellites: superior sensors for higher spatial and spectral resolutions; or constellation of satellites with decreased sensor capability but enhanced temporal resolution. Worldview series, GeoEye-1, TerrSAR-X, and ALOS-2 are examples of earth observation satellites with enhanced spatial resolution. Surrey Satellite Technology Limited (SSTL) pioneered the first earth observation constellation in early 2000. The Disaster Monitoring Constellation (DMC) comprises operators from a few developing countries who have each purchased a DMC microsatellite. These DMC microsatellites were being built by SSTL and are owned and operated by the constellation members. The DMC constellation although small was a great success. In 2014, Planet Labs launched 28 earth observation satellites forming the constellation Flock-1. The satellites were built using the 3U CubeSat bus, and the constellation continued to be replenished and grew in size. In 2017, Planet Labs acquired Terra Bella (previously owned by Google). Now, Planet Labs' constellation comprises approximately 150 active satellites rendering it capable of imaging the entire Earth’s surface in one day. Almost all imagery data downloads for Earth Observation satellites are transmitted on the Earth Exploration Satellite Service allocation in the 8025 MHz- 8400 MHz.

Launching and operating communication satellites at LEO requires the deployment of a large constellation of satellites to ascertain a user has continuous communication throughout the day. There will be frequent handovers from a satellite to another to ensure a terminal on the ground remains connected with the satellite network. The early instances of communications LEO constellations were in the 1990s when the pioneers of LEO constellation, e.g. Orbcomm, Iridium, and Globalstar embarked on offering mobile telephony and data services using Mobile Satellite Services. After a short period of services delivery, it became apparent that the financial requirements for the deployment and maintaining a LEO constellation was astronomically high resulting in a few operators having to file for bankruptcy. For a couple of decades following that no new operators were willing to partake in the deployment of a LEO constellation for communication applications.

There are concerns now that soon the LEO will be proliferated with the deployment of mega-constellations of satellites. The “New Space” entrepreneurs plan to launch more than 15,000 new satellites in space by 2025. The main players of NewSpace: OneWeb plans to launch up to 1,320 satellites to LEO and 720 to MEO; Boeing proposes launching up to 2,956 satellites to LEO; SpaceX intends to provide broadband communications with 4,425 satellites for Ka-band and another 7,518-satellite constellation for V-band; Telesat Canada seeks to field two constellations each of 117 satellites. [5]

Also, the LEO orbit has been the domain for scientific and technology demonstrator, amateur and educational research satellite missions. LEO orbit has been an enabler for many developing countries to experiment with space designs and systems and gain direct insights into the space environment, design knowledge and technology. The availability of CubeSats and cheaper access to LEO has in many ways contributed to space confidence building for the developing countries.

IV. CONCERNS FOR MALAYSIA

A. The GSO Satellite Networks

The thriving global satellite industry has been responsible for a highly saturated GSO with the gold rush taking place in the 1990s. 'First-come, first-served' is the playing field for those already in the game early. The alternative choice itself is not deemed worthwhile because building and launching a satellite utilising the "Planned services" cannot yield attractive returns on investments; as the service area is limited to the national coverage coupled with obsolete technical features rendering the service performance inefficient. Under the Planned bands, Appendix 30/30A, Malaysia's orbital slot allotment is at 91.5° East, and for Appendix 30B, the orbital slot allotment is at 78.5° East. Malaysia has not converted the allotment of its Planned Band into an assignment.

MEASAT Satellite Systems Sdn. Bhd. (previously Binariang) operates all its satellite networks under the "first-come, first-serve" basis. MEASAT Satellite Systems Sdn. Bhd. launched Measat-1 and Measat-2 in January 1996 and November 1996 respectively. Measat-1 was inserted into its GSO slot at 91.5°East, and it carried both the C and Ku- band transponders. Following this, MEASAT Satellite Systems Sdn. Bhd. has a few more satellites launched and co-located at the 91.5°East orbital slot, i.e. Measat-3, Measat-3a and Measat-3b. The frequency assignments brought to use at this orbital location are in the S, C, X and Ku-bands. Also, for Measat-3b, the radio networks have been further extended to include the modification of the Planned band assignment in Appendix 30/30A and 30B under additional systems. [6]

Measat-2 was launched to the 148°East orbital slot carrying C and Ku-band transponders. From October 2009 to September 2011, the satellite network at 148°East was suspended as Measat-2 was relocated to 5.7°East longitude and was named Africasat-2. In Sept 2011, Measat-2 was brought back into operations at the 148°East orbital slot. However, in July 2018, the satellite had reached its end of life and had since been de-orbited. From a regulatory standpoint, the Measat-2 frequency assignment at 148°East is still valid although it is currently under suspension. The validity of this frequency assignment is time-limited, and the firm date for resumed operation is before 12th July 2021. [7] Failure to bring back into use the filed frequency assignments of Measat-2 employing a replacement satellite or an operational satellite moved from another slot to 148°East before the stipulated deadline shall lead to the cancellation of the Measat-2 frequency assignment entry in the MIFR in accordance with No.11.49 of the RR.

In January 2008 Measat-1 was relocated to orbital slot 46°East to bring into use the filed frequency assignments in both the C and Ku-bands. It was also renamed to Africasat-1 and in April 2013 it reached its end of life. In February 2013, Azerbaijan launched Africasat-1a as the replacement satellite for Africasat-1. MEASAT Satellite Systems Sdn. Bhd. and Azerbaijan have since entered in agreement on the usage of the 46°East orbital slot and satellite capacity. [8]

Since the principle of occupancy for GSO follows "use-it or lose-it", to secure Malaysia's presence in the GEO belt, it is imperative to ensure proper management and continuity of space activities at the orbital slots: 46°East, 91.5°East, and 148°East longitudes. There is a need to continue upgrading the technology to remain on par with other satellite providers, and users demand such as higher channel capacity using High Throughput Satellite (HTS). Deploying HTS would require for MEASAT Satellite Systems Sdn. Bhd. to bring into use some of the frequency assignments that have been notified at the ITU-R such as frequency assignments in the Ka-band. The likelihood for Malaysia to launch and operate a satellite using another GEO slot is highly unlikely for reasons explained earlier.

B. Small Satellites and Non-GSO Satellite Networks

Malaysia has launched four satellites to the LEO: TiungSAT-1; RazakSAT; UiTMSat 1 and Innosat 2. TiungSAT-1 was a microsatellite built by SSTL with an Orbital Satellite Carrying Amateur Radio (OSCAR) designation MO-46. It was developed as part of a technology transfer and training programme between Malaysia and SSTL and launched in 2001. TiungSAT-1 was equipped with cameras, digital store-and-forward communications and a cosmic-ray energy deposition experiment. The Tiungsat-1 mission was a success, and it paved the way for a more advanced mission, RazakSAT. RazakSAT was developed as a collaborative work between Astronautic Technology (M) Sdn. Bhd of Malaysia and Satrec Initiative (SatrecI). RazakSAT was built using the SatrecI'sSI-200 bus and carries an electro-optical payload with a spatial resolution of 2.5m and 5m for panchromatic and multispectral, respectively. The satellite was launched to the Near- Equatorial orbit in 2008 but its orbital lifetime was rather short-lived due to system failure. Almost a decade after the RazakSAT launch, in 2018 two CubeSats UiTMSAT 1 and Innosat 2 were placed in the LEO.

All the Malaysian satellites launched to the Non-GSO except for Razaksat utilised the Amateur Satellite Service in the 144MHz - 146MHz (primary service) and 432MHz - 438MHz bands (secondary service). The provisions for secondary operations are that it: shall not cause harmful interference to stations of primary services and cannot claim protection from harmful interference from stations of primary services. However, it may claim protection against harmful interference in the same or another secondary service to which frequencies may be assigned at a later date. Satellites operating in the amateur satellite services generally follow the procedure for Non-GSO satellite networks that are not subject to ITU-R coordination. While there are no requirements for coordination, the network still requires submission of the API. As many satellites are operating in the amateur satellite services, the International Amateur Radio Union (IARU) assists in coordinating the amateur satellite frequency to prevent interference among other operating amateur satellites. Having completed coordination with the IARU, notification for coordinated assignments need to be submitted to the Radio Communication Bureau.[9]

Building and launching nanosatellites and picosatellites which are undertaken by universities using frequencies that are not subject to coordination provide a simplified and fast access to LEO and the spectrum. While this is great, it creates the dilemma of space debris: actual risk and the eventual hindrance to the usage of the space. With the planned mega-constellation and the attractiveness of launching satellites to LEO either for earth observation or experimental and technology demonstrator, it is critical for Malaysia to participate in the global discussions on the long-term sustainability of the space environment. Our interest in having access to a safe space environment is vital, hence Malaysia’s concerns should be reflected and discussed in the international forum. As an interested party, Malaysia should also advocate for sustainable operations in space. Space should be available to support activities in the future, and all potential problems that may adversely impact or preclude space activities must be prevented.

V. A FEW CRITICAL POINTS TO PONDER

In addition to the discussions provided in Section 4, below is a list of questions that requires attention.

Will what appear to be “limitless” LEO resources be obliterated by these mega-constellations? Will the early comer's scenarios seen in GEO be emulated at the LEO and gradually block entry by others? As of now, the ITU-R studies have shown that the planned mega-constellation deployed at LEO may cause interference to GEO satellites. What are the measures taken to address LEO-GEO interferences? Will the intense activities at LEO disrupt the sustainability of the space environment? Who will serve as responsible entities to ensure coordination and governance in space now that the landscape in LEO will be changing dramatically? Who will monitor the thousands of satellites and ensure LEO is collision free? Will there be a governing body that looks into space traffic management similar to air traffic management? Will it be mandatory for future satellites placed in the LEO orbit to have capabilities to de-orbit itself to reduce space debris?

Lastly, will ITU with its current setup be able to address the efficient use and equitable access of orbits and spectrum resources?

VI. REFERENCES

[1] Audrey L. Allison 2014, *The ITU and Managing Satellite Orbital and Spectrum Resources in the 21st Century*, Springer Cham Heidelberg New York Dordrecht London.

[2] Azerspace-1/Africasat-1a enters commercial service, viewed 7 December 2018, www.measat.com/pdf/press/2013/pr050413.pdf

[3] Cahill, S. 2000-1, 'Give Me My Space: Implications for Permitting National Appropriation of the Geostationary Orbit', *Wisconsin International Law Journal*, vol. 19, no. 2, pp. 231-248,

[4] ITU 2016, *Radio Regulations Articles*, Geneva, ITU, Vol. 1, pp. 195 – 220.

[5] ITU, *Filing Procedure for Small Satellite*, viewed on 12 December 2018, https://www.itu.int/en/ITU-R/space/Pages/supportSmallSat.aspx

[6] ITU, *List of Suspended Satellite Networks*, viewed on 7 December 2018, https://www.itu.int/net/ITU R/space/snl/list1149/index.asp

[7] ITU, *Space Network List*, viewed on 7 December 2018, http://www.itu.int/ITU-R/space/snl

[8] Joseph W. Gangestad 2017, *Orbital Slots for Everyone?*, Aerospace Corporation.

[9] United Nations 2002, *United Nations Treaties and Principles on Outer Space*. New York, United Nations.

Rain Attenuation Prediction for Non-Geostationary Sources

Assadeq Abolhaoshat Mansour Albendag[1*] and Ahmad Faizal Mohd. Zain[2]

[1]*College of Technical Sciences, Bani Walid, Libya*

[2]*Academy of Sciences Malaysia, Level 20, West Wing, MATRADE, Jln Sultan Haji Ahmad Shah, 50480, Kuala Lumpur*

Rain attenuation can have a high impact on the service availability of radio communication systems especially that operate in the Ka-band where the rain attenuation is 10 times larger than C-band. Achieving high service availability for satellite link design requires an extensive knowledge about the radio channel behaviour. Satellite systems is one of the most important technology uses to achieve the demands for wireless communications, therefore, an accurate model which is able to predict the rain attenuation is needed indeed to maintain the system availability. This paper presents a new model that is able to predict the earth-space rain attenuation for the non-geostationary sources such as LEO, MEO, and etc. The frequency of the predicted signal that has been carried out in this study is 28 GHz, while the earth station located in Seremban, Malaysia (2.75°N, 101.96°E). The rain attenuation will increase gradually as the satellite moves toward the rain cell edge, then it will decreased linearly till it equals 0dB.

Keywords: component; LEO and MEO satellites; rain attenuation; rain prediction mode; Ka-band fade; rain cell size attenuation

I. INTRODUCTION

Three types of satellite systems are currently used for providing different communication services. The fundamental of these types of satellite systems are different in term of the altitude as well as the coverage footprint. These types of satellites are moving faster than the earth, thus they are not regarded as stationary sources to the receiving station.

Low-earth orbit (LEO) satellite system consists of a group of satellites in circular orbits, at altitude of 500 - 2000km. LEO systems have several advantages such as the cost, simple antennas can be used, better frequency reuse can be achieved. LEO system is located at lower altitude, therefore it's suffering a lower free space loss and propagation delays and the power consumed for both satellite and ground stations are minimum. On the other hand, one of the disadvantages of LEO is its footprint on the earth is smaller where its diameter is about 8000km.

The second type of satellite systems is called Medium-earth orbit system (MEO), is a compromise between LEO and Geostationary-earth orbit system (GEO). MEO satellite is located at an altitude of about 10,000km. The propagation delay, power requirements and antenna gains are much higher than LEO system due to the higher altitude. MEO system is called polar orbit because it is rotating around the poles of the earth. Polar orbit has the advantage of covering different sections of the earth's surface as it is rotating around the earth.

However, the attenuation of radio signals due to the absorption and scattering of electromagnetic energy caused by rain is the main reason for degradation of communication systems above 10GHz. The signal quality will be highly affected since the higher the frequency the signal will be more susceptible to the rain, especially in the tropical regions [1, 2]. Thus the uplink and the downlink signal fading will be clearly noticeable. To enjoy the HAPS technology services, rain attenuation prediction is needed to evaluate the link budget of the area of interest, where there are two different methods that can be used to predict

*Corresponding author's e-mail: as_albendag@yahoo.com

the rain attenuation; the first is the analytical model, which is based on physical laws governing electromagnetic wave propagation, while the second method is to use the empirical model, which contains experimental results as well as the station measurements in different climatic zones [3, 4]. The rain data used in this paper has been collected from Malaysian Metrological Department.

II. METHODOLOGY

The rain attenuation affecting the HAPS earth-space link of the selected earth station will be predicted and analysed with respect to rainfall rate statistics data, the earth station height, signal polarisation, angle of elevation and the earth station latitude. The rain attenuation will be calculated based on the new model which presented in this paper. The parameters used to conduct this work are listed in Table 1.

Table 1. System parameters

Parameter	Value
Satellite frequency (GHz)	28
Rain height (km)	4.5
Station height (km)	0.025
Station latitude	2.751
Elevation Angle	Varies
Rainfall rate (mm/hr)	Varies
Polarisation	Circular

Rain attenuation is a common, yet often very complicated weather phenomenon that degrades the wireless communication signals in the presence of rain. It fades all types of satellite signals e.g. Geostationary Earth Orbit (GEO), Medium Earth Orbit (MEO), and Low Earth Orbit (LEO).

The model uses the reduction factors of the ITU-R rain attenuation model. Attenuation prediction using this model requires the knowledge of some parameters as rainfall rate statistics data, the velocity of both the satellite and the clouds, rain height and the rain cell size. The scenario of how the satellite signal penetrates the rain cell is shown in Figure 1. The penetration of the signal takes place when the satellite moves toward the rain cell, therefore, the signal path affected by rain will increase gradually until the signal path reaches the rain cell edge, then it is seen that the effective path length will gradually decreases till the penetrated signal length equals to zero.

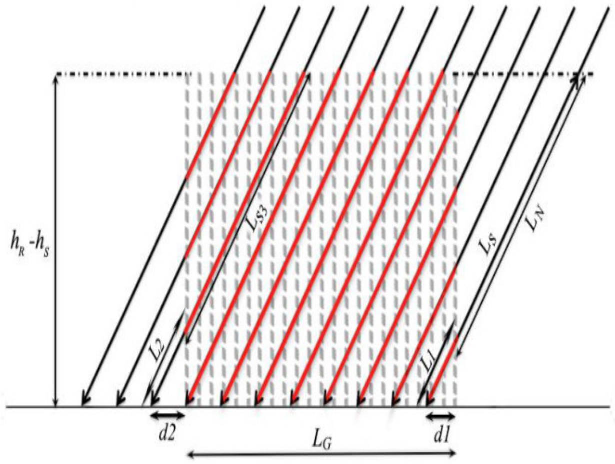


Figure 1. Model Prediction scenario

The attenuation of the satellite signals can be predicted as follows:

To predict the rain attenuation for LEO and/or MEO, the satellite speed must be known because we need to calculate the path length penetrated in the rain at certain time, where in this task, the satellite speed at the ground assumed to be 6.9k/s. To facilitate the calculation of the path length penetrated in the rain, the total distance which going to be crossed by the satellite has been divided into samples with an interval time equal to 0.001 second. The satellite crossed distance at any particular time can be found by

$$d_S = vt \quad (1)$$

Since υ=6.9km/s, the signal penetration destine in the rain equals 0.003km at the first interval.

Once the signal path goes though the rain cell, the effected path will increase proportionally, where the maximum length for the penetrated path will equal $\frac{L_G}{cos}$.

When, the effected path length at the interval is calculated by

$$L_1 = \begin{cases} \frac{d_1}{\cos\theta} & L_1 \leq L_S \\ \frac{h_R - h_S}{\sin\theta} & otherwise \end{cases} \quad (2)$$

where d_1 can be calculated by subtraction the clouds velocity from the satellite velocity if the cloud moves at the same direction with the satellite, while it is equal the summation of clouds and satellite velocities when the satellite and the clouds moving in opposite directions.

In case of same direction, $d_1 = d_s \quad d_c$ (3)

If opposite directions, $d_1 = d_s + d_c$ (4)

At the beginning, the signal path is assumed to be totally penetrated in the rain, where it can be obtained by

$$L_s = \frac{h_R \quad hs}{\sin} \tag{5}$$

The rain attenuation $A_{0.01}$ (dB) for entire signal path at any percentage of time can be determined from

$$A_{0.01} = \ _R L_s v_{0.01} \quad \text{(dB)} \tag{6}$$

where, $_R = kR$ (dB/km) (7)

$_R$ is the amount of rain attenuation [dB] per unit length [km] for any rainfall rate. It is dependent on the frequency and polarisation. k and α are frequency dependent coefficients [5].

The reason of proposing the slant path totally penetrated in the rain is to imagine that the non-affected path is the one that affected, while neglecting the path that truly penetrated in the rain. Eventually, non-affected will be subtracted from the total signal path.

The non-affected signal path L_N is obtained by

$$L_N = L_s \quad L_1 \tag{8}$$

Since it is known that the rain spatial is not uniform, the vertical reduction factor is used to calculate the non-uniformity of the rain.

ITU-R model utilises vertical and horizontal reduction factors $r_{0.01}$ and $v_{0.01}$ respectively [6], where it relates effective path length to the actual path length for different percentage of time. Also, both factors are related to rain rate variation as well as the frequency. The horizontal reduction factor is given by

$$r_{0.01} = \frac{1}{1+0.78\sqrt{\frac{L_G \quad R}{f}} \quad 0.38\left(1 \quad e^{\quad 2L_G}\right)} \tag{9}$$

$$\zeta = \tan^{-1}\left(\frac{h_R - h_S}{L_G r_{0.01}}\right) \quad \text{[degree]} \tag{10}$$

For ζ > θ, $L_R = A\frac{L_G\, r_{0.01}}{\cos}$ [km] (11)

else, $L_R = \frac{(h_R - h_s)}{\sin}$ [km] (12)

If | φ | < 36°, χ = 36 − | φ | [degrees] (13)

else, χ = 0 [degrees] (14)

The vertical reduction factor is given by

$$v_{0.01} = \frac{1}{1+\sqrt{\sin\theta}\left(31\left(1-e^{-(\theta/(1+\chi))}\right)\frac{\sqrt{L_R\gamma_R}}{f^2}-0.45\right)} \tag{15}$$

Therefore the effective L_N is calculated as follows

$$L_{EN} = L_N v_{0.01} \tag{16}$$

The predicted attenuation exceeded for 0.01% of an average year for the signal path L_{EN} can be obtained by

$$A'_{0.01} = \gamma_R L_{EN} \tag{17}$$

To predict the attenuation for the actual signal penetrated by rain, the total attenuation can be found by subtracting the rain attenuation of the imaginary path in the equation (17) from the total attenuation in the equation (6) as follows

$$A_{T0.01} = A_{0.01} \quad A'_{0.01} \tag{18}$$

The second step is to calculate the path length L_2 when the signal path exceeds the rain cell by a distance of d_2 (Taking into account the velocity and the direction of both the satellite and the clouds). The signal path penetrated in the rain will decrease gradually as the satellite moves. Therefore, L_2 has been calculated as follows

$$L_2 = \begin{cases} \frac{d_2}{\cos\theta} & L_2 \leq L_S \\ \frac{h_R - h_S}{\sin\theta} & otherwise \end{cases} \quad (19)$$

The path length will decreased by the amount of L_2 each time the satellite moves, therefore, the path length which affected by rain can be obtained by

$$L_{S3} = L_{S2} \quad L_2 \quad (20)$$

where,

$$L_{S2} = \begin{cases} \frac{L_G}{\cos\theta} & L_{S2} \leq L_S \\ \frac{h_R - h_S}{\sin\theta} & otherwise \end{cases} \quad (21)$$

The effective path length L_{S3} of the signal is found by multiplying the actual path penetrated in the rain by the vertical reduction factor $v_{0.01}$

$$L_{ES3} = L_{S3} \quad v_{0.01} \quad (22)$$

The rain attenuation of the signal path affected by rain can be calculated by

$$A2_{0.01} = \gamma_R L_{ES3} \quad (23)$$

The model is valid to predict the rain attenuation any time percentage of the average year.

III. RESULTS AND DISCUSSION

Rain rate is the volume of water that falls to the surface of the earth in the form of droplets measured by unit area per unit time [mm/hr]. Rain precipitation is the primary source of the electromagnetic energy depletion during the propagation in rainy medium, caused by raindrop absorption.

Figure 2 shows the relation between rain attenuation in dB versus the distance of the horizontal projection of the signal penetrated in the rain. It is seen that the rain attenuation increases in linear approach as the satellite moves. When the satellite moves gradually toward the rain cell, the penetrated signal path will increase, therefore the attenuation will increase gradually until the signal path reaches the rain cell edge L_G, where the rain cell radius assumed to be 1.25 km. At certain length, the signal path (which denoted by the red lines in Figure 1) will suffer the same amount of the attenuation as the satellite moves. The stability of the penetrated path length depends on two factors which are the elevation angle and the rain cell size. When the elevation angle increase and/or the rain cell size is large, the rain attenuation will maintain equal at certain times. This phenomena takes place because of the signal path is suffering the same length in the rain spatial. However, when the elevation angle decrease, the stability of the affected path length will be decreased as shown in Figure 3. As the signal exceeded the rain cell edge, the attenuation will decrease linearly till the penetrated signal length equals to zero.

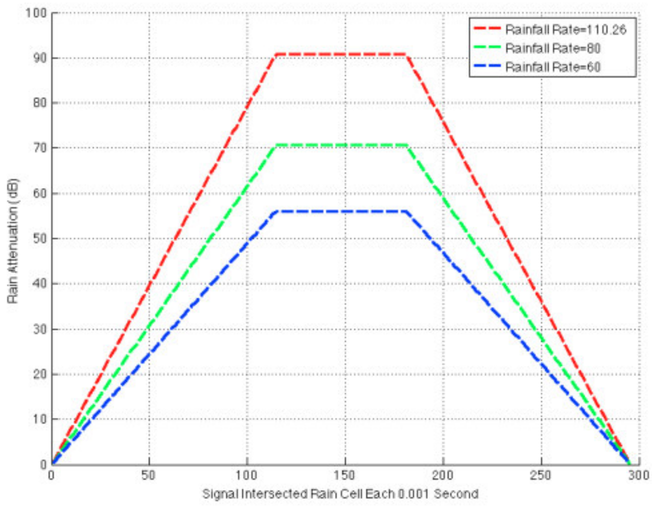


Figure 2. Rain attenuation Vs. Signal intersection distance with rain cell for different rainfall rates

Figure 3 shows the impact of the rain attenuation for different elevation angles. The effected signal path length depends on the elevation angle. When the signal path partially affected by the rain, the attenuation increases as the elevation angle increases. Therefore, it can be noted that the rain attenuation is directly proportional to the elevation angle, where the attenuation approach is rapidly changes as the elevation angle increases.

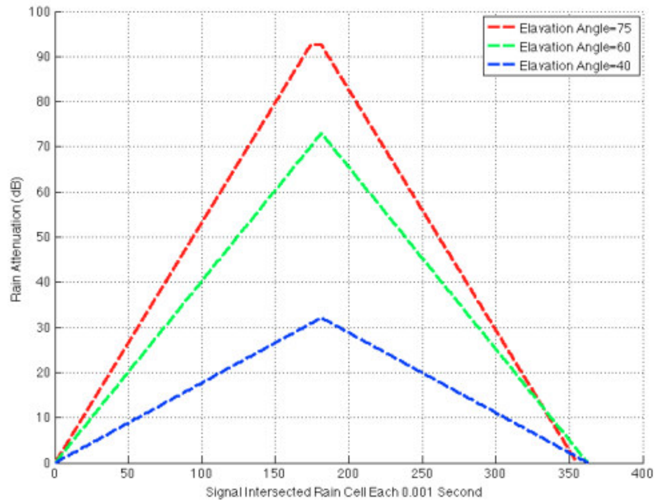


Figure 3. Rain attenuation Vs. Signal intersection distance with rain cell at different elevation angles

When the satellite and the clouds move at the same direction the satellite will takes longer time to cross the rain cell. Figure 4 shows the frequency of the satellite will intersect the signal for different cloud's velocities when the interval time equals 0.001 second. It can be seen that as the cloud moves faster, the chance of the intersection will be higher. In other words, when the clouds velocity became the same with the satellite, the intersection period between the signal and the rain will be equal to infinity till the rain stops.

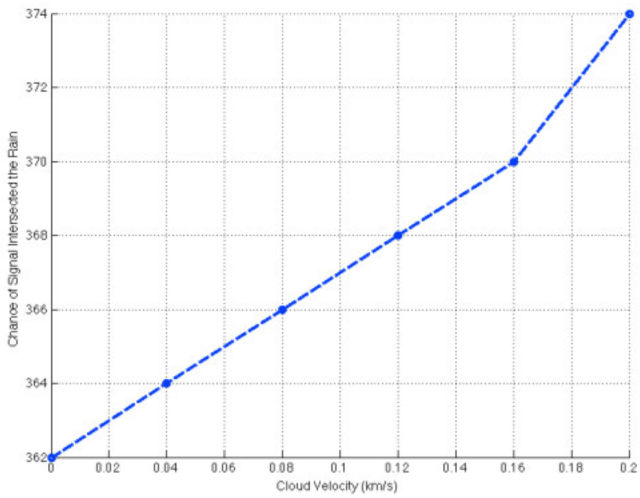


Figure 4. Relationship between the number of the intersections of the signal with the rain cell and cloud velocity, when the satellite and clouds are moving in same direction

Figure 5 illustrates the relation between the cloud velocity and the number of the intersections between the signal and the rain. When the cloud moves against to the satellite, per contra, the intersection duration time will decrease as the speed of the cloud increases. Therefore, the number of the intersections between the signal and the rain will decrease.

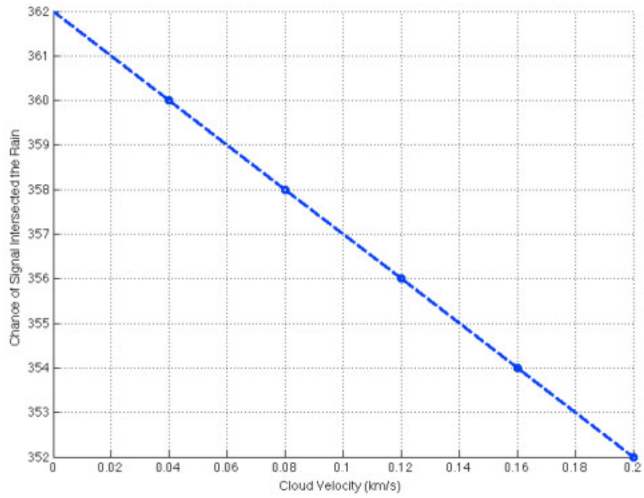


Figure 5. Relationship between the number of the intersections of the signal with the rain cell and cloud velocity, when the satellite and clouds are moving in opposite direction

IV. CONCLUSION

This paper proposed a new model to predict the attenuation of the earth-space links caused by rain. The model is able to predict the rain attenuation affecting the LEO and MEO satellites.

The model represent the earth-space link scenario in an accurate way where it takes into account the most important parameters such as the rain cell size, clouds velocity and the satellite velocity to predict the rain attenuation.

The analysis shows that the rain attenuation linearly increases as the signal path penetrated more into the rain. In the meantime, the rain attenuation linearly decreases as the signal path exceeded the rain cell radius. It is also can be deduced that the rain attenuation has a direct relation with the elevation angle, where the rain attenuation increases as the elevation angle does.

The velocity of the clouds plays an important role in term of the duration of how long the path will be penetrated in the rain. The path will suffer longer time if the clouds are moving in the same direction with the satellite, especially when the velocity of the clouds approaches to the satellite's velocity.

V. REFERENCES

[1] Moupfouma, F & Martin, L 1995, 'Modelling of the rainfall rate cumulative distribution for the design of satellite and terrestrial communication systems', *Int. J. of Satellite Comm.*, vol. 13, no. 2, pp. 105-115.

[2] Ajayi, GO 1990, 'Some aspects of tropical rainfall and their effect on microwave propagation', *International Journal of Satellite Communications*, vol. 8, no. 3, pp. 163-172.

[3] Crane, RK 2003, *Rain attenuation models: Attenuation by clouds and rain: Propagation Handbook for Wireless Communication System*, pp. 225-280. CRC Press, USA.

[4] Ramachandran, V & Kumar V 2005, 'Invariance of accumulation time factor of ku-band signals in the tropics', *Journal of Electromagnetic Waves and Applications*, vol. 19, no. 11, pp. 1501-1509.

[5] ITU, *Specific attenuation model for rain for use in prediction methods*, Geneva, Switzerland, Rec. ITU-R P.838-3.

[6] ITU, *Propagation data and prediction methods required for the design of Earth-space telecommunication systems*, Geneva, Switzerland, Rec. ITU-R P.618-10.

Appraisal of Satellite Applications of RF Wireless Power Transfer

Lillian Joyce Among Olule[1*] and Gnanam Gnanagurunathan[1]

[1]*Department of Electrical and Electronic Engineering,*
University of Nottingham Malaysia, Jalan Broga, 43500 Semenyih, Malaysia

The world's energy demands continue to escalate due to increased population and urbanisation as well as unsustainable current reliance on fossil fuels. Development of more sustainable energy harvesting methods such as Wireless Power Transfer (WPT) can provide alternate, viable green energy sources. This paper reviews the applications of Wireless Power Transfer (WPT) in the context of satellite applications. The origins of WPT are discussed, identifying four predominant technologies and fields of research which are inductive coupling, magnetic resonance, laser based-optical power transmission and Radio Frequency (RF) WPT. Generally, WPT can be segregated into Energy Transport (ET) and Energy Harvesting (EH). The former refers to the utilisation of a dedicated source designed specifically for energy extraction while the latter refers to extraction of energy from available ambient sources. This paper then discusses two major ET and EH applications of RF WPT in the satellite domain; in ET, the more established Solar Powered Satellite (SPS) and in EH Wireless Powered Satellite Sensors (WPSS). In addition to a discussion of the specific requirements for these applications, current research challenges and future research directions are identified.

Keywords: wireless power transfer; satellite; radio frequency; energy harvesting; energy transport; sustainable energy

I. INTRODUCTION

The origins of wireless power transfer (WPT) can be traced back to the 1800's where Heinrich Hertz was proving Maxwell's theory of electromagnetics (Brown, 1984). The concept of WPT or wireless energy transfer however, was pioneered by Nikola Tesla over a hundred years ago, in the late 19th Century (Tesla, 1904). He described transfer of energy between two points without a physical connection. Although he was able to power light bulbs remotely using resonant coils working at relatively high frequencies, the experiments had low efficiency. The results spurred a dream of achieving world-wide wireless power distribution but unfortunately the antenna technology at the time was not yet advanced enough to support it (Brown, 1977) and eventually he lost his funding (Brown, 1984).

The most obvious advantage of WPT is the absence of wires which makes it a flexible, convenient and easy to deploy solution. It also provides the benefits of low cost, sustainability and ability to be deployed in remote locations and harsh environments.

Tesla's research efforts led to the innovation of several methods of WPT which can be segregated into short-range and long-range techniques. As the name suggests, short-range WPT techniques operate over short distances because the power strength is inversely proportional to the cube of the distance (Mur-Miranda *et al.*, 2010). Inductive coupling, which exploits energy transfer through the magnetic field generated between two coils resonating at the same frequency (Sample, Meyer & Smith, 2011) and magnetic resonance coupling, which utilises the resonant evanescent coupling between two resonators for its energy transfer (Karalis, Joannopoulos & Soljačić, 2008) are the two main categories of this technique. Short-range techniques are characterised by high power density and conversion efficiency although they are limited in their applicability to remote and mobile applications. Long-

*Corresponding author's e-mail: kecx5ljl@nottingham.edu.my

range WPT techniques on the other hand like laser-based optical power transmission, and radiative Radio Frequency energy harvesting operate over longer distances. They are however characterised by low conversion efficiencies.

One other key delineation in WPT is the distinction between Energy Transport (ET) and Energy Harvesting (EH) (Visser & Vullers, 2013). This depends on the nature of the wireless source. ET refers to systems which employ a dedicated or intentional source, that is, the energy source is generated specifically for energy extraction. With EH on the other hand, energy is extracted from that available in the surrounding or ambient sources. In the following sections, the RF WPT system will be reviewed, followed by a detailed look at the system requirements for two ET and EH satellite applications, Solar Powered Satellite (SPS) and Wireless Powered Satellite Sensors (WPSS) respectively.

II. RADIO FREQUENCY WIRELESS POWER TRANSFER MECHANISM

The earliest and most popular demonstration of RF WPT was in 1964 when Brown, using the fairly new semiconductor diode technology, created a rectenna (RECtifier and anTENNA) operating at 2.4GHz to fly a helicopter about sixty feet above the antenna (Brown, Mims and Heenan, 1965). The building blocks for this type of system depend on transmission and reception and are illustrated in Figure 1.

At the transmitting end, an RF source generates the RF signal which is emitted by the transmit antenna. Various frequency ranges have been investigated RF WPT application, the most common being 2.45GHz, 5.8GHz 8.5GHz, 10GHz and 35GHz (Jain, 2014).

The Planck-Einstein relation is given in Equation 1. It shows that the energy contained in a photon is the product of Planck's constant h and frequency v.

$$E = hv \tag{1}$$

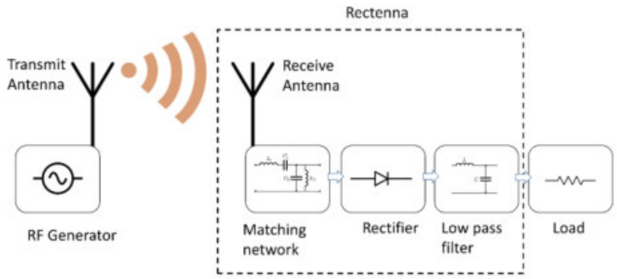


Figure 1. RF WPT concept

Research, however, has shown that the most efficient frequency for RF WPT is 2.45GHz. This is due to the power capacitance achieved at this frequency (Reddy, Hemanth & Mohan, 2013). Additionally, at higher frequencies, the circuit efficiencies of transmitters, receivers and rectifiers is degraded (Shinohara, 2013).

The transmit antenna sends the RF signal within regulatory EIRP limits for the operating frequency band. The signal experiences some attenuation as it propagates through space and is captured at the receiving end by the rectenna. As earlier highlighted, the rectenna comprises an antenna and a rectifier. The receiver antenna is designed to match the incident electromagnetic wave polarisation and is also preferably designed for high gain to maximise the power it receives and ultimately achieve high conversion efficiency. In space applications, high gains are normally achieved through use of arrays.

Between the antenna and the rectifier, a matching network is usually inserted. The matching network enables maximum power transfer by matching the rectifier input impedance to the antenna complex conjugate impedance. The matching circuit blocks reflected power at the operating frequency and prevents harmonics from the rectifier from being re-radiated out by the receive antenna (Soyata, Copeland & Heinzelman, 2016).

The rectifier converts the RF power to DC power. A variety of rectifier topologies circuits have been investigated, the most common being a single diode, bridge rectifier, voltage doubler and voltage multiplier circuits (Soyata, Copeland & Heinzelman, 2016). Rectifier circuits can use either Schottky diode or CMOS technologies as the rectifying element. While CMOS processes can create low loss harvesters, Schottky diodes are more popular as they provide off-the-shelf SMD solutions that are easy to integrate with a PCB and larger power handling capabilities (Valenta & Durgin, 2014). The Schottky process is also undergoing continual performance improvement as the technology advances.

The rectifier circuit may include a low pass filter to block higher order harmonics and to provide proper signal conditioning to the DC output that is supplied to the load.

III. ENERGY TRANSPORT: SOLAR POWER SATELLITE (SPS)

The major satellite application of RF ET is Solar Power Satellite (SPS).This is a system where a geostationary satellite collects solar energy in space, converts it to microwave power and transmits it to a ground station from where it is distributed to the power grid. The concept, as shown in Figure 2, was first proposed in 1968 by Glaser (Glaser, 1968) as an alternative approach to solar energy conversion. A few years later, a detailed feasibility study covering the technical, economic societal and environmental impact of this technology was conducted by the US Department of defense with the support of NASA (Woodcock, 1979) ensued, identifying new and exciting prospects. The system takes advantage of the fact that in addition to the power per unit area of solar power being much higher in space (5-10 times (Sasaki & Tanaka, 2011)), it is also unaffected by weather and absence of sunlight during night hours (Jain, 2014). Further, in spite of the attenuation that the electromagnetic wave experience during the conversion and transport to the ground station, the overall power harvested is still much higher (Sasaki & Tanaka, 2011) than ground based solar harvesting.

Magnetron, klystron and semiconductor amplifiers are utilised as the RF generators as their power conversion efficiency are reasonably high. To balance between antenna size and attenuation, frequencies between 1GHz - 10GHz have typically been employed, with focus on the ISM frequency bands. Although the 2.45GHz band was primarily of interest, efforts are being directed towards the 5.8GHz band due to developments in C-band and RF technologies (Sasaki and Tanaka, 2011).

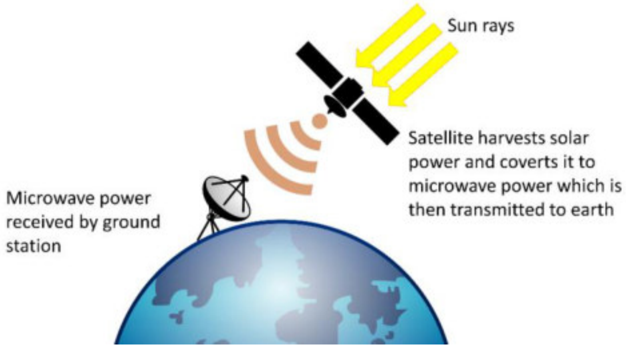


Figure 2. SPS concept

A key area of note in SPS is the ability of transmit antenna to focus the beam accurately on the ground station. This requires precise phase adjustment of the transmit arrays.
On the receiving end, the microwave power is rectified to provide DC power using large rectenna arrays. Schottky diodes are the rectifiers of choice because of their large power handling, their low turn on voltage which allow for more efficient operation at lower powers and low junction capacitance that facilitates maximum frequency of operation (Valenta & Durgin, 2014)

The first practical large scale implementation of SPS was conducted in 1975 with 30kW harvested at 2.388GHz frequency with a distance of 1 mile between the transmitter and a 3.4m x 7.2m rectenna. The transmitter was JPL 26 dish antenna emitting 450kW of power. Although there was a brief period of slow SPS research due of the high cost requirement and immature technology, recent advances have seen a new surge in this research, particularly for resource restrained countries like Japan. Japan Aerospace Exploration Agency is developing hardware subsystems that will facilitate working SPS by 2030 (Strassner & Chang, 2013).

The following areas pose as potential challenges/research directions for SPS:

- Due to the distances involved in SPS and nature in which electromagnetic wave spread out as they propagate, there is need for development of high accuracy beam control to ensure careful focusing of the electromagnetic wave on the desired target.
- Phased Array and sub array antenna with improved performance while ensuring electromagnetic compatibility with the existing communication infrastructure are still highly relevant research areas.

- Commercialisation is the future of SPS, therefore, regulations need to be developed to govern operation and service standards and to satisfy existing national and international requirements for the use of the electromagnetic spectrum.
- Safety procedure and standards need to be developed that align with or enhance current policies and take into account environmental impact. For example impact of microwave beams on bird flight.
- High efficiency power conversion is a perpetual goal for WPT applications to ensure a good proportion of the power received is transferred to the load.
- Improved harmonic blocking filter design to minimise the impact of the harmonic energy from the rectenna arrays is another tenable research field.
- SPS research requires extensive funding.

IV. ENERGY HARVESTING: WIRELESS POWERED SATELLITE SENSORS (WPSS)

A fairly new application of RF EH is for Wireless Powered Satellite Sensors. This technique makes use of leakage or spill over electromagnetic energy on the surface of broadcasting geo stationary satellites (Aubert *et al.*, 2013; Takacs *et al.*, 2013; A. Takacs *et al.*, 2014a; A. Takacs *et al.*, 2014b; Okba *et al.*, 2016, 2017). This energy is harvested and used to power sensors utilised on the satellite, for example for structural heath monitoring (A. Takacs *et al.*, 2014a; Okba *et al.*, 2016).

In satellite-based broadcasting, panel mounted, high gain antennas are employed to establish reliable and durable links. For satellites operating in C, X, Ku and K bands, these antennas emit power ranging from 50W to 100W (Takacs *et al.*, 2013). Some of this energy radiated spills over on to the panels and results in regions of high electric-field levels on the satellite surface, particularly on the earth-side. These high levels are uncharacteristic of terrestrial applications and provide necessary environment to facilitate EH which is typically limited in its application due to low ambient power levels. Another favourable factor is that the antennas radiate with practically constant power levels and this results in a relatively simple DC regulatory circuit. A study done by Thales Alenia Space, using GRASP software from TICRA on a Spacebus class-C satellite (A. Takacs *et al.*, 2014a) identified typical electromagnetic field levels. The effective values for the different frequency bands are shown in Table 1. Provided the data link is operational, these high levels are available on the satellite surface for harvesting.

Table 1. Effective Electric Field Levels (V/m) of different satellite broad cast bands

Band	C-band	X-band	Ku-band	K-band
Electric Field Level	40 V/m	4.5 V/m	106 V/m	127 V/m

One of the earliest reports of this application of ambient harvesting were reported in 2013 (Takacs *et al.*, 2013). A single diode rectifier circuit operating at 17.7GHz was designed. The circuit had a single stub for matching, and was designed to power a temperature sensor. The rectenna demonstrated an output DC voltage of 4.5V for a 9.1kΩ load when used together with a receiving antenna with a gain of 18.6dBi, placed25 cm away from a horn antenna transmitting 25dBm of power. This was done to mimic the electromagnetic field environment where the rms electric field strength is 107V/m.

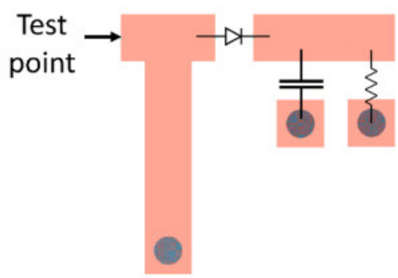


Figure 3. Rectifier topology used in (Takacs *et al.*, 2013)

The same authors, for the same topology and similar experimental setup, investigated the effect of diode type on the rectifier performance (Aubert *et al.*, 2013). They showed that a zero-bias Schottky diode (Aeroflex Metelics MZBD-9161) had better performance for low incident electromagnetic field strengths while high frequency rectifier diode (M/A COM MA4E-1317) had better performance for moderate to high incident magnetic field strengths.

A single diode rectifier was designed for non-optimal loading (Takacs *et al.*, 2014a) to improve on previous designs (Shinohara *et al.*, 2011).. The circuit made use of a double stub matching network and a radial stub low pass filter designed to block the fundamental frequency (17.7GHz) and second order harmonic (35.4GHz) from the load.

A four cross dipole array (an extension of the two cross dipole array (Takacs *et al.*, 2014b)) with a reflector metallic plate was developed to improve the antenna gain to 11dBi (Okba *et al.*, 2016). Using a Skyworks SMS7630 Schottky diode in singe diode topology and a non-resonant matching, 2.3mW of output DC power was obtained at a distance of 21cm from a horn antenna transmitting 22dBm of power. An efficiency of 32% at 12GHz was reported.

In the first demonstration of multiband operation of WPSS, (Okba *et al.*, 2017) a, four-cross dipole array and a broadband/ multiband RF matching band pass filter were employed in conjunction with a single shunt diode and shunt capacitor acting as a rectifier and DC low pass filtering respectively. Maximum efficiencies of 41% at 12GHz, 12% at 17.6GHz and 20% at 20GHz were obtained. Overall, the device was able to harvest DC power greater than 1mW in the 12GHz band for a 300Ω which is sufficient to power a wireless sensor.

A summary of the works discussed above is given in Table 2.

Table 2. Reported works on WPSS

Ref	F (GHz)	E (V/m)	Gr (dBi)	D (cm)	Vout (V)	RL (kΩ)	η_{max}	Diode
(Takacs *et al.*, 2013)	17.7	107	18.6	25	4.5	9.1	-	MA4E-1317
(Aubert *et al.*, 2013)	17.7	107	18.6	25	4.5	9.1	-	MA4E-1317
(Aubert *et al.*, 2013)	17.7	107	18.6	25	1.9	9.1	-	MZBD-9161
(Takacs *et al.*, 2014a)	17.7	121	5	25	1.6	10	15.4%	MA4E-1317
Takacs *et al.*, 2014a)	17.7	91	5	25	0.36	10	11%	MZBD-9161
(Okba *et al.*, 2016)	12	65.5	11	21	~0.83	0.3	32%	SMS7630
(Okba *et al.*, 2017)	12	82.5	11.7	-	~0.036	0.3	41%	SMS7630
(Okba *et al.*, 2017)	17.6	83.4	11.7	-	~0.007	0.3	12%	SMS7630
(Okba *et al.*, 2017)	20.2	83.4	12.7	-	~0.01	0.3	20%	SMS7630

From these few works that have been reported, some key challenges and future research directions are identified:

- All of the reported works base their designs on electromagnetic field profile obtained from the surface of the Spacebus class-C satellite. There is a need to identify if this type of distribution is characteristic of similar satellites or if new energy distribution profiles need to be developed.
- Since the antenna design depends on operating frequency, polarisation, radiation pattern shape and tilt, once electromagnetic field patterns mentioned above have been identified, there is a need to investigate whether current antenna

designs would perform adequately or whether new customised designs need to be innovated.

- Reconfigurable designs that can adapt to changes in incident power levels, (Marian & Allard, 2012) are also a future research direction that could provide improved performance.
- As WPT systems are characterised by low efficiency, there is still a requirement for development of higher efficiency power conversion circuits that are simple and comply with the mechanical, thermal, safety and immunity requirements of space applications.

V. CONCLUSION

RF WPT technologies for satellite applications, specifically the Solar Power Satellites (SPS) and Wireless Powered Satellite Sensors applications (WPSS) have been examined. SPS is an older technology however recent technological development has made possible advancements in this area of research. Commercialisation is still in its infant stages and more work needs to be done before it is practically realisable. WPSS on the other hand is still a very new application as can be seen from the few reported works that have only been tested in the lab environment. The technology however shows a lot of promise especially because designs can easily be adapted from existing ones. Overall, RF WPT can provide a sustainable and green solution for satellite applications.

VI. REFERENCES

[1] Aubert, H *et al.* 2013, 'Microwave energy harvesting for satellite applications', *Electronics Letters*, vol. 49, no. 11, pp. 722–724. doi: 10.1049/el.2013.0372.

[2] Brown, WC 1977, *Electronic and Mechanical Improvement of the Receiving Terminal of a Free-space Microwave Power Transmission System*, NASA contractor report for National Aeronautics and Space Administration, 135194, p. 158.

[3] Brown, WC 1984, 'The History of Power Transmission by Radio Waves', *IEEE Transactions on Microwave Theory and Techniques*, vol. 32, no. 9, pp. 1230–1242. doi: 10.1109/TMTT.1984.1132833.

[4] Brown, W, Mims, J & Heenan, N 1965, *An experimental microwave-powered helicopter*, IRE International Convention Record, doi: 10.1109/IRECON.1965.1147518.

[5] Glaser, PE 1968, 'Power from the Sun: Its Future', *Science*, vol. 162, no. 3856, pp. 857–861. doi: 10.1126/science.162.3856.857.

[6] Jain, R 2014, Cut the Cord : Wireless Power Transfer, its Applications, and its limits

Abstract : Keywords : Table of Contents , Cse. Wustl. Edu, pp. 1–11.

[7] Karalis, A, Joannopoulos, JD & Soljačić, M 2008, 'Efficient wireless non-radiative mid-range energy transfer', *Annals of Physics*, vol. 323, no. 1, pp. 34–48. doi: 10.1016/j.aop.2007.04.017.

[8] Marian, V & Allard, B 2012, 'Strategy for microwave energy harvesting from ambient field or a feeding source', *Power Electronics*, IEEE ..., vol. 27, no. 11, pp. 4481–4491.

[9] Mur-Miranda, JO *et al.* 2010, 'Wireless power transfer using weakly coupled magnetostatic resonators', in *Energy Conversion Congress and Exposition ECCE*, 2010 IEEE. doi: 10.1109/ECCE.2010.5617728.

[10] Okba, A *et al.* , 'Cross dipole rectennas for satellite health monitoring', pp. 15–17.

[11] Okba, A *et al.* 2017 'Rectenna multi-bandes pour des applications micro-ondes', Comptes Rendus Physique, *Elsevier Masson SAS*, vol. 18, no. 2, pp. 107–117. doi: 10.1016/j.crhy.2016.12.002.

[12] Reddy, M, Hemanth, K & Mohan, C 2013, 'Microwave Power Transmission–A Next Generation Power Transmission System', *Iosrjournals.Org*, vol. 4, no. 5, pp. 24–28. doi: 10.5120/274-434.

[13] Sample, AP, Meyer, DA & Smith, JR 2011, 'Analysis, Experimental Results, and Range Adaptation of Magnetically Coupled Resonators for Wireless Power Transfer', *IEEE Transactions on Industrial Electronics*, vol. 58, no. 2, pp. 544–554. doi: 10.1109/TIE.2010.2046002.

[14] Sasaki, S & Tanaka, K 2011, 'Wireless power transmission technologies for solar power satellite', in *2011 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications*, IMWS-IWPT 2011 - Proceedings, pp. 3–6. doi: 10.1109/IMWS.2011.5877137.

[15] Shinohara, N *et al.* 2011, 'Development of 24GHz Rectennas for Fixed Wireless Access', in *2011 XXXth URSI General Assembly and Scientific Symposium*. *IEEE*, pp. 1–4. doi: 10.1109/URSIGASS.2011.6050505.

[16] Shinohara, N 2013, 'Rectennas for microwave power transmission', *IEICE Electronics Express*, vol. 10, no. 21, pp. 1–13. doi: 10.1587/elex.10.20132009.

[17] Soyata, T, Copeland, L & Heinzelman, W 2016, 'RF Energy Harvesting for Embedded Systems: A Survey of Tradeoffs and Methodology', *IEEE Circuits and Systems Magazine*, vol. 16, no. 1, pp. 22–57. doi: 10.1109/MCAS.2015.2510198.

[18] Strassner, B & Chang, K 2013, 'Microwave power transmission: Historical milestones and system components', in *Proceedings of the IEEE*, vol. 101, no. 6, pp. 1379–1396. doi: 10.1109/JPROC.2013.2246132.

[19] Takacs, A *et al.* 2013, 'Design and implementation of a rectenna for satellite application', in *2013 IEEE Wireless Power Transfer (WPT)*, IEEE, pp. 183–186. doi: 10.1109/WPT.2013.6556913.

[20] Takacs, A *et al.* 2014a, 'Microwave power harvesting for satellite health monitoring', *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 4, pp. 1090–1098. doi: 10.1109/TMTT.2014.2303425.

[21] Takacs, A *et al.* 2014b, 'Rectenna design for K band application', in *European Microwave Week 2014: Connecting the Future, EuMW 2014 - Conference Proceedings; EuMC 2014: 44th European Microwave Conference*, pp. 648–651. doi: 10.1109/EuMC.2014.6986517.

[22] Tesla, N 1904, 'The Transmission of Electrical energy without wires', *Electrical World and Engineer*, vol. XLIII, pp. 429–431.

[23] Valenta, CR & Durgin, GD 2014, 'Harvesting Wireless Power: Survey of Energy-Harvester Conversion Efficiency in Far-Field, Wireless Power Transfer Systems', IEEE Microwave Magazine, vol. 15, no. 4, pp. 108–120. doi: 10.1109/MMM.2014.2309499.

[24] Visser, HJ & Vullers, RJM 2013, 'RF Energy Harvesting and Transport for Wireless Sensor Network Applications: Principles and

Requirements', in *Proceedings of the IEEE*, vol. 101, no. 6, pp. 1410–1423. doi: 10.1109/JPROC.2013.2250891.

[25] Woodcock, GR 1979, 'Solar Power Satellite System Definition Study', vol. 1.

Empirical Formula for the Resonant Frequency of an I – shaped Printed Antenna for Nanosatellite Applications

D.K. Cheah[1] and P.C. Ooi[2*]

[1]*Department of Electrical & Electronic Engineering,*
The University of Nottingham, Malaysia Campus, Jalan Broga,
Semenyih 43500 Selangor, Malaysia
[2]*Associate Professor, Department of Electrical & Electronic Engineering,*
The University of Nottingham, Malaysia Campus, Jalan Broga,
Semenyih 43500 Selangor, Malaysia

This paper presents the means of predicting the resonant frequency of an I – shaped microstrip – line - fed antenna via an empirical formula. The antenna was designed and simulated via Advanced Design System (ADS) by Keysight Technologies. The size of this antenna is 65mm x 50mm, with the ground plane fully covering the one side of the substrate was tested using FR4 and Rogers RO4350B. This is a single band antenna with the resonant frequency at 5GHz as the reflection coefficient for this band is less than -10dB. The empirical formula which takes multiple variables into account was verified through simulation and experiment to ensure minimal error with the prediction. It was concluded that the empirical formula is able to predict the resonant frequency with error below 4.5% when comparing the measured and equation results. With the advantages of the microstrip antenna, it has the potential to be deployed on nanosatellites with the various contributing research in the subject.

Keywords: Microstrip antenna; line feed; resonant frequency; empirical formula; satellite communicaion; nanosatellites

I. INTRODUCTION

Nanosatellites are satellites that fall within the 1kg – 10kg category. For comparison purpose, the 1kg nanosatellite, CubeSats in particular, have the dimensions of $10 \times 10 \times 10$cm (S.Gunaseelan, 2016) . With the size and mass constraints on the CubeSats, designers can utilize the advantages of the microstrip antenna for small and lightweight into the nanosatellites. For that, multiple researches have been published to improve the performance of the microstrip antenna deployed (S.Gunaseelan, 2016), (Neveu, 2013), (Figueroa-Torres, 2016). This paper will contribute the ability to predict the resonant frequency with an empirical formula. However, these literatures (S.Gunaseelan, 2016), (Neveu, 2013), (Figueroa-Torres, 2016) confirm that the resonant frequency for nanosatellites should be at 2.4GHz. Fortunately, the proposed antenna design with the resonant frequency at 5GHz can be reconfigured to 2.4GHz as the microstrip antenna is always reconfigurable. With the great advantage for being small, CubeSats can deliver comparable mission quality through formation flying (Chung, 2016) and provide equally competent data rates to communicate with the ground station (Tubbal, 2017) as compared to the equipment in the conventional satellites.

Microstrip antenna is the most common printed antenna. The basic form of this antenna consists of two parallel conductors separated by dielectric substrate. One side of the conductor consists of the radiating metallic patch while

*Corresponding author's e-mail: belle.ooi@nottingham.edu.my

the other conductor acts as a ground plane. The substrate is to provide the mechanical support with the required spacing between the plates. The conductors for these plates are typically copper due to the high conduction property and cost efficiency. The microstrip antenna is highly utilized due to the compact sizes and lightweight properties. The cost efficiency is vital to investigate the performance of the antenna as it ensures efficient allocation of resources. The design of the microstrip antenna is highly suitable for applications in the microwave frequency region as the lower frequencies require the patch to be too large for optimal performance (Garg, 2001).

The ability to predict the resonant frequency of the microstrip antenna is highly desirable. With the empirical formula, the resonant frequency of the microstrip antenna can be determined before the antenna is fabricated to ensure minimum waste of physical resources. Plus, there is an ease of fabrication as the procedure to fabricate this antenna is using the same technology like the printed circuit board (Garg, 2001). Due to its highly configurable nature, various researches had been carried out to propose unique formulae to their own designs (Jose, 2015), (Rahim, 2005). These researches focused on more complex parameters such as the curved and angled edges and the number of modes. The curve and angled edges are slightly more prone to errors as their edges may not be fully covered by the ADS meshes upon simulation. The I – shaped antenna is a simple yet effective solution to this problem as discrepancies upon simulation and measurement is reduced but it will not account for errors caused by external factors such as soldering techniques and quality of the cable used. While the number of modes may be important to investigate other antenna parameters, it is not required to present an accurate empirical formula for the resonant frequency. This paper presents an accurate empirical formula by accounting only the physical properties of the antenna such as the dielectric substrate, thickness of the substrate and the resonating dimensions to predict the resonant frequency. This is a better solution as these parameters can be easily measured with instruments such as callipers and rulers. The presented antenna is single banded with the resonant frequency of 5GHz.

II. ANTENNA DESIGN

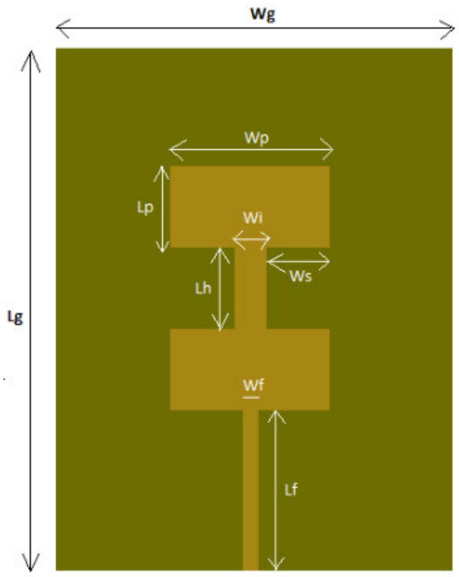


Figure 1. Geometry of the I – Shaped Printed Antenna

The antenna is configured according to the geometry in Fig. 1. The dimensions of the geometry are listed in Table 1. The antenna line feed is excited by the designed 50Ω strip. These are the basic geometries that are altered to derive the empirical formula. The design was fabricated using two substrates, the FR4 and Rogers RO4350B with the thickness of 1.6mm and 1.52mm and dielectric constants 4.5 and 3.48 respectively. The ground plane, Wg and Lg is placed at the back of the substrates, which totals the dimensions to 65mm x 50mm. The feed width, Wf, was altered to 2.4mm upon investigation with the RO4350B substrate for impedance matching.

Table 1. Dimensions of the Geometries

Geometry	Dimension (mm)
Wg	50.0
Lg	65.0
Wp	20.0
Lp	10.0
Wi	4.0
Ws	8.0
Lh	10.0
Wf	2.0
Lf	20.0

III. SURFACE CURRENT DISTRIBUTION

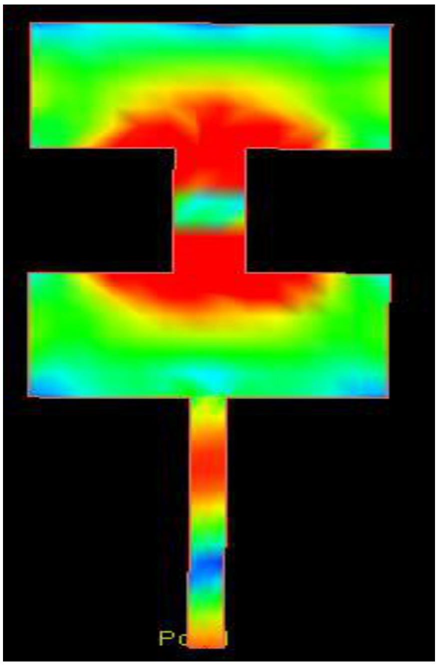


Figure 2. Simulated Current Distribution of the Antenna

The study of resonance can be investigated by examining the current distribution on the antenna. This will help to determine the 'hotspots' for a particular frequency to study the changes in these areas on the resonant frequency (Bedra, 2013). The derivation of the empirical formula is based on this investigation.

Fig. 2 obtained by the ADS simulation shows that the antenna with the resonant frequency of 5GHz has the current concentrating at the bottleneck, Lh and Wi. There is also current concentrating on the feed line but this should happen by default as the feed point provides the energy from an external source before it is allowed to resonate. Thus, the empirical formula is derived by varying the length Lh.

IV. EMPIRICAL FORMULA

The proposed empirical formula to predict the resonant frequency of this antenna is:

$$f_r = \frac{101.3374^5 - 2.7334c\varepsilon_r}{56.6736L_h + 0.8} - (1.0420 \times 10^{10})h \quad (1)$$

where,

c	speed of light
ε_r	substrate dielectric constant
L_h	length of bottleneck
h	thickness of substrate

The derivation assumes all other parameters that are not stated in Equation (1) remain constant always. The boundaries of this formula are:

$$3.2 < \varepsilon_r < 4.5$$
$$5\text{mm} < L_h < 15\text{mm}$$
$$0.7\text{mm} < h < 1.8\text{mm}$$

The empirical formula was derived upon the discovery of the almost linear frequency changes upon varying the variables stated in Equation (1). The coefficients were adjusted as discussed in Section V.

V. SIMULATION AND MEASUREMENT

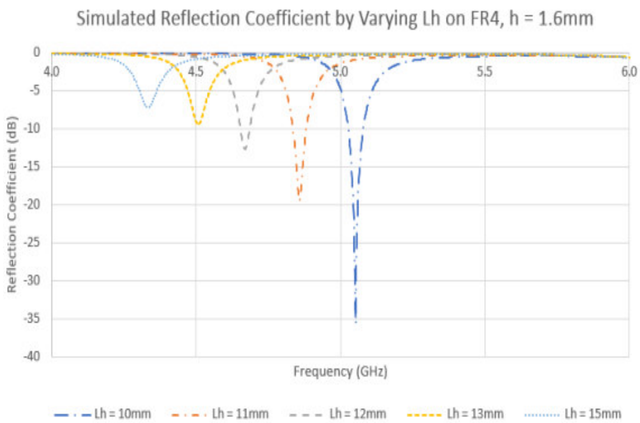


Figure 3. Simulation Result using FR4

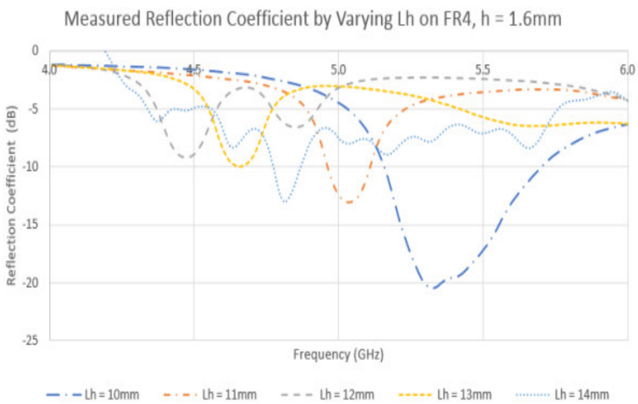


Figure 4. Measured Result using FR4

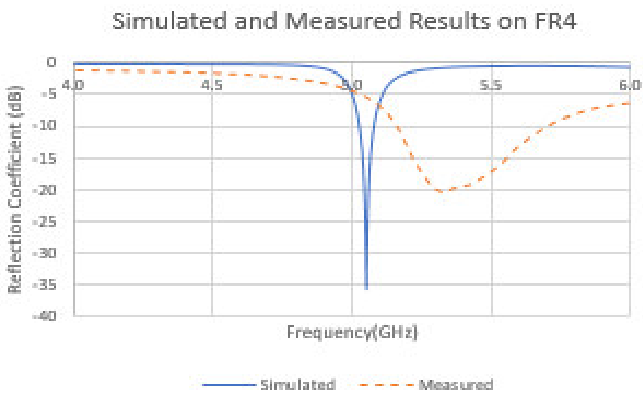


Figure 5. Comparison between Simulated and Measured Results using FR4 with Lh = 10mm

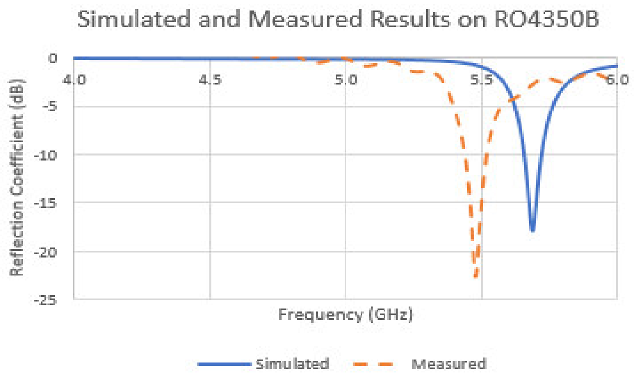


Figure 8. Comparison between Simulated and Measured Results using RO4350B with Lh = 10mm

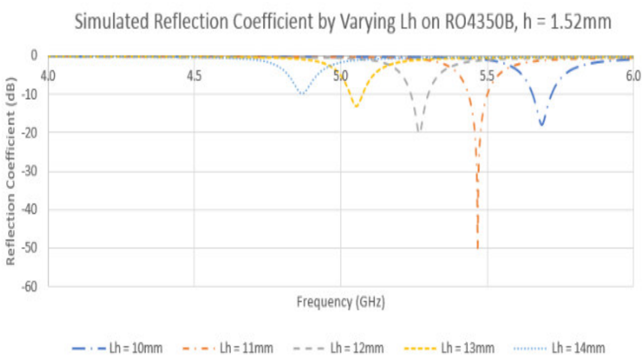


Figure 6. Simulated Result using RO4350B

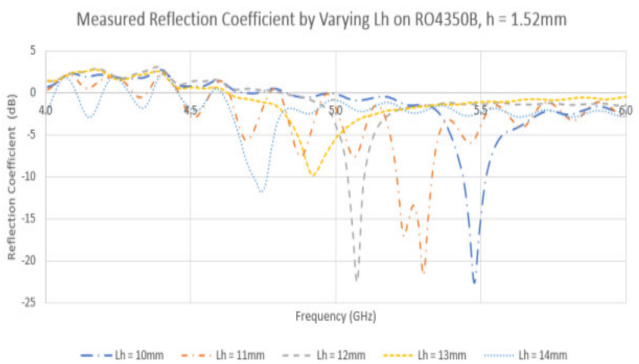


Figure 7. Measured Result using RO4350B

To verify the empirical formula proposed, simulations and measurements of the designed antenna have been performed. The antenna was tested by varying Lh, the dielectric substrate and substrate thickness. The parameters were varied one at a time while the rest remained constant. The simulated and measured results for both substrates can be seen in Fig. 3 – 7. To analyse the accuracy of the simulation, the measured and simulated results were compared as in Figure 8. The errors between the simulated and measured results were used to adjust the coefficients in the formula to reduce the percentage error upon calculations. The analysis for the accuracy of the empirical formula is as Tables 2 and 3.

Table 2. Analysis with the FR4 substrate of 1.6mm thickness

Lh (mm)	**Resonant Frequency(GHz)**		**Percentage Error (%)**
	Measured, f_{rm}	**Equation, f_{rc}**	
10.0	5.320	5.103	4.07
11.0	5.040	4.899	2.80
12.0	4.865	4.711	3.17
13.0	4.655	4.536	2.56
14.0	4.375	4.374	0.02

Table 3. Analysis with RO4350B substrate of 1.52mm thickness

Lh (mm)	Resonant Frequency(GHz)		Percentage Error (%)
	Measured, f_{rm}	Equation, f_{rc}	
10.0	5.478	5.712	4.27
11.0	5.303	5.487	3.46
12.0	5.075	5.276	3.96
13.0	4.918	5.081	3.31
14.0	4.743	4.900	3.20

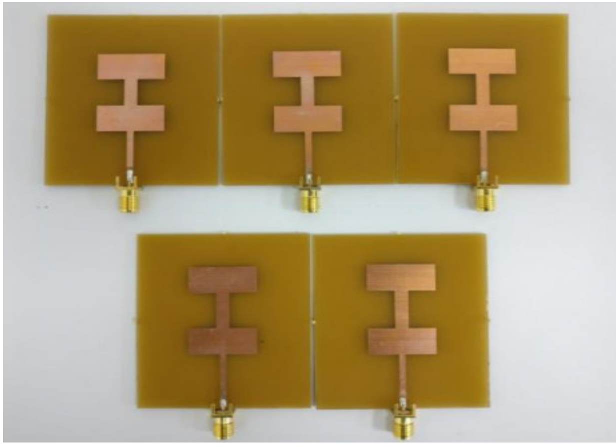


Figure 9. Antenna on FR4 with Lh from 10mm to 14mm

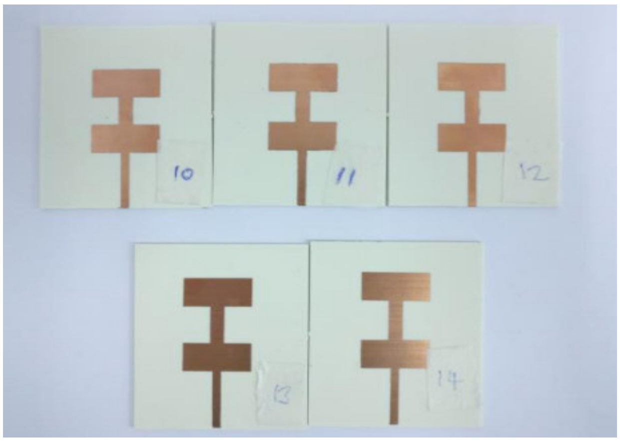


Figure 10. Antenna on RO4350B with Lh from 10mm to 14mm

The physical changes made to the fabricated antenna can be seen in Fig. 8 and 9. The antenna was simulated with ADS and measured using Agilent 8757D Scalar Network Analyzer and Agilent E8257D Signal Generator.

VI. CONCLUSION

The paper has presented an empirical formula to predict the resonant frequency of an I - shaped antenna. Measured results were compared to the calculated results to ensure minimal error upon deriving the formula. The presented empirical formula has an acceptable error below 4.5%. With the reconfigurable property proven in this study, future work can be proposed to modify this antenna to have the resonant frequency at 2.4GHz. Thus, nanosatellites can be better equipped with capabilities to provide high data rate upon missions along with adequate gain and directivity with the microstrip antenna.

VII. REFERENCES

[1] Bedra, S 2013, 'Resonant Frequency of Tunable Microstrip Ring Antenna Printed on Isotropic or Uniaxially Anisotropic Substrate', *Advanced Electromagnetics*, vol. 2, no.2 2, pp. 6-9.

[2] Chung, SJ 2016, 'Review of Formation Flying and Constellation Missions Using Nanosatellites', *Journal of Spacecraft and Rockets*, vol. 53, no. 3, pp. 567-580.

[3] Figueroa-Torres, 2016, 'A Microstrip Antenna Based on a Standing-Wave Fractal Geometry for Cubesat Applications', *Microwave and Optical Technology letters*, vol. 58, no. 9, pp. 2210-2213.

[4] Garg, R 2001, Microstrip Antenna Design Handbook 1 ed., Norwood: Artech House.

[5] Jose, SK 2015, 'Circular-Rectangular Microstrip Antenna for Wireless Applications', *International Journal of Microwaves Applications*, vol. 4, no. 1, pp. 6-10.

[6] Neveu, N 2013, Transparent Microstrip Antennas for CubeSat Applications, https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6737542

[7] Rahim, M 2005, Bow-tie Microstrip Antenna Design, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1635425

[8] S. Gunaseelan 2016, High Gain Patch Antenna for CubeSat, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7566088

[9] Tubbal, FE 2017, S-band Planar Antenna Designs for CubeSat Communications, Thesis, Wollongong: University of Wollongong.

Two-Year Rain Fade Empirical Measurements and Statistics of Earth-Space Link at Ka-Band in Malaysia

Y.A. Ahmad[1*], A.F. Ismail and K. Badron

[1]*Electrical and Computer Engineering Department,*

International Islamic University of Malaysia. PO Box 10. 50728 Kuala Lumpur, Malaysia.

Satellite communication links at a frequency above 10GHz experience severe attenuations due to rain, particularly in tropical regions. Reliable long-term rain fade empirical data for Ka-band satellite links in Malaysia and in other tropical areas are indeed limited. The main objective of this paper is to provide and present the findings of an empirically measured rain fade at the Ka-band of 20.1998GHz and the cumulative distribution analysis. An 8.1m dual Gregorian dish antenna with 21dB/K G/T and a meteorological standard dual type tipping bucket were used to measure the Ka-band beacon signal emanating from the MEASAT-5 satellite and the rainfall intensity, respectively, for a period of two years. Cumulative distribution of rain fades for monthly, annual and monsoon seasons were compiled to reflect accurate changes in the Malaysian weather. The measured rain fades were at 10dB and 29dB for the exceeded percentages of 0.3% and 0.1%, respectively. At rain fade of 33dB, the receiver began to saturate, resulting in a QoS of 99.9% for the Ka-band. These findings provided insights into the actual rain fade experience for the practical implementation of the Ka-band satellite link and for future studies of rain fade models in tropical regions.

Keywords: Satellite link; rain attenuation; Ka-band; tropical region

I. INTRODUCTION

Satellite network industries are moving towards higher operating frequencies like Ka-band to overcome spectrum congestion. The Ka-band uplink uses frequencies between 27.5 and 31 GHz, while the downlink has a frequency range of 18.3 to 18.18 GHz and from 19.7 to 20.2 GHz. The Ka-band is currently in demand because of the high bandwidth which can increase the data rate and data capacity. High throughput satellite (HTS) transmission uses multi spot beams which reduce the cost per bit. The Europeans are shifting to the HTS system which will mainly use Ka-band in the European 2020 project (Mignolo *et al.*, 2013). In Malaysia, the government is pursuing the national broadband initiative where satellite plays an essential role in providing internet access via satellite backhaul to rural areas (Eng, 2009). Presently, the backhauls of the internet to the rural areas are provided by MEASAT via hybrid Ku-Ka frequency band satellite links. However, frequencies above 10GHz are susceptible to weather effects such as rain which can cause severe signal degradation (Yaccop *et al.*, 2013). Thus, the Ka-band at 20GHz is more susceptible to signal degradation by precipitation, which is commonly known as rain fade or rain attenuation. It becomes a significant limitation for this frequency band to be used in tropical regions. The rain fade margin is an essential parameter in earth-satellite link design that needs to be highlighted to overcome signal degradation due to heavy rainfall. Almost all planned Ka-band systems are expected to provide services using smaller earth terminals but they do not have sufficient gain and output power to compensate for propagation effects such as rain (Nebuloni *et al.*, n.d.).

Currently, in Malaysia, the Ka-band link is used for communication between the gateway and the satellite, while the Ku-band is used in the communication between remote areas and the satellite. Understanding the probabilistic nature of the rain fade in the Ka-band would enable us to evaluate and perform a more accurate system planning for a reliable Ka-bank link in the future. In this paper, the 20 GHz beacon was empirically measured, and

*Corresponding author's e-mail: yasser@iium.edu.my

the probabilistic attenuation was analysed based on the measured data. The measured rain attenuation at the Ka-band satellite signal was analysed by generating the probability distribution function (PDF) and the cumulative distribution function (CDF), to obtain the exceeded attenuation at the 20GHz link. This study was undertaken to understand attenuation due to rain for the optimisation of the satellite communication link design under Malaysian tropical weather conditions.

Before a satellite is launched and the system is rolled out, rain attenuation models are typically used to determine rain fade in order to design reliable links. Based on the rain fade value, the appropriate fade margin can be incorporated into the system. There are many models developed to predict rain attenuation one of which is the Simplified Attenuation Model (SAM) (Stutzman & Dishman, 1982). The SAM model is one of the most widely employed attenuation prediction models for earth-space communication links operating at a range of 10 to 35 GHz bands. Stutzman & Dishman opted for a method that is both conceptually and computationally simple for estimating rain-induced attenuation. However, the SAM model offers better results for low range frequencies with rain rates up to 60 mm/h (Kestwal *et al.*, 2014). The 60mm/h value is too low for a tropical region like Malaysia, and the model may underestimate the rain fade. Another standard model is the ITU-R model. ITU-Radiocommunication is one of the three divisions of the International Telecommunication Union (ITU) that standardised telecommunication rules, as well as the global management of radio-frequency spectrum and satellite orbits. The ITU-R P.618-13 (ITU-R 2015) model provides a step-by-step approach for predicting the attenuation on space radio link. The ITU-R model was determined as the most widely accepted model on a global scale (Ismail *et al.*, 2017). However, most models such as the ITU-R model, SAM model, DAH and Yamada are not providing accurate predictions of rain attenuation (Yeo *et al.*, 2009b). Satellite signal strength measurements are an excellent opportunity to study and identify suitable rain attenuation models (Adhikari *et al.*, 2011).

There is a scarcity of direct attenuation measurements with rainfall data to estimate the attenuation due to rain fade in tropical regions since most measurements were made in temperate climate regions (Yussuff & Khamis, 2013). Nevertheless, there was an attempt to characterise the Ka-band link in Malaysia and nearby regions. A six-month measurement of Ka-band rain fade was performed at Universiti Teknologi Malaysia (UTM), Johor and Universiti Tun Hussein Malaysia (UTHM), Johor from July 2015 to Dec 2015 using the Syracuse 3A satellite at 47^{o}E orbital position with 20.245GHz RHCP beacon frequency (Cuervo *et al.*, 2016). The measurement results yielded rain attenuation of about 17dB at the UTM receiver and about 14dB at the UTHM receiver at time exceedance of 1%. The results obtained indicated that the receiving systems began to be saturated at time exceedance of 0.5%. Hence, time exceedance of 0.1% and 0.01% were not measured accurately. The rainfall rate measured in UTM at time percentage of 0.1% and 0.01% were 40mm/hr and 120mm/hr, respectively. The measurement data presented were six months and these were less than that of one year which was required by ITU-R P618-13 (ITU-R 2017). Data measured less than one year should be extrapolated to one year for accurate comparisons with the ITU-R model (Yeo *et al.*, 2009a). Another measurement at the Ka-band was conducted in the Nanyang Technological University, Singapore using the WINDS satellite located at 143^{o}E with an LHCP beacon frequency of 18.9GHz and ground antenna elevation angle of 44.5^{o}. The data were measured for three years, from 2009 to 2011. The average rain attenuations measured were 5dB, 25dB and 43dB for time exceedance at 1%, 0.1% and 0.01%, respectively. The receiver equipment had a good 40dB dynamic range in clear sky condition. The rainfall rates measured were about 15mm/hr, 60mm/hr and 107mm/hr for time exceedance of 1%, 0.1% and 0.01%, respectively (Yeo *et al.*, 2014). There was an attempt to determine the satellite rain fade in Kuala Lumpur, Malaysia during different monsoon seasons using drop size distribution by assuming an imaginary satellite link at 20GHz from MEASAT-3 (Lam *et al.*, 2012). Based on this method, Lam et al. predicted rain fade by inference using local raindrop size distribution data collected in 1992 to 1994 using the synthesised storm technique (SST). The inference resulted in the measurement at time exceedance of 0.1% with rain fade values of about 28dB and 33dB for the Southwest and Northeast monsoon seasons, respectively. The average rainfall rates from 1992 to 1994 were about 145mm/hr and 65mm/hr for time exceedance of 0.01% and 0.1%, respectively. The findings in this paper could be compared with similar findings from the literature.

Rain fade direct measurement has many usages. Among them includes a direct measurement based on empirical procedure which provides opportunities to understand the characteristics of rain attenuation, such as specific attenuation and frequency scaling. Typically, empirical procedures in determining specific attenuation are difficult due to them requiring high sampling time and instantaneous, continuous measurement *(Ostrometzky et al.*, 2016). From a measured attenuation, specific attenuation can be determined using empirical procedures (Ismail *et al.*, 2013). Another significant use of direct measurement results of rain attenuation is that it can be scaled up using the frequency scaling technique. This determines attenuation at a different frequency as described in the ITU-R P 618-13 (ITU-R 2017). Using the frequency scaling technique, Ka-band was possible to be scaled to Q-band, and reasonable prediction was achieved when compared to the actual measurement in Europe (Vilhar *et al.*, 2017).

The high-intensity rainfall phenomenon throughout the year in Malaysia is the primary factor that can severely degrade Ka-band signals. Therefore, satellite link reliability under rain fade operating at Ka-band frequency must be explored for satellites to shift to higher operating frequencies, from Ku to Ka-bands. Despite many existing rain attenuation models, there is still insufficient direct measurements of Ka-band available for Earth-Space link in Malaysia. Long-term empirical measurement is the best method to understand the characteristics of rain fade at 20GHz. To ensure accurate results, industrial grade equipment in satellite communication with a meteorological standard rain gauge was employed.

II. MATERIALS AND METHODS

A. Earth-space link rain fade parameters

The schematic presentation of an Earth-Space link under rain fade is shown in Figure 1 (ITU-R 2015). In the diagram, A represents the frozen precipitation, B equals rain height, C is the liquid precipitation and D illustrates the space-Earth path. The MEASAT-5 satellite in the geostationary orbit located at 119.50E radiated the beacon signal power from the satellite transmitter to the surface of the Earth. As the wave travelled a path length, D from the satellite to the earth surface, the free space path loss would reduce the received power. The symbol h_S denotes the height above sea level. The rain height, h_R, is an important input parameter in predicting rain attenuation in satellite communication. The rain height is obtained by subtracting the rain height with the height of the ground station at sea level. Since, in this experiment, rain attenuation was measured directly, knowledge of the rain height was not critical at this point. During rainy conditions, there would be additional losses due to precipitation. The difference of the signal level during rain condition and clear sky condition was the measurement value of rain attenuation. The beacon signal level was recorded in one-minute intervals. In this experiment, rain attenuation data for the years 2015 and 2016 were measured. By comparing attenuation on rainy days and attenuation during clear sky conditions, the measurement of rain attenuation was obtained.

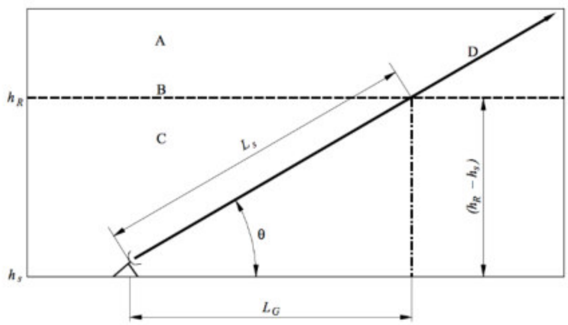


Figure 1. Schematic presentation of an Earth-Space path providing the parameters to input into the attenuation prediction process (ITU-R 2015)

Based on the orbital location of the satellite of 119.50E, the MEASAT earth station antenna was rotated and elevated to the satellite according to the Azimuth and elevation angle. The Azimuth was measured from the true north, and the elevation angle θ was the view angle to the satellite in the geostationary satellite in orbit. The elevation angle θ was then obtained using equation (1) by knowing the information of the Earth station latitude, earth station longitude $l_{es}$and satellite longitude l_{st}, as described in equation 1:

$$\theta = \tan^{-1}\left[\frac{\cos(l_{st}-l_{es})\cos(\varphi)-0.45}{\sqrt{1-cos^2(l_{st}-l_{es})\cos(\varphi)}}\right] \quad (1)$$

The initial elevation angle of the earth station antenna was calculated based on equation (1). The azimuth and elevation angle for this set up were 99.71° and 68.77°, respectively. The Earth station antenna maintained its pointing capability using its automatic tracking and ranging capabilities to compensate for the libration effect of the satellite in orbit. This setup was very accurate due to the tracking and ranging capabilities of the earth station. The Earth station could perform an automatic ranging measurement and corrected itself to track the peak signal strength of the beacon signal.

B. Measurement setup

The measurement was made by recording the beacon signal data from the satellite in orbit at the ground station. Rain fade prediction was measured based on the 20GHz Ka-band beacon link originating from the MEASAT-5 satellite. Figure 2 provides the setup of the experiment. In this setup, the MEASAT-5 beacon signal frequency was 20.1998GHz with a horizontal linear polarisation. The ground station was located in Cyberjaya, Malaysia at the latitude of 2.935°N and longitude of 101.658°E; 20m above sea level. A nearby rain gauge along the satellite path link located at Paya Indah with the latitude of 2.878°N and longitude of 101.619°E measured the rainfall volume.

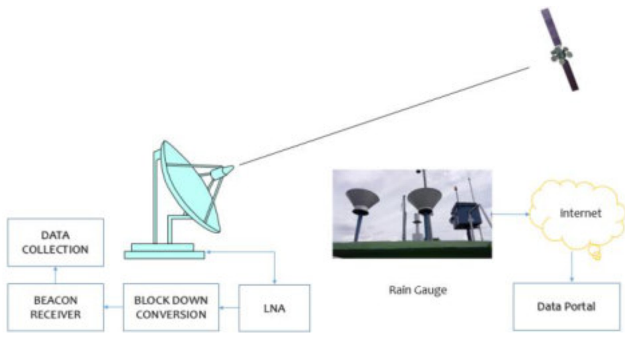


Figure 2. Experimental setup

The ground station used an 8.1m dual reflector Gregorian antenna for receiving the beacon signal. The ground station had a G/T of 21dB/K. The beacon signal received by the antenna was amplified by the low noise amplifier (LNA) to increase the weak signal from the satellite in deep space. The 20.1998GHz frequency was then down-converted to 1.5GHz to enable the receiver to detect and collect the beacon signal. The beacon receiver was a sensitive device with an input signal level of -40dBm to -100dBm. Therefore, the beacon receiver itself had a wide dynamic range of 60dB. The clear sky signal input to the beacon receiver was tuned to -66.5dBm based on the average clear sky signal. The received clear sky signal was tuned during the clear sky condition based on the received power level from the MEASAT-5 beacon signal, G/T of the ground station and coaxial cable loss to the beacon receiver. After tuning, the new dynamic range was 33.5dB. The beacon receiver provided the data via a serial interface. Figure 3 displays the location with respect to the satellite at 119.50E orbital position. The red dot in Figure 3 represents the ground station and the rain gauge position. Table 1 exhibits the specification of the receiving system parameters.

Figure 3. Location of the ground station with respect to the satellite

In order to measure and monitor the rainfall, a rain gauge was required. A nearby rain gauge along the satellite link path was used. The rain gauge was obtained from the Department of Irrigation and Drainage (DID). The DID rain gauge was a remote sensing tipping bucket type. It was a meteorological standard rain gauge with a portable, rugged and lightweight unit that was able to continuously measure the volume of rainfall by using a twin bucket type; hence providing high accuracy and measurement reliability. Each tip of the bucket was able to measure 0.5 mm of rainfall. The data were recorded in one-minute intervals, sent via a modem to the internet and then were made available at the DID portal.

Table 1. Ground station receiving parameters

Antenna Type	Dual reflector Gregorian
Antenna diameter	8.1 m
G/T	21 dB/K
Antenna material	Precision Formed Aluminium
Antenna mount	Azimuth over elevation pedestal type
Clear sky received signal	-66.5 dBm
Operation dynamic range	33.5 dB
Receiver tuning resolution	1 kHz
Minimum carrier over noise C/N_0	35 dB-Hz
Tracking sensitivity	1 V/dB
Data interface	RS-232 / RS-422

C. Data analysis

The measured attenuation data were analysed using probability density function and converted to the cumulative distribution function; finally, the probabilistic value was obtained by calculating the time exceedance. A probability density function or PDF is a method of finding the probability that the value of a variable lies within the same interval. The total occurrences for every one-minute interval of rain intensity were obtained from January until December for both the years 2015 and 2016. The pivot table function in Microsoft Excel was used to achieve the PDF. The cumulative distribution function or CDF was defined as a function whose value was the probability that a corresponding continuous random variable had a value less than or equal to the argument of the function. From the CDF, the rain attenuation time exceedance for 1%, 0.1%, 0.01% and 0.001% could be determined. The formula for obtaining monthly time exceedance is given by:

$$\text{Time exceedence} = \frac{\text{CDF}}{24 \times 60 \times m} \times 100\% \qquad (2)$$

where m is either 28, 29, 30 or 31, depending on how many days is in a particular month. Point rainfall rate exceedance for 0.01% of an average year was also established using the same technique.

III. RESULTS AND DISCUSSION

A. Rainfall intensity

In the present era, the rainfall rate measurement can be obtained using a satellite and a more conventional approach of rain gauge application. The Tropical Rainfall Measuring Mission (TRMM) research satellite is an example of a satellite that is able to provide precipitation analysis (Huffman *et al.*, 2007). A satellite can provide rainfall information on a wider area compared to a rain gauge. Despite the advantage of having satellite data on a larger area, in studies conducted within Malaysia, a rain gauge provides more accurate rain information since the TRMM satellite tends to overestimate the rainfall in Malaysia's seasonal rain (Zad *et al.*, 2018). Despite the inconsistency of rainfall in Malaysia, rainfall is generally divided into two main seasons: the Northeast monsoon and the Southwest monsoon (Hassan *et al.*, 2018). Even though the rainfall can be divided into two main monsoon seasons, heavy rainfall is typically distributed throughout the twelve calendar months of the year (Shayea *et al.*, 2018). In this research, the measured rainfall was taken from the DID rain gauge in Puncak Niaga for two years, from 2015 to 2016. The rainfall recorded by the rain gauge is shown in Figures 4 and 5.

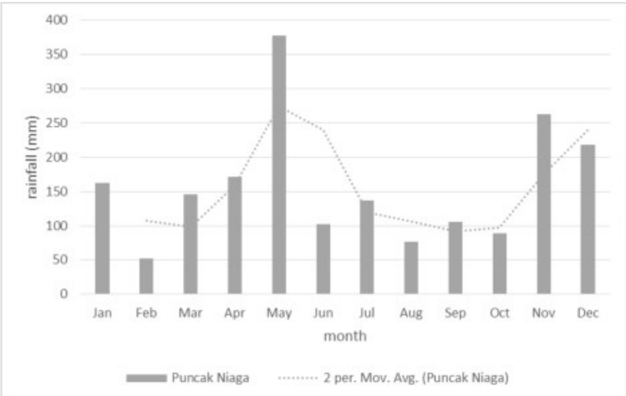


Figure 4. Total rainfall intensity time series for the year 2016 at Puncak Niaga

The rain data were collected in one-minute intervals. The rain volume or intensity collected annually for one year was higher than 2000mm, which resembled the characteristic of tropical rain. It was observed that rain intensity on average was higher in March, April, May, October, November, December and January. The rain distribution in Malaysia is affected by two main monsoon seasons. The Southwest monsoon occurs in May, June, July, August and September. The Northeast monsoon occurs in November, December, January, February and March.

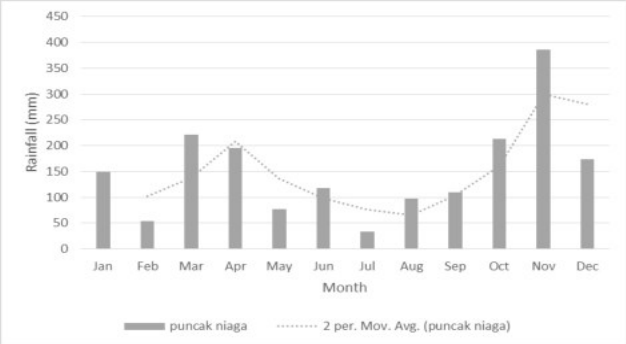


Figure 5. Total rainfall intensity time series for the year 2015 at Puncak Niaga

The cumulative distributions of rainfall rate for the years 2015 and 2016 were investigated. The data availability of the rainfall rate was 100%. In Figure 6, both cumulative distributions for the years 2016 and 2015 as well as the average year are presented.

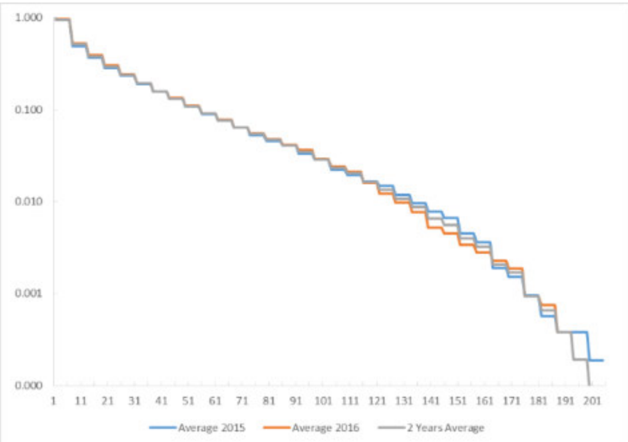


Figure 6. Annual cumulative distributions of rainfall rate

The average cumulative distributions were not much different for the years 2015 and 2016. The average point rainfall rate measured at $R_{0.01}$ time exceedance was 132mm/hr. The $R_{0.1}$ was measured to be 54mm/hr. The measured value of $R_{0.01}$ was 132mm/hr. In comparison to the (ITU-R Recommendation P.837-6 2012) value, the measured local value of $R_{0.01}$ at 132mm/hr was higher than the ITU-R $R_{0.01}$ which was 100mm/hr. Other rainfall rate measurement studies in Malaysia also showed that the $R_{0.01}$ was typically 120mm/hr with a monthly variation of 58mm/hr to 136mm/hr (Shayea *et al.*, 2018). The ITU-R recommends $R_{0.01}$ of 100mm/hr for the entire Peninsular Malaysia; however, it is impractical to obtain correct rain fade prediction based on any model. The obtained $R_{0.01}$ is very important in determining the rain attenuation. This finding is exciting for future works in defining a more accurate model for rainfall rate in Malaysia; particularly for satellite communication link.

B. Monthly cumulative distribution of rain attenuation

The monthly cumulative distributions of rain attenuation measured at a frequency of 20.1998GHz are shown in Figures 7 and 8 for the years 2016 and 2015, respectively. The data measured were from January to November of each year. The data for December was unavailable from the system database due to system maintenance. The time exceedance for the monthly cumulative distribution of rain attenuation significantly varied for each month. For example, the attenuation at the time exceedance at 0.1% differed from 15dB to 32dB and 11dB to33 dB in 2016 and 2015, respectively. The attenuations correlated according to rainfall and rainfall intensity are presented in Figures 4, 5 and 6. The measured exceeded attenuation in May 2016 was noticeably higher than those for all other months, and this correlated with the high rainfall recorded by the rain gauge in May 2016.

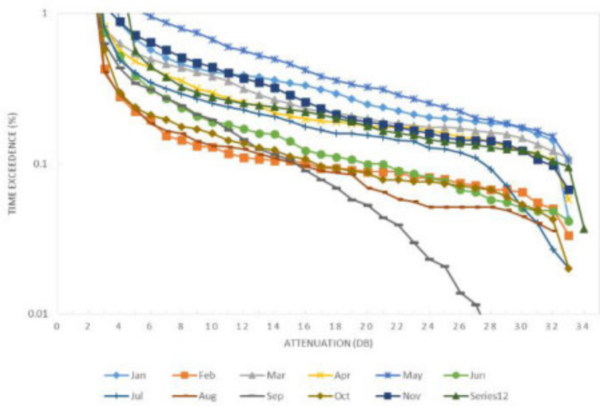


Figure 7. Monthly cumulative distribution function of Ka-band attenuation for 2016

In 2015, and from Figure 8, it was noticeable that in the worst month (November), the measured attenuation was remarkably higher compared to the other months. The outage rain attenuation value of 32.3dB had a high probability of exceedance which was 0.1% relative to the other exceedance probabilities. This indicated that the probability of signal link outage due to rain was higher during this month. Similar to the bar graph in Figure 5, the most severe rainfall intensity was in November with the total rainfall value of 386.1mm. Therefore, it was observed that the relationship was: attenuation increased when the rainfall intensity was higher. In terms of satellite operators, they needed to adapt a mitigation strategy such as increasing the uplink power during higher rainfall rate to overcome the high rain fade. Other than the annual average rainfall, the worst month should be considered as important information in managing rain fade. The attractiveness of the Ka-band in providing higher bandwidth data was useful, particularly in HTS which was unquestionable. Understanding the rain attenuation behaviour (especially in Ka-band for tropical regions) is very important to provide reliable future predictions. Many countries experiencing tropical weather are analysing the effect of Ka-band propagation rather than depending on the ITU-R recommendation, such as in India *(Sujimol et al.*, 2015)(Rapaka & Ramana, 2017) and Singapore (Yuan *et al.*, 2017). The potential use of Ka-band has prompted the European Research Institution to study the Ka-band attenuation effect in Malaysia (Cuervo *et al.*, 2016, 2017). The severity of the Ka-band attenuation also led to the recommendation to avoid it. In a study in Indonesia, a proposal for a hybrid C/Ku-band was made as an alternative to the HTS system (Widjanarko & Gunawan, 2017).

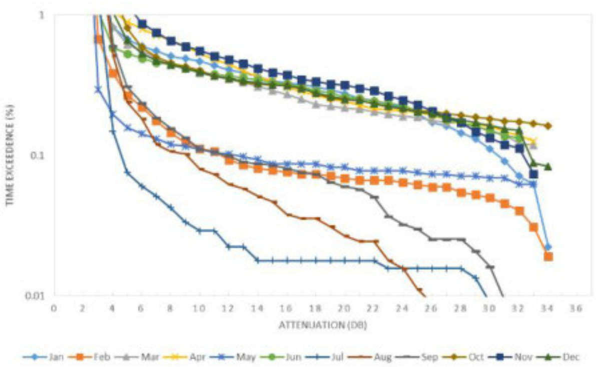


Figure 8. Monthly cumulative distribution function of Ka-band attenuation for 2015

Table 2. Rainfall intensity and attenuation cumulative distributions for a two year period for time exceedance on a monthly basis

Month	Attenuation (dB)							
	2016				2015			
	A0.3	A0.1	A0.03	A0.01	A0.3	A0.1	A0.03	A0.01
January	17.3	32.4	32.7	33.6	18.4	30.1	33.2	34.1
February	3.2	15.8	32.6	32.8	4.3	11	33.4	33.6
March	12.1	32.6	32.8	32.9	14.2	33.1	33.4	33.6
April	8.9	32.3	32.8	32.9	16	33.2	NA	33.5
May	21.2	32.6	NA	32.8	2.6	12.1	NA	33.4
June	5.7	19.4	32.6	32.7	17.3	32.3	NA	32.5
July	6.9	26.9	30.9	33	3	4.1	10.7	28.9
August	3.4	15.4	32.3	32.5	4.3	8.6	18.7	25.5
September	5.9	15.2	23	26.6	4.6	11.5	25.1	30.3
October	3.6	16.2	32.5	32.7	16.8	33.8	34	34.1
November	14.3	30.9	NA	NA	21	32.3	33.9	NA
December	8.2	30.9	NA	NA	17	32.4	34	NA

It is observed from Figures 7 and 8 as well as Table 2 that at exceedance of $R_{0.01}$, the attenuation experienced a sharp drop in values. The sharp drop was recorded at the average of 33.5dB when considering the month with higher rainfall. At this point, the beacon receiver was saturated and hence unable to make an accurate measurement. As presented in the methodology section, the dynamic range of the receiver was 33.5dB with an input signal at clear sky value of -66.5dBm. Hence, the capability of the receiver was only able to accept 33.5dB of attenuation. It was determined that at 20GHz, the rain attenuation was so severe that it was unable to obtain the time exceedance of $R_{0.01}$ for rain attenuation. Therefore, evaluating $R_{0.1}$ would be more accurate in measuring the time exceedance for Ka-band in tropical regions; particularly in Malaysia. Based on this finding, the best Quality of Service available in a year at 20GHz was only 99.9%. Therefore, at 0.1% time in a year (equivalent to 9 hours a year), the satellite communication link at 20GHz would experience a signal outage.

C. Comparison of rain attenuation cumulative distributions based on seasonal monsoons

1. Southwest monsoon

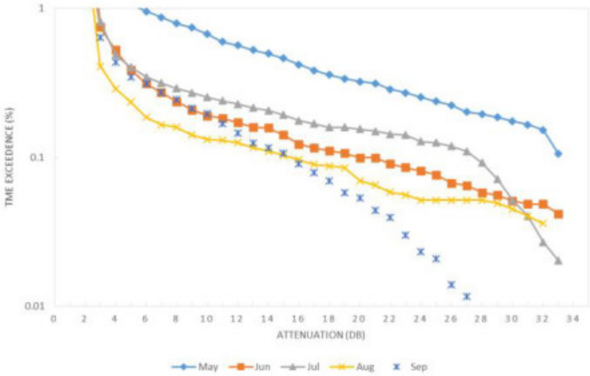


Figure 9. Cumulative distribution function of Ka-band attenuation during the Southwest monsoon, 2016

As mentioned earlier, the Southwest monsoon occurs from the middle of May until September. The Southwest monsoon is typically drier compared to the Northeast monsoon as heavy rain mainly occurs in eastern Malaysia. In west Malaysia, June and July are considered as the dry months of the season. Figure 9 below reveals that during the Southwest monsoon in 2016, the measured attenuation in May substantially exceeded the attenuation observed in the other months at all percentages of time exceedance. This could be related to the rain intensity in May 2016 which was also higher compared to the other months during the Southwest monsoon. The recorded rainfall in May 2016 was 377mm. The month of May experienced the highest rainfall in comparison to June 2016 (102mm), July 2016 (137mm), August 2016 (76mm) and September 2016 (106mm). A higher rainfall does not necessarily mean higher attenuation. Based on the ITU-R recommendation, the rainfall rate affects rain attenuation. Therefore, there is a possibility in the month that has lower rainfall volume to experience higher rain attenuation due to higher rainfall rate. In order to determine the rainfall rate, probability density function and cumulative distribution function statistical analysis provide an accurate rainfall rate exceedance at various percentages.

2. Northeast monsoon

The Northeast monsoon begins in early November until the end of March. The exceeded attenuation from November 2015 to March 2016 is presented in Figure 10. The rain attenuation in November 2015, as shown in Figure 10, was the worst attenuation during the Northeast monsoon. Its attenuation surpassed the other months. In November, the measured time exceedance of 0.1% for rain fade was 32.3dB.

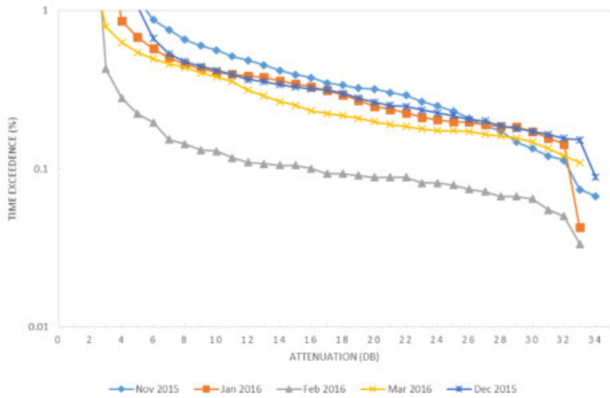


Figure 10. Cumulative distribution function of Ka-band attenuation during the Northeast monsoon

3. Dry season

The months of January, February, June and July are known as the dry season or the inter-monsoon months in Malaysia. However, based on the rain intensity data measured at Cyberjaya, the rain intensity in January is considered high with 162.1mm and 149.6mm for 2016 and 2015, respectively. Based on the data tabulated in Figure 4, February 2016 and June 2016 recorded the lowest rainfall volume. In Figure 11, January suffered the worst signal link outage during the dry months. The time exceedance of 0.1% for the measured attenuation value in January was 32.4dB compared to the driest month in 2016 which was February, with the attenuation value measured at 15.8dB at 0.1% exceedance value.

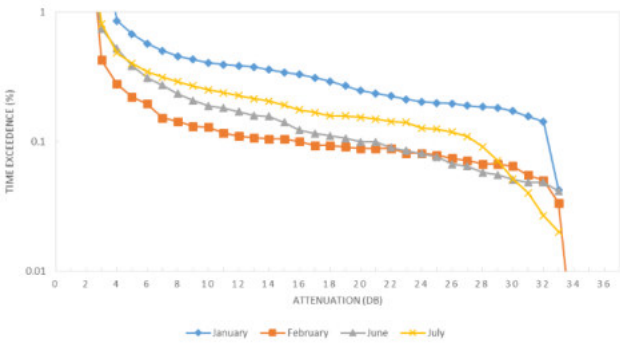


Figure 11. Cumulative distribution function of Ka-band attenuation during the dry season, 2016

D. Rain attenuation annual and seasonal cumulative distributions

Figure 13 presents the time exceedance of rain attenuation's annual cumulative distribution for two years (2015 & 2016), the annual average cumulative distribution for these two years and one seasonal monsoon cumulative distribution. The cumulative distribution analysis indicated that the time exceedance was 0.1% for the annual, annual average and seasonal cumulative distributions. For the Northeast monsoon, the worst month attenuation occurred in November 2015; while for the Southwest monsoon, the worst month occurred in May 2016. As for the dry season, the worst month was in January 2016. In this study, the time exceedance for $R_{0.01}$ was 132mm/hr rainfall rate, and $R_{0.1}$ was measured to be 54mm/hr. However, the receiver only measured the attenuation at 0.01% of time exceedance corresponding to 29dB, 30dB, 30dB, 25dB, 32dB and 28dB for the years 2016, 2015, the annual average, the Southwest monsoon, the Northeast monsoon and the dry season, respectively. It was observed that despite the dry season accumulating less rainfall; it did have higher rain attenuation compared to the Southwest monsoon.

The receiver only measured up to 0.01% of time exceedance because the rain fade at Ka-band at higher time exceedance was too severe. The rain fade surpassed the large dynamic range of the beacon receiver. It saturated the receiver at 33dBm. The receiver began to be saturated when the rainfall rate reached 60mm/hr to 72mm/hr. This value was obtained when the time exceedance of the annual average cumulative distribution function of rain fade in Figure 11 was compared to the annual time exceedance of rainfall rate presented in Figure 6. Therefore, the Ka-band satellite link in Malaysia was only able to deliver Quality of Service (QoS) for 99.9% of a year. This value was lower than the suggested value of 99.99% availability, as recommended by ITU-R.

Even with an industrial grade instrument consisting of a large 8.1m dish antenna, the rain attenuation was difficult to be measured at 0.01% exceedance value. This showed that obtaining a 99.99% communication link at 20GHz or higher Ka-band link was difficult in the tropics; particularly in Malaysia.

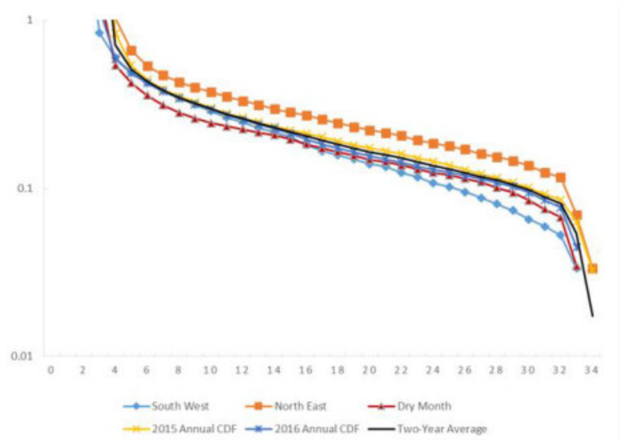


Figure 13. Seasonal cumulative distribution function of Ka-band attenuation for two years

The attenuations of Ka-band due to rain affected Quality of Services (QoS) at 99.7%, 99.9%, 99.97% and 99.97% of the average year and seasonal monsoons as are displayed in Table 3. It was observed that at exceeded value above 0.1%, the Northeast monsoon had a 2dB higher attenuation than the two-year average. At 0.3% exceeded value, the two-year average recorded an attenuation of 10dB. The Northeast monsoon recorded 4dB higher attenuation compared to the two-year average. The rain fade at 0.3% for the Southwest monsoon and dry season recorded 1dB and 3dB lower than the two-year average. The 0.3% exceeded percentage had similar rain attenuation for the years 2016, 2015 and the two-year annual average.

The best quality of service (QoS) that should be aimed for the Ka-band would be 99.90% or equivalent to the attenuation exceedance of 0.1%. There were only 2 or 3 months in the dry season or inter-monsoon duration that would enable the Ka-band to perform better. But this was still considered impractical.

Table 3. Annual and worst month cumulative distributions of rain attenuation

QOS (%)	TE (%)	Attenuation (dB)					
		2016	2015	Two Year Average	Southwest monsoon	Northeast monsoon	Dry season
99.7	0.3	10	10	10	9	14	7
99.9	0.1	29	30	30	25	32	28
99.97	0.03	NA	34	NA	33	34	33
99.99	0.01	NA	NA	NA	NA	NA	NA

IV. CONCLUSIONS

The data of rainfall intensity and rain attenuation for the two-year period were measured and analysed by evaluating them in terms of cumulative distribution function exceeded at a time percentage. The two-year average rainfall rate at 0.01% of time exceedance was 132mm/hr, which was higher than the recommendation by ITU-R. By evaluating the cumulative distribution curves, the two-year average Ka-band rain attenuation measured value for 0.1% of time exceedance was 30dB for the year 2016 as well as for the year 2015. Due to very high rain attenuation at 20.01GHz, the cumulative distribution analysis was only possible up to 0.1% of time exceedance. At 0.01% of time exceedance, the attenuation measured was saturated despite using a very high dynamic range receiving system. It was observed that the receiver began to be saturated at a rainfall rate of 60mm/hr. This showed the severity of rain attenuation at the Ka-band where the rainfall rate value was lesser than the annual average (132mm/hr) rainfall rate exceeded at 0.01%.

From the results obtained, the rain attenuation statistics were subjected to rainfall intensity, as well as monthly and seasonal variations. Based on the measurement, rainfall was throughout the year. It was observed that rainfall was higher from April to May and October to November, while lesser in June, July and February. The rain attenuation was worst during November, except in 2016 when the month of May experienced unusually high rainfall, providing the lowest link availability. Other than the monthly and annual rain attenuation, the Northwest and Southeast monsoon seasons were also evaluated. Providing 99.99% communication reliability was not feasible at 20GHz or Ka-band. The feasible QoS value for Ka-band in Malaysia should be 99.9% or less if a smaller terminal was taken into consideration. For future implementation of a Ka-band receiving system, the dynamic range and receiver sensitivity of a smaller terminal should be evaluated based on the findings in this paper. This paper provided essential and comprehensive findings regarding the performance of the Ka-band link, particularly at 20GHz space to earth link in Malaysia and tropical regions, as well as serves as a reference for future studies in rain attenuation; especially for tropical regions.

V. ACKNOWLEDGEMENT

The authors would like to express gratitude to MEASAT Satellite System Sdn. Bhd. (MEASAT) and the Department of Irrigation and Drainage, Malaysia for supporting this research project.

VI. REFERENCES

[1] Adhikari, A *et al.* 2011, 'Improving rain attenuation estimation: Modelling of effective path length using Ku-Band measurements at a tropical location', *Progress In Electromagnetics Research B*, vol. 34, pp. 173–186.

[2] Cuervo, F *et al.* 2016, 'Ka-band propagation campaign in Malaysia - First months of operation and site diversity analysis', in *2016 10th European Conference on Antennas and Propagation*, EuCAP.

[3] Cuervo, F *et al.* 2017, 'The JOANNEUM RESEARCH SatCom Ka and Q band campaigns in Europe and Malaysia', in *2017 11th European Conference on Antennas and Propagation*, EUCAP, pp. 1476–1480.

[4] Eng, KH 2009, *Malaysia's Drive for High Speed Broadband*, Malaysian Communications and Multimedia Commission, vol. 3, no. 1, pp. 16–19.

[5] Hassan, Z *et al.* 2018, 'Spatial Interpolation of Historical Seasonal Rainfall Indices over Peninsular Malaysia', in *E3S Web of Conferences*.

[6] Huffman, GJ *et al.* 2007, 'The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales', *Journal of Hydrometeorology*, vol. 8, no. 1, pp. 38–55.

[7] Ismail, AF *et al.* 2013, 'Determination of Ku-band specific attenuation parameters based on measurements in the tropics', in *IEEE Antennas and Propagation Society*, AP-S International Symposium (Digest), pp. 2008–2009.

[8] Ismail, AF, Zhiger, S & Hasan, MK 2017, *An Intuitive Link Budget Tool for Military Satellite Communication*, vol. 11, no. 2, pp. 97–106.

[9] ITU-R 2015, *Propagation data and prediction methods required for the design of Earth-space telecommunication systems*, Recommendation ITU-R P. 618-8, 12, pp. 1–24.

[10] ITU-R Recommendation P. 837-6, 2012. Characteristics of precipitation for propagation modelling P Series Radiowave propagation, *Radiowave Propagation*, 6.

[11] Kestwal, MC, Joshi, S & Garia, LS 2014, 'Prediction of rain attenuation and impact of rain in wave propagation at microwave frequency for tropical region (Uttarakhand, India)', *International Journal of Microwave Science and Technology*, 2014.

[12] Lam, HY *et al.* 2012, 'Assessment of seasonal Asia monsoon rain impact on the Earth-space propagation in equatorial Kuala Lumpur'. In *IEEE Antennas and Propagation Society*, AP-S International Symposium (Digest), pp. 1461–1464.

[13] Mignolo, D, Ginesi, A & Michael, H 2013, *Approaching Terabit/s satellite : A system analysis*, Earth.

[14] Mohd Zad, NS, Zulkafli, Z & Muharram, MF 2018, *Satellite Rainfall (TRMM 3B42-V7) Performance Assessment and Adjustment over Pahang River Basin*, Remote Sensing, vol. 10, no. 3.

[15] Nebuloni, R *et al.*, *Assessment of Rain Fade Mitigation Techniques for High Throughput Satellites by a Time Series Synthesizer*.

[16] Ostrometzky, J *et al.* 2016, 'Calibration of the attenuation-rain rate power-law parameters using measurements from commercial microwave networks', in *2016 IEEE International Conference on Acoustics, Speech and Signal Processing* (ICASSP), IEEE, pp. 3736–3740.

[17] Rapaka, P & Ramana, TV 2017, 'Tropospheric scintillation of ku and ka-band satellite signals in south indian region', in *Proceedings - 7th IEEE International Advanced Computing Conference*, IACC 2017. pp. 188–192.

[18] Shayea, I *et al.* 2018, *Real Measurement Study for Rain Rate and Rain Attenuation Conducted Over 26 GHz Microwave 5G Link System in Malaysia*. IEEE Access, 3536(c), pp. 1–1. Available at: http://ieeexplore.ieee.org/document/8306946/.

[19] Stutzman, WL & Dishman, WK 1982, 'A simple model for the estimation of rain-induced attenuation along earth-space paths at millimeter wavelengths', *Radio Science*, vol. 17, no. 6, pp. 1465–1476.

[20] Sujimol, MR *et al.* 2015, 'Rain attenuation using Ka and Ku band frequency beacons at Delhi Earth Station', *Indian Journal of Radio and Space Physics*, vol. 44, no. 1, pp. 45–50.

[21] Vilhar, A, Kelmendi, A & Hrovat, A 2017, *Satellite Propagation Experiment in Ljubljana : Beacon Measurements at Ka- And Q-band*, pp. 3311–3315.

[22] Widjanarko, DI & Gunawan, D 2017, 'A hybrid C/Ku-band high throughput satellite systems as an optimal design for Indonesia', in *Proceedings - International Conference on Signals and Systems*, ICSigSys 2017. pp. 168–174.

[23] Yaccop, AAH *et al.*, 2013, 'Comparison of Ku-band satellite rain attenuation with ITU-R prediction models in the tropics', in *IEEE Antennas and Propagation Society*, AP-S International Symposium (Digest), pp. 2006–2007.

[24] Yeo, JX, Lee, YH & Ong, JT 2009a, 'Ka-band satellite beacon attenuation and rain rate measurements in singapore comparison with ITU-R models', in *IEEE Antennas and Propagation Society*, AP-S International Symposium (Digest), pp. 8–11.

[25] Yeo, JX, Lee, YH & Ong, JT 2009b, 'Modified ITU-R slant path rain attenuation model for the tropical region', in *Conference Proceedings of the 7th International Conference on Information, Communications and Signal Processing*, pp. 40–43.

[26] Yeo, JX, Lee, YH & Ong, JT 2014, 'Rain attenuation prediction model for satellite communications in tropical regions', *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 11, pp. 5775–5781.

[27] Yuan, F *et al.* 2017, Statistical Study of Cloud Attenuation on Ka-Band Satellite Signal in Tropical Region', *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2018–2021.

[28] Yussuff, AIO & Khamis, NHH, 2013, 'Modified ITU-R Rain Attenuation Prediction Model for a Tropical Station', *Journal of Industrial and Intelligent Information*, vol. 1, no. 3, pp. 155–159.

A Compact Broadband Dual Resonance Reflectarray Antenna Embedded on Organic Substrate for Space Applications

M.Y. Ismail[1*], H.I. Malik[1], A.F.M. Zain[2], Sharmiza Adnan[3] and S.R. Masrol[1]

[1]*Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja, 86400 Batu Pahat, Johor Malaysia*

[2]*Academy of Sciences Malaysia (ASM), Menara Matrade, 50480 Kuala Lumpur, Malaysia*

[3]*Forest Research Institute Malaysia (FRIM), Kepong, 52109 Kuala Lumpur, Malaysia*

A novel combination of an organic substrate material with a dual resonant element for wideband frequency operation was presented for satellite communication. Material characterization of the proposed substrate showed permittivity and loss tangent values of 1.63 and 0.046 for X – band operation. A dual resonant element with two variable U – slots presented an independent control of both resonant frequencies. A parametric study was carried out to observe the resonance behavior of the proposed element configuration. Moreover in order to relate the dual U – slot configuration with the frequency response, a mathematical model was also proposed. A strategic combination of the proposed element configuration on an organic substrate demonstrated a wideband frequency response with 10 % fractional bandwidths of 353 and 562MHz for the lower and upper resonances, respectively.

Keywords: Reflectarray antenna; paper substrate; broadband; scattering parameters; modelling

I. INTRODUCTION

The current era of space exploration and communication demands efficient antenna systems to fulfill the progressing satellite communication trends. Traditional reflector antennas have been the mainstream technology for long range communications. Microstripreflectarrays merge the key features of parabolic dish reflectors and phased array antennas (Carrasco & Encinar, 2016). They present planar profile of arrays and the spatial feeding of dish reflectors. Their high gain, low fabrication cost, low profile and ease of deployment present them as an efficient and promising antenna system for space borne applications. Moreover, the beam scanning and switching capabilities prove their effectiveness in modern satellite communications. The modern trends in reflectarray antennas include the introduction of contoured beam reflectarrays, dual reflector configurations, multi-beam operations and integration with solar cell arrays. In order to address the limitation of space in spacecraft payloads, inflatable reflectarray configurations have been introduced. Different configurations of deployable reflectarray antennas have been introduced, with versatile deployment mechanisms to meet the growing requirements of the spacecraft industry. The aim is to reduce deployment complexities in space missions without compromising the antenna performance. The integration of microstripreflectarray with solar panels has also been demonstrated successfully for space applications (An *et al.*, 2014).

Printed microstripreflectarray antennas have opened a new horizon for space antenna applications. Introduction of new methods and techniques for beam steering and scanning application have been previously reported. The use of ferroelectric materials for tunable and reconfigurable reflectarrays provides an efficient solution to replace the bulky mechanical movements of dish reflectors. Moreover the use of liquid crystal substrates ensure beam scanning capabilities along with reduced

*Corresponding author's e-mail: yusofi@uthm.edu.my

system complexity compared to MEMS based switching (Chahat *et. al.*, 2017; Ismail & Inam, 2014; Perez *et. al.*, 2017, Yang *et al.*, 2017).

Dual reflector configurations, analogous to off-set Gregorian feeding in parabolic dish reflectors have also been introduced for microstripreflectarray antennas (Hu *et al.*, 2009; Encinar *et al.*, 2013). The dual reflector configuration provides benefits in terms of bandwidth, beam adjustment and pencil beams for long range space applications. Additionally, reconfigurable components can be placed at the sub-reflector stage for beam switching applications. Another area of particular advantage for reflectarray antennas is the formation of contoured beams using a single array antenna compared to parabolic dish where more than one dish is required to achieve contoured beam patterns (Doyle *et al.*, 2016; Karnati *et.al.*, 2015). Besides all the advantages of microstripreflectarrays, they suffer from a major disadvantage that is the narrow bandwidth compared to parabolic dish reflectors. However this disadvantage can be traded-off for the cost or mechanical complexity of parabolic dish reflectors. Moreover significant numbers of space satellite applications such as DBS only require 5% bandwidth around the operational frequency (Pozar, Targonski & Pokuls, 1999). Thus reflectarray may provide an efficient solution to replace the conventional parabolic dish reflectors.

This article introduced a novel wideband reflectarray element configuration constructed above an organic substrate for space application. It presented a combined scheme of an organic substrate material with dual resonant element to achieve a broadband frequency response. The single layer dual resonance reflectarray antenna provided an efficient solution for dual resonance operation with lesser complexity and independent resonance tunability. Moreover, the proposed material was thoroughly characterized for material properties. Computer simulated models were used to thoroughly investigate and analyze the behavior of the proposed configuration. The dual resonance element configuration was also tested for the scattering parameter response and a comparison had been drawn between the measured and the simulated results for performance evaluation.

II. DIELECTRIC MATERIAL CHARACTERIZATION

The presented novel dielectric substrate material was derived from organic substances. The substrate material was manufactured using a controlled composition of recycled carton paper and banana pulp. It comprised of 75% carton paper and 25% banana pulp fiber. The carton paper was the major portion to identify the material properties while the banana fiber was added as a bonding component to enhance the stress and strain properties of the material. The material was produced in the form of thin sheets and later merged together to achieve a suitable substrate height for a microstrip patch. It was then passed through several rolling and pressing stages to get rid of moisture content.

In order to determine the dielectric properties of the proposed substrate material, characterization was done using a broadband material characterization technique. A dielectric probe was used to characterize the material for X-band frequency range. The complete material characterization set-up is shown in Figure 1. It consisted of a Speag 3.5 mm probe connected to a Rodhe & Schwarz 14GHz network analyzer. The probe was controlled remotely by a software platform installed on the PC.

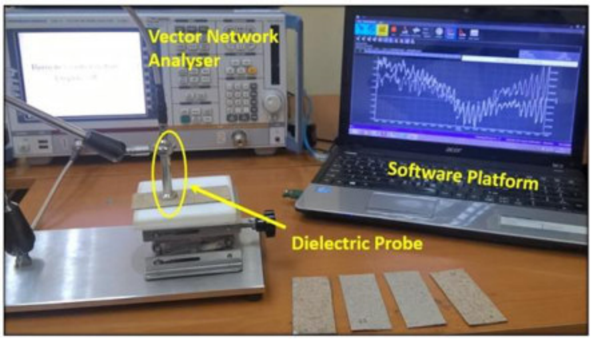


Figure 1. Dielectric material characterization set-up

The whole set-up was thoroughly calibrated for set-up errors using air, copper strip and water as open, short and load respectively. A firm contact between the probe face and the sample under test was established using a movable fixture stand. The results of the dielectric characterization are shown in Figure 2. The characterization results presented the dielectric permittivity and the loss tangent values of the material.

The material showed minor variations of permittivity and loss tangent values over the entire band of operation. The proposed substrate material offered a relative dielectric permittivity of 1.63 along with a loss tangent of 0.046. The values were evaluated as a mean over the entire X – band frequency range.

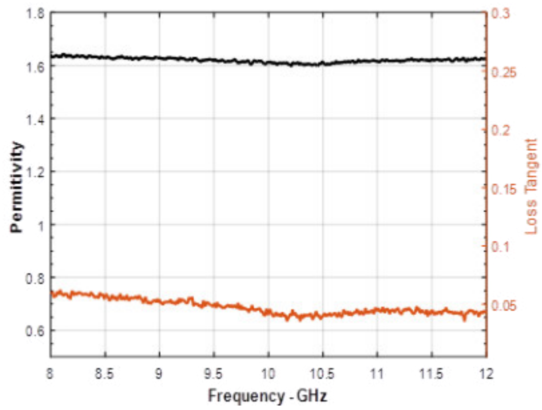


Figure 2. Dielectric material characterization results for the proposed organic substrate material

III. SIMULATION & MODELLING

In order to analyze the behavior of the proposed substrate material as a dielectric, unit microstripreflectarray elements were modeled using a full-wave analysis technique based on the finite integral method. The simulated model was based on unit reflectarray element with perfect electric and magnetic walls. The simulated model is shown in Figure 3. The principle was based on assuming unit reflectarray element placed inside conductive walls, where the walls acted as mirrors for the cell. Thus the unit reflectarray element could be tested for the same mutual coupling and array effects as it experienced in an infinite array. The proposed dual resonant element configuration offered two distinct resonances in X – band operation. This was made possible by inserting two U – slots of variable sizes in a reflectarray rectangular patch element as depicted in Figure 4.

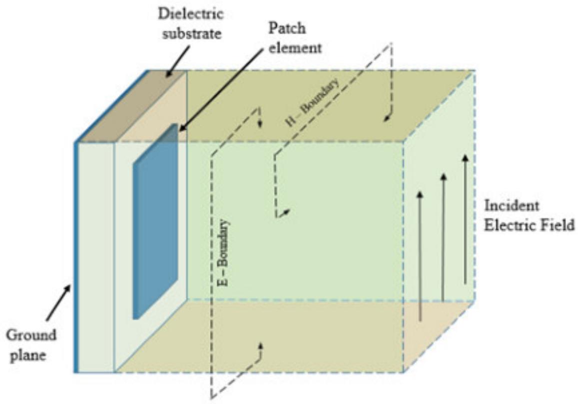


Figure 3. Simulation model of unit reflectarray element with boundary conditions

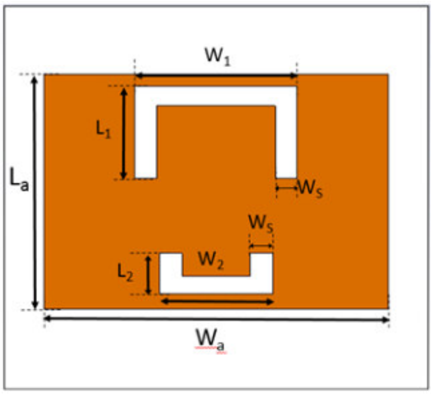


Figure 4. Proposed dual U - slot element configuration

In order to establish a mathematical relationship between the different element dimensions and the resonant frequency, a thorough parametric study was carried out for the proposed element configuration. The selected dimensions were L_a, L_1 and L_2 along with the dielectric permittivity ε_r, since they played important roles in controlling the distribution of the charge carriers on the patch surface. The simulations were then performed to analyze the effect over the resonant frequency. The analysis was done over the X – band operation in order to reduce the complexity. The effects of different parameters over the resonance are presented in Figures 5 – 8.

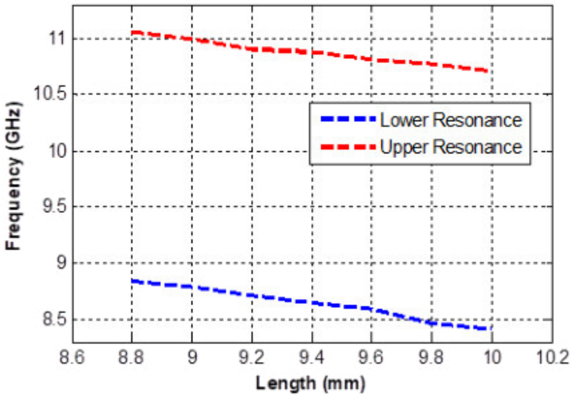


Figure 5. Parametric study - L_a

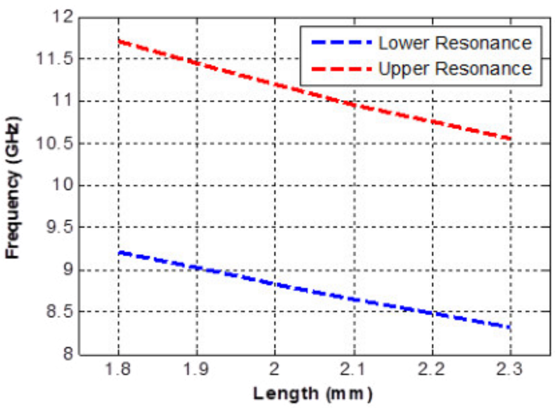


Figure 6. Parametric study – ε_r

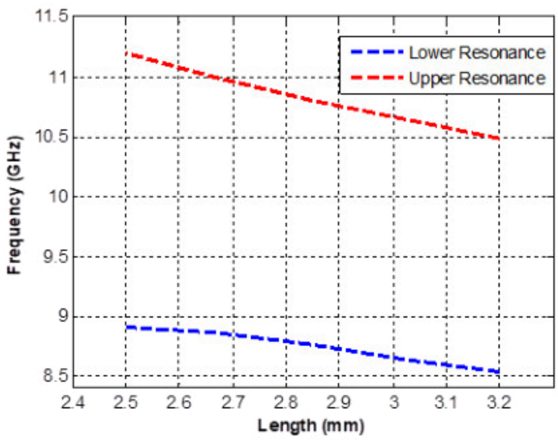


Figure 7. Parametric study – L1

Figure 5 presents the effects of the length of the microstrip patch element on the resonant frequency. It could be seen that the element length affected both the upper and the lower resonant frequencies. Dielectric permittivity of the material was also taken in consideration. It could be seen from Figure 6, that the dielectric permittivity, εr was varied from 1.8 to 2.3. The variation of dielectric permittivity resulted in an equal

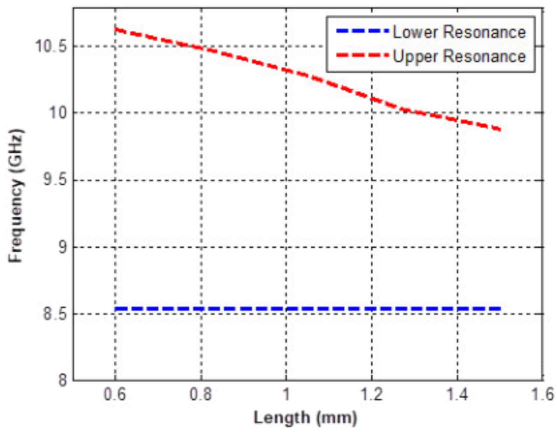


Figure 8. Parametric study - L_2

effect on both the resonances. As the dielectric permittivity, ε_r was varied from 1.8 to 2.3, the resonant frequency decreased from 9.2 to 8.35GHz and 11.7 to 10.55GHz for the lower and upper resonances, respectively. The decrease in resonant frequency was observed to be uniform for both resonances. The effects of the arms of U – slot were also monitored. Figure 7 shows the effects of the arm length L_1 over the resonance behavior. It could be seen that with the increase in arm length from 2.5 to 3.2mm, the resonant frequency changed from 8.9 to 8.5GHz and 11.25 to 10.50GHz for the lower and upper resonances, respectively. This showed that L_1 dimension significantly affected the upper resonance than the lower resonance. The last parameter taken into consideration was L_2, the arm length of the smaller U – slot. The effects of L_2 on the resonance behavior are presented in Figure 8. It could be seen that L_2 had no effect on the lower resonance. As shown in Figure. 8, when L_2 was varied from 0.6 to 1.5mm, the upper resonance was shown to vary from 10.65 to 9.80GHz while the lower resonance remained constant at 8.55GHz. This happened due to the special element configuration with unequal U – slots. The current paths taken by the surface charge carriers could be manipulated using the dimension L_2 which resulted in an independent tuning for both the resonances.

In order to establish a relationship between the stated parameters and the resonance behavior, a mathematical relation was developed. The model was developed by using the empirical data generated from the commercially available CST computer model. The developed model was established for X – band operation to estimate the two resonances for the proposed element configuration.

The mathematical relations are presented below

$$F_1 = 23.15 - 0.09\,L_a - 0.137\,L_1 - 0.9\,\varepsilon_r \quad (1)$$

$$F_2 = 28.6 - 0.48\,L_a - 0.17\,L_1 - 1.15\,\varepsilon_r - 0.14\,L_2 \quad (2)$$

Where F_1 is the lower resonance and F_2 is the upper resonance of the dual U – slot element configuration. Equations (1) and (2) relate the resonant frequency of the proposed element configuration with the element dimensions and the dielectric material permittivity. It's could be noticed from equation (1) that the term for the arm length L_2 was not present, which demonstrated the independence of the lower resonance from the arm length L_2. Thus, with the known values of L_a, L_1, L_2 and ε_r both the upper and lower resonances of the dual U – slot element configuration could be estimated.

IV. FABRICATION & MEASUREMENTS

In order to realize a reflectarray antenna over the proposed substrate material, unit reflectarray elements were fabricated. The proposed substrate material was not robust enough to withstand the CNC milling or wet chemical etching process. Therefore, the elements were fabricated using a 70μm thick adhesive copper tape. In the literature, conductive printing inks based on silver nano-particles had been used for printed antennas. The dual U – slot element configuration was cut into the element to attain a dual resonance operation.

The fabricated elements were then passed through a dimensional measurement process where each element dimensions were precisely measured using a

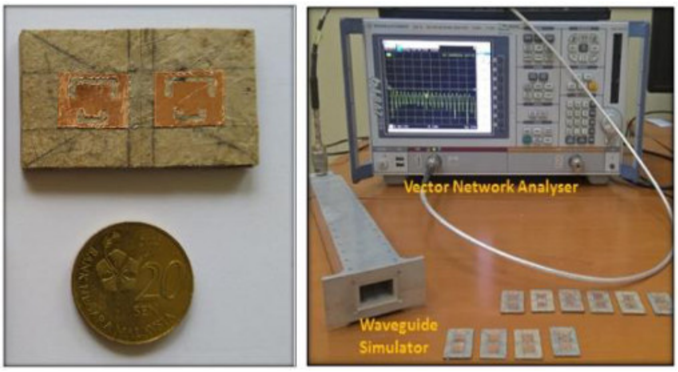


Figure 9. Fabricated samples and scattering parameter measurement set-up

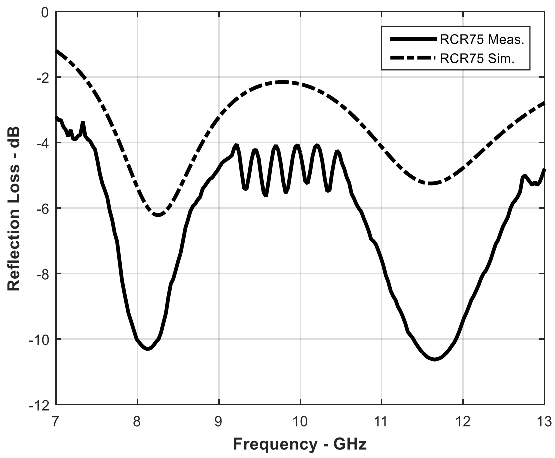


Figure 10. Comparison between reflection loss curves

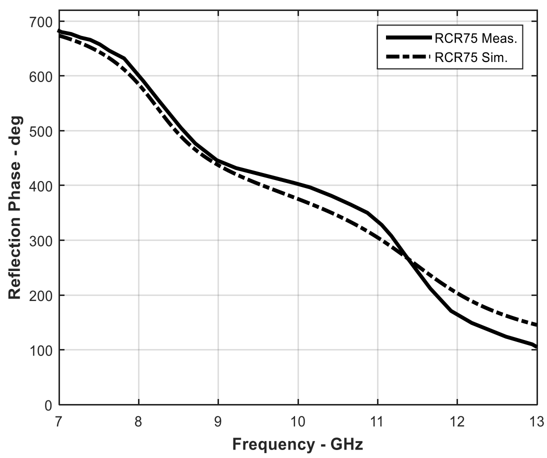


Figure 11. Reflection phase curves for dual U - slot element

measurement microscope. The fabricated elements and the scattering parameter measurement set-up are depicted in Figure 9. The measurement set-up shown in Figure 9 consisted of an X – band tapered waveguide simulator attached to a network analyzer. The fabricated elements were placed inside the waveguide aperture to record the scattering parameters. Multiple elements were fabricated and tested to ensure repeatability of the results. Figure 10 and Figure 11 show the reflection loss and reflection phase results. As shown in Figure 10, it could be seen that the element presented a dual resonance behavior with two distinct resonances in the X – band frequency range. The ripples presented in the measured results were due to the non-ideal nature of the waveguide simulator. The findings from Figure 10 and Figure 11 are tabulated in Table 1.

Table 1. Scattering parameter results for dual U - slot element configuration

Substrate Height (mm)		Resonant Frequency (GHz)	Reflection Loss (dB)	10% Bandwidth (MHz)	Phase Range (°)	FOM (°/MHz)
RCR75 (3.04 mm)	Simulation	8.18, 11.41	-6.90, -7.02	478, 732	541	0.13, 0.15
	Measurement	8.11, 11.65	-10.30, -10.63	353, 562	591	0.19, 0.17

As shown in Table 1, the proposed element configuration showed a dual resonance behavior at 8.11 and 11.65GHz for the lower and upper resonances, respectively. A 10% bandwidth had also been defined by moving 10% above the maximum reflection loss level for the reflection loss curves. The reflection loss curves showed a 10% bandwidth of 353 and 562MHz for the lower and upper resonances, respectively. The reflection phase range demonstrated a phase range of 591°. It showed maximum phase gradients at the resonance point with 0.19 and 0.17°/MHz for the lower and upper resonances, respectively. The reflection phase gradient was maximum at the point of resonance since at the resonance the impedance was purely resistive.

A comparison between the measured and the simulated results showed a good agreement of the reflection phase range and the reflection loss. The wider phase range of the proposed design scheme would help to minimize the phase errors. Moreover, the dual resonance operation in the X – band could be used efficiently for satellite communication operations. In addition, the proposed antenna provided an efficient combined bandwidth of 915MHz for both the resonances to address the needs of the wideband satellite communication systems.

V. CONCLUSION

Modern satellite systems require broadband antenna systems to support the ever increasing data links and communication. This research focused on the introduction of an innovative dielectric substrate material to address the narrow bandwidth microstripreflectarray antenna. The proposed material showed low dielectric permittivity values of 1.63 at a loss tangent of 0.046 over the X – band frequency range. In order to achieve a dual resonance operation with a wider phase range, a dual U – slot element configuration was introduced with independent control for both the resonances. Scattering parameter measurements showed broadband frequency response of 353 and 562MHz, respectively. The proposed reflectarray element with broadband dual resonance operation could help to improve the microstripreflectarray limitations. Thus, the reflectarray antenna performance would be enhanced for various applications with broadband requirements such as synthetic aperture radars, DBS applications and radar applications.

VI. REFERENCES

[1] An, W, Xu, S, Yang, F, Member, S & Gao, J 2014, ‘A Ka-band reflectarray antenna integrated with solar cells’, *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 11, pp. 5539–5546. doi: 10.1109/TAP.2014.2354424.

[2] Carrasco, E & Encinar, JA 2016, ‘Reflectarray antennas : A review’, *Forum for Electromagnetic Research Mehtods and Application Technologies* (FERMAT), vol. 16, no. 1. Available at: https: e-fermat.org/articles/carrasco-art-2016-vol16-jul-aug-002.

[3] Chahat, N, Agnes, G, Sauder, J & Cwik, T 2017, ‘One meter deployable reflectarray antenna for earth science radars’, in *the proceedings of IEEE Antennas and Propagation Society International Symposium*, pp. 245–246. doi: 10.1109/APUSNCURSINRSM.2017.8072165.

[4] Doyle, D, Woehrle, C, Wellems, D & Christodoulou, CG 2016, ‘Environmental concerns with liquid-crystal-based printed reflectarrays in space’, *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1919–1922.doi: 10.1109/LAWP.2016.2538085.

[5] Encinar, JA, Tienda, C, Barba, M, Carrasco, E & Arrebola, M 2013, ‘Analysis, design and prototyping of reflectarray antennas for space applications’, in *Loughborough Antennas and Propagation Conference*, LAPC, IEEE, pp. 1–5. doi: 10.1109/LAPC.2013.6711840.

[6] Hodges, RE, Chahat, NE, Hoppe, DJ & Vacchione, JD 2016, ‘The mars cube one deployable high gain antenna’, in *the proceedings of IEEE Antennas and Propagation Society International Symposium*, APSURSI, pp. 1533–1534. doi: 10.1109/APS.2016.7696473.

[7] Hu, W, Arrebola, M, Cahill, R, Encinar, JA, Fusco, V, Gamble, HS, Alvarez, Y & Las-Heras, F 2009, ‘94 GHz dual-reflector antenna with reflectarray subreflector’, *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 10, pp. 3043–3050. doi: 10.1109/TAP.2009.2029275.

[8] Ismail, M & Inam, M 2014, ‘Design of liquid crystal based tunable reflectarray antenna using slot embedded patch element configurations’, *International Journal of Electrical, Robotics, Electronics and Communications Engineering*, vol. 8, no. 10, pp. 1313–1318. doi: 10.1999/1307-6892/9999435.

[9] Karnati, KK, Shen, Y, Zhu, W, Trampler, ME, Ebadi, S, Wahid, PF and Gong, X 2015, ‘Tunable and flexible electronics employing monolithically-integrated BST thin film’, *IEEE International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP)*, IEEE, pp. 1–3. doi: 10.1109/IMWS-AMP.2015.7324953.

[10] Perez-Palomino, G, Barba, M, Encinar, JA, Cahill, R, Dickie, R & Baine, P 2017, ‘Liquid crystal based beam scanning reflectarrays and their potential in SATCOM antennas’, in *the 11th European Conference on Antennas and Propagation*, EUCAP, pp. 3428–3431. doi: 10.23919/EuCAP.2017.7928474.

[11] Pozar, DM, Targonski, SD & Pokuls, R 1999, ‘A shaped-beam microstrip patch reflectarray’, *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 7, pp. 1167–1173. doi: 10.1109/8.785748.

[12] Yang, X, Xu, S, Yang, F, Li, M, Hou, Y, Jiang, S & Liu, L 2017, ‘A broadband high-efficiency reconfigurable reflectarray antenna using mechanically rotational elements’, *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 8, pp. 3959–3966. doi: 10.1109/TAP.2017.2708079.

Effects of Varying Altitude on Aerodynamic Attitude Stabilization in LEO for (1U, 2U, 3U) CubeSat

Asma Mohammad Nusrat Aman[1*] and Roselina Arelhi[1]

[1]*University of Nottingham Malaysia, Jalan Broga, Semenyih 43500, Selangor, Malaysia*

Small satellites continue to be used as a platform to inexpensively and rapidly demonstrate new technologies and scientific research. Therefore, cheaper alternatives to attitude control such as passive control methods are usually proposed for such missions. Making use of aerodynamic drag is one low-cost method to passively control a satellite's attitude. In lower Earth orbits, the magnitude of aerodynamic drag varies with satellite altitude. This study analyzes the effects of varying the altitude on passive aerodynamic attitude stabilization in low Earth orbit for CubeSats. CubeSats considered are 1U, 2U and 3U and the effects on each are presented and analyzed. This will help aid the selection of the appropriate aerodynamically stabilized CubeSat size for the relevant intended altitude in low Earth orbit. Moreover, the choice of altitude remains a trade-off between lower mission lifetime and better aerodynamic attitude stabilization.

Keywords: Aerodynamic attitude stabilization; CubeSat; low earth orbit

I. INTRODUCTION

There has been a growing trend in using small satellites as cheaper and quicker alternatives to demonstrate new technologies and scientific research by various universities. A class of small satellites, known as CubeSats, were first developed in 1999 by Professors Jordi Puig-Suari of California Polytechnic State University and Bob Twiggs of Stanford University, in an attempt to promote the design and manufacture of small low earth orbiting satellites for scientific research purposes and to study novel technologies (Selva and Krejci, 2012). CubeSats are miniaturized satellites that are based on standardized units of mass and volume. The basic CubeSat unit measures 10x10x10 cm^3 (often called "1U"). They weigh no more than 1.33kg per unit. Several CubeSat units could be combined to form larger CubeSats such as the 2U CubeSat (20x10x10 cm^3) and 3U CubeSat (30x10x10 cm^3). They usually piggyback on launch of larger satellite missions, to save fuel cost, and mostly deployed into Low Earth Orbits (LEO). Many are deployed from the International Space Station (ISS), at an average altitude of 408km (Melina, 2017).

When a CubeSat is deployed, it initially spins out of control (tumbles) in space. The angular velocities therefore need to be stabilized before any attitude control takes place. This is known as detumbling the CubeSats. Magnetic detumbling is considered, which makes use of magnetorquers and a B-dot algorithm. Pointing in a particular direction is essential to maximize solar power, for Earth observation, and to follow some pointing requirements for scientific instruments so that the CubeSat mission is successful. Therefore, attitude stabilization (control) needs to be achieved. This is done by passive or active methods. Passive attitude control methods such as gravity-gradient stabilization, passive magnetic control, and aerodynamic stabilization make use of the disturbance torques present in the space environment to control the CubeSat's attitude. Gravity-gradient torques are a result of the differences in the Earth's gravitational pull on the CubeSat body; passive magnetic control is where the interaction between the magnets in the CubeSat and the Earth's prevalent magnetic field in LEO result in torques; and the aerodynamic torques are caused due to aerodynamic drag, which is predominant in lower orbits/altitudes.

*Corresponding author's e-mail: ecxaa2@nottingham.edu.my

These are cheaper alternatives and are mainly used for coarse pointing requirements, as the Earth's magnetic field and aerodynamic model is highly variable and unpredictable.

Passive attitude control by means of aerodynamic stabilization relies solely on aerodynamic torque to stabilize the attitude against other disturbances and the CubeSat's own spin. The aerodynamic torque is dependent on the altitude of the satellite, the atmospheric density at that altitude, the dimensions of the CubeSat, and the orbital velocity. LEO is defined as a satellite orbit with altitudes less than 1000km (Samwel, 2014). Altitudes ranging from 300-800km above the Earth's surface present drag forces strong enough to alter the satellite's attitude (Khalil & Samwel, 2016). The lower the altitude, the higher the atmospheric density, and hence the more prevalent the aerodynamic drag and higher amounts of aerodynamic torques act on the CubeSat (in the opposite direction of travel). Additionally, lower altitudes result in higher orbital velocities for the CubeSats, which ultimately lead to orbital decay and shorter lifetimes for missions.

Therefore a trade-off between mission lifetime and the adoption of passive aerodynamic stabilization is to be achieved, where the altitude selection plays a vital role in deciding whether the passive attitude control method is appropriate. This paper explores the aerodynamic attitude stabilization for different CubeSat sizes (1U, 2U, and 3U), at varying altitudes in LEO. This may aid in selecting the most suitable altitude for aerodynamically stabilized CubeSats in the future, and in deciding whether aerodynamic stabilization is the best option for a specified orbit (as the options may be limited due to mission launches available at the time for CubeSat deployment). For simplification purposes, no orbital parameters were considered and so a circular orbit is assumed for each altitude. Hence, the orbital velocity of the CubeSat remains constant throughout the orbit. First, the generic CubeSat dynamic models and the disturbance torque models used for simulation are introduced. The simulation carried out by Matlab/Simulink was inspired by (Alvenes, 2012). The results show varying levels of attitude stabilization for a range of altitudes (400-1000km) in LEO, for each CubeSat size.

II. MODELLING

A. CubeSat Dynamic Models

The CubeSats are modelled as rigid bodies (three degrees of freedom) with the center of mass coinciding with the center of gravity. The rotational motion along all three axis (yaw, pitch and roll) are studied. Figure 1 shows the models for the 1U, 2U and 3U CubeSats considered. The models are assumed to have cubic/prism structures.

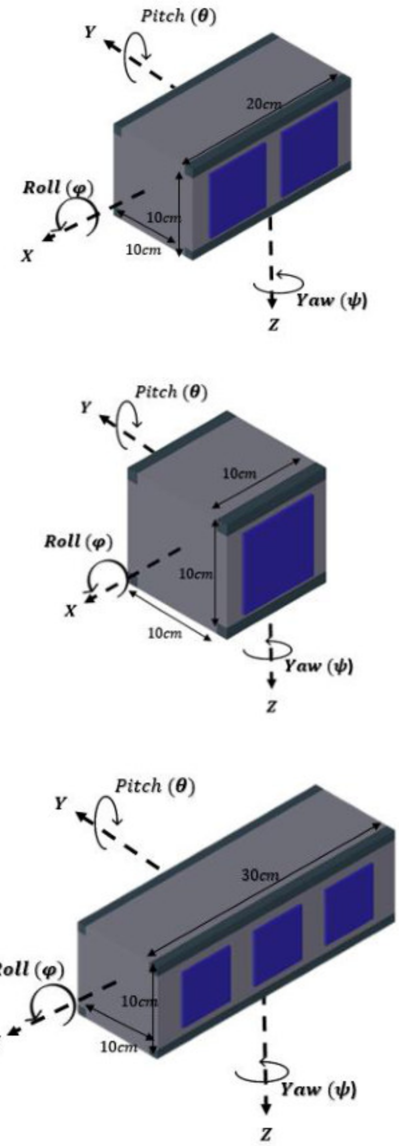


Figure 1. 1U, 2U, and 3U CubeSat models showing dimensions and Euler angle representation for each

The coordinate frames of reference used in this analysis are the Earth-Centered-Inertial (ECI) and CubeSat body coordinate frames. For analyzing the attitudes, CubeSat equations of motion are defined. They are described by Euler angles (yaw, pitch, roll) in the *Z,Y,X* directions, as shown in Figure 1. Moments about each axis will affect the CubeSat attitude, and hence those need to be modelled.

The overall dynamics equation is given as described by (Hughes, 1986) in Equation 1.

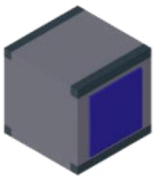
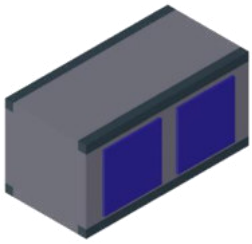
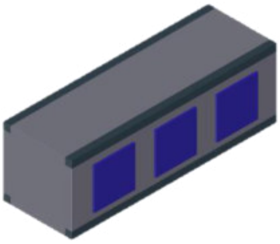
$$\boldsymbol{I}\dot{\omega} + \omega \times (\boldsymbol{I}\omega) = \tau_{total} \quad (1)$$

where τ_{total} is the sum of all the disturbance torques in Nm, $\omega = [\omega_x \ \omega_y \ \omega_z]^T$ represents the angular velocities (*degrees/sec*) in roll, pitch and yaw; $\boldsymbol{I}$ is the inertia matrix about the center of gravity. Assuming homogenous displacement of mass along the principal axes, the inertia matrix is given as a diagonal matrix

$$\boldsymbol{I} = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \quad (2)$$

The inertia matrix was calculated for each CubeSat and given in Table 1, along with mass and dimensions of each CubeSat. Since only the depth (x-value) of each CubeSat varies, the inertia parameters I_y and I_z remain the same for each, i.e., I_x plays a key factor in counteracting the disturbance torques that are modelled in Section 2.2. Moreover, this is because aerodynamic drag acts in the opposite direction of the velocity vector, or direction of travel (x-axis).

Table 1. 1U, 2U, and 3U CubeSat parameters

CubeSat	**Mass (*kg*)**	**Dimensions (*cm*³) (*X,Y,Z*)**	**Inertia Matrix**
1U 	1.33	10 × 10 × 10	$\begin{bmatrix} 0.0022 & 0 & 0 \\ 0 & 0.0022 & 0 \\ 0 & 0 & 0.0022 \end{bmatrix}$
2U 	2.66	20 × 10 × 10	$\begin{bmatrix} 0.0044 & 0 & 0 \\ 0 & 0.0111 & 0 \\ 0 & 0 & 0.0111 \end{bmatrix}$
3U 	3.99	30 × 10 × 10	$\begin{bmatrix} 0.0067 & 0 & 0 \\ 0 & 0.0333 & 0 \\ 0 & 0 & 0.0333 \end{bmatrix}$

B. Disturbance Torques

To simulate a representation of the disturbances on the CubeSats, three major disturbance torques were considered: the gravity-gradient torque, magnetic torque, and aerodynamic torque. τ_{total} from Equation 1 is a sum of all of these torques. Each of these torques vary with altitude; however, the effects of aerodynamic torque will be studied to analyze aerodynamic attitude stabilization.

The gravity-gradient torque is caused by the variation in Earth's gravitational forces exerted on the CubeSat body (Karataş, 2006). It is therefore prominent in the z-direction, and the gravity-gradient torque is given by (Tudor, 2011)

$$\tau_g = 3(\frac{\mu}{R^3})z_o \times \boldsymbol{I} \cdot z_o \quad (3)$$

where R is the distance from the center of Earth to the satellite ($R = R_{Earth} + h_{altitude}$) in meters, $\boldsymbol{I}$ is the inertia matrix, and z_o is the z-axis in the orbit frame (towards nadir).

For simplification purposes, the Earth's magnetic field has been modelled as a dipole. Magnitude of magnetic field is given by Equation 4.

$$B = \frac{\mu_o}{R^3} \quad (4)$$

where B is magnetic field strength (*Tesla*) and μ_o is permeability of free space ($\mu_o = 4\pi \times 10^{-7} H/m$).
If D is the sum of all magnetic moments on a satellite, the magnetic torque acting on the satellite τ_m (*Nm*) will be given by

$$\tau_m = D \times B \quad (5)$$

where τ_m is the magnetic torque (*Nm*) on a satellite and B is the local magnetic field's strength (*Tesla*) which varies with altitude and latitude.

The expression for aerodynamic drag torque (Hughes, 1986) is given as

$$\tau_a = \rho V_{orbit}\left[V_{orbit} A_{drag} c_p \hat{V}_{orbit} - (\boldsymbol{I} + \hat{V}_{orbit}\boldsymbol{J})\omega\right] \quad (6)$$

where ρ is atmospheric density (kg/m^3), V_{orbit} is orbital velocity of CubeSat (m/s), A_{drag} is the area perpendicular to the velocity vector (x-direction of travel), c_p is center of pressure, $\hat{V}_{orbit}$ is unit velocity direction, $\boldsymbol{I}$ is moment of inertia, $\boldsymbol{J}$ is the new moment of inertia matrix for drag, and $\omega = \left[\omega_x \ \omega_y \ \omega_z\right]^T$ is angular velocity (*degrees/sec*). The atmospheric density and orbital velocity both vary with altitude. Within the same altitude/orbit, the atmospheric density also tends to vary slightly. For analysis of worst-case scenario, the maximum atmospheric density values are considered in the calculation of aerodynamic torque. These values are given in Table 2 (Wiley J. Larson & Wertz, 2006). The new moment of inertia $\boldsymbol{J}$ is due to the fact that the center of pressure and center of mass of the CubeSat may not be aligned and therefore a torque is generated as a result (Alvenes, 2012).

Table 2. Satellite altitudes and corresponding values of maximum atmospheric density (Wiley J. Larson & Wertz, 2006)

Altitude (km)	**Maximum Atmospheric density (kg/m³)**
400	7.55E-12
500	1.80E-12
600	4.89E-13
700	1.47E-13
800	4.39E-14
900	1.91E-14
1000	8.84E-15

III. RESULTS AND DISCUSSION

The dynamic models involved differential equations of the Euler angles representing satellite attitude. The aerodynamic torque code created by (Bråthen, 2013) was used, according to Equation 6. Additionally, (Alvenes, 2012) presents a detumbling controller for CubeSats, which was also incorporated into the model, so detumbling may be achieved and the attitude stabilization analysis is improved. Once the CubeSats are deployed into their circular orbit, they are assumed to take a random orientation before attitude stabilization commences. The initial attitude of the CubeSats in the simulation was set to (random) values of $\begin{matrix}\boldsymbol{\varphi}\\ \boldsymbol{\theta}\\ \boldsymbol{\psi}\end{matrix} = \begin{bmatrix}1\\2\\3\end{bmatrix}$. The simulation is carried out for 6 circular orbits, with no specified inclination (as orbital parameters are not included in the modelling). Other than the B-dot controller for the detumbling phase, no active control is included, and hence the attitude stabilization is to rely solely on aerodynamic drag effects. As mentioned earlier, maximum values for atmospheric density are considered for analyzing the worst-case scenarios. The satellite mass, dimensions, and inertia matrix parameters were altered to represent each CubeSat; while the altitude, atmospheric density, and orbital velocity are varied for analysis of effects of aerodynamic attitude stabilization in each altitude. Results of the simulations are presented in graphical form, showing the time histories of Euler angle representation of CubeSat attitude.

Simulations for 1U CubeSat 

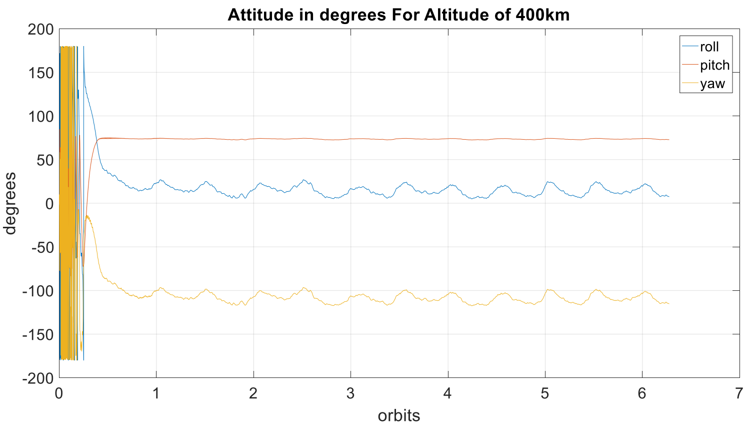


Figure 2. Plot of attitude for altitude of 400km for 1U CubeSat

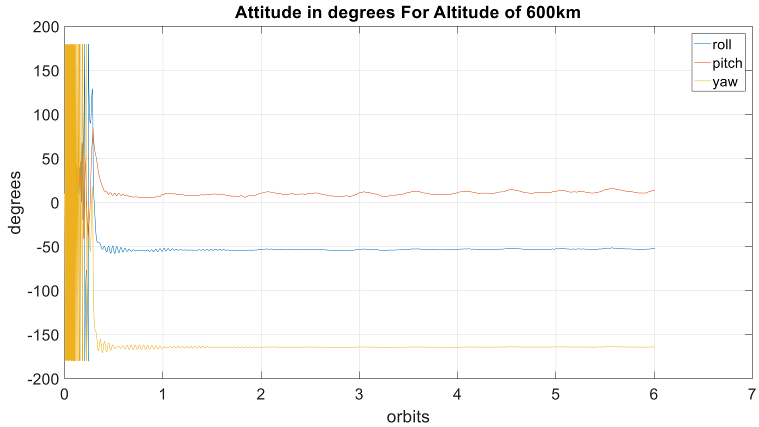


Figure 3. Plot of attitude for altitude of 600km for 1U CubeSat

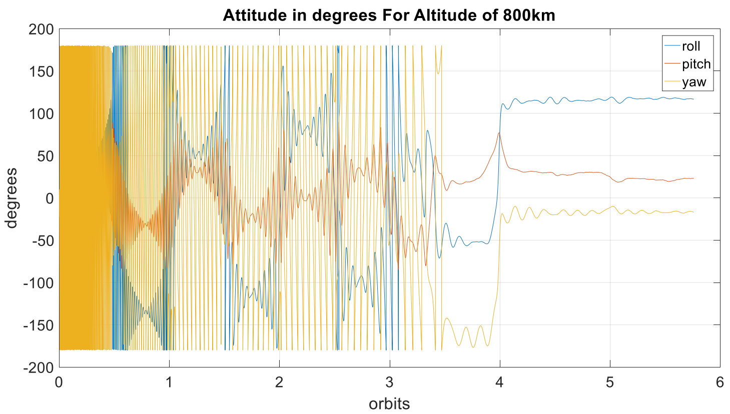


Figure 4. Plot of attitude for altitude of 800km for 1U CubeSat

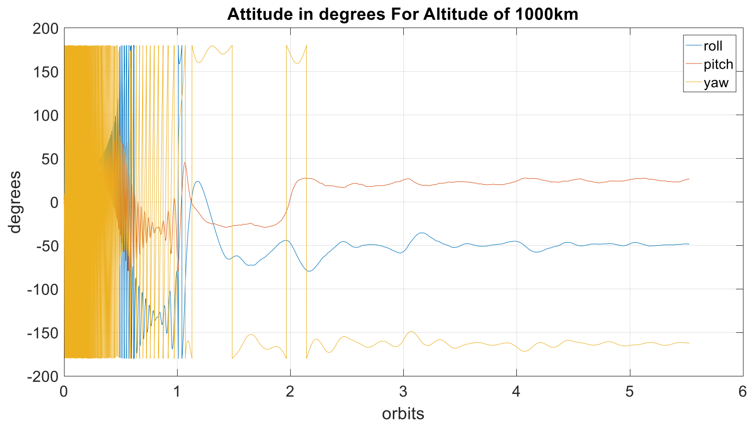
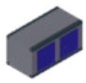


Figure 5. Plot of attitude for altitude of 1000 km for 1U CubeSat

For an altitude as low as 400km, where the atmospheric density is higher, the aerodynamic drag is adequately significant to act as a stabilization mechanism for the 1U CubeSat as seen in Figure 2. The settling time and attitude stabilization is within the first orbit, and the attitude is seen to be stabilized within acceptable limits. Since the 1U CubeSat has the smallest size, its moments of inertia are the lowest and hence it is easily maneuvered by strong aerodynamic torque. At a higher altitude of 600km (Figure 3), the attitude is stabilized even quicker (lower settling time) as compared to 400km. A more stable balance (between aerodynamic moments and the CubeSat's own moments of inertia) is said to be achieved in terms of aerodynamic stabilization of all three axes. For an altitude of 800km (Figure 4), aerodynamic stabilization is not achieved as easily as in lower altitudes.

It can be seen that the attitude continues to oscillate up to 4 orbits, and remains uncontrolled. The reason for this is that the aerodynamic drag is not as significant and hence acts as a disturbing torque more than a stabilizing torque. Hence, for 1U CubeSats at such an altitude, passive aerodynamic stabilization alone is not sufficient for attitude control. Moving on to higher altitudes of 1000km, Figure 5 shows that stabilization is ultimately achieved for pitch and yaw orientations. The yaw angle takes longer (higher settling time) and this may be due to spin in the *z*-direction. However, at such high altitudes, it may be useful to also consider effects of solar radiation pressure torques.

Simulations for 2U CubeSat



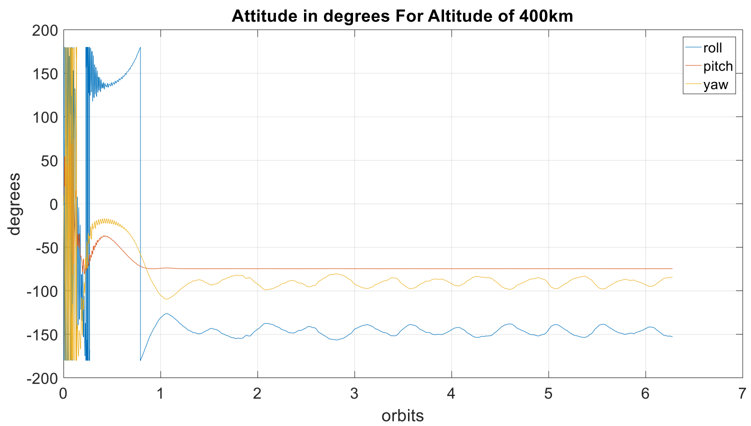


Figure 6. Plot of attitude for altitude of 400km for 2U CubeSat

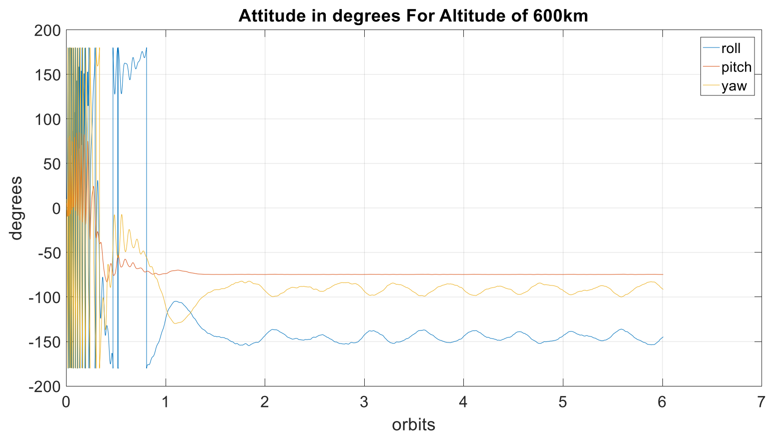


Figure 7. Plot of attitude for altitude of 600km for 2U CubeSat

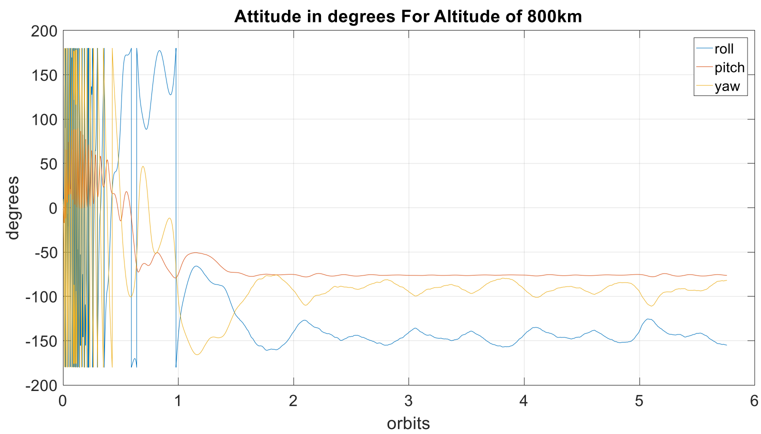


Figure 8 – Plot of attitude for altitude of 800km for 2U CubeSat

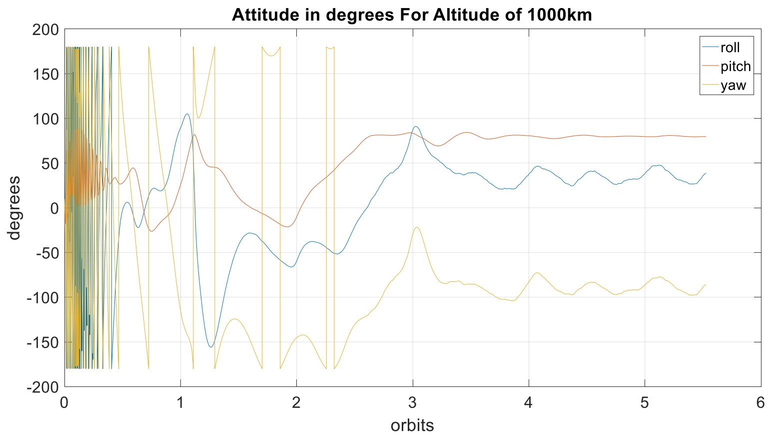
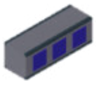


Figure 9 – Plot of attitude for altitude of 1000km for 2U CubeSat

For an altitude of 400km, the aerodynamic drag is significant enough to stabilize the 2U CubeSat as seen in Figure 6. Although the cross-sectional area perpendicular to aerodynamic drag is the same (10x10 cm^2) as that for 1U CubeSat, the depth of the 2U CubeSat is doubled and so the moments of inertia and center of mass are different. Hence, the 1U CubeSat achieves aerodynamic stabilization (Figure 2) quicker than the 2U CubeSat as the sum of torques needed to stabilize the 2U CubeSat are much higher. At a higher altitude of 600km (Figure 7), the attitude is stabilized, although there is a slight overshoot in the roll angle. Nonetheless, it signifies that aerodynamic stabilization is enough for coarse pointing requirements of a 2U CubeSat; but for accurate pointing, active control methods may stabilize the attitude better. The same phenomenon is realized for an altitude of

800km (Figure 8). At very high altitude of 1000km, where the atmospheric drag is less significant (Figure 9), the attitude remains uncontrolled by passive means alone.

Simulations for 3U CubeSat



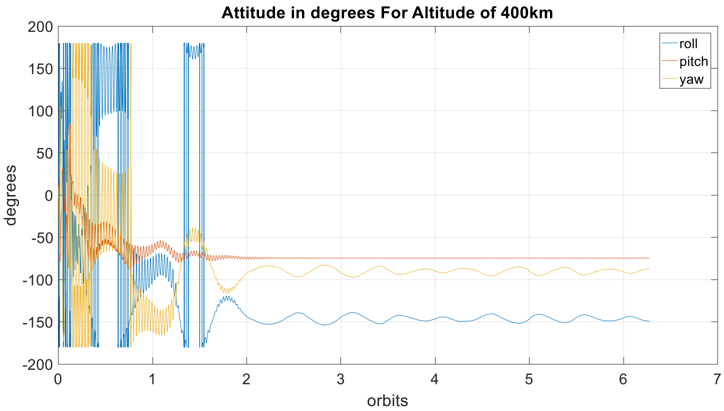


Figure 10. Plot of attitude for altitude of 400km for 3U CubeSat

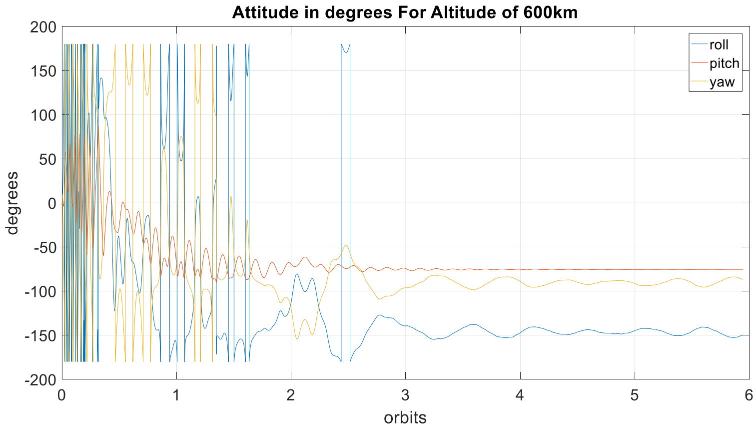


Figure 11. Plot of attitude for altitude of 600km for 3U CubeSat

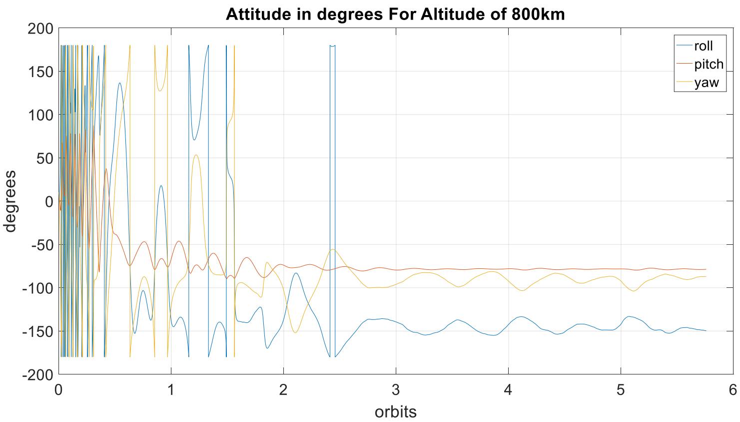


Figure 12. Plot of attitude for altitude of 800km for 3U CubeSat

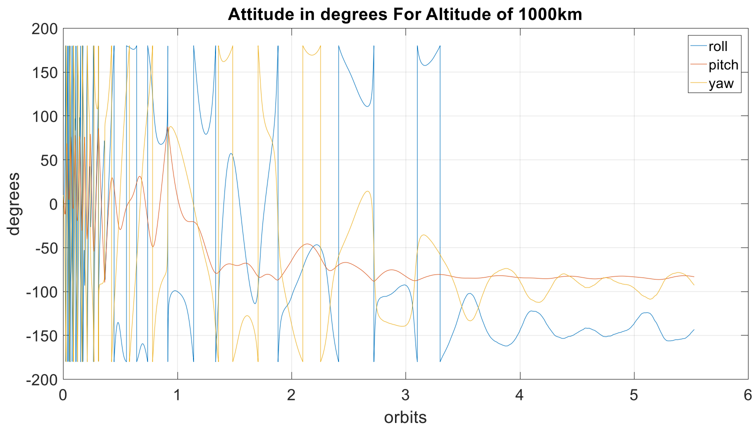


Figure 13. Plot of attitude for altitude of 1000km for 3U CubeSat

The 3U CubeSat is three times the 1U CubeSat in mass and depth (*x*-axis length). It has the highest moments of inertia of all three CubeSats presented and hence is the most difficult to maneuver. This implies that for passive control alone, it will take more time for the attitude to be stabilized in all three orientations. For an altitude of 400km, the aerodynamic drag torque is strong enough to stabilize the 3U Cubesat as seen in Figure 10. As expected, it takes longer than 1 orbit for stabilization to be achieved. For the altitude of 600km (Figure 11), the settling time is even longer than 2 orbits. The same phenomena is realized for an altitude of 800km (Figure 12). Aerodynamic attitude stabilization is not achieved within 2 orbits, due to the low aerodynamic torques that are not strong enough to stabilize the 3U CubeSat. At 1000km (Figure 13), almost no attitude stabilization is achieved due to passive aerodynamic stabilization means. Active control methods that incorporate attitude error correction mechanisms and actuators to correct attitude in real-time may be employed for enhanced attitude control.

IV. CONCLUSION

The study has effectively presented the behavior of 1U, 2U and 3U CubeSats in LEO, under the influence of aerodynamic torque. This was in addition to the B-Dot controller implementation for the detumbling phase, to ensure that the angular rotations are reduced so the effects on attitude alone may be observed. At an altitude of 1000km, aerodynamic attitude stabilization is not useful since the effect of aerodynamic drag and hence torque is insignificant. The only exception is the 1U CubeSat, since it requires less amount of aerodynamic torque for stabilization, due to its smaller size. However, as the altitude was lowered, reasonable aerodynamic attitude stabilization was achieved. This could be used for coarse pointing requirements, as the attitudes in some orientations still remain uncontrolled, but within acceptable limits. Moreover, the simulations involved simplifications to the model, as only the effect of varying altitude was investigated. Orbital parameters were not taken into consideration. For a more detailed analysis, orbital parameters could be altered and their effects can be analyzed further, to account for orbital perturbations. Additionally, CubeSats with aerodynamic attitude stabilization are usually equipped with deployables, which change the aerodynamic drag (as opposed to the simpler cubic/prism structure presented here). More accurate models for the Earth magnetic field and aerodynamic drag could aid in a better understanding of the results.

V. REFERENCES

[1] Alvenes, F 2012, *Satellite Attitude Control System*, Norwegian University of Science and Technology.

[2] Bråthen, G 2013, *Design of Attitude Control System of a Double CubeSat*, p. 112, available at http://www.divaportal.org/smash/record.jsf?pid=diva2:617039.

[3] Hughes, PC 1986, *Spacecraft Attitude Dynamics*, John Wiley & Sons.

[4] Karataş, S 2006, *Leo Satellites: Dynamic Modelling, Simulations and Some Nonlinear Attitude Control Techniques*, p. 95, available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.467.4448&rep=rep1&type=pdf.

[5] Khalil, KI and Samwel, SW 2016, 'Effect of Air Drag Force on Low Earth Orbit Satellites During Maximum and Minimum Solar Activity', *Space Research Journal*, Science Alert, vol. 9, no. 1, pp. 1–9. doi: 10.3923/srj.2016.1.9.

[6] Melina, R 2017, *International Space Station: By the Numbers*, available at: https://www.space.com/8876-international-space-station-numbers.html.

[7] Samwel, SW 2014, 'Low earth orbital atomic oxygen erosion magnitude effect on spacecraft materials', *Space Research Journal*, vol. 7, pp. 1–13.

[8] Selva, D & Krejci, D 2012, 'A survey and assessment of the capabilities of Cubesats for Earth observation', *Acta Astronautica*, vol. 74, pp. 50–68. doi: 10.1016/j.actaastro.2011.12.014.

[9] Tudor, Z 2011, *Design and implementation of attitude control for 3-axes magnetic coil stabilization of a spacecraft*, NTNU.

[10] Wiley J Larson & Wertz, JR 2006, *Space Mission Analysis And Design*. Third Edit. El Segundo, CA: Microcosm Press and Springer.

Development of UiTMSAT-1: An Approach to Lean Satellite Concept

S.N. Mohamad Rahim[1], S.N.K. Mustafa[1], M.H. Azami[1], S.B.M. Zaki[1,2], S.A. Enche Ab Rahim[1], M.H. Jusoh[1*], M. Cho[2], and BIRDS-2 Members[2]

[1]*Faculty of Electrical Engineering, Universiti Teknologi MARA (UiTM), Shah Alam, Selangor, Malaysia*

[2]*Laboratory of Spacecraft Environmental Interaction Engineering (LaSEINE), Kyushu Institute of Technology (Kyutech), Japan*

This paper presents the development of the UiTMSAT-1 nanosatellite and the approach towards a lean satellite concept. The lean satellite concept comes from extensive reports and discussions among many satellite developers and space players with the increased capability and technology in producing small satellites from the introduction of the CubeSat Project. The concept makes aware the importance of low-cost technology and fast delivery system of the satellite as compared with the traditional satellite development process. The UiTMSAT-1, which is the Universiti Teknologi MARA (UiTM)'s first nanosatellite, underwent the lean satellite concept and scheduled development in its BIRDS-2 project. A work breakdown structure was created to have a well-defined description of the divisions involved in the UiTMSAT-1 nanosatellite development. UiTM, as the stakeholder of Malaysia's team in the BIRDS-2 project contributed during the whole process including the installation of the UiTM ground station to track and monitor the nanosatellites. A brief analysis was presented based on the UiTMSAT-1's housekeeping data of approximately three months preliminary observations since its deployment into orbit.

Keywords: UiTMSAT-1; nanosatellite; lean satellite concept

I. INTRODUCTION

CubeSat is a cubic-like structured small satellite. It has a standardized platform of 1U with a limited weight of not more than 1.33kg and 10 cm length for each side. The standard was introduced by the CubeSat Project in 1999 which intended to decrease the satellite development duration and cost, and to increase launch opportunity (Mehrpavar *et al.*, 2014) with standardized satellite buses structures, and subsystems. This project enabled academia and commercial corporations to perform space research and exploration at an affordable cost. It led to many studies and research work on the development of a small satellite. Continuing from the CubeSat introduction, studies were conducted on the design of small satellites for low earth orbit (LEO) store-and-forward (S&F) automatic packet reporting system (APRS) applications (Addaim *et al.*, 2007; 2008a; 2008b). The research concentrated on designing reliable LEO nanosatellites with APRS capability and S&F technology for data collection purposes. The design used low-cost components which made the technology achievable and practical.

Advancing to the year 2009, the Institute of Space Technology (IST) in Pakistan started a student satellite program called ICUBE based on the conceptual development of the CubeSat Project. The program gave students the educational values, skills and first-hand experience in developing satellites (Mahmood *et al.*, 2011). The program's main objective was for students to be involved in the designing, developing, integrating and launching processes of picosatellites. The second objective of the program was related to the communication, in-orbit operation and collection of the satellite's data. As a result of the program, their first satellite, ICUBE-1, was

*Corresponding author's e-mail: huzaimy@salam.uitm.edu.my

developed and launched in 2013. The existence of ICUBE-1 proved that the CubeSat Project was beneficial in creating an educational project within academia.

In addition, in 2017, the INSPIRE-II, with its purpose of technology and thermospheric research, was deployed from the International Space Station. INSPIRE-II was a 2U CubeSat which was part of the satellite constellation of the QB50 project. The CubeSat was developed by a group of undergraduate and postgraduate students from the University of Sydney, Australia (Soh *et al.*, 2013). Similarly, an educational project on satellite development also emerged in Canada at the initiative of the Canadian CubeSat Project (Canadian Space Agency 2018). This project offered post-secondary institutions' students the opportunity to participate in a space mission. The project allowed the winning teams the opportunity to design and build their own CubeSat satellites. From the above mentioned examples, it could be concluded that the introduction of the CubeSat Project had inspired many research studies in space exploration and nanosatellite technology.

II. LEAN SATELLITE CONCEPT

The ability and feasibility to produce small satellites had increased for both academia and commercial corporations like Planet Labs (Boshuizen *et al.*, 2014) with the introduction of the CubeSat Project. In fact, small satellites like CubeSat had gained popularity due to their lower cost and fast delivery. Due to that, the term "Lean Satellite Concept" was introduced at the International Workshop on Small Scale Satellite Standardization (IWS4) in November 2014 (Cho *et al.*, 2015). Usually, the conventional satellite developers emphasized more on the functionality and linearity of the satellites with thorough testing procedures on the design and the requirement to avoid any risk, for example in the ICUBE-1 CubeSat which was developed by using the proven commercial off-the-shelf (COTS) components (Mahmood *et al.*, 2011). On the other hand, the lean satellite concept proposed a low-cost, non-traditional risk-taking approach in its design by a smaller number of team members (Cho, & Graziani, 2017). Furthermore, the delivery time of the satellite based on this concept was shorter than that of the conventional satellite, thanks to the simplified procedures which focused on the significance tests as per the satellite's specifications and requirements.

Furthermore, the development of CubeSat by using the lean approach which utilized non-space-grade COTS components in its design reduced the development cost of the satellite and made the satellite technology more accessible to those who had limited funds/budget. Consequently, the participation from universities in the research and development of CubeSat had increased. Following the new concept, satellite development activity had been structured to fit the lean approach such as in the Horyu-4 project (Masui *et al.*, 2015) and the AOBA-VELOX III project (Cho & Fukuda 2017).

The introduction of the lean satellite concept also created many opportunities for undergraduate and graduate students to receive hands-on experience in developing satellites such as in the Joint Global Multi-Nation Birds Satellite (BIRDS) projects. The BIRDS project was hosted at the Kyushu Institute of Technology (Kyutech), Japan. This project provided a platform for students from developing nations to learn about satellite development (Khan *et al.*, 2015). Until today, there had been four BIRDS projects conducted by Kyutech, with UiTMSAT-1 being the outcome of the BIRDS-2 project.

III. UiTMSAT-1

In the BIRDS-2 project, three identical IU CubeSats were developed. These CubeSats were built by a group of students from four nations; Japan, Malaysia, the Philippines, and Bhutan. Two UiTM (Malaysia) students with another nine students; three from Japan, two from the Philippines, and four from Bhutan made up the

BIRDS-2 members. UiTMSAT-1 was the name for Malaysia's nanosatellite, MAYA-1 and BHUTAN-1 were the names for the Philippine's and Bhutan's nanosatellites, respectively. These nanosatellites were launched to the International Space Station (ISS) by using the SpaceX Falcon 9 rocket from Cape Canaveral Air Force Station, Florida, USA on June 29th, 2018, and were successfully deployed into the LEO orbit by 'Kibo', the Japanese experimental module, on August 10th, 2018. These nanosatellites had been orbiting and transmitting their beacons in continuous wave (CW) Morse code which had been successfully received by the multiple BIRDS ground stations network.

UiTMSAT-1 went through several developmental stages like any conventional satellite such as mission definition review (MDR), preliminary design review (PDR), critical design review (CDR) and flight model (FM) as shown in Figure 1. As a result of the lean satellite concept approach, the development of UiTMSAT-1 from the project's kick-off until its delivery to the Japan Aerospace Exploration Agency (JAXA) took approximately 15 months compared to the conventional developmental process cycle which had more and complex stages.

Figure 1. Different developmental stages of UiTMSAT-1

The first developmental stage was MDR, which was held about one month after the project's kick-off. In the MDR, a presentation review was done to:

1. Define the main objective of the project.
2. Introduce the team members of the project with task/mission assigned.
3. Discuss the mission proposed for the project.

Each proposed mission went through some considerations of its merits, the mission mode (block diagram and flow chart), the requirement of the mission mode (system requirement, design requirement, and verification requirement), the mission feasibility (as CubeSat had several restrictions in power, size, interface, cost, weight), the key tasks in the development process (design schematic, required environment test), and finally the mission's success levels had to be determined (full, medium, and minimum). At the end of the review, the missions for UiTMSAT-1 were established.

After the MDR, the students worked on the development of the breadboard model (BBM) and individual subsystem test. Following the progress of UiTMSAT-1, a presentation review was conducted at the Preliminary Design Review (PDR) stage. The activities during the PDR presentation included:

1. Make a full Requirement Allocation Sheet (RAS) in a table for all missions and bus system.
2. Present the work breakdown structure (WBS) which included missions, bus system, management, procurement and inventory, integration and testing, integration and testing with a ground station (GS), outreach and advertisement, data distribution, frequency coordinator, safety review.
3. Review flow chart of work plan before and after PDR.

At this PDR presentation stage, the members also presented every mission and subsystem with an updated objective, success levels, block diagram, flow chart and requirement mission mode. Additionally, the test results of the individual and integration functionality of components on the BBM such as the functional test of the flash memory and the connectivity test of the sensor to the MCU, the result analysis and the task schedule before CDR were also discussed. Through this review, the members managed to verify mission feasibility before designing the engineering model (EM) of UiTMSAT-1.

The development of the EM started with the proposed schematic and board design agreed during the PDR. All components, boards, battery box, and the structure were purchased. The developed EM underwent comprehensive requirement testing and the progress was discussed during the CDR presentation. The objectives of this review were to verify the integration mission and subsystem's result before developing the FM. The key points which were reviewed at this stage were:

1. The flow chart of work plan before and after CDR.
2. The updated objective, success levels, block diagram, flow chart and requirement mission mode for each mission and subsystem with detailed schematics on board.
3. The results of the thermal vacuum test (TVT) and the vibration test (VT).
4. The result of the individual (and integration) functionality test of EM.
5. The analysis result for each mission and subsystem.
6. The mission and subsystem's task schedule before FM.
7. The presented end-to-end test (GS-satellite wired or wireless) result.
8. The presented long-distance test (GS-satellite wired or wireless) result.
9. The presented long duration test (GS-satellite wired or wireless) result.
10. The presented antenna deployment test result.

Lastly, the UiTMSAT-1 FM review was conducted. The activity before the review included a re-purchase on the EM design to make minor changes and improvement based on the comments from the CDR stage. With the changes, several testing procedures were re-done such as the space environment tests, the antenna deployment test and the testing of GS-satellite (wireless) which included end-to-end test, long-distance test, and long duration test.

Furthermore, solar simulation test of each solar panel board was also performed to complete the integration of UiTMSAT-1's FM with a solar panel. Despite taking the lean concept approach, the completed FM passed the strict safety requirement review and inspection by JAXA engineers before its delivery to JAXA. This delivery was made possible with detailed supervision via the work breakdown structure planned.

IV. WORK BREAKDOWN STRUCTURE (WBS)

The UiTMSAT-1 project was composed of four divisions as shown in Figure 2. It incorporated the lean satellite concept in the development, service, and crossing work elements to ensure a successful project.

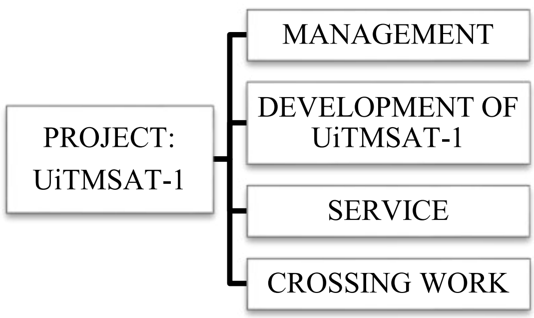


Figure 2. WBS of UiTMSAT-1

A. Management

For UiTMSAT-1, there were two bodies involved in the scheduling management and procurement parts management to maintain the project flow:

1. Laboratory of Spacecraft Environmental Interaction Engineering (LaSEINE),

Kyutech: The development activities of UiTMSAT-1 were centered at LaSEINE.

2. Center for Satellite Communication (UiTMSAT), Faculty of Electrical Engineering, UiTM: Monitored the progress and actively participated at each development stage review.

B. Development of UiTMSAT-1

The development of the UiTMSAT-1 included structure, four subsystems and missions as shown in Figure 3. Its bus subsystems consisted of the communication (COM), the electrical power system (EPS) – main circuitry for nanosatellite power supply, the on-board computer (OBC), the altitude determination and control system (ADCS) part to control the nanosatellite orientation in space. Respecting the lean satellite concept approach, non-space-grade COTS components were used in the development of UiTMSAT-1. The usage of these components reduced the development cost, but it required accepting certain risks related to the chosen components. Nonetheless, specific test procedures were executed to ensure the reliability and good functionality of UiTMSAT-1.

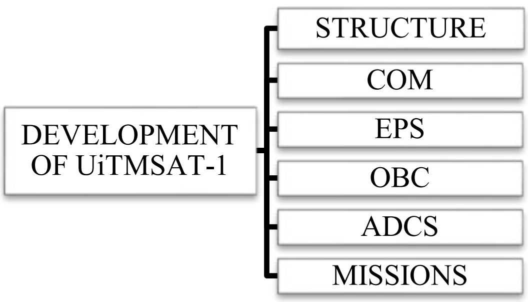


Figure 3. Components in the development of UiTMSAT-1

Figure 4 shows the internal boards' configuration of UiTMSAT-1 that was designed for EM. The design of the boards was based on the missions and systems.

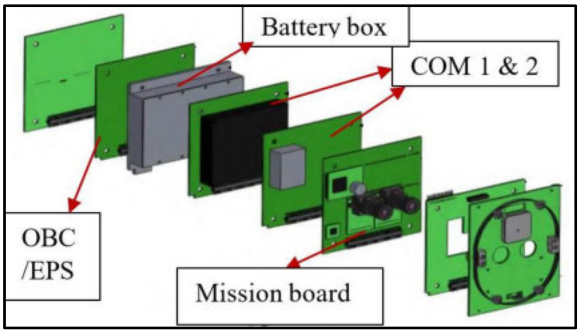


Figure 4. Boards layout of UiTMSAT-1 (Maeda *et al.*, 2017b)

1. On-board computer (OBC)

The roles of the OBC were to organize telecommands, supervise the health status and generate beacon signal for UiTMSAT-1. Its design specification was from the legacy of the HORYU-II and BIRDS-1 satellites of Kyutech (Maeda *et al.*, 2017a). One temperature sensor was assigned to monitor the OBC's temperature as the OBC could only be operated in the range of -55 to +125 degrees Celsius.

2. Electrical power system (EPS)

The UiTMSAT-1's EPS consisted of the battery box and solar panels. Battery played an important part in powering the nanosatellite. The battery would store, regulate and distribute the required power for the whole system and the mission's operation. Hence, it was carefully designed with a special box which fitted six Ni-MH batteries in 3S-2P configuration (3 series, 2 parallel). These batteries had built-in heaters to regulate the thermal constraints in space and temperature sensor for monitoring. Abnormality of the battery sensors' data might indicate a malfunctioning battery.

3. Communication boards 1 and 2

Communication board 1 (COM 1) contained an ultra-high frequency (UHF) transceiver for

UiTMSAT-1's beacon, uplink, and downlink communication. A thermal sensor was placed at this board as part of the housekeeping data. Any anomaly in the data from the sensor at COM 1 would provide an indication about the condition of the communication subsystem. COM 2 functioned similarly as COM 1 where it held the APRS/S&F transceiver for two technology demonstration missions (S&F and APRS digipeater). These missions could not be executed if the COM 2 board was not working.

4. Mission board

The mission board held ADCS and missions related modules such as camera, Global Positioning System(GPS), anisotropic magnetoresistance magnetometer (AMR-MM), APRS digipeater (APRS-DP) and store-and-forward (S&F). These electronic modules would dissipate heat when in use; hence specific rules were required to execute the command. Any temperature irregularity might disturb the function of the mission's module and its technology demonstration purpose. There were six technology demonstration missions which were:

1. Camera: Two camera modules (COTS) installed on UiTMSAT-1 to capture 5 Megapixel (MP) of Earth images of the participating country.
2. Demonstration of a COTS APRS-DP: This technology offered real-time digital communication service to the amateur radio community.
3. Demonstration of an S&F system for remote data collection: Using the terminal node controller (TNC) and very high frequency (VHF) transceiver of APRS-DP, this mission aimed to simulate S&F technique with UiTMSAT-1 capability.
4. Demonstration on the COTS GPS technology: With 80-mW low power GPS, UiTMSAT-1 was capable to display its coordinates in space.
5. Anisotropic magnetoresistance magnetometer (AMR-MM): A sensor onboard the UiTMSAT-1 to measure the magnetic field in space, which offered data coupling possibility with measured magnetic field executed on the Earth's ground.
6. Single event latch-up detection (SEL): Hereditary mission from BIRDS-1, which aimed to observe any correlation of SEL occurrence related to locations and time of the orbiting CubeSat and space weather environment.

C. Development of UiTMSAT-1

Meanwhile, UiTM Shah Alam installed a satellite ground station as Malaysia's satellite Earth station for the overall BIRDS project. This would be further discussed in section V.

D. Crossing Work

Crossing work division involved the integration of the developed satellite for complete testing. Comprehensive testing procedures included integration testing with UiTMSAT-1 subsystems and missions, plus the integrated testing between the UiTMSAT-1 and a ground station (GS).

The development, assembly and testing processes were done at LaSEINE of Kyutech. The assembly process of UiTMSAT-1 was done inside Kyutech's clean room. Several testing procedures were carried out based on the specified environmental requirement to fit the safety review requirement for nanosatellites. Aligned with the lean satellite concept in its risk-taking and short delivery time approaches, UiTMSAT-1's space radiation test was not carried out, but two significant tests were conducted to verify that the developed model of UiTMSAT-1 fulfilled the qualification requirement. The specific tests conducted were the thermal vacuum test and the vibration test.

Based on the Japanese Experiment Module (JEM) Payload Accommodation Handbook Small Satellite Deployment Interface Control Document (JAXA 2015), the environmental conditions for thermal and vibration were:

1. Thermal environment
   i. In H-II Transfer Vehicle (HTV): +5 ~ +32 degrees Celsius
   ii. SpaceX: +18.3 ~ +30 degrees Celsius

2. Vibration (Launch) environment
   i) H-II Transfer Vehicle (HTV): 8.34 g
   ii) SpaceX: 8.67 g

The main purposes of the thermal vacuum testing were to meet the qualification requirements under vacuum condition and extreme temperature, besides the thermal stressing environment. The machine would reproduce the extreme hot and cold temperatures in the vacuum condition of space. Functionality test of the UiTMSAT-1 was performed before, during and after the TVT to ensure the satellite could withstand the environment and pass the functionality test.

Another test done on UiTMSAT-1 was a vibration test. By utilizing the HTV and SpaceX launch vehicle profiles, UiTMSAT-1 went through the vibration testing process to confirm it could endure the launch condition. The satellite experienced vibrations and loads comparable to the assumed condition on the launch. This testing ensured the condition of UiTMSAT-1 and its functionality after the launching.

Additionally, UiTMSAT-1 also underwent several other integration testing procedures such as the functionality test (individual and integrated subsystem), screening battery test, fit (frame) test using J-SSOD, antenna deployment test using the despatch chamber, radiation pattern test in an anechoic chamber, radiation test at Kyushu University in Japan, solar panel assembly and the Solar Simulation test. The integration testing of UiTMSAT-1 with a ground station included the end-to-end test (wireless) for near and far distance, anechoic test, long distance test at a 5-km distance (between the ground station at Kyutech and Mount Sarakura in Japan) and long duration test (one-week test with solar simulator).

V. UiTM GROUND STATION

The UiTM ground station was installed at UiTM Shah Alam, Malaysia to support UiTMSAT-1's monitoring and the BIRDS-2 project. It has been in operation since December 2017. The ground station employed amateur radio frequency and had two different Yagis. These antennas operated in the range of 144 - 148MHz for the VHF Yagi antenna and 430 - 438MHz for the UHF Yagi antenna.

The UiTM ground station is a member of the BIRDS Ground Station Network with its main mission in monitoring BIRDS-2 nanosatellites. Besides UiTM's GS and Kyutech's GS, the BIRDS Ground Station Network consisted of another eight participating countries of the BIRDS Project (Pradhan *et al.*, 2018) as illustrated in Figure 5. All the GS members have been monitoring and updating the health status of UiTMSAT-1, MAYA-1, and BHUTAN-1 nanosatellites since their deployment. The Lean satellite concept with its low-cost approach was used in the design of the satellite ground station. The use of amateur radio frequency bands in the ground station setup allowed lower cost in comparison with the commercial communication radio frequency bands. Additionally, more satellite's data could be obtained effortlessly with this network of ground stations.

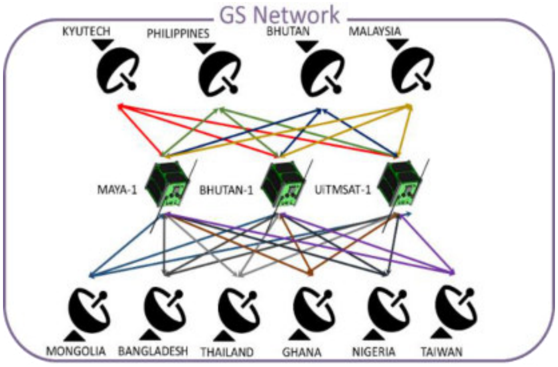


Figure 5. BIRDS ground station network

Among the devices and equipment installed at the ground station were:

1. ICOM 9100 Radio Transceiver.
2. G-5500 Rotator and GS-232 Computer Interface Rotator.
3. Terminal Node Control (TNC): TNC was connected to the ICOM radio transceiver, it was also connected to the control PC using USB interface. It had several units of LED that worked as an indicator for each receive and transmit activity generated from the satellite and control PC.

During the time the satellite passed over the station, with guidance from SATPC32 for satellite tracking, the ground station operator could receive several CW Beacons of the tracked satellite. The UiTM ground station had a few computer softwares to aid the beacon capturing process. For example, CWGet, this was the software to decode the satellite's CW Morse code beacon via sound card into readable text. Its set up only needed a radio/receiver and computer with a sound card. The readable Morse code character was displayed for the operator to do further analysis. Figure 6 shows a screenshot of the CWGet software.


Figure 6. UiTMSAT-1's beacon reception display on CWGet. The dotted box was zoomed-in to display the text "BIRDMY". BIRDMY was the UiTMSAT-1's satellite identification

VI. PRELIMINARY OBSERVATIONS: HOUSEKEEPING (HK) DATA

The BIRDS-2 nanosatellites were monitored at the UiTM ground station day and night. The satellite tracking operation was scheduled by the BIRDS-2 members. The schedule allowed the ground station operator to track nanosatellites alternately between UiTMSAT-1, MAYA-1, and BHUTAN-1; one chosen nanosatellite per day. The HK data observations were done by analyzing the CW Morse code beacon for UiTMSAT-1 nanosatellite specifically since its deployment. The analysis was useful for improving future satellite building. The CW Morse code beacon had 20 Hex characters that carried the satellite's health status. The beacon transmission was a repetitive process which went on for 30 seconds and was silent for 85 seconds for the transmission command from the ground. With 435.375MHz as the communication frequency, the CW beacon transmitted at a rate of 20 words/min (Maeda *et al.*, 2017a).

The plottings presented in Figures 7-9 were specifically for UiTMSAT-1 with each parameter of the HK data observed; which were the observations on UiTMSAT-1's battery temperature, OBC temperature and battery voltage, respectively.

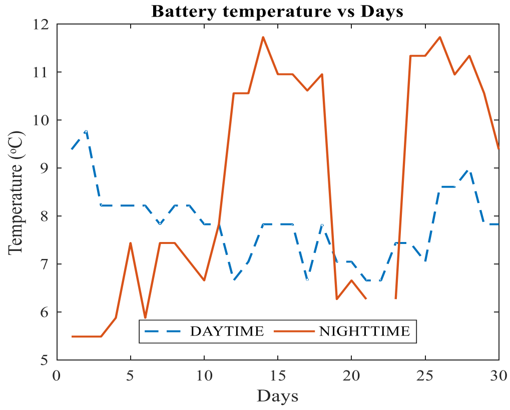


Figure 7. UiTMSAT-1's battery temperature observations

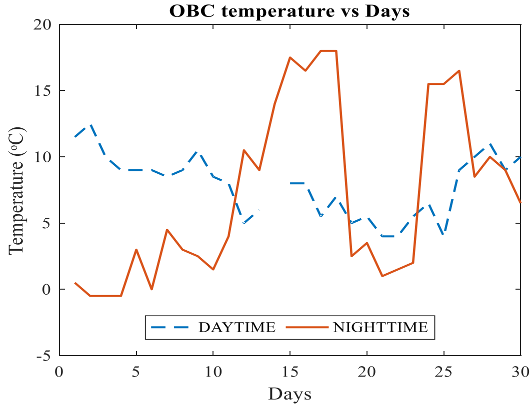


Figure 8. UiTMSAT-1's OBC temperature observations

Based on Figures 7 and 8, the difference between the temperature values of the battery and the OBC varied slightly between nighttime and daytime. One main contributor to the temperature value was the electronic activity and usage of the satellite components which it would generate heat such as the OBC's MCU processing component inside the UiTMSAT-1. Besides, the external surface of the nanosatellite was hotter than the internal area during daytime due to sunlight exposure. With the extreme temperature and vacuum conditions of the space environment, it took some time for the satellite to reach equilibrium. Hence, the heat transfer process from the hotter external to the colder internal occurred slowly. Therefore, if the next satellite passing occurred during the eclipse period or at nighttime, the decoded data would show an increased value compared to the daytime.

Another parameter observed was the battery voltage of UiTMSAT-1 as given in Figure 9. The HK data showed that the voltage was higher during the daytime. This was due to the satellite's battery and solar panel operating. When the satellite received sunlight, the power supply was switched to the solar panel component. The UiTMSAT-1's solar panel was generating the required power for the satellite operations and for charging the satellite's battery with the received sunlight. Hence, the overall battery voltage increased. In contrast, the solar panel was not active during the nighttime, and the operational power was supplied from the charged battery. This discharge activity caused an increase in the current flow thus showing an increased current value for the battery and lowered the battery voltage – based on Ohm's law. This discharge process also dissipated heat and contributed to the higher value of a battery's temperature.

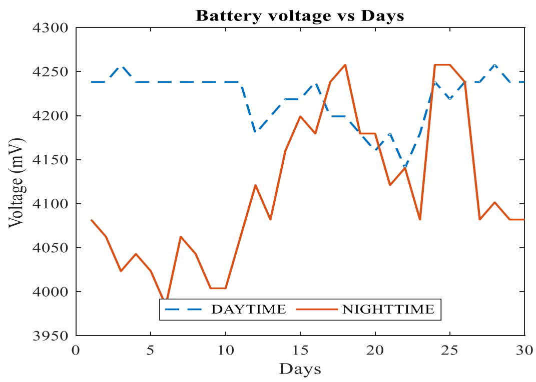


Figure 9. UiTMSAT-1's battery voltage observations

VII. CONCLUSION

As UiTMSAT-1 was the first nanosatellite launched into space by Malaysian academic operators, this project stressed on technology development and demonstration. It involved a multinational collaboration and applied the lean satellite concept approach. Based on the fast delivery of UiTMSAT-1 and the design with non-space-grade COTS components, the lean satellite concept approach was exhibited. UiTMSAT-1's HK preliminary results analyzed at the UiTM ground station also supported the accomplishment of the lean satellite concept approach.

VIII. ACKNOWLEDGEMENT

The work was supported by JSPS Core-to-Core Program, B. Asia-Africa Science Platforms, *Dana Kecemerlangan Akademik* UiTM and the Ministry of Education, Malaysia. The authors would like to extend their appreciation to the BIRDS-2 members and collaborators for their great support and guidance.

IX. REFERENCES

[1] Addaim, A, Kherras, A and Zantou, EB 2007, 'Design of Store and Forward Data Collection Low-cost Nanosatellite', in *2007 IEEE Aerospace Conference*, 3-10 March 2007, Big Sky, MT, USA.

[2] Addaim, A, Kherras, A and Zantou, EB 2008a, 'Design and analysis of store-and-forward data collection network using low-cost LEO Nanosatellite and intelligent terminals', *Journal of Aerospace Computing, Information, and Communication*, vol. 5, pp. 35–46.

[3] Addaim, A, Kherras, A and Zantou, EB 2008b, 'DSP implementation of integrated store-and-forward APRS payload and OBDH subsystems for low-cost small satellite', *Aerospace Science and Technology*, vol. 12, pp. 308–317.

[4] Boshuizen, CR *et al.* 2014, 'Results from the Planet Labs Flock Constellation', in *28th Annual AIAA/USU Conference on Small Satellites, 4-7 August 2014*, Utah, USA.

[5] Cho, M & Fukuda, H 2017, 'Flight results of new technology onboard a lean satellite HORYU-IV', in *International Proceedings of IEEE Region 10 Conference (TENCON), 22-25 November 2016*, Singapore.

[6] Cho, M, Hirokazu, M & Graziani, F 2015, 'Introduction to lean satellite and ISO standard for lean satellite', in RAST 2015 – in *Proceedings of 7th International Conference on Recent Advances in Space Technologies,16-19 June 2015*, Istanbul, Turkey.

[7] Japan Aerospace Exploration Agency (JAXA) 2015, *JEM Payload Accommodation Handbook Small Satellite Deployment Interface Control Document*, vol. 8, pp. 1–101.

[8] Maeda, G *et al.* 2017a *BIRDS Project Newsletter*, no. 15, viewed 1 September 2018, <http://birds.ele.kyutech.ac.jp/>.

[9] Maeda, G *et al.* 2017b, *BIRDS Project Newsletter*, no. 21, viewed 1 September 2018, <http://birds.ele.kyutech.ac.jp/>.

[10] Mahmood, R *et al.* 2011, 'ICUBE-1: First Steptowards Developing an Experimental Pico-satellite at Institute of Space Technology', *Journal of Space Technology*, vol 1, no. 1, pp. 5–10.

[11] Masui, H *et al.* 2015, 'Activity and strategy for lean satellite in Kyushu Institute of Technology', in *RAST 2015 - Proceedings of 7th International Conference on Recent Advances in Space Technologies, 16-19 June 2015*, Istanbul, Turkey.

[12] Mehrpavar, A *et al.* 2014, *Cubesat design specification*, The CubeSat Program, California Polytechnic State.

[13] R. Khan, A *et al.* 2015, 'Five-nations CubeSat Constellation; An Inexpensive Test Case for Learning and Capacity Building', in *3rd IAA Conference on University Satellite Missions and CubeSat Workshop& International Workshop on Lean Satellite Standardization, 30/November - 5/December 2015*, Rome, Italy.

Report: Supporting Space Technology Development

National Space Agency of Malaysia

I. INTRODUCTION

The National Space Agency hosts the National Space Centre in Banting, Selangor. This Centre houses the facilities for space technology development. This note highlights the various facilities that make up the Assembly Integration and Test (AIT) machines and the Mission Control Centre.

Figure 1. The National Space Centre in Banting, Selangor.

II. SATELLITE ASSEMBLY, INTEGRATION AND TEST CENTRE (AITC)

The Satellite Assembly, Integration and Test Centre (AITC) completed in 2011, is a facility that will provide those testing conditions as what will be experienced by the spacecraft and its payload. The cost of a building a spacecraft is never cheap, thus, making it even more important to have it thoroughly tested on the ground to ensure the survivability of the spacecraft exceeds the expectations. Therefore, the AITC facility is constructed to accommodate the testing requirements of both ground-based instruments and fully qualified space-flight hardware.

It offers a wide spectrum of test services, such as the vibration and acoustic test, thermal and vacuum test, electromagnetic compatibility test, as well as mass properties and alignment measurement, all under one roof.

Environmental Conditions of the Facility:

Temperature:	22 ± 3°C
Humidity:	55 ± 10% RH
Particle (<0.5μm):	100,000 unit / ft^3
Ground Connection:	< 1.0 Ω

- ✓ DUT Receiving Airlock
- ✓ Spacious high bay for integration works
- ✓ Mechanical ground support equipment such crane, forklift, etc., are available

Services offered at this facility:

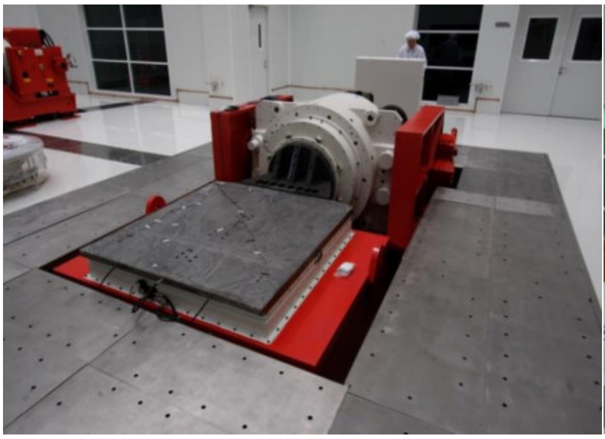
- Sine and/or Random Vibration Test
- High Intensity Acoustic Test
- Thermal and Vacuum Test
- EMI/EMC Test
- Mass Properties Measurement
- Alignment Measurement

Figure 2. Interior of the AIT facility.

A. Vibration Test

The vibration test is used to simulate the low frequency caused by the launch vehicle during the launch process, to ensure that the satellite can withstand the maximum expected flight environment. Vibration tests are conducted to verify the strength and stiffness of the satellite and whether the satellite can function normally after being exposed to such vibrations. This test is critical to ensure that the design and analysis of the satellite's structure meet the requirements of the launcher.

It can also be used to conduct vibration tests for other non-space industries.



Main Specification	Model V994	Model V9
Max Sine Thrust	289 kN	105 kN
Max Random Thrust	267 kN	105 kN
Max Velocity	2.0 m/s	3.0 m/s
Useful Frequency	5 – 1700 Hz	5 – 2700 Hz
Max Load (10g Vector)	2693 kg	1070 kg

B. Acoustic Test Chamber

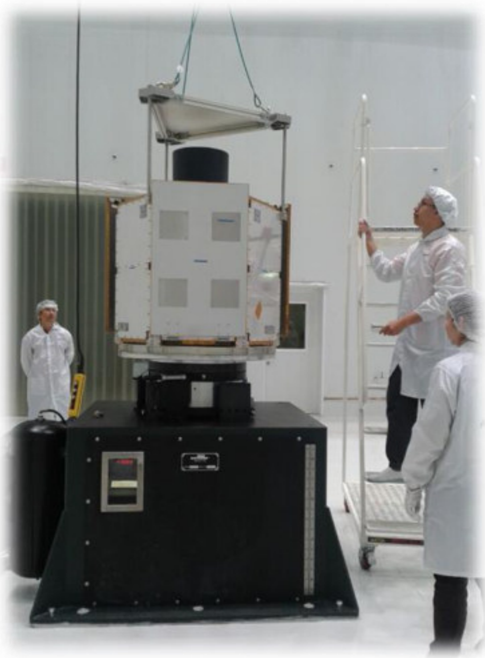
The acoustic chamber is used to simulate the launch process, where a tremendous amount of noise generated in the exhaust plume flowing from the nozzle as the launch vehicle lifts off. The exhaust gas velocity can go as high as 10,000 feet per second, and some of the acoustic energy reflects off the ground and propagates into the vehicle's nosecone. This energy is radiated as sound pressure into the internal volume of the nosecone, where the spacecraft is located in the launch vehicle. In this facility, the noise is generated using gaseous nitrogen coupled with noise producer to transform the kinetic energy of the gas into an acoustic waveform which is then directed into the chamber through specific horns.

Main Specification	
Chamber Volume	≅ 999.5 m^3
Overall Sound Pressure Level	155 dB
Frequency Range	20 – 10,000 Hz
Sound Generating System	Gaseous Nitrogen (GN2)

C. Acoustic Test Chamber

The mass property measurement system will be used to determine and measure precisely and accurately the physical properties of the satellite, its subsystems and payloads, i.e. to determine the centre of gravity and moment of inertia of the satellite in order to provide for satellite positioning control during orbit insertion and attitude control.

Main Specification	
Max Test Weight • Static • Dynamic	 1300 kg 1000 kg
Max Moment of Inertia	1463 kgm²
Range of Spin Speed	30 – 300 rpm
Min Achievable Readout at 100 rpm	44 kgmm²



D. Thermal Vacuum Test Chamber

Thermal vacuum chambers are used to simulate the harsh cycle of extreme temperature (hot and cold) in vacuum condition as experienced by the satellite. The thermal vacuum test which will be performed using TVC is extremely important to ensure that the satellite can survive the harsh environment of space. The test is aimed to verify that each component and subsystem is well protected against the harsh environment so that it will always be operating in its desired temperature range.

Main Specification	
Operational Volume	3.7 m (ϕ)
Ultimate Pressure	10^{-7} mbar
Pumping Rate	10^{-6} within 5 hours
Temperature Range	-180°C – 150°C

E. EMI / EMS Test Chamber

An EMC chamber is used to test and ensure that the electrical and electronic parts in a satellite will not generate electromagnetic disturbances, which may influence other parts of the satellite. In other words, it deals with problems of noise emission as well as noise immunity of the electrical and electronic components and system. It has the capability to conduct EMI/EMC testing in full accordance with MIL-STD-E.

Main Specification	
Operational Area	5m Compliance Full Anechoic Chamber
Frequency Range	20 Hz – 40 GHz

F. Alignment Measurement System

The alignment measurement system is used to undertake precision geometrical alignment measurement specifically for satellite component alignment. The system comprises two units of theodolites complete with alignment optics, one unit of the rotary table, one unit of the flat table and two units of vertical tooling stand as well as data acquisition system.

Main Specification	
Theodolite System Accuracy	0.5 arcsecond
Rotary Table • Indexing Accuracy • Repeatability	 ± 5 arcsecond ± 1 arcsecond

III. MISSION CONTROL FACILITY

Mission Control Facility is owned and operated by the National Space Agency that handles the communications for both uplink and downlink between the ground station and spacecraft especially for Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellite. It has been equipped with a dual function antenna system (S+X Band) with 7.3 meter diameter parabolic dish which can provide Tracking, Telemetry & Control (TT&C) in S-Band and Payload Data Reception in X-Band at maximum data rate 640Mbps. The antenna system can perform in various mode of operation in Auto Track, Program Track and Manual Track on both Right Hand Circular Polarization (RHCP) and Left Hand Circular Polarization (LHCP). The antenna system has a capability in receiving in both data signal RHCP and LHCP simultaneously.

A. Antenna System Specification

This facility has been in operational since 2005 and had successfully provided the services to a number of space missions either local or international such as GIOVE-A Mission from European Space Agency (ESA) and Rocket Launcher GSLV-D05 Mission from Indian Space Research Organization (ISRO).

	S-BAND (TT&C)	**X-BAND (PAYLOAD DATA RECEPTION)**
FREQUENCY		
Uplink	2025 MHz – 2110 MHz	-
Downlink	2200 MHz – 2290 MHz	8000 MHz – 8400 MHz
Effective Isotropic Radiated Power (EIRP)	55dBW	N/A
Gain over Temperature (G/T)	19 dB/K	32 dB/K
Data Rate	Receive: Cortex Quantum XL (up to 20Mbps) Transmit: 10 bps – 10kbps (low) 100bps – 1Mbps (high)	Receive: Payload Data: Cortex HDR XXL (max. up to 640Mbps)
Modulation Supported	Cortex Quantum (PCM/PM, PCM/FM, BPSK, QPSK, OQPSK, SOQPSK, GMSK or AQPSK)	Cortex HDR XXL and Viasat VHR1200 (BPSK, QPSK, OQPSK, UQPSK, 8PSK,16APSK,16QAM)
Link Coding	Descrambling Reed-Solomon Convolutional Viterbi	

Station Location:

- Longitude : 101.50778 °E (101° 30’ 28” E)
- Latitude : 2.78433 °N (2° 47’ 3.59” N)


FASILITI KAWALAN MISI
UTC
4: 17:04
MALAYSIA
12: 17:04
12: 17:04


ViaSat


mosti

IV. OPTICAL CALIBRATION LABORATORY

Optical Calibration Laboratory building was completely built on 10 March 2006. It was the pioneering lab in Malaysia that can calibrate the optical system of a satellite. This lab was fully operational on 6 April 2006 where there is a clean room located inside. It is a double storey building with control room for the clean room, dust control area, loading area on the ground floor while the first floor is a research office.

The services that can be offered to the customer is the radiometric characterisation and calibration include:

i. Dark Response;
ii. Pixel Characterization;
iii. Dynamic Range;
iv. Response Linearity;
v. Noise Characterization;
vi. Equivalent Noise Radiance;
vii. Radiance Saturation;
viii. Signal To Noise Ratio; and
ix. Absolute Radiometric Coefficient.

Environmental conditions of the lab:

Temperature	18 ± 2 °C
Humidity	50 ± 5 %
Particle	Dust particles smaller than 0.5μm: less than 10 000 units/ft^3
Ground connection	less than 10 Ω
Lightning	500 Lux

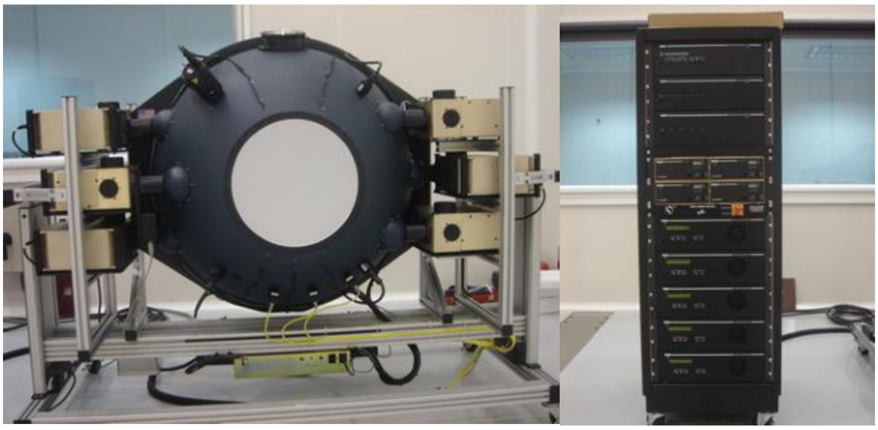
Components:

- Integrating Sphere
  - A 40-inch sphere capable of producing a uniform light source from 400 - 2400 nm.

Peak Radiance	1000 W/m2/sr/µm at ~0.6 µm
Luminance Range	0 – 34000 cd/m^2
Spectrum Simulating	~100% Earth Albedo
Variable Correlated Colour Temperature	3200K to 5900K

- ASD Spectroradiometer
  - Capable of measuring spectral distribution from 350 nm to 1050 nm.
  - Used for monitoring the spectral distribution of light inside the Integrating Sphere.
- Turn Table
  - With 2250 (W) x2000 (L) mm and 1500mm height, it can support the maximum 400kg load with 2000 x 2000 mm footprint size at one time.

- Used to place the satellite/device under test on top of the table and can rotate from its horizontal position to vertical position (90°) in order to align the satellite/device under test imaging system with Integrating Sphere exit port.



Integrating Sphere

Determination of a Localized Mean Sea Surface Model for Malaysian Seas Using Multi-Mission Satellite Altimeter

Muhammad Izzat Zulkifle[1], Ami Hassan Md Din[1,2*], Mohammad Hanif Hamden[1] and Nadia Hartini Mohd Adzmi[3]

[1]*Geomatic Innovation Research Group (GnG),* [2]*Geoscience and Digital Earth Centre (INSTEG), Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Johor, Malaysia*
[2]*UTM-Centre for Industrial and Applied Mathematics (UTM-CIAM), Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia*

Mean Sea Surface (MSS) is the displacement of the sea surface in respect to a numerical model of the earth and it nearly takes after geoids. However, the coastal tide gauges provided to certain coastal areas are limited to ocean studies. Tide gauges are usually installed at coastal areas and only a few stations have long records and adequate geographical distribution. To solve these problems, the use of Satellite Altimeter technology is required. The aim of this study was to produce a new localized mean sea surface model over Malaysian seas using multi-mission satellite altimeters from 1993 to 2017. To understand variations in SSH during the monsoon season, sea surface height climatology data were generated and the average sea surface height data were used to determine the localized MSS of Malaysian Seas. Satellite altimeters are important to producing MSS models that support oceanographic and geophysical studies such as sea level rise studies and tidal predictions. A comparison between altimetry data and tide gauge observations showed good agreement with correlations higher than 0.9 and a Root Mean Square Error (RMSE) lower than 0.1 meter. Then, a localized mean sea surface model was generated using the spatial average of SSH climatology data for a 25 year time period to obtain a high-resolution MSS model. Localized MSS is an important reference for several applications such as charting datum, sea level change, and derivation of mean dynamic topography.

Keywords: Sea surface height; mean sea surface; RADS; multi-mission satellite altimeter

I. INTRODUCTION

Sea surface height is estimated by satellite altimeters, which estimate the vertical of the ocean's surface in respect to a reference surface (ellipsoid) as shown in Figure 1. Mean sea surface is an estimation of the mean of SSH varieties with respect to a discretionary reference ellipsoid computed during a specified time period (Anderson *et al.,* 2009). Development of a localized mean sea surface model is important for Malaysian seas. This is because the MSS model is an important reference for the charting of datum and sea level changes. SSH has also given benefits such as supporting oceanographic and geophysical studies in sea level rise, tidal predictions, and marine geoids. For the past centuries, the main technique used to measure sea level change in the Malaysian region was by using traditional coastal tide gauges that were limited to certain areas. Thus, there are no long-term tide records for the deep ocean due to a gap in sea level change data from tide gauges in Malaysia. Satellite altimeter technology can improve the temporal and spatial resolution of SSH to obtain a global MSS model with high

*Corresponding author's e-mail: amihassan@utm.my

accuracy and high resolution (Jin *et al.*, 2016). By using multi-mission satellite altimeter, regional marine geoid model can be determined. Nornajihah (2017) carried out the study to determine marine geoid over Malaysian seas using multi-mission satellite altimeter by employing the Least Square Modification with Additive Corrections (LSMSA) approach. Moreover, the satellite altimeter technique can also quantify sea level trends as shown in the study by Hamid *et al.* (2018) on optimizing the processing procedures for data from RADS to determine the finest sea level trend and its implication for Malaysian seas.

Currently, the Space Research Centre of the Technical University of Denmark (DTU) and the Centre National e'Etudes Spatiales (CNES) are the only two institutions still publishing the MSS model. The aim of this study was to develop a localized Mean Sea Surface for Malaysian Seas based on a combination of multi-mission altimeters from 1993 to 2017. Altimetry data were used to process SSH and to compare sea level anomaly with altimetry and tidal data for validation. The average of the SSH climatology data for several years was used to map new localized MSS models and variability in Malaysia's seasonal monsoon.

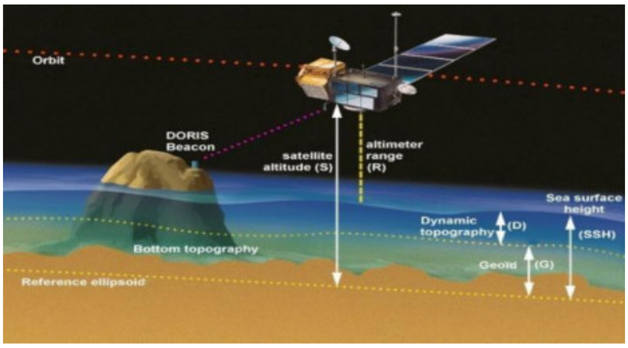


Figure 1. Principle measurement of Jason-2 for oceanographic data observation

Sea surface height, h_{SSH} can be explained based on the following expression of instantaneous sea surface height

$$h_{SSH} = H_{SALT} - R_{Obs} \quad (1)$$

where; h_{SSH} is the instantaneous sea surface height (SSH) from the reference ellipsoid, H_{SALT} is the altitude of the altimeter above the reference ellipsoid and R_{Obs} is the travel time taken between the transmitter to the sea surface and reflection (comeback) back to the receiver on-board. The height of the satellite is determined relative to the reference ellipsoid through the Precise Orbit Determination and Global Positioning System (GPS) (Fu *et al.*, 2001; Din *et al*, 2014). According to Andersen *et al.* (2012), the data undergoes various range corrections using range observations from satellite altimeters to the surface of the ocean or sea. The range corrections need to be applied in the sea surface height formula to obtain an accurate sea surface height. In this study, every atmospheric, instrument, and geophysical correction was conducted as shown in Table 2 to obtain SSH

$$h_{SSH} = H_{SALT} - R_{Obs} - \Delta h_{dry} - \Delta h_{wet} - \Delta h_{iono} - \Delta h_{ssb} - h_{atm} - h_{load} - h_{solidearth} - h_{pole} - h_{oceantide} \quad (2)$$

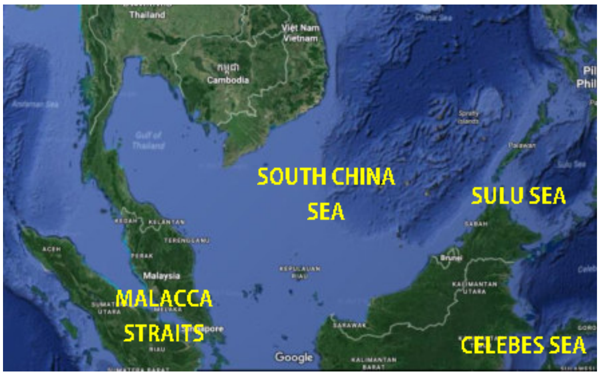
where: R_{Obs} is the formula of c x t/2. *c* is the speed of the radar pulse neglecting refraction and *t* is the travel time observed by the onboard Ultra-Stable Oscillator (USO), Δh_{wet} is the correction for wet tropospheric, Δh_{dry} is the correction for dry tropospheric, Δh_{iono} is the correction for ionospheric, Δh_{ssb} is the correction for sea state bias, h_{atm} is the correction for dynamic atmospheric, h_{load} is load tide effect, $h_{solidearth}$ is solid earth tide effect, h_{pole} is pole tide effect and $h_{oceantide}$ is ocean tide effect.

II. DATA AND METHODS

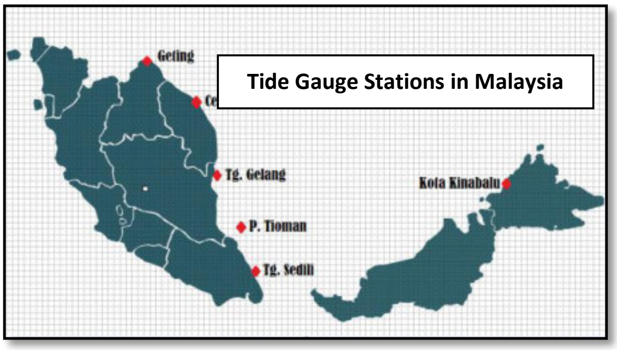
A. Study Area and Data Used

1. Study Area

The area of interest covered Malaysian seas. Malaysian seas within the region of the Malacca Strait, South China Sea, Sulu Sea, and Celebes Sea were selected in this study. The study area ranges from latitude 0°N to 14°N and longitude from 95°E to 125°E as shown in Figure 2.



(a)



(b)

Figure 2. (a) Area of Study Selected; (b) Tide Gauge Stations in Malaysia

2. Satellite Altimetry and Tidal Data

The altimetry data used in this study involved multi-mission satellite altimeter data, which consisted of ten (10) satellite altimeter missions of Topex, Poseidon, Jason-1, Jason-2, Jason-3, ERS-1, ERS-2, Envisat-1, Cryosat-2, Saral, and Sentinel-3A. All the data covered a 25-year period from 1st January 1993 to 31st December 2017. Then, six (6) selected areas for tide gauge data namely Geting, Cendering, Tg. Gelang, PulauTioman, Tg. Sedili, and Kota Kinabalu as shown in Figure 2 were used in this study and also chosen for data verification for the satellite altimetry data. Tidal data was obtained from the Permanent Service for Mean Sea Level (PSMSL) website from 1993 to 2016 (24 years). Tidal data did not require any complicated processing. It only needed cleaning outlier or poor data before utilizing them to perform the analysis.

B. Multi-mission Altimetry Data Processing in RADS

The Radar Altimeter Database System (RADS) is altimeter processing software used to process sea surface height data from satellite altimeters using UBUNTU (Linux) as its operating system (OS). Based on this study, the altimeter data for the study area of Malaysian seas covered 0° N ≤ Latitude ≤ 14° N and 95° E ≤ Longitude ≤ 125° E for extraction. The flow of SSH processing is shown in Figure 3. All corrections were applied to all data using the RADS software as shown in Table 1. Then, crossover adjustment was executed. The area for the crossover was much larger than the actual size of the study area to ensure adequate crossover information. Crossover adjustment minimized the height differences at the crossover location between the ascending and the descending tracks to limit the track and long wavelength errors. Through crossover adjustment, the orbit error of the multi-mission satellites was reduced using NASA product orbit accuracy from Topex/Poseidon, Jason-1, Jason-2, and Jason-3.

Furthermore, data filtering and gridding were implemented. Data filtering was to ensure that the data was free from errors such as unmodeled tides, orbit errors, or residual surface height variability (Anderson *et al.*, 2008; Din *et al.*, 2014). The filtering value used was 1.5 sigma because it yielded the best result for obtaining reliable SLA time series (Hamid *et al.*, 2018). Applying the best sigma in data processing could achieve significant improvements of SLA over the regular RADS product. The data-sparse captured by multi-mission satellite altimeter was then gridded to a specific grid cell size that eventually overspread as points on a grid. The block size for data gridding was 0.25° x 0.25°. This was because Hamid *et al.* (2018) stated that the block size 0.250 was the best parameter for data gridding and it was chosen based on the smallest RMSE values obtained. Data extraction was performed after all of the procedures and corrections were done. Then, data were gridded for multi-mission satellites. Data gridding could be done using either daily or monthly averages before sea surface height was plotted.

Table 1. The correction and model applied for RADS altimeter processing

Correction/Model	Editing (m)		Description
	Min	Max	
Orbit/Gravity field			All satellites: EIGEN GL04C ERS: DGM-E04/D-PAF
Dry troposphere	-2.4	-2.1	All satellites: Atmospheric pressure grids (ECMWF)
Wet troposphere	-0.6	0.0	All satellites: Radiometer measurement
Ionosphere	-0.4	0.04	All satellites: Smoothed dual-freq, ERS: NIC09
Dynamic atmosphere	-1.0	1.0	All satellites: MOG2D
Ocean tide	-5.0	5.0	All satellites: GOT4.10
Load tide	-0.5	0.5	All satellites: GOT4.10
Solid earth tide	-1.0	1.0	Applied (Elastic response to tidal potential)
Pole tide	-0.1	0.1	Applied (Tide produced by Polar Wobble)
Sea state bias	-1.0	1.0	All satellites: CLS non-parametric ERS: BM3/BM4 parametric
Reference	1.0	1.0	DTU15 mean sea surface
Engineering flag			Applied
Applied reference frame biases			Jason-1, Jason-2, Jason-3, and Topex

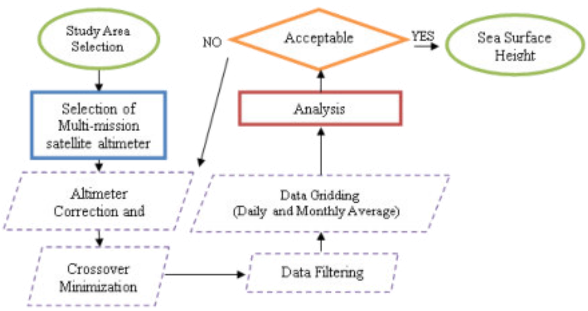


Figure 3. Flow chart of the SSH processing

C. Multi-mission Altimetry Data Computation of Mean Sea Surface

Sea surface height is the main data that needs to be processed and extracted to produce mean sea surface information. Thus, 25 years of SSH climatology data were spatially averaged to obtain the mean sea surface.

$$MSS_{local} = \frac{1}{n}\sum_{i=l}^{n} xi \quad (3)$$

where: MSS_{local} is the localized mean sea surface model, xi is climatology data for Sea Surface Height (SSH), n is the number of points and i is the value of sea surface height. Mean sea surface data was derived using Equation 3 above. All data were merged from several year observations from selected satellite altimeters and gridded using a localized MSS model for Malaysian Seas.

D. Computation of Correlation Coefficient and Root Mean Square Error (RMSE)

Correlation can be defined as a statistic which measures how strong a relationship is between two variables. In this case, the two variables are satellite altimeter data and tide gauge data. Generally, a correlation coefficient known as Pearson's correlation is commonly used in linear regression. The formula used to calculate the correlation coefficient is as follows

$$R = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2][n\sum y^2-(\sum y)^2]}} \quad (4)$$

where: $R$is the correlation coefficient, $\sum xy$ is the sum of tidal and altimetry data, $\sum y$ is the sum of altimetry data, $\sum y^2$ is the sum of Square of Altimetry Data, $\sum x$ is the sum of Tidal Data, $\sum x^2$ is the sum of square of tidal data and n is the number of points.

According to Dancey & Reidy (2004), the value of correlation coefficient, R can be categorized in the form of R values. R value of 1 indicates perfect relationship, 0.7 to 0.9 shows a strong correlation between the two data and 0.4 to 0.6 explains a moderate correlation. Nevertheless, R value that is less than 3 indicates weak correlation between the data. Therefore, in terms of verification, this assumption is valid only if good correlation and RMSE between satellite altimetry and tide gauge time series is achieved (Trisirisatayawong *et al.*, 2011). For RMSE, it is a standard deviation of the residuals where it depicts how concentrated the data is around the best fit. The formula used to calculate RMSE for this study is as follows

$$RMSE = [\sum_{i=1}^{n}(TG - SALT)^2 /n]^{\frac{1}{2}} \quad (5)$$

where: $RMSE$ is the root mean square error, TG is the tide gauge monthly data, $SALT$ is satellite altimetry monthly data and n is the number of points.

III. RESULTS AND DISCUSSION

A. Data Verification: Altimeter verses Tide Gauge

This section discusses the pattern, correlation coefficient and RMSE between tide gauge and satellite altimeter data. In this study, sea level anomaly trends were plotted to understand and analyze tidal characteristics based on the shape of the Malaysian seas as shown in Figure 4.

The correlation coefficient and RMSE between the satellite altimeter data and the Tg. Gelang, Pulau Tioman, Tg. Sedili, Geting, Cendering and Kota Kinabalu tide gauge stations were calculated and plotted. Based on the correlation coefficient and RMSE results in Table 2 and Figure 5, the correlation coefficient between monthly tide gauge data and satellite altimeter data for every selected area was higher than 0.9. As mentioned in section 2.4, it showed that satellite altimetry data had very strong correlation with the selected tide gauge data. The positive trend line shown in Figure 5 explained that the satellite altimetry data went up in almost perfect correlation with the tide gauge data. Moreover, the RMSE for every selected area was less than 0.1m. This meant that both data were concentrated around the best fit line and they did not deviate much between each other. In conclusion, the altimeter processing in this study was successful and that the altimetry data had a decent potential for sea level anomaly and sea surface height determinations using RADS.

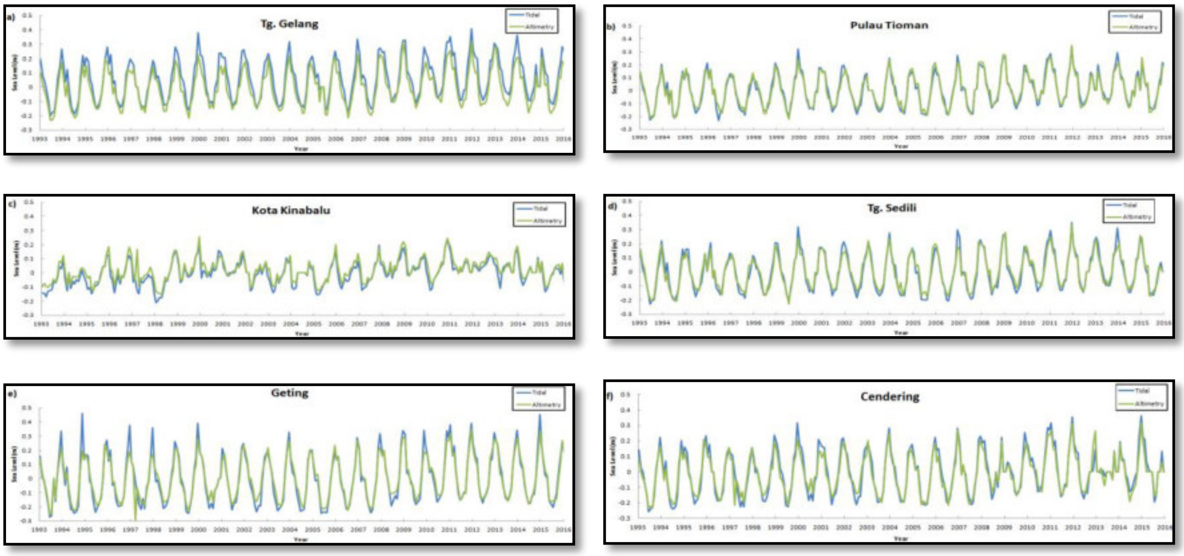


Figure 4. Sea Level Patterns from 1993 to 2016 between Altimetry and Tidal Data

Table 2. Correlation Coefficient and RMSE for selected areas

Tide Gauge Station	Tg. Gelang	P. Tioman	K. Kinabalu	Tg. Sedili	Geting	Cendering
Correlation	0.975	0.955	0.934	0.966	0.969	0.961
RMSE (cm)	6.80	2.88	3.68	3.54	4.59	4.23

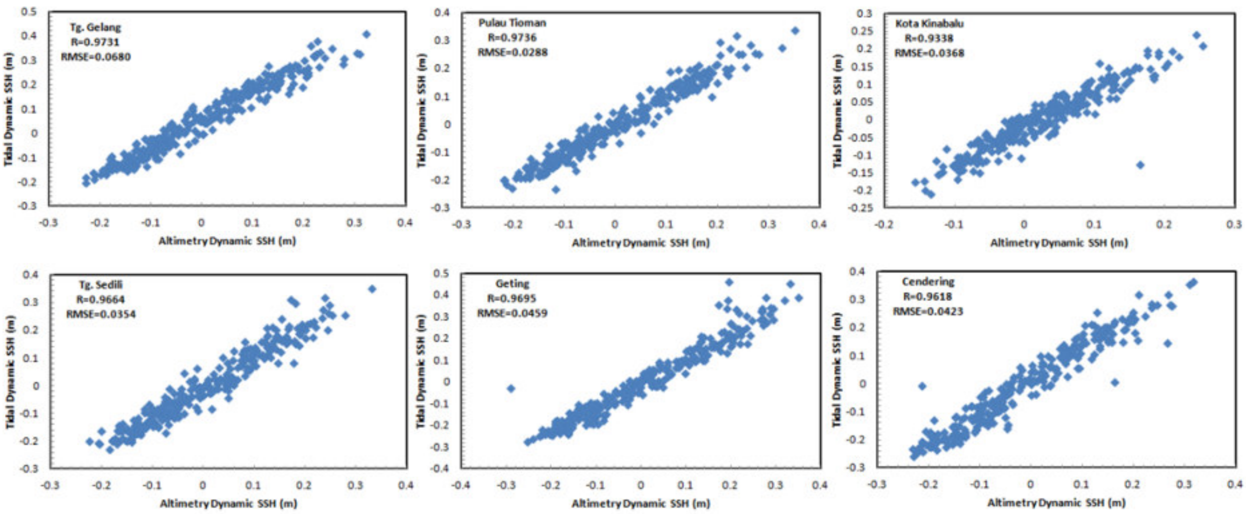
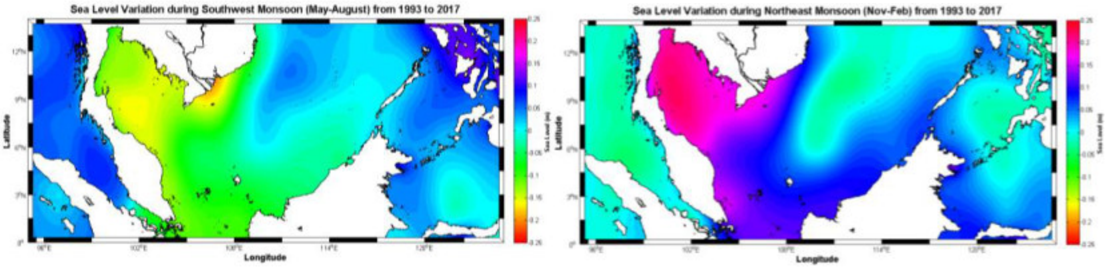


Figure 5. Correlation Coefficient Pattern between Altimetry and Tidal Data

B. Data Sea Level Variations Due to Monsoon Season

The average sea surface height was plotted in light of the two noteworthy Malaysian monsoon seasons, which are the Southwest Monsoon from May to August and the Northeast Monsoon from November to February to produce SSH profiles using climatology information. Sea surface height variations during the Southwest Monsoon are expanding in stature in the Straits of Malacca and declining in the South China Sea (Sang *et al.*, 2015a). Sea surface height variations during the Northeast Monsoon are higher in the South China Sea than during the Southwest Monsoon. Figure 6 shows the sea level variations during the Southwest Monsoon and the Northeast Monsoon. It showed that sea surface height was highest in the South China Sea and lowest in the Straits of Malacca. This was because the east coast states of Peninsular Malaysia and western Sarawak experienced heavy rainfall (Sang *et al.*, 2015b).



(a) (b)

Figure 6. (a) Sea Level Variations during the Southwest Monsoon (May-August); (b) the Northeast Monsoon (November-February)

C. Data SSH Model for Malaysian Seas

Sea surface height (SSH) data for each month were plotted for the selected years using monthly climatology data. The altimetry data below were analyzed to independently verify climatology descriptions from 1993 to 2017. Differences in monthly climatology SSH were marginal and were not seen, by all accounts, critical as shown in Figure 7 for January to December.

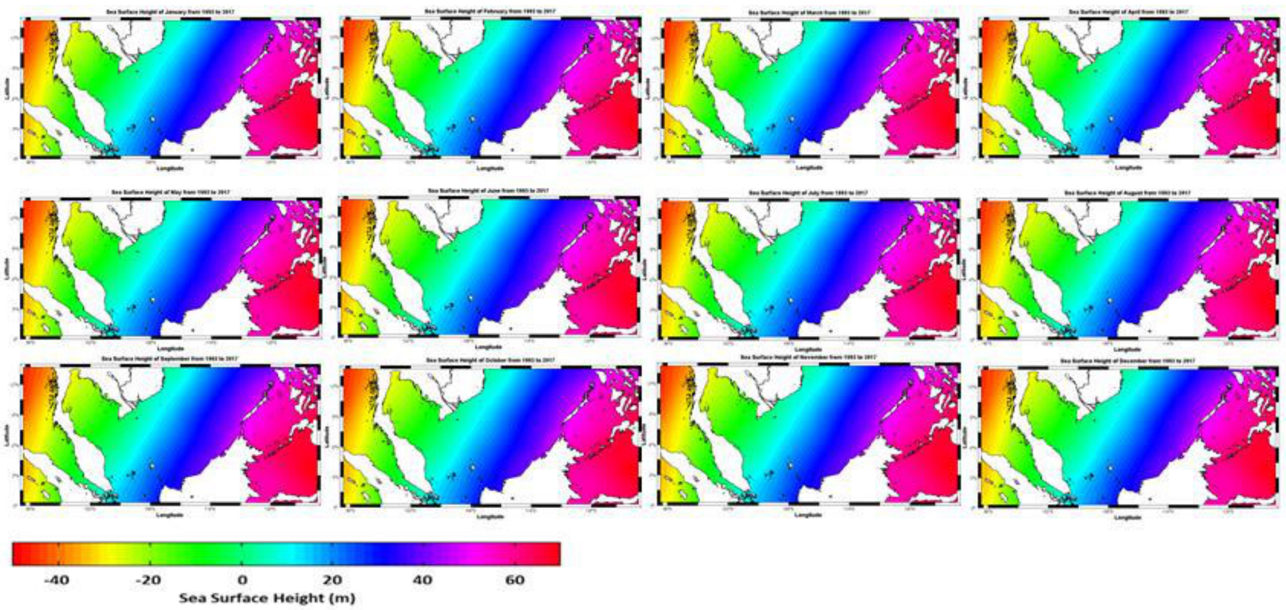


Figure 7. Sea Level Variations January to December from 1993 to 2017

D. Localized MSS Model for Malaysian Seas

Mean sea surface is related to sea level anomalies and sea surface height. The localized MSS model was plotted as shown in Figure 8. It was derived from satellite altimeter data acquired from Topex/Poseidon, Jason-1, Jason-2, Jason-3, Envisat, ERS-1, ERS-2. Cryosat, Saral and Sentinel. Figure 8, shows that the mean sea surface increases eastwards from Peninsular Malaysia towards Sabah and Sarawak. According to Kamaruddin *et al.* (2017), the South China Sea is an open area and has its greatest wind speeds between November to February. Wind speed is one of the factors that contribute to the effect of mean sea surface level. Then, the localized MSS model patterns were affected due to the surface current of the South China Sea. According to Kamaruddin *et al.* (2016), seasonal ocean circulations in the South China Sea are controlled by the Northeast monsoon and the Southwest monsoon.

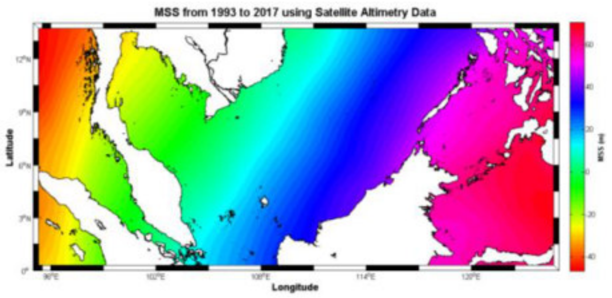


Figure 8. Localized MSS Model for Malaysian Sea

IV. CONCLUSION

Multi-mission satellite altimeter are good instruments that can act as a replacement to traditional tools like coastal tide gauges in the Malaysian region, as traditional tools can only provide data for certain ocean areas. Satellite altimeters can provide good information on sea surface height over Malaysian Seas. Through RADS technology, geophysical corrections were applied to derive sea level anomaly and sea surface height for Malaysian Seas in this study. A comparison between altimeter data and tide gauge observations showed good agreement with correlations, R higher than 0.9 and RMSE less than 0.1m for Tg. Gelang, Pulau Tioman, Tg. Sedili, Geting, Cendering and Kota Kinabalu. Therefore, multi-mission altimeters and tide gauge techniques are competitive. The localized MSS model is an important reference that can integrate geophysical and oceanographic studies on sea level change, vertical datum determination, and global tide model.

V. ACKNOWLEDGEMENT

The author would like to thank TU Delft, NOAA, and the Department of Survey and Mapping Malaysia (DSMM) for providing altimetry and tidal data, respectively. Special thanks to the Geomatic Innovation Research Group (GnG), Faculty of Geoinformation and Real Estate, and Universiti Teknologi Malaysia for helping to complete this research project. We are grateful to the Ministry of Education Malaysia and Universiti Teknologi Malaysia for funding this research under Research University Grant (VOTE number: Q.J130000.2527.19H26).

VI. REFERENCES

[1] Andersen, OB 2008, *Marine Gravity and Geoid from Satellite Altimetry*, Geoid Determination: Theory and Methods, pp. 1–48.

[2] Andersen, B & Knudsen, P 2009, 'DNSC08 mean sea surface and mean dynamic topography models', *Journal of Geophysical Research (Oceans)*, vol. 114 (C11).

[3] Andersen, OB 2012, *Marine Gravity and Geoid from Satellite Altimetry*, Lecture Notes in Earth System Sciences, 110, pp. 401-451.

[4] Dancy, C & J Reidy 2004, *Statistics without maths for psychology*, Harlow: Pearson Education Limited.

[5] Din, AHM, Ses, S, Omar, KM, Naeije, M, Yaakob, O, Pa'suya, MF, 2014, 'Derivation of Sea Level Anomaly Based on the Best Range and Geophysical Corrections for Malaysian Seas using Radar Altimeter Database System (RADS)', *Jurnal Teknologi (Sciences & Engineering)*, vol. 71, no. 4, pp. 83–91.

[6] Fu, LL & Cazenave A, 2001, *Altimetry and Earth Science, A Handbook of Techniques and Applications*, International Geophysics Series, 69, Academic Press, London.

[7] Hamid, AIA, Din, AHM, Hwang, C, Khalid, NF, Tugi, A & Omar, K 2018, 'Contemporary Sea Level Rise Rates around Malaysia: Altimeter Data Optimization for Assessing Coastal Impact', *Journal of Asian Earth Sciences*, vol. 166. doi 10.1016/j.jseaes.2018.07.034.

[8] Jin, T, Li, J, Jiang, W 2016, 'The global mean sea surface model WHU2013', *Geodesy and Geodynamics*, vol. 7, no. 3, pp. 200-209.

[9] Kamaruddin, AH, Pa'suya, MF, Omar, KM, Din, AHM 2016, 'Ocean Surface Circulation Along Peninsular Malaysia's Eastern Continental Shelf from Nineteen Years Satellite Altimetry Data', in *Control and system Graduate Research Colloquium* (ICSGRC).

[10] Kamaruddin, AH, Pa'suya, MF, Omar, KM, Din, AHM 2017, 'Long-term Sea Level Trend from Tidal Data in Malaysia', in *Control and system Graduate Research Colloquium* (ICSGRC).

[11] Naeije, M, Scharroo, R, Doornbos, E, & Schrama, E 2008, *Global Altimetry Sea Level Service: GLASS*, NUSP-2 report GO, 52320.

[12] Nornajihah binti Yazid 2017, 'Marine Geoid Determination over Malaysian Seas Using Satellite Altimeter and Gravity Missions', MSc Thesis. Universiti Teknologi Malaysia, Skudai.

[13] PSMSL 2017, *Permanent Service for Mean Sea Level*, viewed 20 November 2017, http://www.psmsl.org/

[14] Sang, YW, Fakaruddin, FJ, Salleh, FZ, Adam, MKM, Chang, NK, Yunus, F & Abdullah, MH 2015a, *Characteristics of the 2015 Southwest Monsoon in Malaysia*, Malaysian Meteorological Department.

[15] Sang, YW, Yik, DJ, Chang, NK, Adam, MKM, Fakaruddin, FJ, Salleh, FZ, Yunus, F & Abdullah, MH 2015b, *Analysis of the Northeast Monsoon 2014/2015*, Malaysian Meteorological Department.

[16] Scharroo, RE, Leuliette, W, Lillibridge, JL, Byrne, D, Naeije, MC, Mitchum, GT 2012, 'RADS: consistent multi-mission products', in *Proceedings of the symposium on 20 years of progress in radar altimetry*, Venice, Eur. Space Agency Spec. Publ., ESA SP-710; 2013.

[17] Trisirisatayawong, I, *et al.* 2011, 'Sea level change in the Gulf of Thailand from GPS-corrected tide gauge data and multi-satellite altimetry', *Global and Planetary Change*, vol. 76, no. 3.

[18] Yahaya, NAZ, Musa, TA, Omar, KM, Din, AHM, Omar, AH, Tugi, A, Yazid, NM, Abdullah, NM, & Wahab, MIA 2016, *Mean Sea Surface (MSS) Model Determination for Malaysian Seas Using Multi-Mission Satellite Altimeter*, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives 42 (4W1):247–52. https://doi.org/10.5194/isprs-archives-XLII-4-W1-247-2016

Interpretation of Sea Level Variability Over Malaysian Seas Using Multi-Mission Satellite Altimetry Data

Mohd Rusnariansah Mohd Ehsan[1], Ami Hassan Md Din[1,2,3*],
AmalinaIzzati Abdul Hamid[1] and Nadia Hartini Mohd Adzmi[4]

[1]*Geomatic Innovation Research Group (GIG),* [2]*Geoscience and Digital Earth Centre (INSTEG),*
Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia,
81310 Johor Bahru, Johor, Malaysia
[3]*Associate Fellow, Institute of Oceanography and Environment (INOS),*
Universiti Malaysia Terengganu, Kuala Terengganu, Terengganu, Malaysia
[4]*UTM-Centre for Industrial and Applied Mathematics (UTM-CIAM),*
Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

Geographically, West Malaysia is a peninsula surrounded by seas which have their own characteristics and sea water behavior that are influenced by several factors such as the effects of the monsoon season, water circulation, tidal characteristics, El Nino and La Nina phenomena and so on which may affect coastal as well as marine activities. Traditionally, sea level change is observed using tide gauges installed along the Malaysian coastal area. However, the data obtained are limited to the tide gauge station area, the sea level data for the deep sea cannot be obtained and there is no long term record of observation. Therefore, altimeter satellites are used as a new alternative which enable sea level data to be obtained from space observations and to monitor sea level changes via the TOPEX, ERS-1, ERS-2, Jason-1, Jason-2, Jason-3, Envisat, Saral, Cyrosat and Sentinel missions which are available since 1993, thus complementing the tidal gauges. This study focused on the variability of sea levels in Malaysian Seas including the magnitude and trend of the sea level, its characteristics due to seasonal monsoon effects including sea current circulation, tidal characteristics, special events such as El Nino and La Nina, the shape and the characteristics of the Malaysian sea, by using multi-mission satellite altimetery. The acquisition and processing of sea level data were performed by using the radar altimeter database system (RADS). The results of this study indicated that Malaysia's sea levels varied by monsoon seasons, whereas the influence of water circulation, El Nino and La Nina effects were significant for semi-enclosed sea areas such as the Celebes Sea. During the Northeast Monsoon, the sea level of the South China Sea area was higher than in the other areas, while during the Southwest Monsoon, the sea level of the Malacca Straits was higher. The phenomena of El Nino and La Nina, the shape and characteristic of Malaysia's seas, tidal characteristics and ocean circulation also contributed to sea level variability. The results of this study can be used by various agencies in planning and developing Malaysian coastal areas as well as in assisting the development of community economies such as fishery and tourism activities.

Keywords: Sea level rise; sea level variability; satellite altimeter; Malaysian seas

*Corresponding author's e-mail: amihassan@utm.my

I. INTRODUCTION

Since the start of the recent century, global mean sea level (GMSL) has been rising. Ocean temperature rising and ice sheet melting are the primary contributors to the increase in sea level rise besides the effects of regional to worldwide factors such as ocean circulation variability, El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (Stammer *et al.*, 2013). When the monsoons strike, the effects of wind and other factors will influence the sea level variability in terms of the sea level quantity, the effects of nutrients in the sea and the development of eddy, pressure and temperature along the coast of Malaysia. In the Malaysian region, four (4) types of monsoons occur, which is Northeast Monsoon (November to February), Southwest Monsoon (May to August), First-inter Monsoon (March and April) and Second-inter Monsoon (September and October) that cause different weather effects. The different effects brought about by the different monsoon characteristics such as wind speed, ocean circulation and atmospheric variability affect the variability of the sea level in addition to the effects generated by global warming, climate and others.

The difference between land-sea temperature caused by solar radiation is a factor of the monsoon season but the tilting of the Earth caused seasonality (Huffman *et al.*, 1997). The East Asia Summer Monsoon (EASM) occurs during the boreal winter in which rainfall reaches maximum, whereas the East Asia Winter Monsoon (EAWM) occurs when rainfall reaches maximum during the boreal summer (Wang *et al.*, 2014). According to Hamid *et al.*, (2018), satellite altimetery can provide to centimetres accuracy when compared to tide gauge data. As an alternative method from the traditional tide gauge stations, satellite altimetery can be used to solve the gap problem in monitoring sea level changes.

Hence, this research was conducted to study the magnitude and trend of the sea level, its characteristics due to seasonal effects including current circulation, tidal characteristics, specific events such as El Nino and La Nina and the shape and characteristic of the Malaysian seas by using multi-mission satellite altimetery, an alternative for monitoring sea level changes especially for the deep oceans. The area of study covered Malaysian seas, which included the South China Sea, Malacca Straits, Sulu Sea and the Celebes Sea.

II. DATA AND METHODS

A. Data Acquisition and Processing

The satellite altimetry data were extracted and processed by using the Radar Altimeter Database System (RADS) within a 25 year period from January 1993 to 2017 based on sea level anomalies (SLAs). RADS is a processing software that processes altimeter data and conveniently enable users to define suitable corrections to be applied to their data. In this study, the altimeter data extracted ranged between $0^{o}N \leq Lat \leq 14^{o}N$ and $95^{o}E \leq Long \leq 125^{o}E$, which covers the Malaysian seas.

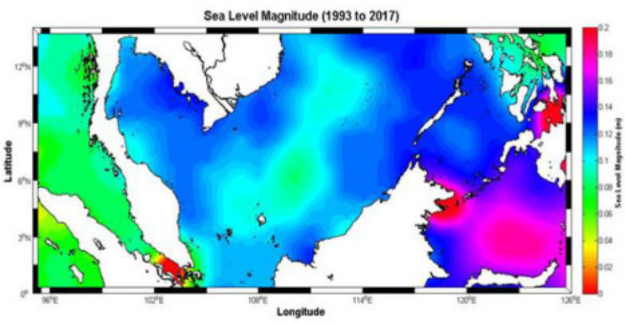
B. Sea Level Anomaly (SLA) Derivation and Extraction

Ten (10) satellite altimeter missions were selected in this study namely TOPEX/Poseidon, ERS-1, ERS-2, Jason-1, Jason- 2, Jason-3, ENVISAT, Saral, Cryosatand Sentinel for the SLA extraction purpose. The period of this satellite altimetry data was within 25 years. However, a few corrections were compulsory to be applied to the sea level derived from satellite altimetry in order to produce accurate and reliable results. The corrections for satellite altimetry data were orbital altitude, sea state bias, altimeter range correction for instrument, dry and wet tropospheric corrections, ionospheric delay, ocean tide loading, solid earth and ocean tides, inverse barometer corrections and pole tide electromagnetic bias. The bias can be reduced by applying these models for each satellite altimeter mission in RADS. Crossover adjustments were performed to integrate data processing for multi-mission satellites after the extraction of sea level data from RADS. In order to obtain "standard surface" for sea surface height (SSH), crossover adjustment was performed due to the instance of orbit error factors and the inconsistency of satellite orbit frame. The minimization was accomplished by adjusting ESA satellites simultaneously with the orbit of the NASA satellites, which were held fixed. The accuracy of satellites launched by NASA (NASA-class) outperformed the orbit accuracy and measurements of the satellites launched by ESA (ESA-class) (Hamid *et al.*, 2016; Hamid *et al.*, 2018).

III. RESULTS AND DISCUSSION

A. Sea Level Trend and Magnitude

The sea level magnitude in Malaysian seas from 1993 to 2017 is shown in Figure 1. The mean SLA differences between 2017 and 1993 indicated a rise in sea level during this 25 year period. Sea level magnitude in the Malacca Straits ranged between 0.02m to 0.08m, while in the South China Sea the magnitude was a little bit higher than in the Malacca Straits, being up to 0.14m. However, in the Sulu Sea and the Celebes Sea, the sea level was much higher compared to the other two Malaysian seas, being up to 0.2m. The sea level rise over Malaysian seas is presented in Figure 3 and it was clearly shown to be different for each sea. The Malacca Straits average sea level rise was 3.64mm/year +- 0.13mm, which was the second lowest for the four seas.



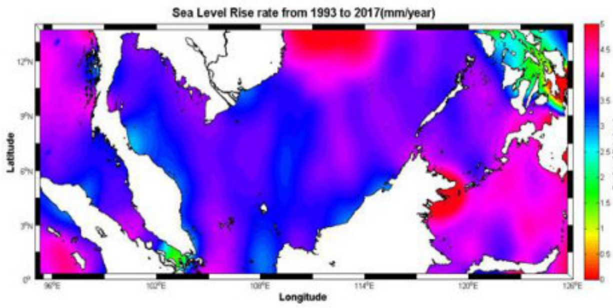


Figure 1. Sea level magnitude and sea level rise rate from 1993 to 2017

The rate was influenced by the depth and the shape of the Malacca Straits. In addition, the annual cycle was disturbed by many higher harmonics (Din *et al.*, 2014, Khairuddin *et al.*, 2019). The time series in the Malacca Straits as shown in Figure 3(a) illustrated an irregular long term tidal anomaly pattern. The South China Sea's mean sea level rise was the lowest among the four seas being 3.55mm/year +- 0.06mm. It consisted of deep basin, shallow shelf and periodic pattern of monthly sea level following the characteristics of mixed tide rather than the diurnal characteristic (Hamid *et al.*, 2016). The Celebes Sea was the highest being 4.24mm/year +- 0.10mm followed by the Sulu Sea which was 3.82mm/year +- 0.10mm. The Sulu Sea and the Celebes Sea are enclosed seas, isolated from the surrounding by a chain of islands such as Borneo and the Philippines Archipelago while the Celebes Sea surrounds Borneo, the Philippines Archipelago and Sulawesi Island. (Wang *et al.*, 2006; Din *et al.*, 2015; Hamid *et al.*, 2016; Hamid *et al.*, 2018). This might explain the significant high sea level rise rates around the Sulu and the Celebes Seas, compared to the other locations. The value of the mean sea level rise for each sea from 1993 to 2017 using robust-fit regression analysis is shown in Table 1.

Table 1. Mean Sea Level Rise

Seas	Mean Sea Level Rise	Stand Error
Malacca Straits	3.64 mm/year	+- 0.13mm
South China Sea	3.55 mm/year	+- 0.06mm
Sulu Sea	3.82 mm/year	+- 0.10mm
Celebes Sea	4.24 mm/year	+- 0.10mm

B. Sea Level Trend and Magnitude

In the Malaysian region, the main factor that clearly affects sea level variation is the monsoon seasons i.e.Northeast Monsoon and Southwest Monsoon. During these different monsoons, there is a distinct effect of wind and ocean circulation that brings different SLA patterns.

1. Northeast Monsoon and Southwest monsoon

Northeast monsoon causes heavy rainfall especially in the east coast of Peninsular Malaysia and western Sarawak. Based on Figure 2, only the Malacca Straits sea level variations remained stable with (0-0.04 m).

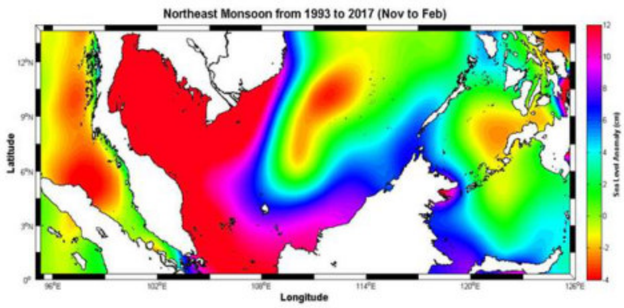


Figure 2. SLA during the Northeast Monsoon

This was because, during that time, winds blew from the Sumatra coast towards the west coast of Peninsular Malaysia with the current flow to the Thailand coastal and the Andaman region (Ku Mansor *et al.*, 2017; Khairuddin *et al.,* 2019). However, for the South China Sea, Sulu and Celebes seas, there were significant changes in variations of sea level. In the South China Sea, some parts decreased in sea level, while others increased. During this time, surface water moved in the anticlockwise direction. Water moved from Vietnam towards the Gulf of Thailand. In the Gulf of Thailand, the surface water flowed in a clockwise direction and after that moved to the south along the coast of Peninsular Malaysia. Along the coast of Borneo, surface water moved along the coast in a southerly direction. This indicated the sea levels along the coast of Peninsular Malaysia were higher than those in the other areas. In addition, surface water deflected to the left in the middle of the sea, and then moved southwards along the coast of Indochina. In the middle of the sea, the sea surface circulation pattern with a gyre moved in an anticlockwise direction. For the Sulu Sea, the sea levels increased by 0.04 to 0.06m, while the Celebes Sea slightly decreased by 0 to 0.02m. The sea level in the Sulu Sea was influenced by the circulation of the South China Sea and the Celebes Sea was influenced by the inflow and outflow of sea water from the Sulu Sea. According to Han *et al.*, 2009, during this time, water flowed inwards to the Sulu Sea at the Mindoro Straits and combined with the Balabac Straits current which flowed eastwards and then outflowed into the Celebes Sea at the Sibutu Passage. The slightly decreasing sea level in the Celebes Sea was because the surface outflow and inflow at the Sibutu Passage towards the Sulu Sea were balanced.

The Southwest Monsoon (May – August) originates from the deserts of Australia and signifies a drier season or weather with minimum rainfall throughout the country except for Sabah in east Malaysia. From Figure 3, there was a significant variation in the sea level around the Malaysian seas. For the

Malacca Straits, the sea level slightly increased by 0.04-0.06m. The current from the Andaman Sea entered the Straits of Malacca then flowed to the Thailand coastal water (Ku Mansor *et al.*, 2017). Both the Sulu and the Celebes Seas slightly decreased with range of 0 to -0.02m. The southwestward currents that brought water from the South China Sea were pushed to the central Sulu basin. However, the outflow current at the Sibutu Passage was basically balanced by the surface inflows into the Sulu Sea from the Mindoro, Balabac, Tablas and Dipolog Straits (Han W. *et al.*, 2008). The Southwest monsoon had a slight effect on the sea level changes. For the South China Sea, the sea level predominantly decreased with range from 0 to -0.04m. According to Pa'suya *et al.*, (2013), during the southwest monsoon, surface water flowed northwestwards at the southern part of the east coast of Peninsular Malaysia towards the coastal area. This was because of the eddy system that influenced the sea surface current and it continued flowing along the east coast of Peninsular Malaysia. After that, the current changed direction about 6°N-7°N to north-eastwards and continued moving along the southeast of the Vietnam coastal area. Then, the current moved southwards with a part of the current turning around 3°–6°N eastwards and reached the Natuna Island and the west of Borneo Island. After reaching Borneo Island, the current turned in a northwest direction.

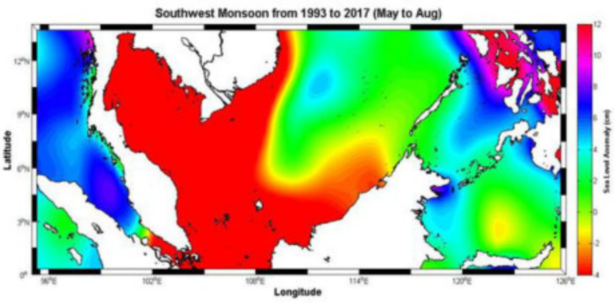


Figure 3. SLA during the Southwest Monsoon

2. El-Nino & La-Nina Events

In this research, the El Nino and La Nina year events were based on the record of the Oceanic Nino Index (ONI) (ONI, 2017). The value of ONI was calculated by averaging the sea surface temperature anomalies in an area of the east-central equatorial Pacific Ocean region (5S to 5N; 120W to 170W).

i. Time Series Analysis of Sea Levels in Malaysian Seas

The effects of El Nino & La Nina could also clearly be seen on small or semi-enclosed areas such as the Malacca Straits. Based on Figure 3, the Malacca Straits is a semi-enclosed area in which the effects of the events could be clearly seen. Therefore, the 1997-1998 and 2002-2003 El Nino effect and the 2010-2011 La Nina effect could be clearly seen in the Malacca Straits. The South China Sea is a vast open sea and theoretically the effects of El Nino & La Nina events were barely seen. The time series indicated a stable time series and there was no sudden drop and sudden rise in SLA. The Sulu Sea is a semi-enclosed area surrounding east Borneo and the Philippines Archipelago and the effects of El Nino and La Nina could clearly be seen. For example, from Figure 3(c), during 1997-1998, the water level falling below 0 was more frequent, indicating strong El-Nino event affecting the sea level. The Celebes Sea is a semi-enclosed area surrounding Borneo and Sulawesi. The effects of these events could also be clearly seen for a particular period recorded by the ONI. The water level dropped during 1997-1998 and during 2015-2016, which clearly indicated strong El Nino event during those times. During 2010-2011, the water level jumped upwards, indicating a moderate La Nina event. The sea level drop also indicated a moderate El Nino during the 2009-2010 period. Therefore, there were certain periods of El Nino and La Nina events recorded by ONI which affected the Malaysian Seas. A summary of the El-Nino & La-Nina events that could be clearly seen are presented in Table 2.

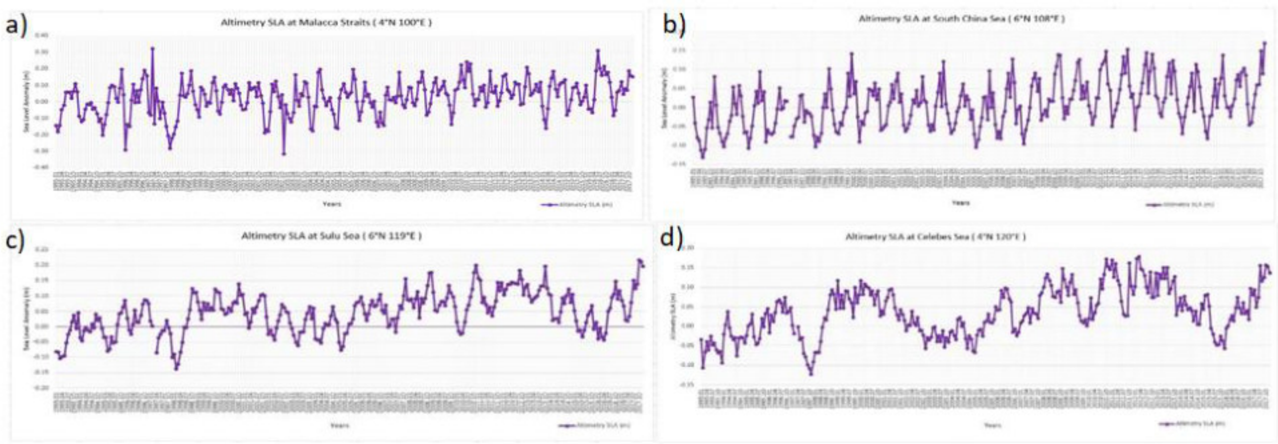


Figure 3. (a) Time Series of SLA at the Malacca Straits (4°N 100°E); (b) South China Sea (6°N 108°E); (c) Sulu Sea (6°N 119°E); and (d) Celebes Sea (4°N 120°E)

Table 2. Selected El-Nino & La-Nina events (ONI, 2017)

El-Nino		La-Nina
Very Strong	**Moderate**	**Moderate**
1997-1998 2015-2016	2002-2003 2009-2010	2007-2008 2010-2011

3. Very Strong El-Nino (1997 to 1998 and 2015 to 2016)

Based on Figure 4, the results showed that during the very strong El Nino (1997-1998) the sea level trend around Malaysian seas significantly decreased from 0 to -0.12m. The minimum residual SLA during El-Nino (1997-1998) was -0.12m, which indicated the sea level fell below the benchmark from 0 to 0.12m. Also, the map was in total contrast with the normal sea level trends as mentioned in Figure 6 with the dominant scale color changing from green to red orange during the El Nino event. However, during the very strong El Nino (2015-2016), the results were the opposite; the sea level trends did not drop but remained positive with significant increases in sea levels, especially at the Malacca Strait with a range of 0.06 to 0.08m. There were several factors that induced this result. First, the selected the El Nino event from ONI was based on the sea surface temperature from the east central Pacific Ocean. Second, it might have relationship with the ocean circulation in and out from the Andaman Sea.

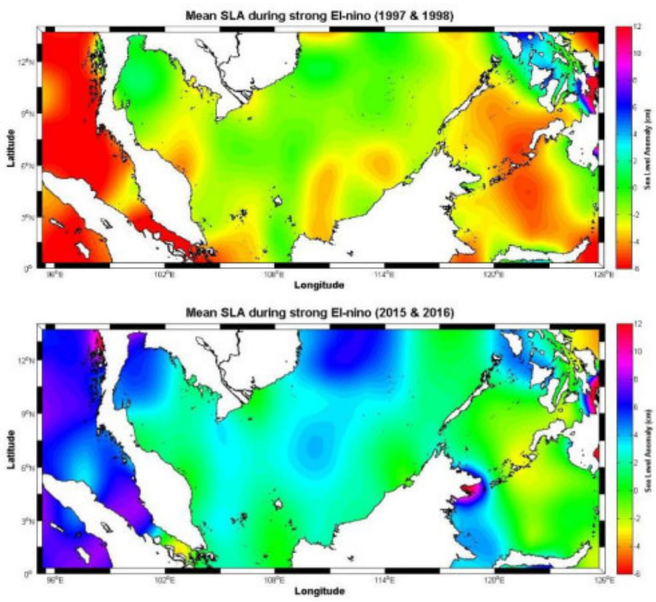


Figure 4. Mean SLA from 1997 to 1998 (top) and 2015 to 2016 (bottom) using Altimetry Data during the Very Strong El Nino event

4. Moderate El-Nino (2002 to 2003 and 2009 to 2010)

The sea level trend during 2002 to 2003 showed that the areas around the Malacca Straits, Sulu and Celebes Seas were the most affected with drops in sea level of between 0 to 0.025 m (see Figure 5). However, the trend of the sea level around the South China Sea remained normal with 0 to 0.02 m.

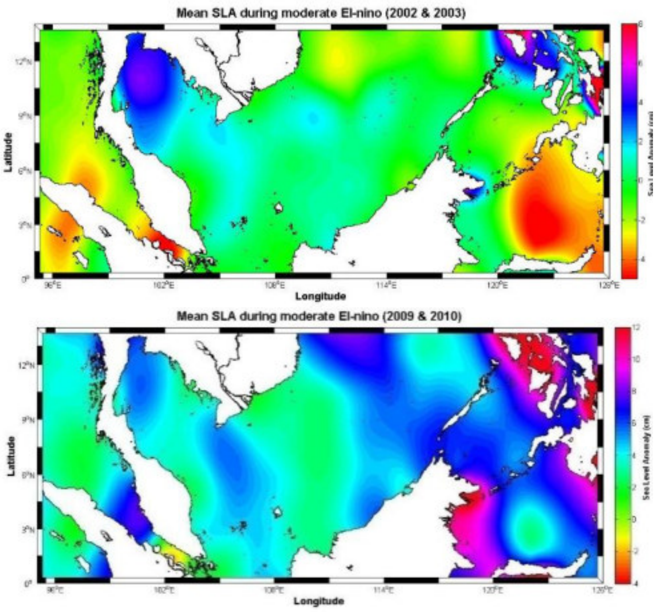


Figure 5. Mean SLA from 2002 to 2003 (top) and 2009 to 2010 (bottom) using Altimetry Data during the Very Strong El Nino event.

This was because the South China Sea is an open sea, while the Malacca Straits, Sulu and Celebes Seas are closed or semi-closed seas with close exposure to the surroundings which caused more effects during this event. However, during the moderate El Nino from 2009 to 2010, there was insignificant rise in sea level around all Malaysian seas with 0.04 to 0.10 m as indicated in the blue to magenta color scale. This result indicated that the moderate El Nino from 2009 to 2010 insignificantly influenced sea level variation in the Malaysian seas.

5. Moderate La-Nina (2007 to 2008 and 2010 to 2011)

Based on the ONI record, strong La Nina event occurred before 1993. However, Satellite Altimeter was not fully operational until 1993, which was why there was no altimetry data and analysis on the strong La Nina. Based on the results in Figure 6, during the moderate La Nina event in 2007 to 2008, the sea level trends were constant (normal) at the Malacca Straits and the South China Sea with 0 to 0.04 m. However, at the Sulu and Celebes Seas there were drastic increases in sea levels from 0.04 to 0.10 m. This was because the Sulu and Celebes seas are enclosed basins, which could be highly affected by temperature changes as compared to the open seas like the South China Sea. Next, during the la Nina event from 2010 to 2011, the sea level trends around Malaysian seas were significantly rising with the range from 0.04 to 0.11 m. The sea levels around the Malaysian seas during the 2010-2011 La Nina were slightly increased which might be due to an on-going sea level rise around the world. A summary of the analysis on the El Nino and La Nina events is shown in Table 3.

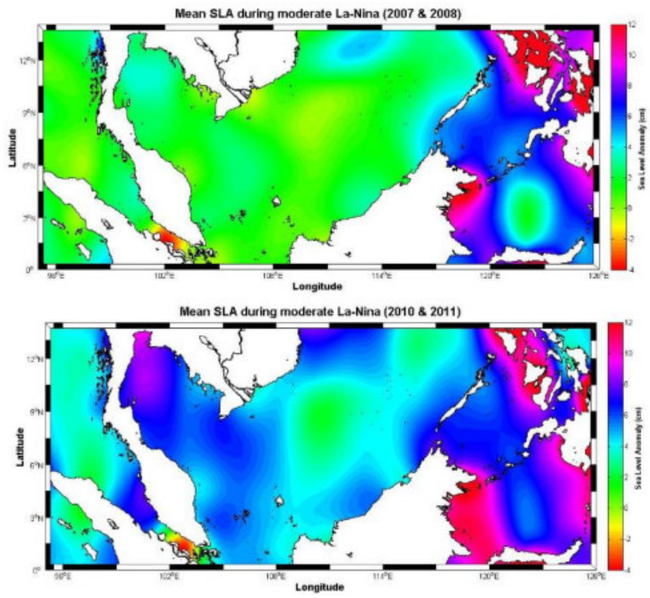


Figure 6. Mean SLA from 2007 to 2008 (top) and 2010 to 2011 (bottom) using Altimetry Data during the moderate La-Nina event.

Table 3. Summary of Sea Level Range during the El-Nino & La-Nina Events

Event/Malaysia Seas	**El-Nino**			
	Very Strong		**Moderate**	
	1997-1998	2015-2016	2002-2003	2009-2010
Malacca Straits	-3 to -4 cm	4 to 8 cm	-1 to -4 cm	2 to 8 cm
South China Sea	0 to -4 cm	0 to 4 cm	-1 to 2 cm	2 to 6 cm
Sulu Sea	2 to -4 cm	-2 to 2 cm	1 to -4 cm	4 to 8 cm
Celebes Sea	1 to -4 cm	-2 to 0.04m	1 to -4 cm	6 to 10 cm
Event/Malaysia Seas	**La-Nina**			
	Moderate			
	2007-2008		2010-2011	
Malacca Straits	1 to 3 cm		2 to 8 cm	
South China Sea	1 to 3 cm		2 to 9 cm	
Sulu Sea	4 to 7 cm		6 to 10 cm	
Celebes Sea	2 to 12 cm		4 to 12 cm	

IV. CONCLUSION

After an overview on the results of the SLA processing and assessment, information had been gathered to conclude this study. By using satellite altimetery, all the sea level data could be gathered on Malaysian seas over a 25 year period. The monsoon seasons in the Malaysian region have had a high impact on sea level changes especially during the Northeast monsoon and the Southwest monsoon. The sea level increased by up to 0.12 m at the South China Sea, which was influenced by the wind and ocean surface circulation. The size of the basin also brought a higher impact especially for the El-Nino and La-Nina events, in which the water level dropped significantly during El-Nino at the small basin seas like the Celebes Sea and the Sulu Sea. Malaysian seas also rose due to sea level rise occurring globally, with the highest value, 3.82 mm/year, in the Sulu Sea and the lowest value in the South China Sea with 3.55 mm/year. The results from this study provide reliable, multi-mission satellite altimeter data for interpreting sea level changes in Malaysian seas and the results of the magnitude and pattern of the sea levels during the monsoon seasons in Malaysia. Moreover, these results are specifically beneficial in the determination of the sea levels in Malaysian seas for policy making, environmental planning, marine engineering, economic activity, agriculture, coastal development and coastal defense by the responsible agencies and professionals. They can also be used for studying environmental issues such as the flood issue, global warming, climate change and marine issues, especially in the Malaysian region.

V. ACKNOWLEDGEMENT

The authors are gratefully to TU Delft, AltimetricsLlc, NOAA and the Department of Survey and Mapping Malaysia (DSMM) for providing altimetry and tidal data, respectively. We are grateful to the Ministry of Education Malaysia and Universiti Teknologi Malaysia for funding this research under Research University Grant (Vote number: Q.J130000.2527.19H26).

VI. REFERENCES

[1] Din, AHM, Ses, S, Omar, KM, Naeije, N, Yaakob, O & Pa'suya, MF 2014, 'Derivation of Sea Level Anomaly Based on the Best Range and Geophysical Corrections for Malaysian Seas using Radar Altimeter Database System (RADS)', *Jurnal Teknologi*, vol. 71, no 4. doi: https://doi.org/10.11113/jt.v71.3830.

[2] Din, AHM, Md Reba, MN, Omar, KM, Razli, MRM, Rusli, N, 2015, 'Sea level rise quantification using multi-mission satellite altimeter over Malaysian Seas', in *Proceedings of The 36th Asian Conference on Remote Sensing*.

[3] Hamid, AIA, Din, AHM, Khalid, NF, and Omar, KM 2016, *Acceleration of Sea Level Rise Over Malaysian Seas from Satellite Altimeter, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLII-4/W1, 277-286, https://doi.org/10.5194/isprs-archives-XLII-4-W1-277-2016.

[4] Hamid, AIA, Din, AHM, Hwang, C, Khalid, NF, Tugi, A & Omar, K 2018, 'Contemporary Sea Level Rise Rates around Malaysia: Altimeter Data Optimization for Assessing Coastal Impact', *Journal of Asian Earth Sciences*, 166. 10.1016/j.jseaes.2018.07.034.

[5] Han, W, Moore, AM, Levin, J, Zhang, B, Arango, HG, Curchitser, E, Di Lorenzo, E, Gordon, AL, & Lin, J 2009, 'Seasonal surface ocean circulation and dynamics in the Philippine Archipelago region during 2004–2008', *Dynamics of Atmospheres and Oceans*, vol. 47, no. 1, pp. 114-137. doi:https://doi.org/10.1016/j.dynatmoce.2008.10.007

[6] Huffman, GJ, Adler, RF, Arkin, P, Chang, A, Ferraro, R, Gruber, A, Janowiak, J, McNab, A, Rudolf, B, & Schneider, U 1997, 'The Global Precipitation Climatology Project (GPCP) Combined Precipitation Dataset', *Bulletin of the American Meteorological Society*, vol. 78, no. 1, pp. 5-20. doi:10.1175/1520-0477(1997)078<0005:TGPCPG>2.0.CO;2

[7] Khairuddin MA, Din AHM, Omar AH 2019, 'Sea Level Impact Due to El Nino and La Nina Phenomena from Multi-mission Satellite Altimetry Data over Malaysian Seas', In Pradhan B. (eds) GCEC 2017. GCEC 2017. Lecture Notes in Civil Engineering, vol 9. Springer, Singapore.

[8] Ku Mansor, KNAA., Pa'suya, MF, Azwan, AM, Tengku, AT, Che, AM, & Din, AHM 2017, 'Ocean surface circulation in strait of malacca using satellite altimeter and low cost GPS-tracked drifting buoys', In *the proceeding of 2016 7th IEEE Control and System Graduate Research Colloquium*, ICSGRC 2016 - (pp. 175-180). [7813323] Institute of Electrical and Electronics Engineers Inc., 175-180. doi:10.1109/ICSGRC.2016.7813323

[9] Pa'suya, MF, Omar, KM, Peter, BN, Din, AHM, Akhir, MFM 2013, 'Seasonal variation of surface circulation along Peninsular Malaysia' east coast', *Jurnal Teknologi*, vol. 71, no.4. doi: https://doi.org/10.11113/jt.v71.3823.

[10] Stammer D, Cazenave A, Ponte RM, Tamisiea ME 2013, 'Causes for contemporary regional sea level changes', *Annu Rev Mar Sci*, vol. 5, no. 21, p. 46.

[11] Wang, J, Qi, Y, Jones, ISF 2006, 'An analysis of the characteristics of chlorophyll in the Sulu Sea', *J. Mar. Syst*, vol. 59, pp. 111–211.

[12] Wang, P, Li, Q, & Li, CF 2014, 'Chapter 2 - General Outline of the China Seas', eds P Wang, Q Li, & CF Li, in *Developments in Marine Geology*, Elsevier, vol. 6, pp. 11-72.

Accuracy Assessment of the Tandem-X DEM in the Northwestern Region of Peninsular Malaysia Using GPS-Levelling

M.F. Pa'suya[1,2*], A.F.A. Bakar[1], A.H.M. Din[2,3], M.A.C. Aziz[1], M.A.A. Samad[1] and M.I. Mohamad[1]

[1]*Green Environment & Technology (GREENTech) Research Group, Center of Studies for Surveying Science and Geomatics, Faculty of Architecture, Planning & Surveying, Universiti Teknologi MARA, Perlis, Arau Campus, 02600 Arau, Perlis*

[2]*Geomatic Innovation Research Group (GnG), Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia*

[3]*Geoscience and Digital Earth Centre (INSTEG), Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia*

This study provided a unique accuracy assessment of the TanDEM-X DEM and two other DEMs; SRTM and AW3D30; using three sets of GPS data around northwestern Peninsular Malaysia. Firstly, the absolute vertical accuracy of all DEMs provided by Department Survey and Mapping Malaysia (DSMM) was examined by 7755 ground control points (GCPs), which were distributed across the northwestern region. The root-mean-square error (RMSE) of 3.980m and mean error of 2.464m indicated a good agreement of TanDEM-X DEM and GCPs, followed by AW3D30 (RMSE=5.206m) and SRTM (RMSE=6.684m). Secondly, the vertical accuracy assessment of TanDEM-X DEM and the others two DEMs was conducted by comparing the elevation of GPS data around four different land-covers; coastal, hills, foothills and agriculture to study the effects of different land-covers to DEMs accuracy. Again, at the coastal, foothills and agriculture region, TanDEM-X DEM showed the lowest RMSE of 0.66m, 3.8m and 0.41m, respectively. Surprisingly, the accuracy of TanDEM-X DEM at the hill region was lower than those of AW3D30 and SRTM DEM with RMSE of 55.51m. This study also managed to assess the best geoid model to convert the elevation of TanDEM-X DEM to the orthometric height. Three geoid models were tested using local mean sea level at 38 Benchmark around the Perlis region. The results showed that the Malaysia geoid model, MyGEOID, gave the lowest RMSE of 2.277m , followed by EGM2008 (RMSE=2.504m) and EGM96 (RMSE=2.675m).

Keywords: Digital elevation model; SRTM; ALOS AW3D30; TanDEM-X

I. INTRODUCTION

The advent of the TanDEM-X mission (TerraSAR-X add-on for Digital Elevation Measurement) (Bartusch *et al.*, 2008) opened a new era in the modelling of the highly accurate Digital Elevation Model (DEM). The new TanDEM-X Digital Elevation Model could be considered as the most consistent, highly accurate and most complete global DEM data set of the Earth's surface (Wessel *et al.*, 2018). In general, the mission was a joint effort between the German Aerospace Center (DLR) and DLR's industrial partner; AIRBUS Defence and Space. Launched in 2010, the aim of the mission was to construct a globally

*Corresponding author's e-mail: faiz524@perlis.uitm.edu.my

homogeneous digital surface model based on the aggregation of the bistatic X-Band interferometric synthetic aperture radar acquisitions. This technique was also successfully implemented for constructing the Shuttle Radar Topography Mission (SRTM) model in 2000 but its coverage was principally limited to a latitude range from 56°S to 60°N due to the inclined orbit of the Space Shuttle and its mapping geometry. By using two twin satellites TerraSAR-X and TanDEM-X operating in the X band, which flew in a close helix formation (Zink *et al.*,2014), the mission successfully collected interferometric data for the area between 90 degrees north latitude and 90 degrees south latitude.

Nowadays, the accuracy of the TanDEM-X DEM had been analysed by many scientists around the world using various methods such as by using ICESat data (Rao *et al.*, 2014; Rizzoli *et al.*, 2017), other DEM model data (Rexer & Hirt, 2016), airborne LiDAR (Rao *et al.*, 2014; Woroszkiewicz, Ewiak & Lulkowska, 2017) and Global Positioning System (GPS) data (Gesch *et al.*, 2012; Erasmi *et al.*, 2014; Rao *et al.*, 2014; Wessel *et al.*, 2018). According to Woroszkiewicz, Ewiak and Lulkowska (2017), the absolute accuracy of the DEM was 10m and the relative vertical accuracy was below 2m and 4m for areas with a terrain slope greater and smaller than 20 degrees, respectively. Although numerous studies had been carried out for accuracy assessments of TanDEM-X DEM in different parts of the world, the accuracy of DEMs over Peninsular Malaysia had never been studied. Therefore, the primary goal of this study was to analyse the vertical accuracy of TanDEM-X DEM over Northwestern Peninsular Malaysia (Figure 1) using GPS data and another two DEMs, SRTM and ALOS World 3D (AW3D-30). To our knowledge, this paper is the first to report a vertical accuracy assessment of these DEMs in this region.

II. MATERIALS AND METHODS

A. Global DEM Data

The TanDEM-X Global DEM data over the study area was provided by the German Space Agency (DLR) under the project "Towards 1 Centimetres Geoid Model At Southern Region Peninsular Malaysia Using New DEM Model-TanDEM-X" with spatial resolutions of 12m (0.4 arcsec) and 30m (1 arcsec). The TanDEM-X elevations corresponded to ellipsoidal heights referenced to the WGS84 ellipsoid. However, in this study, only spatial resolution of 30m was assessed. SRTM with spatial resolutions of 30m (SRTM-30) were freely downloaded from the USGS website. The absolute vertical error of SRTM-30 was approximately 5m [10] and these DEMs were released publicly in 2003. The horizontal and vertical references of the SRTM DEMs were the WGS84 and the EGM96 geoids, respectively. ALOS World 3D (AW3D-30) was released in 2015 by the Japan Aerospace Exploration Agency (JAXA). This GDEM was generated using the traditional optical stereo matching technique as applied to images acquired by the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) sensor on-board the Advanced Land Observing Satellite (ALOS). Based on preliminary validation using 5,121 independent checkpoints distributed around the world, the accuracy claimed of AW3D-30 was 4.40m (Tadono *et al.*, 2015).

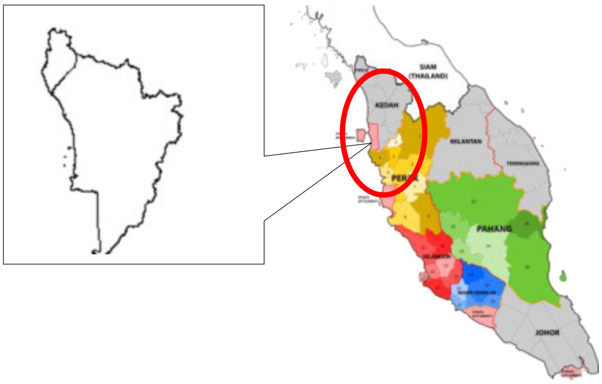
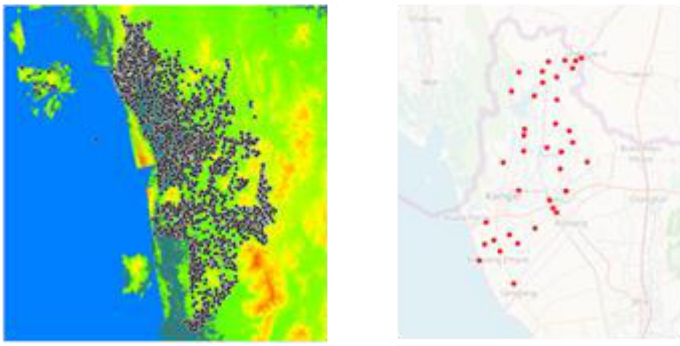


Figure 1. Northwestern Peninsular Malaysia

B. Elevation from GPS Observation

The elevation from GPS observation is a highly accurate (millimetre to centimetre) set of GCPs. In this study, three sets of GCPs were used to analyse the accuracy of GDEMs. The first set of GCPs was measured and provided by the Department of Surveying and Mapping

Malaysia (DSMM). These GCPs consisted of 7755 GPS points, which were distributed across the Perlis and Kedah region as shown in Figure 2(a). The coordinates of the points were provided in the Geocentric Datum of Malaysia 2000 (2006) with elevation reference GRS80. Since all GDEMs were referenced to the WGS84, the locations (latitude and longitude) and heights (ellipsoidal height) were transformed into WGS84. The second set of GCPs was 38 GPS observations that were conducted on the Standard Benchmark (SBM) and Benchmark (BM) over the Perlis region using the static method with 2 hour observation periods, 1-sec sampling rate and above 15° for elevation mask. The distribution of BM is shown in Figure 2(b).



(a) (b)

Figure 2. Distribution of the 7755 GPS points (a) and 38 GPS on benchmark (b) for DEMs validation

In the GPS data processing, two Malaysia Real-Time Kinematic GNSS Network (MyRTKnet) stations were used as the control stations. The mean sea level value ($H_{levelling}$) for each BM and SBM was provided by DSMM. The last sets of GCPS consisted of 337 points along the coastal region, 93 GPS points at agriculture area (paddy field), 37 points at the top of hill and 75 points at the foothill as shown in

Figure 3 to assess the effects of varying land-covers on elevation accuracy.

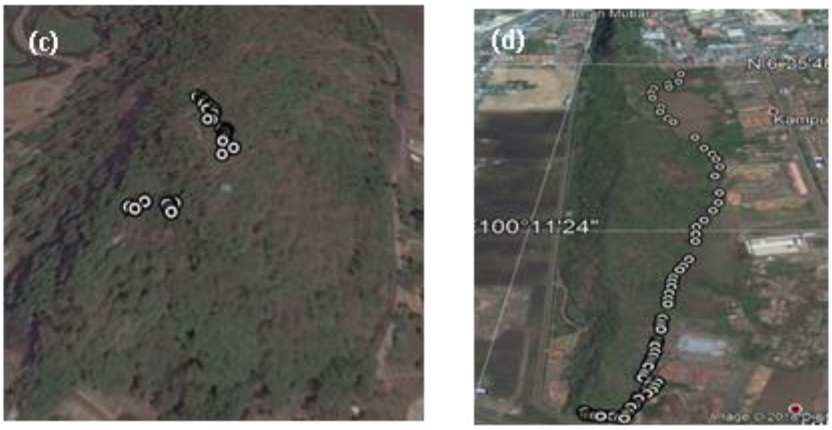


Figure 3. Distribution of GCPs along the coastal region (a), agriculture region (b), hill (c) and foothill (d)

C. Orthometric height conversion

TanDEM-X elevations corresponded to ellipsoidal heights referenced to the WGS84 ellipsoid, while values in SRTM and ALOS AW3D30 were altitudes (orthometric heights) referenced to the EGM96 geoid height (Farr *et al.*, 2007; Mukul, Srivastava & Mukul, 2015; Tadono *et al.*, 2015). In order to synchronize the height reference, the orthometric heights of SRTM and ALOS AW3D30 were converted to ellipsoidal height by adding the geoid undulation or separation N to the orthometric height

$$h = H + N \quad (1)$$

In this study, the geoid height value from the EGM96 model was extracted using the F477.F program provided by NGA at http://earthinfo:nga:mil/GandG/wgs84/gravitymod/egm96/egm96:html by using the bilinear interpolation method and added to SRTM and ALOS AW3D30 DEMs to gain ellipsoidal heights referenced to WGS84.

III. RESULTS AND DISCUSSION

A. Vertical Accuracies of the DEMs

The results of the elevation differences between the three DEMs and 7755 GCPs over Kedah and Perlis are listed in Table 1. Among the three DEMs, TanDEM-X DEM exhibited the lowest RMSE and mean error values of ±3.980m and 2.464m, respectively. The DEM also showed high positive correlation values of 0.9937. Out of this, the AW3D30 DEM performed significantly better in terms of RMSE and mean error compared to the SRTM GDEM but higher than the TanDEM-X DEM. As shown in TABLE 1, the RMSE and mean error of AW3D30 were ±5.206 and 3.619, respectively. The SRTM DEM had the highest RMSE and mean error compared to the other two DEMs where the RMSE and mean error of SRTM DEM were 6.684m and 4.877m, respectively. Comparing the elevation with GCPs data, SRTM and AW3D30 also showed positive and high correlation with GCPs data as shown in Table 1.

Table 1. Error statistics (in meters) from vertical accuracy of the DEMs using 7755 GCPs

DEM	RMSE	Mean	Min	Max	Corr.
SRTM	6.684	4.877	0.001	46.547	0.9874
AW3D30	5.206	3.619	0.003	92.840	0.9922
TanDEM	3.980	2.464	0.001	48.185	0.9937

B. Land-cover Effects

The RMSE values of the SRTM, AW3D30 and TanDEM-X DEM according to land-cover types are shown in Figure 4. Under different land-covers, the accuracy of TanDEM-X was found to be consistent over the two DEMs. For the agriculture, coastal and foothill areas, the TanDEM-X model was found to be the most accurate as this DEM had the lowest RMSE of ±0.41m, ±0.66m and ±3.08m among the three. It was followed by AW3D30 where the computed RMSE at the agriculture, coastal and foothill areas were ±1.58m, ±1.50m and ±6.22m, respectively.

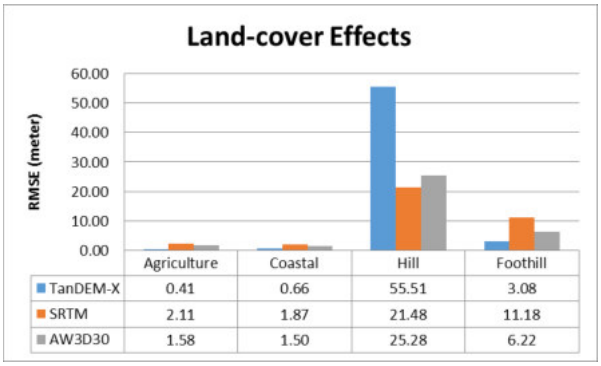


Figure 4. RMSE of three DEMs according to land-cover types

Among the three, SRTM exhibited the lowest accuracy where the RMSE at the three regions were ±2.11m, ±1.87m and ±11.18m, respectively. However, it was interesting to discuss the accuracy of the DEMs at hills. Among the three contrasts to the other land-cover regions, the results of SRTM at the hill showed that its accuracy was better than TanDEM-X and AW3D30. The computed RMSE of ±21.48m of SRTM was slightly better than the accuracy of AW3D30. RMSE of Tandem-X at the hill region was higher than the other DEMs where the computed RMSE was ±55.51m.

C. TanDEM-X DEM Conversion Using GGM and Local Geoid model

As mentioned before, the TanDEM-X elevations corresponded to ellipsoidal heights referenced to the WGS84 ellipsoid. However, the elevation from the TanDEM-X DEM was unsatisfactory in scientific application as it did not have any physical meaning and must be transformed to orthometric heights (H), which were referred to geoid combining geoidal heights (N) and elevation TanDEM-X DEM (h_{TX})

$$H = h_{TX} - N \quad (2)$$

Therefore, a total of 38 GPS on the Benchmark data which represented the local mean sea level value (LMSL) had been used in this study to analysis the best geoid model from the three geoid models namely EGM2008, EGM96 and MyGEOID to transform the TanDEM-X elevation to orthometric height. To analyse the best geoid model, the orthometric height derived using TanDEM-X DEM and geoid model had been compared with the local mean sea level (LMSL) value at the Benchmark. The geoid height values, N from EGM96 and EGM2008 were extracted from the models using the F477.F and Alltrans EGM2008 softwares, respectively. Meanwhile, the Malaysia local geoid model (MyGEOID) was provided by DSMM.

Figure 5 shows the comparison of the orthometric heights computed from TanDEM-X DEM and three geoid models with LMSL. In terms of vertical pattern, it was very clear that all the orthometrics derived from the DEM model and geoid almost fitted well with LSML. However, the orthometric height derived using MyGEOID exhibited the lowest RMSE and mean error of 2.277m and 1.702m. On the other hand, the orthometric height derived by EGM2008 and TanDEM-X was found to be more accurate and fit with the LMSL compared to EGM96 with RMSE and mean error of about ±2.504m and 1.89m, respectively. The RMSE value of the orthometric height derived by EGM96 was a little lower than EGM2008 with RMSE and mean error of ±2.675m and 1.964m respectively.

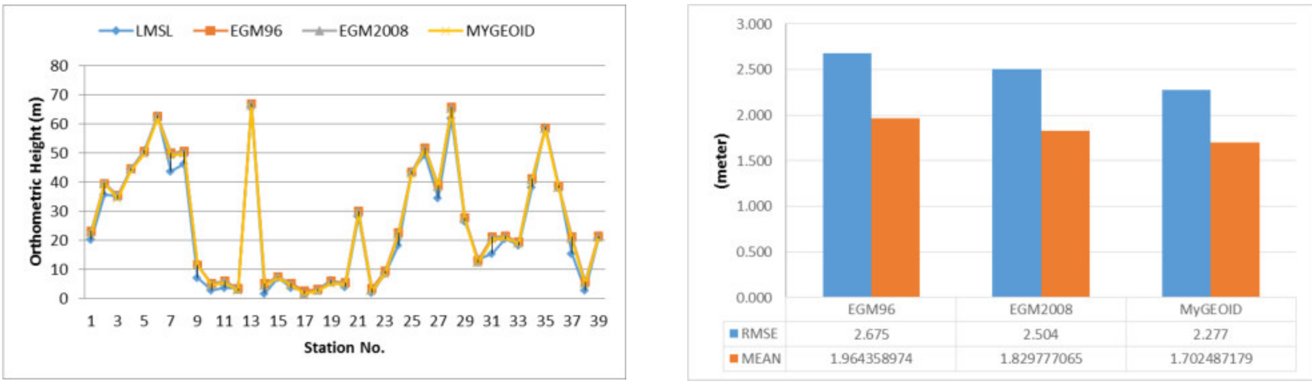


Figure 5. Statistical error of orthometric height from TanDEM-X DEM using different geoid models

IV. CONCLUSION

To our knowledge, this paper is the first to discuss the accuracy of TanDEM-X DEM and AW3D30 DEM in Peninsular Malaysia especially at the Northwestern region. Overall, the vertical accuracy assessment using 7755 GPS data in Northwestern Peninsular Malaysia (Kedah and Perlis) showed that DEM from TanDEM-X DEM was found to be the most accurate among the three DEMs, followed by AW3D30 DEM and SRTM DEM. The result for TanDEM-X DEM showed that its accuracy was better than the expected absolute height accuracy of 3.5m [5]. The superiority of TanDEM-X DEM over the AW3D30 and SRTM DEM was also found to be consistent when compared with different land-cover types. However, the accuracy of TanDEM-X DEM at the hill region was the worst among the three DEMs. This was unexpected result and needed to be further tested. Conversion of TanDEM-X DEM (refer to ellipsoid) to orthometric height using geoid model showed that EGM2008 was better than EGM96. By using the local geoid model, MyGEOID, the accuracy of the orthometric height derived using TanDEM-X DEM was improved.

V. ACKNOWLEDGEMENT

The authors would like to thank the German Aerospace Center (DLR) for providing TanDEM-X DEM under the project “Towards 1 Centimeters Geoid Model At Southern Region Peninsular Malaysia Using New DEM Model-TanDEM-X” (Proposal ID: DEM_OTHER1156). Special thanks to the Department of Survey and Mapping Malaysia (DSMM) for providing BM/SBM and GCPs value at the northwestern region of Peninsular Malaysia. The original AW3D30 and SRTM-30 data is provided by Japan Aerospace Exploration Agency (JAXA) and USGS.

VI. REFERENCES

[1] Erasmi, S *et al.* 2014, 'Evaluating the quality and accuracy of TanDEM-X digital elevation models at archaeological sites in the Cilician Plain, Turkey', *Remote Sensing*, vol. 6, no. 10, pp. 9475–9493. doi: 10.3390/rs6109475.

[2] Farr, TG *et al.* 2007, 'The Shuttle Radar Topography Mission', (2005), pp. 1–33. doi: 10.1029/2005RG000183.1.INTRODUCTION.

[3] Gesch, D *et al.* 2012, *Validation of the Aster Global Digital Elevation Model Version 2 Over the Conterminous United States*, ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXIX-B4(September), pp. 281–286. doi: 10.5194/isprsarchives-XXXIX-B4-281-2012.

[4] Mukul, M, Srivastava, V & Mukul, M 2015, 'Analysis of the accuracy of Shuttle Radar Topography Mission (SRTM) height models using International Global Navigation Satellite System Service (IGS) Network', *Journal of Earth System Science*, vol. 124, no. 6, pp. 1343–1357. doi: 10.1007/s12040-015-0597-2.

[5] Rao, YS *et al.* 2014, *Quality assessment of TanDEM-X DEMs using airborne LiDAR, photogrammetry and ICESat elevation data*, ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, II-8(December), pp. 187–192. doi: 10.5194/isprsannals-II-8-187-2014.

[6] Rexer, M & Hirt, C 2016, 'Evaluation of intermediate TanDEM-X digital elevation data products over Tasmania using other digital elevation models and accurate heights from the Australian National Gravity Database', *Australian Journal of Earth Sciences*, vol. 63, no. 5, pp. 599–609. doi: 10.1080/08120099.2016.1238440.

[7] Rizzoli, P *et al.* 2017, 'Generation and performance assessment of the global TanDEM-X digital elevation model', *ISPRS Journal of Photogrammetry and Remote Sensing*, The Authors, 132, pp. 119–139. doi: 10.1016/j.isprsjprs.2017.08.008.

[8] Tadono, T, Takaku, J, Tsutsui, K, Oda, F, & Nagai, H 2015, Status of "ALOS World 3D (AW3D)" global DSM generation in *Proceedings of the 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, pp. 3822-3825.

[9] Wessel, B *et al.* 2018, 'Accuracy assessment of the global TanDEM-X Digital Elevation Model with GPS data', *ISPRS Journal of Photogrammetry and Remote Sensing*, The Authors, 139, pp. 171–182. doi: 10.1016/j.isprsjprs.2018.02.017.

[10] Woroszkiewicz, M, Ewiak, I & Lulkowska, P 2017, 'Accuracy assessment of TanDEM-X IDEM using airborne LiDAR on the area of Poland', *Geodesy and Cartography*, vol. 66, no. 1, pp. 137–148. doi: 10.1515/geocart-2017-0007.

Review on Space Science Research in Malaysia

Zainuddin M.Z.[1], Abdullah M.[2,3], Abidin Z.Z.[1], Bahari S.A.[2], Asillam M.F.[4*], Hashim M.H.[5] and Radzi Z.[5]

[1]*Department of Physics, Faculty of Science, University of Malaya*

[2]*Space Science Centre (ANGKASA), Institute of Climate Change (IPI), Universiti Kebangsaan Malaysia*

[3]*Centre of Advanced Electronic and Communication Engineering (PAKET), Faculty of Engineering and Built Environment (FKAB), Universiti Kebangsaan Malaysia*

[4]*Perdana School of Science, Technology and Innovation Policy, UTM*

[5]*National Space Agency of Malaysia (ANGKASA), Ministry of Energy, Science, Technology, Environment & Climate Change (MESTECC)*

The Malaysia in space science R&D is still in its infancy stage. Internationally, space science has a major role and has impacted our society over the last 50 years and will continue providing returns on investment. The Return on Investment (ROI) could be in the form of new knowledge that provides understanding to world problems such as those relating to the Earth-Sun relationship. These can be directly or indirectly beneficial. The main output from space science R&D is new knowledge which is "priceless". Other than that space science will provide economic opportunities as well as wealth creation and social well-being. In Malaysia, space science R&D has progressed but there are a lot of windows for improvement. This review article looked at several milestones in the Malaysian space science R&D program as well as at its current challenges. Recommendations are made for the improvement of the space science R&D program in Malaysia.

Keywords: Space science; research; R&D

I. INTRODUCTION

In Malaysia, astronomy has become an anchor for space science research and the educational program followed by space weather and just recently it continues with microgravity sciences. The definition (COPOUS, 2014) of space science spans a wide variety of scientific fields, ranging from astrophysics, human and robotic space exploration, and satellite-based communications and position services all the way to life sciences. However, in Malaysia, space science R&D only focused on three main categories: astronomy which comprises of optical astronomy and radio astronomy, space weather and microgravity sciences.

Almost every aspect of life in the present society depends on radio navigation and communication technology. This technology is susceptible to the space environment which increases the risk to space technology. Severe conditions in space weather can cause socioeconomic losses including navigation errors, communication breakdown, satellite power problems and damage to power grids as well as causing the effects of space and aviation radiation. In the case of high class solar flare, it can in fact penetrate the Earth's atmosphere, affecting communication signals and disrupting power transmission which can result in significant economic losses. This is the case in advanced countries which have pioneered space science and technology.

Space science also continues to be of fundamental importance to the ability of nations to utilise space technology and its applications for the benefit of their societies in that it advances our knowledge about the universe and humankind's role and destiny in it. This science also stimulates the development of new technology,

*Corresponding author's e-mail: mhdfairos@gmail.com

applications and solutions that enable us to address the challenges facing humanity, and inspires people from all walks of life, young and old. Due to the space programs taking place on the edge of knowledge (Hof *et al.*, 2012), space science is an ideal tool for global capacity-building in science and technology.

In Malaysia, the space science program is championed by the National Space Agency of Malaysia (ANGKASA). It started with the establishment of the National Planetarium (1993), BAKSA (1994) and ANGKASA (2002). ANGKASA with the support of the local universities also plays an important role in human capital development. In 1993, the Space Science Studies Division also known as BAKSA was established under the Prime Minister's Department. This division transferred to the Ministry of Science, Technology & Environment (MOSTE) in 1995. In 2002, ANGKASA was formed to set-up the National Space Policy including to coordinate the national space program. Then in 2004, BAKSA merged with the National Space Agency (ANGKASA). ANGKASA is the agency mandated by the government to develop the space sector for the nation. The National Space Policy's goal is to have the capability and capacity to capitalize space as a strategic sector for national well-being towards achieving Vision 2020 and beyond. It is mandated to develop the country's potential in the space sector to support the development of the new economy, generate knowledge and strengthen the national security infrastructure. It envisions harnessing space as a platform for knowledge generation, wealth creation, and societal well-being. ANGKASA has actively been involved in various projects locally and internationally, namely, in space technology, space applications, and space sciences to achieve this vision. In addition, ANGKASA conducted many astronomy related research seminars such as the first Telescope Seminar in 1996 (Othman, 2004) and secured funding for astronomy researches in universities. It rekindled and ignited research on astronomy in Malaysia by a handful of researchers in the universities. A summary of institutional space science in Malaysia is presented in Table 1 below.

Table 1. Summary of institutional space science in Malaysia

Year	Primary Milestone
1988	Malaysia became national member of the International Astronomical Union (IAU)
1989	Establishment of the Planetarium Division under Prime Minister's Department. *Objective: To develop and operate the National Planetarium at Lake Gardens, Kuala Lumpur*
1993	Establishment of Space Science Studies Division (BAKSA) *Objective: Extended purview covering space science and space technology*
1995	BAKSA transferred to Ministry of Science, Technology & Innovation (MOSTE)
2002	Establishment of the National Space Agency of Malaysia (AAN) *Objective: To set-up National Space Policy including to coordinate national space programme*
2003	Establishment of Institute of Space Science (ANGKASA UKM), Universiti Kebangsaan Malaysia
2004	AAN combined with BAKSA to become the National Space Agency of Malaysia (ANGKASA), *Ministry of Energy,* *Science, Technology, Environment & Climate Change (MESTECC)* Objective: *Mandated to spearhead the nation's venture into space*
2016	National Planetarium separated from ANGKASA and became a division under MESTECC

In order to strengthen space science research in Malaysia, the Joint-Committee for Space Related R&D was established on 4 November 2004 chaired by the Director General of ANGKASA (Othman & Asillam, 2005). The committee is responsible to coordinate and prioritize the space science program in Malaysia.

II. ASTRONOMY

In Malaysia, records indicated that research on astronomy in the field of astrometry related to crescent visibility observations in Johor Bahru was started officially in 1934 by Syed Alwi bin Tahir Al-Hadad from The Sultan Abu Bakar Mosque tower. This was the only official research in astronomy that had been recorded as having been conducted in Malaysia. In 1989, Malaysia established the Planetarium Division headed by Professor Emeritus Datuk Dr Mazlan Othman with the objective to develop and operate the National Planetarium at Kuala Lumpur. The National Planetarium consists of three main segments i.e.: space theatre; space exhibition gallery and National Planetarium Observatory (NPO). The first light of NPO was in January 1993 (Othman, 2004). NPO also for the first time was involved in observing and recording the collision of comet Shoemaker Levy-9 with Planet Jupiter which started at 0340 on 17 July 1995 and lasted for six days (Othman, 2004). Since then, the development of astronomy has evolved. Research on astronomy in Malaysia is divided into two parts, optical astronomy and radio astronomy details of which are presented in the next section.

A. Optical Astronomy

Astronomy in Malaysia started with optical astronomy. NPO was set-up for education purposes; several astronomy R&D activities took place such as differential photometry, CCD and filter study, telescope alignment, sunspot study and space weather research since 1993 (Othman, 2004).

Seminar Telescope was organised in 2002 attended by professional astronomers and NGOs. Resolution of the seminar was presented and agreed by the participants for Malaysia to have their own observatory. This observatory could serve as a training platform for human capital development and as a "bridge" for professional astronomers in Malaysia to embark on international collaborations on astronomy research. Due to that, in 2004, Malaysia started developing the Langkawi National Observatory (LNO) provide a 50cm Ritche-Chriterien robotic telescope which can be controlled remotely through the Internet and also a robotic 15cm multi apo-chromatic refracting telescope. LNOs first light was at the end of 2006. The 50cm robotic telescope is capable to gather data for scientists interested in doing research in the field of photometry, spectroscopy and astrometry. Robotic observatories with small telescopes can make significant contributions to astronomy observations. They provide an encouraging environment for astronomers to focus on data analysis and research while at the same time reducing time and cost for observation and travelling. Using LNO as a national platform, there are opportunities for Malaysian astronomers to enhance researches in the fields mentioned above and to look for global and regional partners for collaborations. One of the areas targeted is to catalogue the equatorial astronomical phenomenon (Loon *et al.*, 2015; Ngeow & Luo, 2017; Zainuddin *et al.*, 2011; Tahar *et al.*, 2017).

There are three professional observatories operating telescopes with diameter 50cm and larger in the optical regime namely LNO, Al-Khwarizmi Complex in Melaka and Balai Cerap Teluk Kemang in Negeri Sembilan. Among the optical astronomy researches conducted in Malaysia since 1997 were the Be stars phenomena, early and late type stars monitoring using spectroscopy technique, short period eclipsing binary stars light curve using photometry technique, crescent visibility observation technique, lunar and solar eclipses, light pollution campaign, tracking asteroids and joining the United Nation Office of Outer Space (UNOOSA) international campaign on Earth-Sun relationship and space weather for the International Heliophysical Year (IHY) in 2007 and the International Space Weather Initiative (ISWI) in 2012. The above mentioned research topics secured grants from the E-Science Fund, Ministry of Energy, Science, Technology, Environment & Climate Change (MESTECC), Fundamental Research Grant Scheme (FRGS) Ministry of Higher Education (MOHE), Research University grant scheme, ANGKASA Space Science Fund and the Department of Islamic Development Malaysia (JAKIM).

All the above mentioned research topics had their own objectives for example as the be stars' phenomena topic tried to predict the evolution of the stars using spectroscopy and photometry technique while the early and late type stars topic looked at the spectrum of these stars at the 400nm to 800nm wavelength range. In the latter topic also, interest in the strength of the h-alpha, helium and some iron lines was with the intension to compile an atlas of the M stars in the 400nm to 800nm ranges. The short period eclipsing binary stars' light curve topic tried to compile light curves catalogue for short period binary stars in the equatorial region by using the broadband standard UBV magnitude system and corrected the atmospheric turbulence by using adaptive optics from SBIG. Crescent visibility technique tried to predict the best time for viewing young crescent by measuring the sky brightness, contrast and the width of the crescent and also measured the atmospheric refraction near the horizon. This project which began in April 2000 took approximately 20 years. Furthermore, Universiti Malaya (UM) developed techniques on photography of the young crescent using digital SLR camera. At the same time, UM also provided training to personnel who were interested in observing the young crescent. Solar eclipses were looking into the corona and found that the temperature at the surface was 6000°K while in the corona it was 2,000,000°K. Basically this topic was investigating the atmosphere of the sun particularly the chromospheres and corona but also monitoring the sunspot using h-alpha and Ca II K filters for the IHY and ISWI projects coordinated by ANGKASA. At the same time, it is very important to educate the public on the awareness of light pollution that affects astronomy and life as a whole.

In conjunction with the International IHY 2007, Malaysia through ANGKASA developed a solar telescope system at LNO with 15cm apo-chromatic telescope capable of gathering data on three different wavelengths namely solar continuum, H-alpha and Calcium K lines which were used for sunspot and flare monitoring and counting activities with the data being made available to local researchers for their R&D activities. The 2.0 space weather programmes at the national level also began. With this program, research on astronomy was expanded into radio astronomy which would be explained in the next section.

B. Radio Astronomy

Due to the high cloud cover rate in Malaysia with less than 200 days of clear night sky to do astronomical observations throughout the year, radio astronomy is a promising alternative to compliment optical astronomy. Radio astronomy is increasingly becoming an important research field in Malaysia especially since the establishment of the Radio Cosmology Laboratory in UM in the year 2005. Formal radio astronomy education is only offered at the postgraduate level at universities with UM leading the number of current and graduated students. However, a few other universities in Malaysia have also included basic radio astronomy topics in their teaching syllabuses.

In terms of instrumentation, there are many antennas being constructed to study the Radio Frequency Interference (RFI) in selected sites in Malaysia, including discones, log-periodic and feedhorn antennas. At the same time, low noise amplifiers (LNA) are also being built and used in studies. As mentioned before, the most significant instrumentation landmark of the radio astronomy research in UM is the construction of the UPSI-UM Radio Telescope, which is located at one of the selected sites for the Radio Quiet Zone (RQZ) i.e. at the Universiti Pendidikan Sultan Idris (UPSI) in Tanjung Malim, Perak. It is located geographically about 80km to the north of Kuala Lumpur. The telescope operates at L-Band and aims to study the core of galaxy clusters in order to investigate the evolution of these objects. Future upgrades for the telescope to other frequencies in order to study other astrophysical properties of galaxy clusters and also galaxies are also planned, pending successful research grant applications. As a feasibility study for the scientific targets of the UPSI-UM Radio Telescope, observations were made with a similarly sized and designed radio telescope at the Jodrell Bank Observatory and the results showed that the science was indeed doable with the new telescope. Another radio observatory site had also been identified by the same RQZ identification study that selected the UPSI-UM Radio Telescope. This observatory is located at the University of Malaya's Glemi Lemi Research Centre in Jelebu, Negeri Sembilan.

From the scientific research point of view, the Radio Cosmology Research Lab had been involved in studies in Astrophysics and Cosmology not just at the radio wavelengths, but also at other frequencies for completeness. Research of radio waves coming from the Sun is also a priority of the radio astronomy study in UM as proven by our work in establishing the solar radio burst array, as mentioned before. Another branch of radio astronomy that has been pursued is radio spectrum protection through spectrum management study. In Malaysia, the Radio Cosmology Research Lab has formed working collaborations with Universiti Kebangsaan Malaysia (UKM), Universiti Putra Malaysia (UPM), Universiti Teknologi Malaysia (UTM), Universiti Pendidikan Sultan Idris (UPSI), Universiti Sultan Zainal Abidin (UniSZA) and Universiti Teknologi Mara (UiTM). Significantly, UM had signed a memorandum of Agreement (MOA) with UPSI regarding radio astronomy research using the UPSI-UM Radio Telescope which is built on their campus site in Tanjung Malim. It is also worth noting that these universities also have a few researchers in radio astronomy especially in the instrumentation side of it.

In summary, radio astronomy in Malaysia has progressed quite well since 2005 especially after the establishment of the Radio Cosmology Research Lab in UM. It has still a long way to go to reach the level comparable to research institutes aboard such as the radio astronomy research in JBCA, but the general opinion is that it is on the right track. Challenges in the future remain the lack of research fundings especially in terms of sponsoring postgraduates students to venture into this research field. It is hoped that the establishment of Malaysia's future own large radio telescope will be helpful in terms of elevating the status of radio astronomy in Malaysia. Together with that, it is hoped that, one day, having a radio astronomical observatory equivalent to the Jodrell Bank Centre of Astrophysics in the United Kingdom (JBCA) will materialize. The direct spin-off technological contribution of this research field relating to telecommunications technology is also hoped to assist in terms of funding opportunities.

C. Recommendations and the way forward

Due to the high cloud cover in Malaysia, and the limited equipment in observatories, Malaysia should consider multi-wavelength observations for astronomy R&D. Other than that, Malaysia should consider to strengthen a Virtual Observatory programme by using archived astronomical data. In order to strengthening the LNO, this observatory should be uplifted to become a Center of Excellence (CoE) for astronomy R&D. As a CoE on astronomy R&D, the program at LNO should cover science and R&D, technology and skills to support equipment development for R&D purposes and be the venue for space enculturation which benefited the surrounding community etc. To expedite the process of being a CoE, an integrated strategic approach such as LNO joining the consortia with local universities and initiating twining programmes with other reputable observatories would be a good start. It also required a long term National R&D astronomy road map to map the output and outcome with the National Space Policy (NSP) and the Science, Technology & Innovation Policy. In addition, it is important to have sustainable research grant support by the government to pursue R&D in astronomy and the evaluation team must comprise of prominent experts in the same area. This will develop human capital in Malaysia, for example, in order to strengthen the LNO and other R&D observatories. There must be well trained staffing and there must be a post for an astronomer with at least a PhD in astronomy supported by a team of researchers, computer science experts and engineering staff for instrument development and maintenance. There are many observatories around the world which are surrounded by a Radio Quiet Zone (RQZ) but there is none available in Malaysia. Due to that, it is important to establish the first radio quiet zone for radio astronomy research in Malaysia (Umar *et al.*, 2013). In supporting this zone, it is needed to establish spectrum management in order to protect the frequency used for radio astronomy from any interruption. Therefore, there is a need to establishing a working collaboration among the local universities (a consortium) in order to set-up professional grade radio telescope systems. This consortium should be able to link to international programs.

Beside astronomy, space science also included space weather research. Space weather R&D is important because severe conditions in space weather can cause socioeconomic losses including navigation errors, communication breakdown, satellite power problems, and damage to power grids, effects of space and aviation radiation. In the case of a high class solar flare, it can in fact penetrate the Earth's atmosphere, affecting communication signals and disrupting power transmission which can result in significant economic losses. This is the case in developed countries which have pioneered space science and technology. The rapid advances in space technologies in these countries led to the emergence of space weather research in the past 20 years. The next section would discuss details on space weather research in Malaysia.

III. SPACE WEATHER

The official definition of space weather was officially introduced on 16 June 1994 in a meeting at the National Science Foundation (NSF) of the United States of America. Space Weather refers to the condition on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and which can endanger human life or health. Adverse conditions in the space environment can cause disruptions of satellite operations, communications, navigations, and electric power distribution grids, leading to a variety of socioeconomic losses. Since 1994, the NSF initiated the space weather roadmap in the US, but even there, there were many obstacles. There was a need to convince the stakeholders and industry on the importance of space weather. Looking back at the efforts taken by the NSF in the US to create and establish a space weather program, they looked almost the same as what Malaysia faced a few years ago.

In Malaysia, space weather research focusing on the ionosphere started in 1944, the same year as Singapore and the Philippines did. In contrast, work on the ionosphere in Vietnam was reported in 1962 using the ionosonde installed at Phu Thuy, Vietnam (Thu *et al.*, 2016). In Thailand, study on the ionosphere started in 1965 during which ionospheric and magnetic observations were made at Bangkok, Thailand during the annular solar eclipse on November 23, 1965 which was carried out by the Stanford Research Institute (SRI). Research on the ionosphere over Penang in 1944 was to study the characteristics of the ionospheric F2 layer near the geomagnetic equator. Studies done on space weather over SEA are listed in Table 2.

Table 2. Record of the earliest studies on space weather in SEA

Country	Year	Reference
Indonesia	1941	Maeda 1986
Singapore*	1944	Maeda 1986
Penang*	1944	Maeda 1986
Manila, Philippine	1944	Maeda 1986
Thailand	1965	Laan 1967
Vietnam	1962	Thu *et al.*, 2016

(*In 1944, Penang and Singapore were both under Malaya; however, after Malaya's independence in 1957, Singapore then separated and became an independent country of its own in 1965 although it was part of Malaysia from 1963 to 1965 while Penang remained one of the states in Malaysia).

No continuous study on the ionosphere over Malaysia was carried out after 1944 until 1969 when one radiosonde was installed in Kota Kinabalu, Sabah (Seidel *et al.*, 2001). In 1997, the Communications Research Laboratory or currently known as the National Institute of Information and Communications Technology (NICT), Japan collaborated with Universiti Sains Malaysia (USM) to test the reliability of the ionospheric model over Penang (Igarashi *et al.*, 1999). It was only after 1998 that local researchers started to work on the ionosphere, mostly using Total

Electron Content (TEC). The next section would elaborate further on the studies conducted by local researchers on space weather.

A. National Space Weather Initiative

The International Heliophysical Year (IHY) in 2007 and the International Space Weather Initiative (ISWI) in 2012 were two international programmes in which Malaysia was involved actively in the space weather program. ANGKASA led these two initiatives by establishing a National committee comprising various experts from government agencies, industries and universities. In conjunction of with the celebration of IHY, Malaysia participated in another space weather research through setting up the Earth's magnetic field sensor system, named the Magnetic Data Acquisition System (MAGDAS) at the LNO. The objective of the sensor was to closely monitor the variability of the earth magnetic field due to solar activities. This project was a joint project between ANGKASA, Space Science Centre (ANGKASA UKM) (formerly known as

Institute of Space Science (ANGKASA UKM)) and the University of Kyushu, Japan (Mou MAGDAS 2007). During the ISWI initiative, Malaysia actively participated and hosted several space weather sensors for R&D as listed in Table 3.

B. Research Activities in Malaysia

Space weather involves cross-disciplinary research from pure to applied science and engineering. In Malaysia, most space weather researchers are from the engineering discipline; it is only recently that researchers from the sciences and other disciplines including surveyors have shown interest in the area. The following sub-sections outline space weather research in Malaysia, particularly the ones that are related to the ionosphere; however, the list is limited to the authors' knowledge from the available references. Past and current research are based on the equipment used, mostly Global Positioning System (GPS) data. A lot of the research had been mainly conducted at the ANGKASA UKM in collaboration with national and international institutions. The highlights covered the observations based on the available equipment that led to modelling in some parts, and this was an extension of a review article on Malaysia by Bahari *et al.* (2015, 2018).

1. Equipment and Data Availability

Ionospheric study in Malaysia was performed using equipment such as in-situ measurements (Radiosonde and Ionosonde) and GPS. The equipment available in Malaysia is summarised in Table 3.

Table 3. Equipment in Malaysia for space weather research

Instrument	Location (Lat, Long)	Data Availability	Owner	Note/Reference
Ionosonde	1° 51' N, 105° 5' E	2004 – 2009	UTHM	Discontinued [Zain *et al.*]
MyRTKnet	Peninsular (57 stations) and Sabah Sarawak (21 stations)	2003 -	JUPEM	https://ebiz.jupem.gov.my/v1/GeodeticProduct.aspx
GISTM	2.92°N, 101.78 ° E (UKM)	2010 -	UKM	Bahari *et al.* (2015)
	6.19° N, 99.51 ° E (Langkawi)	2011 -	UKM	Bahari *et al.* (2015)
	1.47°N, 110.42 ° E (UNIMAS, Sarawak)	2011 -	UKM	Bahari *et al.* (2015)
	1° 51' N, 105° 5' E		UTHM	http://fkee.uthm.edu.my/waras/FACILITIES.html
	2.31° N, 102.32° E	2014 -	UTEM	Aon *et al.* (2014)
GPS-UKM	2.92°N, 101.78 ° E (UKM)	2005 -	UKM	http://www.ukm.my/angkasa/kemudahan/
			UTM	

			UTM	
			UTM	
			National Space Agency	
			National Space Agency	
			UTEM	
MAGDAS	6.19⁰N,99.51⁰E(Langkawi)	2004 – 2007 and continued 2008 -	UKM and National Space Agency	Hamid *et al.* (2015)
	6.02⁰N, 116.07 ⁰ E (Sabah)	2013 -		http://magdas.serc.kyushu-u.ac.jp/station/index.htm
	3.72⁰ N, 101.53⁰ E (Perak)	2016 -		http://magdas.serc.kyushu-u.ac.jp/station/index.htm
	2.78⁰N,101.51⁰E (Banting)	2016 -		http://magdas.serc.kyushu-u.ac.jp/station/index.htm
AWESOME	UKM	2009 -	UKM	Salut *et al.* (2012)
CALLISTO	ANGKASA	2012	ANGKASA	Abidin *et al.* (2015)
ISKANDAR net	Malaysia (7 stations)	2012-	UTM	Musa *et al.* (2012)
Solar telescope system	6.19⁰N,99.51⁰E(Langkawi)	2007 -	LNO, ANGKASA	ANGKASA Annual Report
SID	2.92⁰N, 101.78 ⁰ E (UKM)	2012	UKM	Wong *et al.*, (2012)

To complement the Malaysian regional data, a global database was also used. For GPS data a huge amount of data for the IGS network are available. However, Malaysia is not a contributor to this network and her GPS geospatial data are classified as restricted data. Neighbourhood data such as Scripps Orbit and Permanent Array Center (SOPAC), South East Asia Low-latitude IOnospheric Network (SEALION) network data are available instead. As for MAGDAS, data from INTERMAGNET, INTRAMAGNET are available online and can be used. (Yumoto & Group, 2006).

C. Discussion and the way forward

1. Data

Huge data should be gathered at least for research and national use to be in line with developed countries and to complement international data. Taking advantage of our location over the equatorial region it is essential to have reliable data network. Existing data networks such as the ones in UTM and ANGKASA UKM can be further enhanced into a national big data centre to augment space weather research and to guarantee accessibility to the data to be used.

2. Observations

Currently, only five countries operate space weather data services, namely Japan, Belgium, Australia, Germany, and the United States. Malaysia's location at the equatorial region warrants the development of a space weather data service which would be valuable to space weather researchers and the government.

3. Modelling

The local and regional models thus far cover only Peninsular Malaysia. Therefore, data from Sabah and Sarawak should be considered to include all parts of Malaysia. Since the ionosphere does not vary rapidly except during times of disturbances, the Peninsular Malaysia regional model might be suitable for Sabah and Sarawak. This model could then be extended to cover the SEA region. A regional model would contribute to the global model, making it more accurate and precise. Further research on ionospheric delay covering the region of Malaysia should be conducted and regional empirical model over Malaysia should be developed for future space weather development. The rapid development of satellites such as Beidou, Glonass and Galileo currently, which operate at different signals from GPS, necessitate that these signals are considered in the future to obtain more precise and accurate simulations. In addition, the existing model does not consider ionospheric irregularities which are high at the equatorial region and play important roles in the delay or advancement of the GNSS signals. If the millimetre accuracy is considered, this characteristic of the ionosphere needs to be included and taken into account.

Based on the authors' record, currently there are two ionospheric models available online in Malaysia namely Ionosphere and space weather system and equatorial ionospheric index (EIX). However these models are not enough to provide better services in space weather. Hence, the models should include more parameters such as geomagnetic maps, radio frequency maps etc., as these could save national assets in orbit and on Earth and at the same time avoid business disruptions caused by space weather effects. In the other words, Malaysia should consider developing an Automated Early Warning System for Space Weather. This system becomes a tool to manage and mitigate the risks posed by severe space weather with the potential to cause widespread economic and societal disruptions. By fulfilling the above matter, space weather R&D can move towards operations which can serve national and international needs. The last segment of space science research in Malaysia is microgravity which would be discussed in the next section.

IV. MICROGRAVITY PROGRAM

Microgravity R&D is the latest space science R&D program in Malaysia. Malaysia's first microgravity R&D started in 2006 as part of the preparation for Malaysia entering the National Astronaut Program (NAP). Due to NAP, we were able to be involved in experiments in space and to setup ground facilities to simulate the microgravity environment on Earth especially in Malaysia. This program was sponsored by ANGKASA and executed by University Kebangsaan Malaysia Medical Molecular

Biology Institute (UMBI) when they sent experimental packages in collaboration with the University of Colorado to the International Space Station (ISS) via the US Shuttle. They sent the nematode *Caenorhabditis elegans* (C-elegans), a small worm about 1mm in length (UMBI 2008, 2014). The aim was to study the effects of long term space flight on a worm model (UMBI, 2014). The microgravity sciences became more significant and important during the NAP in 2007. In general, the Malaysian microgravity program was divided into two phases; during NAP and post NAP (Junus, L, 2012).

A. National Astronaut Program (NAP)

NAP was the result of negotiations of offset agreements between the Government of Malaysia and the Government of Russia for the purchase of 18 Sukhoi SU-30 MKM fighter jets. As a result of these counter measures, the Russian Government agreed to train two Malaysian Angkasawan candidates and then send one of them to the International Space Station (ISS).

The launch of NAP to ISS on 10th October 2007 was a big milestone for Malaysia in the development of the Malaysian microgravity and space exploration program. It provided opportunities for Malaysian scientists to embark on researches on microgravity sciences. One of the objectives of the NAP was to conduct science in space under microgravity environment (Junus, L, 2012, 2014). There were three main microgravity experiments flown to the ISS during the NAP mission (ANGKASA, 2010; Junus, L, 2012) namely Microbes in Space (MiS), Cells in Space (CiS), Protein Crystallization in Space (PiS) and Food in Space (FiS). For MiS, the study was on the effects of microgravity on the motility of bacteria, drug resistances as well as changes in gene expression led by UKM and UM researchers. While for the CiS experiment, it involved cancer cells and endothelial cells led by UKM and UiTM. The objective was to study the effects of microgravity and space radiation on cells focusing on changes in the structure and function at the cellular and molecular level. A comparison of crystal growth of lipases on Earth with the growth in microgravity lead by UPM was done under the PiS experiment.

The Angkasawan had also carried out two experiments from the European Space Agency (ESA) on Space Mission Sickness and Lower Back Pain and one experiment from the Japan Aerospace Exploration Agency (JAXA) on Passive Dosimeter for Life Sciences Experiment (PADLES) (ESA, 2008). Through NAP, researchers from various local research institutes such as universities including ANGKASA and MESTECC gained the experience and capabilities of managing, developing, implementing and evaluating microgravity science programs (Junus,L, 2012). Another one of the tangible outcomes was the establishment of a group of researchers trained or at least exposed to space science (UMBI, 2014). After the successful 2007 microgravity sciences during NAP, Malaysian researchers continued their interest in space science R&D.

B. National Astronaut Program (NAP)

The second phase of the microgravity R&D program was from 2008 until now which is the after NAP (or post PAN). In this phase, the program was divided into two segments namely space based and ground based. Microgravity sciences on ISS have been and are being implemented until now. At this phase, the program carried out the activity through an international collaboration.

1. Space based

On 2nd and 3rd September 2008, ANGKASA organized a Scientific Workshop on Microgravity which was officiated by the Minister of MESTECC. This workshop was the first open platform for the results of the microgravity experiments during the NAP to be presented. JAXA showed strong interest in continuing its collaboration with ANGKASA and University Putra Malaysia (UPM). As a result, a total of 24 samples of high quality of proteins with high potential for industrial usage were sent to the Japanese Experiment Module (JEM), ISS for protein crystallization experiments through six flights during 2009-2013 and these were successfully completed.

The most significant outcomes from this project can be applied in industry such as the development of high quality enzymes for pharmaceuticals and also oleochemicals. The direct impact of this programme was the development of a crystallization laboratory and protein analysis in UPM (Junus,L, 2014). Other than that, the UiTM group successfully conducted an experiment for the simulation for of a mission to Mars with the Institute for Bio-Medical Problems (IBMP) in Russia (Junus, L, 2012).

Malaysia had also widened her scope on microgravity R&D in space agriculture when she was involved in the Space Seed for Asian Future (SSAF) program in 2010. The program objective was to study the effects of local chili *Capsicum annuum* (MC11) seed growth in ISS also through collaboration with JAXA under the platform of APRSAF (Junus, L *et al.*, 2012; JAXA[1], 2012). The seeds were launched to ISS by the HTV2 (transfer vehicle to ISS) and retrieved by the Space Shuttle Endeavour (STS-134/ULF6) (JAXA[2], 2012). The results of the study found that the chilli seeds grown during the quarantine process had no negative impact and were confirmed to be safe for use in agricultural activities in Malaysia and there was no physical difference between the returned seeds brought back from ISS and the control seeds on earth (Junus,L, 2011).

In 2013, Malaysia once again collaborated with JAXA under the Asia-Pacific Regiobal Space Agency Forum (APRSAF) platform. Under 2nd program of SSAF, Malaysia was involved in observing the effects of microgravity on the germination of adzuki bean (red bean) in ISS compared to its germination when on Earth. The germination data were shared and utilized by 79 schools throughout the country. Scientific studies on seed germination in the condition of microgravity showed some changes in morphological structures compared to germination on Earth, especially in the direction of extension of the stems and roots (Junus,L, 2014).

2. Ground Based

Malaysia also had increased opportunities in microgravity R&D when she actively participated in the Asian Student Parabolic Flight Program organized by JAXA under APRSAF platform (Takaoki, M *et al.*, 2011; Noh, MF, 2016). ANGKASA with various local universities successfully developed eight prototypes of experiments to be tested under the microgravity environment performed via parabolic flights from 2007 to 2013 which were conducted at Nagoya Airport in Nagoya, Japan (Takaoki, M *et al.*, 2011; Ayop, S *et al.*, 2016). Participants learned implementing microgravity missions from planning, experimental development, experimental execution, data analysis, coordination and international cooperation.

Malaysia achieved a feat in microgravity when the Malaysian Agriculture Research and Development Institute (MARDI) and ANGKASA successfully bid for a free single axis clinostat each through participation in the Zero-Gravity Instrument Project (ZGIP) organized by the United Nations Office for Outer Space Affairs (UNOOSA) in 2013. The program was under the framework of the United Nations (UN) in an effort to empower the field of space science and its applications among member countries. Every bidder from around the world had to submit an activist proposal paper in the form of research and education of clinical applications to UNOOSA (Junus, L, 2014).

In addition to research and international cooperation, the Malaysian microgravity R&D was also being conducted by local researchers. For agriculture, ground based microgravity experiments and researches were implemented in collaboration with MARDI on the Studies of the Effects of Microgravity Simulation Environment on Selected Malaysian Rice (Junus, L, 2014).

Research on life sciences under microgravity sciences was also conducted under the collaboration of UMBI and ANGKASA by using special equipment called Random Positioning Machine (RPM) that simulated the effects of limited microgravity. The RPM was successfully installed on 25th March 2014 at UMBI (UMBI, 2014). The collaboration resulted in the establishment of UMBI-ANGKASA Microgravity Laboratory at UMBI UKM Medical Center (Junus, L, 2014). This was the first ever simulated microgravity system in the country (UMBI, 2014). UMBI and ANGKASA continued the study on C-*elegans* in microgravity and went on to focus on further validating the effects of long term space flight on an animal model.

3. The Second National Astronaut Program (NAP2) and Microgravity Research.

As of now, the Government has yet to propose to continue the mission of the NAP2 to the International Space Station (ISS) in the near future but at the same time it does not intend to cancel the second national astronaut mission to ISS which was originally scheduled for 2011. According to the MESTECC, the ministry has to give priority to the agenda of translating local research and development (R & D) products as the nation's wealth generators through the commercialization process. However, the Government decided to continue the microgravity R&D program to be implemented by sending the experiments to space but without an astronaut (Noh, MF, 2016).

C. Recommendations and the way forward

In almost a decade, Malaysia has undergone many experiences in microgravity research from space based to ground based. Collaboration with international agencies is the best way to realize the program although Malaysia is a non-ISS country. The microgravity R&D should be continued or this experience would disappear forever. Due diligence studies must be conducted in order to decide on updates, outputs and outcomes from the first astronaut program and from the current microgravity sciences program. Besides that, audited and updated inventories of all experts and equipment related to microgravity sciences should be done in deciding to pursue the Angkasawan program. For the new microgravity program, it is recommended to focus on the strategic and economic (ROI) returns especially in nano and bio technology. A new framework for a microgravity sciences program which involved directly selected industries in Malaysia should be introduced. This framework should relate to effectively using microgravity and the other characteristics of the space environment to enhance our understanding of fundamental biological and physical processes and finally to apply this knowledge and technology to improve our nation's competitiveness, education, and the quality of life on Earth.

At the same time, Malaysia needs to encourage active participation of local students and teachers to use microgravity sciences as tools for education and research. Most importantly, this program must adopt a socio-economic-political strategy. Such a strategy of practice is to ensure that these missions will benefit all parties and not only those directly related to the program. Therefore, it is critical for the Government to adopt a more holistic approach in drafting the details of the microgravity program by taking into consideration the views of all stakeholders such as industry, academia, scientists, and politicians as well as the general public.

V. CONCLUSION

The world is facing great challenges and space science R&D offers some solutions, for example in combating global climate change, protecting the Earth from asteroid impacts while at the same time increasing economic opportunities, advancing technical and science knowledge and improving our technically competent workforce (Fisk, 2008). This in in-line with (Schopper, 2016) claims that scientific progress and technical innovations are increasingly considered as necessary elements for economic growth. Overall, the progress of astronomy research in Malaysia had shown a steady growth in the field of optical astronomy, microgravity program, space weather and radio astronomy. The Malaysian astronaut program and the availability of observatories had tremendously boosted the interest of the people in astronomy in Malaysia. Malaysia was recognised by IAU to organise the International Young Astronomer program (ISYA) in 2007 and the COSPAR Regional Capacity Building Workshop on Space Optical and UV Astronomy in 2008. The space weather research group from UKM and UTM is very active in ionospheric geomagnetic R&D. UKM is also conducting an International Seminar known as International Conference on Space Science and Communication (IconSpace) once every two years beginning from 2009. The radio astronomy research group is actively involved in planning to build a radio telescope in Malaysia and it collaborates with international partners from Australia and China. Last but not least it is much hoped that the research budget in the future for astronomy research be allocated with sufficient amounts of funds. As we already have well trained people in the field of astronomy, sufficient grants will encourage and flourish astronomy research in Malaysia.

The space science R&D is very challenging. The National Space Policy (NSP) shows that the government is focusing more on space technology and applications which will contribute to commercialization. However, the main outputs from space science research are more on the enhancement of knowledge and other intangible outputs. Looking at the coordination framework, only space weather is mentioned in general but not microgravity sciences and astronomy. All these challenges occur because there is the lack of a framework to demonstrate the value of the space science program until the realization of economic benefits. Such a framework that shows the process from a new knowledge to economic benefits should become a catalyst to the development, analysis and implementation of the space science program in order to support the Malaysian space program. To make this framework workable, an integrated roadmap for space science R&D is required which strongly links space education, space technology and space applications. Therefore, the need of an integrated framework beginning from R&D activities until the realization of economic and strategic benefits is paramount (Asillam & Subari, 2017).

In order for the space science sectors to contribute high value new knowledge which resulted from R&D activities in Malaysia, several actions need to be taken such as the need of space science R&D-related infrastructures that meet international standards to support local research activities and in preparation for participation in international initiatives to pursue new knowledge.

Due to the high cloud cover, the astronomy program should integrate both optical and radio astronomy to complement each other in order to achieve multiwavelength observations. At the same time, it is timely to start a new program which is observation from space via a small CubeSAT program etc. To jump-start the above initiative, Malaysia should actively participate in global space science related initiatives such as IAU, Committee on Space Research (COSPAR), UNOOSA and others international programs.

To further develop niche areas that meet national needs, solve current problems and promote Malaysian leadership at the international level, space science R&D in Malaysia should focus to support the challenges in space technology development in Malaysia. R&D on Near Equatorial Orbit (NEqO) to have understanding of the equatorial environment in and from space would be unique for us to solve our own environmental limitations and technology challenges and this new knowledge is really significant both locally and internationally. Due to that, Malaysia should consider establishing an international network of NEqO. NEqO R&D activities must lead to engineering programs and commercialization especially in developing new algorithms, new softwares etc.

Space science R&D is a fundamental need if Malaysia would like to advance and use space technology and space application for the socioeconomic development of the nation (Asillam, MF & Subari, 2017). Last but not least, space science R&D is the foundation to assure the sustainability of the national space program.

VI. REFERENCES

[1] A 'Microgravity' Laboratory in UMBI: A Collaboration With The National Space Agency (ANGKASA), 2014, viewed on 22 March 2018, http://www.ukm.my/umbi/news/20140808-microgravity-laboratory-umbi-collaboration-national-space-agency-angkasa/

[2] Abidin, ZZ, Anim, NM, Hamidi, ZS, Monstein, C, Ibrahim, ZA, Umar, R, Shariff, NNM, Ramli,N, Aziz, NAI & Sukma, I 2015, 'Radio frequency interference in solar monitoring using CALLISTO', *New Astronomy Reviews*, vol. 67, pp. 18-33.

[3] Ahmad, N, Loon, CW, Syukor, MS, Haron, S, Zainuddin, MZ & Tahar, MRM 2015, 'The Astronomical Seeing Measurement at Langkawi National Observatory', in *Proceeding of the 2015 International conference on Space Science and Communication (IconSpace), 10-12 August*, Langkawi, Malaysia.

[4] Ahmad, N, Zainuddin, MZ, Yahya, MS, Malasan, HI & Buil, C 2015, 'Spectral variations of the be disk of δ-Scorpii during the 2011 periastron passage', *New Astronomy*, vol. 36, pp. 80-85.

[5] Aon, EF, Shaddad, RQ, Othman, AR & Ho, YH. 2014, 'Analysis of ionospheric scintillation for Global Navigation Satellite System at UTeM, Malaysia', in *2014 IEEE 10th International Colloquium on Signal Processing & its Application (CSPA2014), 7-9 Mac 2014*, Kuala Lumpur, Malaysia. 37-41.

[6] Appanah, Y, Hassan, SYSI, Gargash, BC, Igarashi, K & Minakoshi, H, 1999, 'Preliminary Ku-Band satellite beacon signal measurement results at Tronoh, Malaysia', in *International Conference on Robotics, Vision and Parallel Processing for Automation (ROVPIA 99), 16-18 July 1999*, Ipoh, Malaysia.

[7] *Asian "Kibo" Mission Planning: "Space Seeds for Asian Future" Program: Malaysia Space Seed (Astroseed) Program 2012*, viewed on 20 February 2018, http://iss.jaxa.jp/en/kuoa/pdf/ssaf_2012.pdf.

[8] Asillam, MF, & Subari, MD 2017, 'Space Science and Nation's Development: Evaluating the Benefits of Space Science', *JOSTIP*, vol. 3, no. 2.

[9] Ayop, SK, Hashim, MH, Jaafar, R, Yaacob, MIH, Ismail, AT & Hong, KK 2016, 'Report on Post Asian Student Team Parabolic Flight 2013 Activities by Malaysian Team', *International Journal of Microgravity Science and Application*, vol. 33, no. 2, pp. 330211-1 - 330211-4.

[10] Bahari, SA & Abdullah, M 2018, *A Brief Review: Response of the Ionosphere to Solar Activity Over Malaysia*, eds W Suparta, M Abdullah & M

Ismail, in Space Science and Communication for Sustainability. Springer, Singapore, pp. 95-100.

[11] Chin, WL & Zainuddin, MZ 2013, 'Solar spectrum observation with intermediate resolution spectrograph', in *AIP Conference Proceeding 1528, 19-21 November 2012*, Pahang, Malaysia.

[12] COPOUS 2014, *Report on the United Nations/Austria Symposium on Space Science and the United Nations*, Graz, Austria, 22-24 September 2014, UNOOSA (Vol. A/AC.105/1).

[13] Fisk, LA 2008), 'The impact of space on society: Past, present and future', *Space Policy*, vol. 24, no. 4, pp. 175–180. https://doi.org/10.1016/j.spacepol.2008.09.001

[14] Hamid, NSA, Liu, H, Uozumi, T, Gopir, GK, Hadin, HA & Yoshikawa, A 2015, 'Longitudinal and solar activity dependence of equatorial electrojet at Southeast Asian sector', in *2015 International Conference on Space Science and Communication (IconSpace), 10-12 August 2015*, Langkawi, Malaysia.

[15] Hof, B, Koopmans, C, Lieshout, R & Wokke, F 2012, *Design a Methodology to Evaluate the Direct and Indirect Economic and Social Benefits of Public Investment in Space*.

[16] ICSWSE, 2018, *MAGnetic data acquisition systems/ Circum-pan pacific magnetmeter network data (MAGDAS / CPMN)*, viewed on 20 June 2018, < http://data.icswse.kyushu-u.ac.jp/>.

[17] Ismail, K, Asillam, MF & Zin, AAM 2014, 'Human Resource Development Issues in the Field of Islamic Astronomy: Analysis of the Langkawi National Observatory, Malaysia', *International Journal of Social Science and Humanity*, vol. 4, no. 6, pp. 463.

[18] Jabatan Ukur dan Pemetaan Malaysia (JUPEM), 2018, viewed on 20 June 2018, < https://ebiz.jupem.gov.my/v1/GeodeticProduct.aspx

[19] Junus, L 2012, *Penyelidikan Angkasa, Mega*, Utusan Malaysia, pp. 1-4.

[20] Junus, L 2014, *Kejayaan Penyelidikan Mikrograviti*, Mega Sains, Utusan Malaysia, pp. 6-7.

[21] Junus, L, Ahmad, AF & Azis, ND 2012, *Program Space Seed, Sains & Teknologi*, viewed on 23 February 2018, http://ww1.utusan.com.my/utusan/Sains_&_Teknologi/20121029/st_01/Program-Space-Seed.

[22] Junus, L. 2011, *Benih Cili dari Angkasa*, Mega Fokus, Utusan Malaysia, pp. 2-4.

[23] Laan, JEVD 1967, *Ionospheric and magnetic observation at Bangkok, Thailand during the annular solar eclipse on November 23, 1965*, Special Technical Report 32, US Army Electronics Command Fort Monmouth, New Jersey.

[24] Loon, CW, Zainuddin, MZ, Ahmad, N, Shukor, MS & Tahar, MR 2015, 'Acquirement of the observatory code of Langkawi National Observatory', in *AIP Conference Proceedings 1657, 18-19 November 2014*, Kuala Lumpur, Malaysia.

[25] Maeda, K 1986, 'Fifty years of the ionosphere', *Journal of the Radio Research Laboratory*, vol. 33, no. 140, pp. 103-167.

[26] *Malaysian Astronaut to Work on ESA Experiments*, 2008, viewed on 28 February 2018, http://www.esa.int/Our_Activities/Human_Spaceflight/Research/Malaysian_astronaut_to_work_on_ESA_experiments.

[27] Malaysia Ionosphere, 2018, *Ionosphere and space weather system*, viewed on 22 June 2018, http://myiono.angkasa.gov.my

[28] Mat Jusoh, Z 2010, *Merintis Masa Depan: Impian Menjadi Kenyataan, Putrajaya*, Utusan Publization & Dsitributors Sdn. Bhd., pp. 31-94.

[29] Musa, TA, Leong, SK, Abdullah, KA & Othman, R 2012, 'ISKANDARnet IOMOS : Near real-time equatorial space weather monitoring and alert system in Peninsular Malaysia', *Space Weather*, vol. 10, pp. S11003.

[30] Nawawi, MSAM, Niri, MA & Zainuddin, MZ 2013, 'Kenampakan anak bulan di Teluk Kemang: analisis mengikut pandangan Fiqh oleh Yusuf al-Qaradawi dan perspektif astronomi', *Jurnal Syariah*, vol. 21, no. 1, pp. 63-74.

[31] Nawawi, MSAM, Niri, MA, Man, S, Ahmad, K & Zainuddin, MZ 2015, 'Relevensi Penggunaan Imkarnurrukyah dalam penentuan awal bulan Ramadan dan Syawal di Malaysia', *Jurnal Falak*, vol. 1, pp. 99- 120.

[32] Ngeow, C –C & Luo, SC 2017, 'Limiting magnitudes and night sky brightness at the Langkawi National Observatory based on observations of standard stars', *IOP Conf. Series: Journal of Physics: Conf. Series* ,vol. 852.

[33] Nizam, NK, Nawai, MSAM, Niri, MA, Man, S & Zainuddin, MZ 2014, 'The use of telescope during the observation of lunar crescent's from fiqh's perspective & astronomical considerations', *Jurnal Fiqh*, vol. 11, pp. 33-58.

[34] Othman, M & Asillam, MF 2005, *Halatuju Penyelidikan Astronomi di Malaysia*, USM, Pulau Pinang.

[35] Noh, MF 2016, *Misi hantar angkasawan negara kedua ditangguh lagi*, viewed on 17 April 2018, https://www.bharian.com.my/node/213274.

[36] Othman, M 2004, *A Decade of Space 1994-2004*, Kuala Lumpur: Malayia Space Agency.

[37] Pham, HTT, Amory-Mazaudier, C, Le Huy, M. & Elias, AG 2016, 'f o F 2 long-term trend linked to Earth's magnetic field secular variation at a station under the northern crest of the equatorial ionization anomaly', *Journal of Geophysical Research: Space Physics*, vol. 121, no. 1, pp.719–726.

[38] Razelan, MM, Said, NMM, Chong, HY, Aziz, AHA & Zainuddin, MZ 2015, 'Spectral line asymmetry of Arcturus', in *AIP Conference Proceedings 1657, 18-19 November 2014*, Kuala Lumpur, Malaysia.

[39] Razelan, MM, Said, NMM, Aziz, AHA, Chong, HY & Zainuddin, MZ 2013, 'Spectral line profiles of alpha orionis', in *AIP Conference Proceeding 1528, 19-21 November 2012*, Pahang, Malaysia.

[40] Saadon, MH & Zainuddin, MZ 2013, 'H-α profile of m-type red giant stars by using astronomical spectroscopy technique', in *AIP Conference Proceeding 1528, 19-21 November 2012*, Pahang, Malaysia.

[41] Said, NMM, Razelan, MM, Aziz, AHA, Chong, HY & Zainuddin, MZ 2013, 'Equivalent width of H-α in 22 Vulpeculae', in *AIP Conference Proceeding 1528, 19-21 November 2012*, Pahang, Malaysia.

[42] Said, NMM, Razelan, MM, Chong, HY, Aziz, AHA & Zainuddin, MZ 2015, 'Determination of pulsation period of iota Herculis', in *AIP Conference Proceedings 1657, 18-19 November 2014*, Kuala Lumpur, Malaysia.

[43] Said, NMM, Razelan, MM, Chong, HY, Aziz, AHA & Zainuddin, MZ 2015, 'On Corelation of microturbulence and the line depth of S II line profile in iota Herculis', in *AIP Conference Proceedings 1657, 18-19 November 2014*, Kuala Lumpur, Malaysia.

[44] Said, NMM, Razelan, MM, Chong, HY, Aziz, AHA & Zainuddin, MZ 2015, 'Corelation between microturbulence and nonradial pulsations in iota Herculis', in *AIP Conference Proceedings 1657, 18-19 November 2014*, Kuala Lumpur, Malaysia.

[45] *Sains Mikrograviti 2010*, viewed on 28 February 2018, http://www.angkasa.gov.my/sites/default/files/artikel/publication/Booklet%20Program%20Khas%20Sains%20Mikrograviti.pdf.

[46] Salut,MM & Abdullah, M 2012, *Very low frequency remote sensing of ionosheric disturbances caused by lightning discharges*, Innovate : Research Bulletin Engineering and Built Engineering, pp. 5

[47] Schopper, H 2016, 'Some remarks concerning the cost/benefit analysis applied to LHC at CERN', *Technological Forecasting and Social Change*, vil. 112, pp. 54–64. https://doi.org/10.1016/j.techfore.2016.02.007

[48] Seidel, DJ, Ross, RJ & Angell, JK 2001, 'Climatological characteristic of the tropical tropopause as revealed by radiosondes', *Journal of Geophysical Research*, vol. 106, no. 8, pp. 7857-7878.

[49] Shukor, MS & Zainuddin, MZ 2015, 'Perbandingan Metodologi Kajian Penentuaan Masuk nya Fajar Sadiq dan hilangnya Syafaq Ahmar: Kajian kecerahan langit', *Jurnal Falak*, vol.1, pp. 133- 140.

[50] Tahar, MR, Kamarudin, F, Umar, R, Kamarudin, MKA, Sabir, NH, Ahmad, K, Rahim, SA & Baharim, MSA, 2017, 'Spatial Model of Sky Brightness Magnitude in Langkawi Island, Malaysia', *Research in Astronomy and Astrophysics*, vol. 17, no. 4, pp. 1-5.

[51] Takaoki, M, 2011, *Chapter 10 Parabolic Flight Experiments by Students from the Asia-Pacific Region*, viewed on 20 June 2018,

http://www.jspacesystems.or.jp/library/archives /jaros/space%20utilization%20view/h22_10a.pdf .

[52] *The Worm Laboratory*, 2008, viewed on 22 March 2018, http://www.ukm.my/umbi/the-worm-laboratory/

[53] Thomas, RM, Cervera, MA, Eftaxiadis, K, Manurung, SL, Saroso, S, Effendy, RAG, Hassan,WSW, Rahman, H, Dalimin, MN, Groves, KM & Wang, Y 2001, 'A regional GPS receiver network for monitoring equatorial scintillation and total electron content', *Radio Science*, vol. 36, no.6, pp. 1545 - 1557.

[54] Umar, R, Abidin, ZZ & Ibrahim, ZA 2013, 'The importance of Radio Quiet Zone (RQZ) for Radio Astronomy, in *AIP Conference Proceedings*, vol. 1528, no. 32, pp. 32-37.

[55] UMBI, 2014, *A microgravity Laboratory in UMBI: A colloboration with National Space Agency (ANGKASA)*, viewed on 19 June 2018, http://www.ukm.my/umbi/news/20140808-microgravity-laboratory-umbi-collaboration-national-space-agency-angkasa/

[56] Wahid, K, Nawawi, MSAM & Zainuddin, MZ 2015, 'Study on Sky Brightness and Length of shadow To Determine The Early Time of Dhuha Prayer', *Asian Journal of Applied Sciences*, vol.3, no.2 , pp. 271-276.

[57] *Winners of Space Seed competition in Malaysia 2012*, viewed on 20 February 2018, http://iss.jaxa.jp/en/kuoa/news/kuoa_121029.html.

[58] *Wireless and Radio Science Centre (WARAS), 2018*, viewed on 20 June 2018, <http://fkee.uthm.edu.my/waras/FACILITIES.html>.

[59] Wong, PW, Abdullah, M Hasbi, AM & Bahari, SA 2012, 'Development of VLT Receiver System for Sudden Ionospheric (SID) Detector', in *2012 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE 2012), 11-13 December 2012*, Melaka, Malaysia, pp. 98-103.

[60] Yumoto, K & Group, M 2006, 'MAGDAS Project and Its Application for Space Weather', in *36th COSPAR Scientific Assembly, 16 - 23 July 2006*, Beijing, China.

[61] Zain, AFM & Abdullah, S 2005, 'The first preliminary ionospheric sounding in Malaysia', *Geophysical Research Abstract*, vol. 7, pp. 01021.

[62] Zainuddin, MZ, Haron, S, Niri, MA, Ahmad, N, Nawawi MSAM, Man, S, Rodzali, MZ, Ramli, R, Wahab, RA, Ismail K & Zaki, NHA 2013, 'Sky brightness condition during total solar eclipse on July 22, 2009', *Middle-East Journal of Scientific Research*, vol. 13, no.2, pp. 220-223.

[63] Zainuddin, MZ, Muhyidin, MA, Ahmad, N & Sadon, MHM 2011, 'The Pleiades Using Astronomical Spectroscopic Technique within the Range of H-α Region", in *AIP Conference Proceedings*, vol. 1328, no. 1 , pp. 56-58.

[64] Zainuddin, MZ, Nawawi, MSAM, Man, S & Niri, MA 2015, 'Analisis Perbandingan Unjuran Kalendar Berdasarkan Kriteria Altidud 2 dan Elongasi 3 atau 8 jam Dengan Kriteria Altitud 3 dan Elongasi 5', *Jurnal Falak*, vol. 1, pp. 1-43

[65] Zaki, NHA, Zainuddin, MZ, Ali, AK, Wahab, RA, Nawawi, MSAM, Niri, MA & Ismail, K 2014, 'The Determination of Subuh Prayer Time by using Rubu' Mujayyab in Malaysia', *Jurnal Fiqh*, vol.11, pp. 97-118.

[66] Zaki, NHA, Ali, AK & Zainuddin, MZ 2013, 'Ilmu al-Miqat: pentakrifan, sejarah dan kepentingan', *Jurnal Usuluddin*, vol. 36, pp. 2012-05.

[67] Zaki, NA, Zainuddin, MZ, Ali, AK, Nawai, MSAM, Ismail, K, Niri, MA & Wahab, RA 2014, 'Comparing the accuracy of the modern and traditional calculation methods in the determination of prayer times in Malaysia', *Online Journal of Research in Islamic Studies*, vol. 1, no. 2, pp. 31 – 44.

Variation of Equatorial Electrojet Current Profiles over Solar Phases

W.N.I. Ismail[1], N.S.A. Hamid[1,2*], M. Abdullah[2,3], N.H.M. Shukur[1] and A. Yoshikawa[4,5]

[1]*School of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*

[2] *Space Science Centre (ANGKASA), Institute of Climate Change, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*

[3]*Centre of Advanced Electronic and Communication Engineering (PAKET), Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*

[4]*Department of Earth and Planetary Sciences, Faculty of Sciences, 33 Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan*

[5]*International Center for Space Weather Science and Education (ICSWSE), Kyushu University 53, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan*

Equatorial electrojet (EEJ) current is an intense eastward electric current flowing at about 100-120km altitude within ±3° latitude in E region of the equatorial ionosphere. This study reported dependence of EEJ longitudinal profile on the three phases of solar cycle 24 (SC-24). The analysis was carried out using EUEL index, calculated from the northward H component of geomagnetic field. This work utilised data from various ground-based magnetometer networks such as MAGDAS, INTERMAGNET and IIG. The results of this study showed that the highest and lowest value of EEJ longitudinal profiles varies with solar phases. The nature of the longitudinal disparity in the EEJ strength indicates that it is strongest in American sector and lowest in African sector during solar minimum in 2008. However, during solar maximum in 2013 the highest EEJ intensity was recorded in Southeast Asian sector. On the other hand, the lowest value of EEJ current was recorded in African sector in 2008 which was found to be shifting to Indian sector started in 2011. In addition, we discovered the transition point of the highest value of EEJ started in 2012, while the transition point of minimum value EEJ started in 2010.

Keywords: Equatorial electrojet; transition point; solar cycle 24

I. INTRODUCTION

The current that flows eastward in the ionosphere equatorial region (±3°) with a very high intensity is known as the equatorial electrojet, EEJ (Chapman & Raja Rao, 1965; Onwumechili, 1992). The combination of primary electric field that generated by the dynamo E layer with the northward direction of geomagnetic field produce two currents which are the downward Hall current and the eastward Pederson current. The downward Hall current leads to an accumulation of charges resulting in the upward polarised electric field. This polarised electric field set up to oppose the flow and produce a strong eastward current known as EEJ (Barreto, 1992; Prolss, 2004; Yamazaki *et al.*, 2016).

Since its discovery, the variability of EEJ has been widely studied using different approaches, for example by using ground magnetometers (Chapman and Rao, 1965; Rigoti *et*

*Corresponding author's e-mail: shazana.ukm@gmail.com

al., 1999; Hamid *et al.*, 2014). Numbers of previous study reported that the EEJ current varies with longitude. Most of researchers utilised the ground based magnetometer to obtain the EEJ longitudinal profile (Doumouya *et al.*, 2003) however, the application of satellite data is also getting more widespread in the recent years (Doumouya *et al.*, 2004; Lühr *et al.*, 2013). Nowadays, numbers of ground based magnetometer network have been growing globally such as International Real-Time Magnetic Observatory Network (INTERMAGNET), Indian Institute of Geomagnetism (IIG), Magnetic data Acquisition System (MAGDAS)/ circum-pan Pacific Magnetometer Network (CPMN) (Yumoto and MAGDAS group 2007) and a few stand-alone stations (Hamid *et al.*, 2018). Some researchers have focused on the longitudinal variation of EEJ towards some parts of region only. Shume *et al.* (2010) in their study have focused on the EEJ variability in Brazil and Peru region and reported that EEJ current is higher in West coast (Jicarmarca) compared to the east coast (Sao Luis). Other researchers focused on the behaviour of EEJ in the Indian region only and at a certain phase of solar cycle (Rastogi *et al.*, 2004; Chandrasekhar *et al.*, 2014). Limitation to certain regional and period in these previous researches might not be able to summarise the global longitudinal profile of EEJ current.

Expansion of regional EEJ study by Hamid *et al.* (2015) through the derivation of the empirical model from six longitude regions have shown that EEJ current is strongest in South American sector and weakest between Indian and African sector. However, the usage of simultaneous data has limited their study to solar minimum in 2009. Recent study by Hamid *et al.* (2017) and Rabiu *et al.* (2017) have also confirmed that EEJ current is highest at South American sector. This study aims to clarify the dependence of longitudinal profile on different solar phases as most of previous studies have limit their research in certain period of time. Thus, in order to get the longitudinal profile of EEJ, the similar method by Hamid *et al.* (2017) and Ismail *et al.* (2017) was applied.

II. METHOD AND ANALYSIS

This study uses the continuous data from the year of 2008 to 2014. The data were taken from twelve stations situated in South American sector (ANC-FUQ), African sector (ILR-TAM and AAB-NAB), Indian sector (TIR-ABG) and Southeast Asian (LKW-KTB and DAV-MUT) sector. Figure 1 illustrates the position of the observatory used and Table 1 lists all the geographic and geomagnetic coordinates. Each pair of the station is a combination of two stations that are located outside the dip equator and at dip equator. Analysis was carried out using the equatorial electrojet index named EUEL that was derived from H component (Uozumi *et al.*, 2008). The northward geomagnetic H component that measured by ground based magnetometer is selected since this component was dominant in equator region. The variations of H component are including contribution from internal source and external sources such as ionospheric and magnetospheric currents. Therefore, the other sources effect was eliminated in order to get the EUEL index that represents EEJ current a single station. In contributing to this index, the global magnetic variation, including the disturbances at the equatorial region represented by EDst index (Equatorial Disturbance in storm time) were removed. The disturbance particularly is from storm sudden commencement (SSC) and ring current. EDst index is derived from the mean value of H component that observed at nightside (LT=18-06) (Hamid *et al.*, 2013).

Next, EEJ strength is represented by the average data of EUEL for each year after normalisation technique is applied to the stations that are not located at 0° dip equator. This method was introduced by Hamid *et al.* (2014) in order to avoid the latitudinal variation effect of EEJ. The normalisation technique will give two normalise currents which are Sq and total currents obtain from EUEL at off-dip equator and near dip equator stations respectively. For instance, normalisation of EUEL at DAV station will give total current while normalisation of EUEL at MUT will give Sq current. The difference between both currents will results in EEJ current. A spline interpolation will be used to obtain the longitudinal profile of EEJ over three phases of SC-24. The results were compared statistically in order to determine the percentage difference of the average data for all years and six sectors. The mathematical method for calculating the difference in average value of the EEJ current, Ą is expressed by:

$$Ą(\%) := \left|\frac{\Delta A_y - \Delta A_{Y-1}}{\Delta A_{Y-1}}\right| \times 100 \quad (1)$$

where ΔA_y represents the average of EEJ on theparticular year and ΔA_{Y-1} represents the year before.

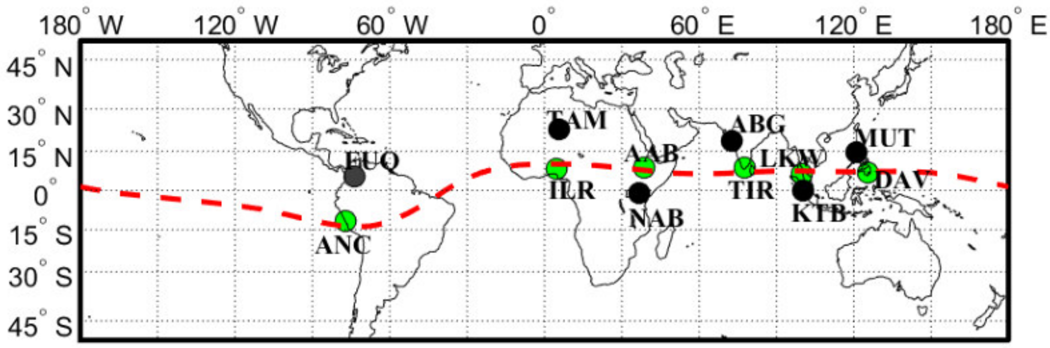


Figure 1. Map of geomagnetic observatories used in this study

Table 1. Geographic and Geomagnetic coordinate of all stations

Sector	Station		Geographic		Geomagnetic	
	Name	Code	Lat. (°)	Lon.(°)	Lat. (°)	Lon.(°)
South	Ancon	ANC	-11.77	-77.15	0.77	354.33
America	Fuquene	FUQ	5.40	-73.73	15.72	357.99
Africa	Iiorin	ILR	8.50	4.68	-1.82	76.80
	Tamanrasset	TAM	22.8	5.5	25.4	80.6
	Adis Adaba	AAB	9.04	38.77	0.18	110.47
	Nairobi	NAB	-1.16	36.48	-10.65	108.18
India	Tirunelvelvi	TIR	8.70	77.80	0.21	149.30
	Alibag	ABG	18.62	72.87	10.36	146.54
Southeast	Langkawi	LKW	6.30	99.78	-2.321	171.29
Asia	Kototabang	KTB	-0.20	100.32	-10.63	171.93
	Davao	DAV	7.00	125.40	-1.02	196.54
	Muntinlupa	MUT	14.37	121.02	6.79	192.24

III. RESULTS AND DISCUSSIONS

A. The dependence of EEJ longitudinal profile on solar phases

In order to analyse the dependence of EEJ profile on solar phases, the results were separated according to phases which are in a solar minimum (2008 and 2009), inclination phase (2010 and 2011), and also the maximum phase of SC-24 in 2012, 2013 and 2014, as illustrated in Figure 2. The black and red solid lines represent the linear interpolation whereas the dotted blue line shows the spline interpolation. In all figures, spline interpolation was applied to the years with complete data from all stations. The analysis reveals that the variation of EEJ longitudinal profile has solar cycle dependence. The analysis starts with solar minimum ($F10.7_{avg}$ = 72) as presented in Figure

2(a), which indicates that the highest value of EEJ current was recorded at ANC (South American sector) for both years 2008 and 2009. Meanwhile, the lowest value EEJ strength was at AAB (African sector) and TIR stations (Indian sectors) in 2008 and 2009 respectively. On the other hand, LKW data (Southeast Asia) are unavailable in 2009.

Next is inclination phase ($F10.7_{avg}$ = 97) as shown in Figure 2(b). During this phase, the highest EEJ peak is 72.15 nT which is recorded at ANC station, followed by LKW station with magnitude around 57.94 nT. This observation is comparable with solar minimum phase. On the other hand, AAB station shows some increment comparing to TIR station. This increment has surpassed the TIR station as much as 12.27 nT.

Lastly, the analysis is continued for the year of solar maximum ($F10.7_{avg}$ = 130) as illustrated in Figure 2(c). In 2012, the magnitude of EEJ between ANC and LKW stations show comparable values. On the contrary, in 2013 the magnitude of EEJ is highest at LKW station where the value is 101.1 nT compared to ANC station which is only 79.98 nT. LKW station remains to have the highest value of EEJ until 2014. On the other hand, minimum value of EEJ magnitude was recorded at TIR station in 2012. However, it is important to note that data at ILR and AAB stations are unavailable for the same year, thus this observation is rather inconclusive. All average data of EEJ magnitude from the year of 2008 to 2014 is presented in Table 2.

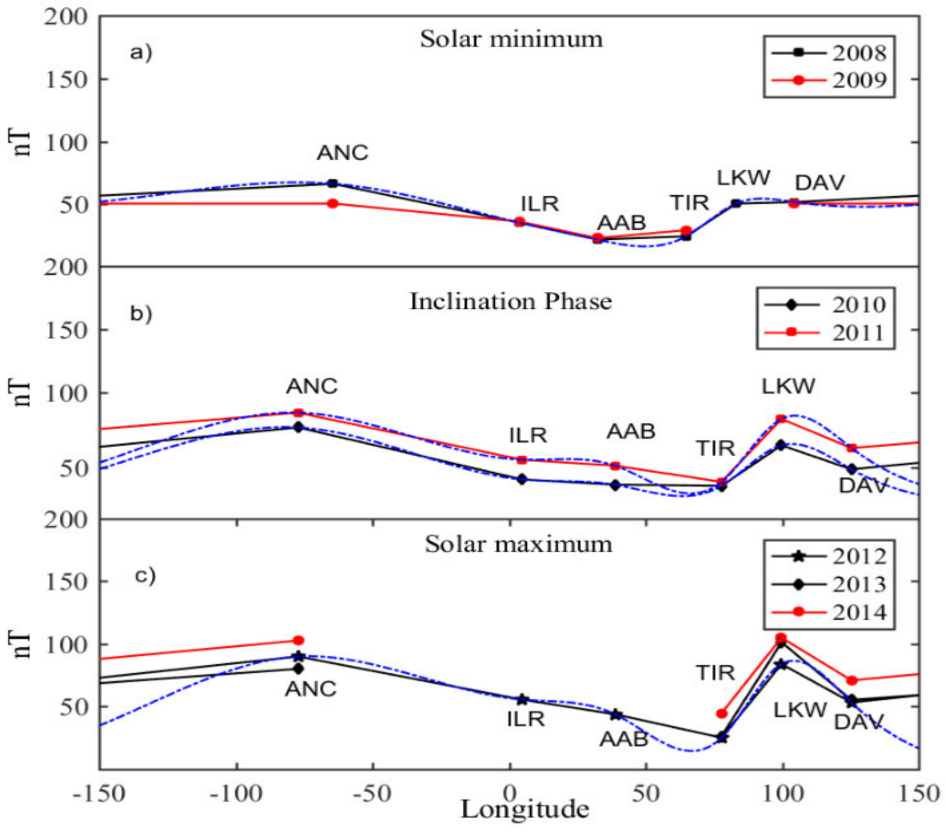


Figure 2. Longitudinal profile of EEJ for (a) solar minimum (2008 and 2009); (b) inclination phase (2010 and 2011); and (c) solar maximum (2012, 2013 and 2014). Dotted blue line represents the spline interpolation

Table 2. The average value of EEJ current (nT)

Sector	Station	Year						
		2008	2009	2010	2011	2012	2013	2014
South America	ANC	66.43	50.77	72.15	83.86	89.81	79.98	102.55
Africa	ILR	35.49	36.43	30.93	46.61	55.5	NaN	NaN
	AAB	22.40	23.33	26.7	40.99	43.8	NaN	NaN
India	TIR	24.63	29.61	25.77	28.72	25.11	26.23	44.55
Southeast Asia	LKW	50.64	NaN	57.94	78.66	83.78	101.1	104.81
	DAV	51.91	50.77	38.87	52.25	53.17	55.21	70.79

Previous studies by Doumouya *et al.* (2003) and Hamid *et al.* (2017) showed that EEJ current is always higher at South American sector. However, this study reveals that this is only recognisable during solar minimum and inclination phases. ANC station recorded the strongest EEJ strength in 2008 until 2011 before shifting to LKW station from 2012 onwards. The lowest EEJ strength was observed at AAB station in 2008 and then changed to TIR station in 2011. This implies that there is a shift in highest and lowest values. This concludes the shifts of the highest and the lowest EEJ magnitude to Southeast Asia sector and India sector during solar maximum and minimum respectively.

It is well known that the intensity of EEJ current is proportional to solar activity level (Hamid *et al.*, 2013; Chandrasekhar *et al.*, 2014; Rabiu *et al.*, 2017). However, as mention before, most of them were focusing on certain region and period such as study by Hamid *et al.* (2013) that used data in Southeast Asia during inclination phase on 2011. The data used in this study cover period from solar minimum until solar maximum and thus the EEJ values were expected to be increased with solar activity level. An analysis was further performed to clarify the yearly changes of EEJ intensity by calculating the

percentage difference of EEJ average values. The results are presented in Table 3. It is revealed that in certain years, there are some stations that show declination in EEJ yearly values. During 2009, ANC station experienced the biggest declination of 23.57% with respect to 2008. Other than that, ILR station shows a declination as much as 15.09% while TIR station having 12.96% decrement during 2010. At the same year, DAV station also shows 23.44% of decrement, whereas ANC station with increment of 42.11%. In 2011, all stations show increment in EEJ intensity with ILR and AAB exhibit the percentage value as much 50.69% and 53.52% respectively. DAV station shows an increment of 34.42% while the LKW stations exhibited an increment of 35.76%. Overall, ANC has the highest decrement during 2009 with respect to 2008, while the highest increment is monopolised by TIR station throughout maximum solar phase (2013 - 2014). Based on this statistical analysis, it is concluded that EEJ current at some stations did not experience a significance increment or decrement in intensity over different years due to the same phases of solar activity. An example is EEJ intensity at DAV station on 2008 and 2009 are comparable as both year are in solar minimum phase. However, if the comparison is made between solar minimum (2008 or 2009) and maximum (2014), there is a clear increment in EEJ intensity (refer Table 2). This clarifies that EEJ intensity increases with solar activity level.

Table 3. The percentage difference (%) of average value of EEJ current with respect to previous year

Stations	Year					
	2009	2010	2011	2012	2013	2014
ANC	-23.57	42.11	16.23	7.09	-11.05	28.15
ILR	2.64	-15.09	50.69	19.07	NaN	NaN
AAB	4.15	14.59	53.52	6.85	NaN	NaN
TIR	20.21	-12.96	11.44	-12.56	4.46	69.84
LKW	NaN	NaN	35.76	6.59	20.67	3.67
DAV	-2.19	-23.44	34.42	1.76	3.83	28.21

B. Transition point of the strongest and lowest EEJ strength

The reveals of shifted location of EEJ highest and lowest values lead to further analysis in identifying the transition points. Transition points are regarded as the year when the location of highest and lowest values of EEJ current started to change. Figure 3(a) shows the average values of EEJ current at ANC (EEJ_{ANC}) and EEJ current at LKW (EEJ_{LKW}) from 2008 till 2014. This graph allows the detection of transition point for highest EEJ values. This figure shows that 2013 is the year when EEJ_{LKW} first exceed EEJ_{ANC}. The different values of EEJ between these two stations (EEJ_{ANC}—EEJ_{LKW}) were calculated and the results are presented in Table 4. The finding shows that the different are positive up to the year of 2012. The negative value of 21.12 nT in 2013 confirmed that EEJ_{LKW} surpass EEJ_{ANC} during this year, and thus the year can be regarded as the transition point of EEJ highest value.

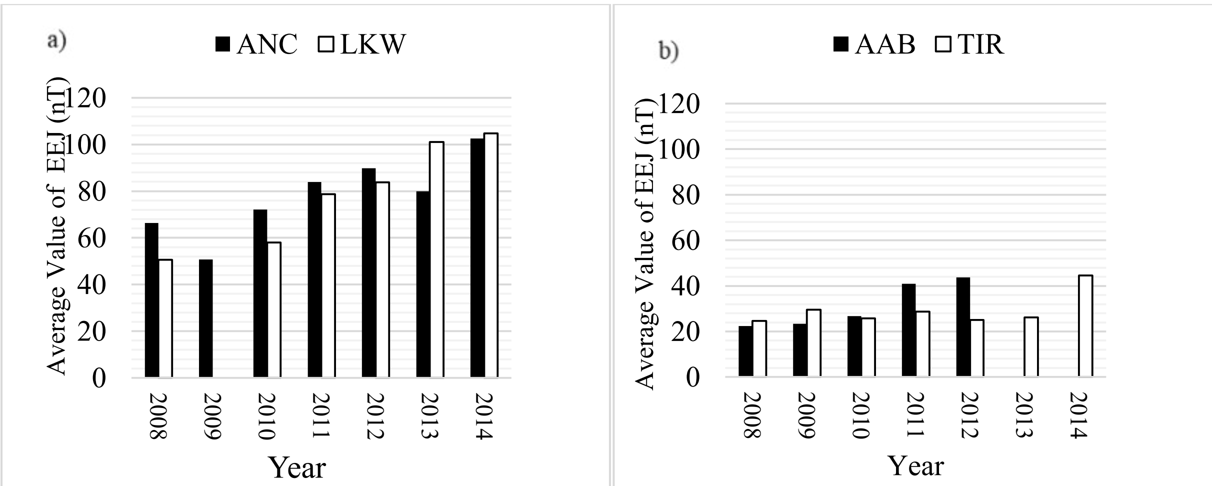


Figure 3. The Average value of EEJ current at (a) ANC and LKW and at (b) AAB and TIR

Table 4. Difference of EEJ current at ANC (EEJ_{ANC}) and LKW (EEJ_{LKW}) and difference of EEJ current at AAB (EEJ_{AAB}) and TIR (EEJ_{TIR})

Stations	Years 2008	2009	2010	2011	2012	2013	2014
EEJ_{ANC} - EEJ_{LKW}	15.79	NaN	14.21	5.2	6.03	-21.12	-2.26
EEJ_{AAB} - EEJ_{TIR}	-2.23	-6.28	0.93	12.27	18.69	NaN	NaN

The average values of EEJ current were further investigated at AAB (EEJ_{AAB}) and TIR (EEJ_{TIR}) in order to detect the transition point for lowest value of EEJ current. The differences between EEJ_{AAB} and EEJ_{TIR} show negative values of 2.23 nT and 6.28 nT in 2008 and 2009 respectively (refer Table 4). On the following years, the values start to become positive indicating that the EEJ_{AAB} surpass the EEJ_{TIR}. This is confirmed by Figure 3(b), where the plot illustrates that 2010 is the year when EEJ_{AAB} current exceed EEJ_{TIR}. Thus, it is clarified that the transition point of lowest EEJ value starting in the year that shows positive values. As conclusion, this is the first time the transition point is reported in the EEJ longitudinal profile since almost all solar phases were covered.

IV. CONCLUSION

In this paper, the longitudinal profile of EEJ current using the average yearly data from the year 2008 to 2014 was identified. During the year of solar minimum and inclining phase from 2008 to 2011, the EEJ value was strongest at ANC station in the South American sector. However, in 2013 and 2014 that are during solar maximum, the highest value of EEJ was recorded at LKW station which is located in Southeast Asian sector. On the other hand, from 2008 to 2010, the lowest EEJ strength was recorded at AAB station which is located in African sector. Nonetheless, in 2011, the lowest EEJ value then shifted to Indian sector which is measured at TIR station. Moreover, it was observed that there is a transition point of the EEJ current where it can be detected in the particular year. The transition point for highest value of EEJ strength has been detected in 2012 while the transition point of lowest value of EEJ was recorded in 2010. Thus, this study confirms the longitudinal profile of EEJ varies with solar cycle phases. Future work is necessary to compare the variability of EEJ current between ground and satellite-based data.

V. ACKNOWLEDGEMENT

The authors thank all the member of the MAGDAS project for their contribution to this study. We also thank INTERMAGNET for promoting high standards of magnetic observatory practices (www.intermagnet.org). Thank you to Universiti Kebangsaan Malaysia for the grant of GUP-2016-016. Akimasa Yoshikawa was supported in part by MEXT/JSPS KAKENHI Grant 15H05815. We acknowledge the National Oceanic and Atmospheric Administration (NOAA) for providing Kp index data and OMNIWeb at http://omniweb.gsfc.nasa.gov for providing F10.7 data. We thank the National Geophysical Data Center (NGDC) of the magnetic inclination component values.

VI. REFERENCES

[1] Barreto, LM 1992, *The Equatorial Electrojet: a Brief Review*, Geofisica Internacional.

[2] Babatunde Rabiu, A, Folarin, OO, Uozumi, T, Hamid, NSA, & Yoshikawa, A 2017, 'Longitudinal variation of equatorial electrojet and the occurrence of its counter electrojet', *Annales Geophysicae*, vol. 35, no. 3, pp. 535–545.

[3] Chapman, S, & Raja Rao, KS 1965, 'The H and Z variations along and near the equatorial electrojet in India, Africa and the Pacific', *Journal of Atmospheric and Terrestrial Physics*, vol. 27, no. 4, pp. 559–581.

[4] Heelis, RA 2004, 'Electrodynamics in the low and middle latitude ionosphere: A tutorial', *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 66, no. 10, pp. 825–838.

[5] H Lühr, and C Manoj 2013, 'The complete spectrum of the equatorial electrojet related to solar tides: CHAMP observations', *Annales Geophysicae*, vol. 31, pp. 1315-1331.

[6] Hamid, NSA, Liu, H, Uozumi, T, & Yumoto, K 2013, 'Equatorial electrojet dependence on solar activity in the Southeast Asia sector', *Antartic Record*, vol. 57, no. 3, pp. 329-337.

[7] Hamid, NSA, Uozumi, T, Yumoto, K, Veenadhari, B, Yoshikawa, A & Sanchez, JA 2014, Relationship between the equatorial electrojet and global Sq currents at the dip equator region', Earth, Planet and Space, vol. 66, no.146, doi: 10.1186/s40623-014-0146-2.

[8] Hamid, NSA, Liu, H, Uozumi, T, & Yoshikawa, A 2015, 'Empirical model of equatorial electrojet based on ground-based magnetometer data during solar minimum in fall', Earth, Planets and Space, vol. 67, no. 1, pp. 205.

[9] Hamid, NSA, Ismail, WNI, & Yoshikawa, A, 2017, 'Longitudinal Profile of the Equatorial Electrojet Current and Its Dependence on Solar Activity', *Advance Science Letter*, vol. 23, pp. 1357-1360.

[10] Hamid, NSA, Annadurai, NMN, & Yoshikawa, A 2018, 'Pemerhatian Arus Ionosfera semasa Suar Suria Kuat Menggunakan Data Magnetometer Dasar', *Sains Malaysiana*, vol. 47.

[11] Ismail, WNI, Hamid, NSA, Abdullah, M, Yoshikawa, A, & Uozumi, T 2017. 'Longitudinal Variation of EEJ Current during Different Phases of Solar Cycle', *Journal of Physics: Conference Series*, vol. 852, no.1.

[12] Onwumechili, CA 1992, 'Study of the Return Current of the Equatorial Electrojet', *Journal of Geomagnetism and Geoelectricity*, vol. 44, pp. 1–42.

[13] Prolss, GW 2004, *Physics of the Earth's Space Environment*, Germany : Springer Berlin

[14] Phani Chandrasekhar, N, Arora, K, & Nagarajan, N 2014, 'Characterization of seasonal and longitudinal variability of EEJ in the Indian region', *Journal of Geophysical Research: Space Physics*, vol. 119, no.12, pp. 10242–10259.

[15] Rigoti, A, Chamalaun, FH, Trivedi, NB, & Padilha, AL 1999, 'Characteristics of the Equatorial Electrojet determined from an array of magnetometers in N-NE Brazil', *Earth, Planets and Space*, vol. 51, no. 2, pp. 115–128.

[16] Rastogi, RG, Kitamura, T, Kitamura, K 2004, 'Geomagnetic field variations at the equatorial electrojet station in Sri Lanka, *Peredinia'. Ann. Geophys.*, vol. 22, pp. 2729–2739.

[17] Shume, EB, Denardini, CM, De Paula, ER, & Trivedi, NB 2010, 'Variabilities of the equatorial electrojet in Brazil and Perú', *Journal of Geophysical Research: Space Physics*, vol. 115, no. 6, pp. 1–9.

[18] Uozumi, T, Yumoto, K, Kitamura, K, Abe, S, Kakinami, Y, Shinohara M, Yoshikawa, A, Kawano, H, Ueno, T, Tokunaga, T, McNamara, D, Ishituka, JK, Dutra, SLG. Damtie, B, Vafi, D, Obrou, O, Rabiu, AB, Adimula, IA, Othman, M, Fairos, M, Otadoy, RES and MAGDAS Group 2008, 'A New Index to Monitor Temporal and Long-Term Variations of the Equatorial', *Earth*

Planets Space, vol. 60, no. 7, pp. 785–790.

[19] V Doumouya, BR Arora, Y Cohen, and K Yumoto 2003, 'Local time and longitude dependence of the equatorial electrojet magnetic effects', *Journal of Atmospheric and Terrestrial*, vol. 65, pp. 1265-1285.

[20] V Doumouya, and Y Cohen 2004, 'Improving and testing the emprical emprical equatorial electrojet model with CHAMP satellite data', *Annales Geophysicae*, vol. 22, pp.3323-3333.

[21] K Yumoto & Magdas Group 2007, 'Space weather activities at SERC for IHY: MAGDAS', *Bull. Astr. Soc. India*, vol. 35, pp. 511-522.

[22] Y Yamazaki & A Maute 2016, 'Sq and EEJ- A review on the Daily Variation of the Geomagnetic Field Caused by Ionospheric Dynamo Currents', *Space Sci Rev*, vol. 206, no. 1–4, pp. 299–405. doi:10.1007/s11214-016-0282-z

The Risk of Light Pollution on Sustainability

Muhamad Syazwan Faid[1*], Nur Nafhatun Md Shariff[1] and Zety Sharizat Hamidi[2,3]

[1]*Academy of Contemporary Islamic Studies, Universiti Teknologi MARA, Shah Alam, Malaysia*
[2]*Faculty of Applied Sciences, Universiti Teknologi MARA, Shah Alam, Malaysia*
[3]*Institute of Science, Universiti Teknologi MARA, Shah Alam, Malaysia*

Light pollution is an anthropogenic by-product of modern civilisation and substantial economic activity, sourced from artificial lighting. In the literature, it is conceded that light pollution is a major concern for astronomers since it directly disrupts night-time celestial observations hence hampering research of astronomical importance. However, it is found recently, that light pollution not only has impacts in the field of astronomy, it also impedes the ecological balance of wildlife, and affects adversely human health. In addition, light pollution is also regarded as one of the leading risk factors of economic sustainability considering the consumption of a substantial amount of electrical energy by artificial lighting. Contemplating the risk of light pollution on sustainability, this paper aimed to review selected articles on the adverse effects of light pollution and consider how these threats hamper the notion of sustainability. In our study, it was hypothesised that light pollution was directly proportional to the unsustainability of the economy, astronomical observations, ecosystem and human health, with threat level on par with air and water pollution. We conclude that light pollution is not a threat that should be taken lightly, and that initiatives to curb the dangers of light pollution should be taken seriously.

Keywords: Astronomy; light pollution; risk

I. INTRODUCTION

One of the massive debacles of urbanisation is the disruption of the natural ecosystem, which includes night sky light alteration. The alteration is in the form of human-made light, or artificial light which produces a sky glow, making the sky brighter and which deforms the natural brightness and colour of the night sky. This phenomenon is considered pollution towards the Biosphere and it is called light pollution (Shariff *et al.*, 2016).

The proliferation of the human population corresponds with growth in the economy and social infrastructure. However, this unavoidable economic growth and urbanisation resulted in increased light output through street lights and giant building spotlights which are the primary causes of light pollution (Walker, 1977). This trend keeps increasing, without people realising it could damage the environment and the health of living things (Cinzano, Falchi, & Elvidge, 2001). The truth is that people find other issues more critical although they are concerned about the environment.

Being concerned about this problem, we examined how light pollution pollutes our environment, in terms of human health, ecological balance, and astronomical observations. By reviewing its effects, we can identify how light pollution disturbs the very notion of economic sustainability.

II. METHODOLOGY

Literature study was conducted to achieve the objective of the thesis. In the methodology, parameters were constructed to ensure a converging focus on the objective. The parameters outlined under this research

*Corresponding author's e-mail: msyazwanfaid@gmail.com

questioned firstly, how light pollution polluted our environment? Secondly, how was this in turn affecting the notion of sustainability?

Literature searches were conducted on the topics of light pollution to get an overview of the latest developments on the effects of light pollution on the Biosphere. The literature research was conducted by using various databases like ScienceDirect, Springer Link, Elsevier, Taylor and Francis Online, Emerald Insight and Scientific Journals. Conference proceedings, reports, books, guidelines, online newspapers, open-access articles, governmental and various organisations' websites and legislations were also included in the study. The latest peer-review articles on the topic were mainly used.

III. EFFECTS OF LIGHT POLLUTION ON HUMAN HEALTH

Naturally, humans need a steady cycle of day and night hours throughout their life. The exposure to artificial light imitates the sun's brightness that disrupts the efficacy of melatonin in the phase shifting circadian rhythm (Navara & Nelson, 2007). This disruption can cause widespread interruptions of multiple body systems, resulting in severe medical consequences for individuals, such as lousy job performance, increase in weight and even as bad as cancer (Smolensky, 2013). Exposure to overly lit light during night-time disrupts the production of melatonin in humans. This promotes the growth of cancer cells as melatonin can function to suppress cancer cell growth. A study found that populations that had the highest light pollution exposure at night incurred more risk of prostate cancer compared to populations that had lower exposure to light pollution (Kloog, Haim, Stevens, & Portnov, 2009). This included rotating shift workers due to their exposure to irregular cycles of light (Kubo *et al.*, 2006). This was supported by an experiment in Iceland which found that men having a higher level of 6-sulfatoxymelatonin, a main breakdown product of melatonin, had a 75 percent decreased risk of prostate cancer (Sigurdardottir *et al.*, 2015).

In addition, a decrease of melatonin was found to be highly correlated to breast cancer, with lesser associations between melatonin level and colorectal, larynx, liver and lung cancers (Kloog, Stevens, Haim, & Portnov, 2010). Women, especially night shift worker are exposed to the risk of breast cancer. A study found intensive light exposure during the night could induce breast tumour growth (Blask *et al.*, 2005). Women at home are also not safe from the risk of breast cancer , as it was found that the intensity of bedroom light, particularly short-wavelength light (~460 nm) was almost directly proportional (95%) to the risk of breast cancer (Kloog, Portnov, Rennert, & Haim, 2011). This explained why the risk of developing breast cancer was up to five times higher in industrialised nations than in underdeveloped countries (Stevens, 2006).

One of the initial objectives of street lighting was to prevent crime and ensure safety for pedestrians. However excessive street lighting did not guarantee safety as we thought. One research demonstrated that pedestrians favoured having their immediate surroundings lighted rather than the pavement ahead (Haans & de Kort, 2012). In fact, it was found that in England and Wales, the initiative of switching off night light did not necessarily cause a rise of crime (Steinbach *et al.*, 2015), as the daytime crime and the night time crime rates remained the same (Farrington & Welsh, 2008). This showed that the risk of excessive lighting at night for humans outweighed its benefits. So it is wise to reconsider the design structure and exposure time of artificial lights at night, both outdoor lighting and in-house lighting.

IV. EFFECTS OF LIGHT POLLUTION ON ECOLOGICAL BALANCE

Besides humans, light pollution also had adverse impacts on animal sustenance. In the past, throughout the synodic month, the brightness of the night was determined by the cycle of a celestial object, namely the moon. The night sky brightness cycled from brightest during the full moon and became dimmest during the new moon. Animals, bugs, and all other creatures especially nocturnal animals acclimatised their life activity depending on the synodic month cycle. Unfortunately, when the period of night sky brightness was disturbed by artificial light, it hampered their harmonious life cycle (Davies, Bennie, Inger, & Gaston, 2013). The nightly routine of insects (Frank, 2006), birds (Merkel & Johansen, 2011) and turtles (Witherington & Bjorndal, 1991) became threatened as artificial lighting distorted their nocturnal nature (Hölker, Wolter, Perkin, & Tockner, 2010) which encompassed foraging, mating, hatching and night navigation activities (Kyba, Ruhtz, Fischer, & Hölker, 2011).

For example the hatchlings of sea turtles could provide evidence of impairment of night navigation. A brightly lit beach impaired turtle hatchlings during their each navigation to the ocean (Kamrowski, Sutton, Tobin, & Hamann, 2014). This was due to the freshly-hatched sea turtles often mistaking the artificial lighting as a cue to navigate to the ocean (Salmon & Witherington, 1995). A not so properly designed artificial lighting could also intimidate the sea turtles from choosing a nesting location (Salmon, 2003). Most of sea turtle species, including loggerhead and green turtles tended to avoid a brightly lit beach as a nesting location (Witherington & Martin, 1996). An initiative that could be done is to separate the nesting beaches and the brightly lit industrial zone by a buffer of at least 1.5km, and with all the installed lightings shaded (Pendoley & Kamrowski, 2016).

Mammals are also not safe from the risk of light pollution. Bats for example, endured a lot of side effects of improper artificial lightning, due to their nocturnal nature (Hölker, Moss, Griefahn, Kloas, & Voigt, 2010). For instance, *Pipistrellus pipistrellus*, a species of bat, can tolerate artificial light and hunt moths which usually congregate near street lamps (Rydell & Baagoe, 1996). In contrast, other species such as *Myotis* spp., *Plecotus auritus* and *Rhinolophus hipposideros,* avoid brightly lit locations while navigating (Stone, Jones, & Harris, 2009) and foraging (Lacoeuilhe, Machon, Julien, Le Bocq, & Kerbiriou, 2014). Under naturally dark conditions, bats excrete ample seed rain even in deforested habitats and connect distant forest fragments. But, artificial light could disrupt bat-mediated seed dispersal if the bats avoid lit areas (Lewanzik & Voigt, 2014). Reduced seed dispersal among plants leading to changes in vegetation composition could be a side effect of light pollution on pollinating and seed-dispersing species (Bennie, Davies, Cruse, Inger, & Gaston, 2015).

Moth populations are facing significant declines throughout the world (Carvalheiro *et al.*, 2013). Among the potential culprits of this decline is artificial lights at night *(Potts et al.*, 2010). This decline perhaps could be explained by the nature of moth in flying around streetlights at night which increased their predation by bats and other predators that take advantage of these artificial feeding stations (Kuijper *et al.*, 2008). This decline could in turn affect the insect pollination routine (Macgregor, Pocock, Fox, & Evans, 2015). Action to install longer wavelength lamps could effectively reduce the adverse effects of light pollution on the moth population routine (van Langevelde, Ettema, Donners, Wallis De Vries, & Groenendijk, 2011).

Artificial light had a wide range of behavioural effects on birds. Black-tailed godwit (*Limosa limosa*) was found to mate far away from artificial street lights (Molenaar, Sanders, & Jonkers, 2006). Brightly lit lamps such as offshore platforms were found to impair and attract birds and divert them from their migratory path (Poot *et al.*, 2008). Artificial light at night also captivated seabird fledgelings, causing high mortality (Rodríguez, Rodríguez, & Negro, 2015). Researchers found that bright lights at night caused onset of activity and dawn songs in several songbird species. This caused the songbird to perform before its supposed routine time at dawn (Silva, Samplonius, Schlicht, Valcu, & Kempenaers, 2014). It could be assumed that artificial lighting at night also impacted the sleep behaviour of birds (Steinmeyer, Schielzeth, Mueller, & Kempenaers, 2010). The disruption of sleep behaviour might cause birds to wake up earlier and potentially sleep less or discontinuance of activity could be delayed (Raap, Pinxten, & Eens, 2015; Russ, Rüger, & Klenke, 2015). Research on impaired sleep behaviour and nocturnal activity on bird population longevity had not been extensive but undoubtedly they could hamper the population statistics of the feathered vertebrate.

V. EFFECTS OF LIGHT POLLUTION ON ASTRONOMICAL OBSERVATION

In astronomy, the visibility of celestial bodies in the sky is dependent on the brightness contrast of the night sky and the celestial bodies (Schaefer, 1993). The human eye has a certain contrast threshold (Tousey & Hulburt, 1948) in detecting a faint celestial object in the sky (Crumey, 2014; Shariff, Hamidi, & Faid, 2017). The detection of a celestial object on a particular night sky is quantified as the Bortle scale. A highly polluted sky with a low magnitude of sky brightness would lower the amount of visibility of celestial objects to both naked and optical aided observations (Faid *et al.*, 2018; Falchi *et al.*, 2016) since the contrast between the brightness magnitude of the celestial object and the night sky would be smaller. This explains why light pollution is becoming a major concern to astronomers considering its effects on ground-based observations (Hamidi, Abidin, Ibrahim, & Shariff, 2011). Therefore, it is critical to examine the light pollution level at the observation site to examine its impacts on astronomical data.

Table 1. The condition of the sky under various profiles of light pollution. Cited from (Faid *et al.*, 2016) with a few additional data.

Sites	Population Type	Magnitude and Standard Deviation	Milky Way	Astronomical ObjectS and Constellations
Kuala Lumpur	Urban	17.59/0.92	Not Visible at all	The Pleiades Cluster was visible, but very few other objects could be detected. The constellation was dimmer and lacked the main star.
Teluk Kemang	Suburban	19.28/0.70	Not Visible at all	The Pleiades Cluster was the only object visible to all except for the experienced

				observer. Only the brightest constellation was discernible and they were missing stars.
Mersing	Excellent Dark-Sky Site	21.30/0.30	Visible	Zodiacal light was bright enough to cast weak shadows. Clouds in the sky were visible only as dark holes in a starry background. Several Messier globular clusters appeared as naked-eye objects.

A common misconception is that more light equal safer, better and more pleasant living conditions (Mizon, 2002; Schwartz, 2003). Earlier surveys had indicated that better lighting did not necessarily lead to better living. Reduced light at night exposure was considered the main element for improving outdoor activities and for enhancing the quality of living in residential areas in Finland (Lyytimäki & Rinne, 2013). The public would then appreciate the natural sculpture of the sky, the milky way and all the stars above (Gallaway, 2010).

VI. EFFECTS OF LIGHT POLLUTION ON ECONOMIC SUSTAINABILITY

The enormous emission of artificial lights on unnecessary locations is indeed a waste of resources. Wasting energy has substantial economic and environmental impacts. In the U.S. alone, in 2018 a yearly average of 3.600 billion kilowatt-hours of energy was generated for electrical consumption, equaling to the cost of USD362 million (EIA, 2018). Nineteen percent of it was used for lighting, and 16.85 percent of the lighting usage went to outdoor lighting, mostly to illuminate streets and parking lots. Considering 30 percent of outdoor lighting was poorly illuminated, this meant that in a year, a total of 35 billion kilowatt-hours of electricity was wastefully produced for outdoor lighting at the cost of USD3.5 billion a year (Ashe, Chwastyk, Monasterio, Gupta, & Pegors, 2010; Gallaway, Olsen, & Mitchell, 2010).

Assuming 36.6kWh required a gallon of gasoline, human consumption of electrical energy was equivalent to the usage of over 968 million gallons of gasoline or 3,664.28 million litres (Department of Physics & Florida Atlantic University, 2014). The cost of electric production in 1991 was only USD0.7 billion (Hunter & Crawford, 1991), which was ten times smaller. The tenfold increase of unnecessary electrical usage on artificial lightning indicated a stagnant concern on light pollution despite the large numbers of researches on light pollution. This clearly shows that light pollution is a threat, not only to astronomical research, public health and the ecological balance, but it is also one of the main risk factors of economic sustainability.

VII. CONCLUSION

Light pollution is a serious problem with implications for wildlife, human health, scientific research, energy consumption, global warming, and the ageless pastime of observing the night sky. Light pollution is a threat, not only to astronomical research, public health, ecological balance, but also to the economy making it one of the main dangers to the notion of sustainability. A well-rounded initiative needs to be pioneered to curb the effects of light pollution.

VIII. ACKNOWLEDGEMENT

Geran FRGS 2019, 600-IRMI/FRGS 5/3 (100/2019).

IX. REFERENCES

[1] Ashe, M, Chwastyk, D, Monasterio, C de, Gupta, M, & Pegors, M 2010, *2010 U.S. Lighting Market Characterization*.

[2] Bennie, J, Davies, TW, Cruse, D, Inger, R, & Gaston, KJ 2015, 'Cascading effects of artificial light at night: Resource-mediated control of herbivores in a grassland ecosystem', *Philosophical Transactions of the Royal Society B: Biological Sciences*. https://doi.org/10.1098/rstb.2014.0131.

[3] Blask, DE, Brainard, GC, Dauchy, RT, Hanifin, JP, Davidson, LK, Krause, JA, ... Zalatan, F 2005, 'Melatonin-depleted blood from premenopausal women exposed to light at night stimulates growth of human breast cancer xenografts in nude rats', *Cancer Research*. https://doi.org/10.1158/0008-5472.CAN-05-1945.

[4] Carvalheiro, LG, Kunin, WE, Keil, P, Aguirre-Gutiérrez, J, Ellis, WN, Fox, R, ... Biesmeijer, JC 2013, 'Species richness declines and biotic homogenisation have slowed down for NW-European pollinators and plants', *Ecology Letters*. https://doi.org/10.1111/ele.12121.

[5] Cinzano, P, Falchi, F, & Elvidge, C 2001, 'Global monitoring of light pollution and night sky brightness from satellite measurements', *Contract*, pp. 1–6.

[6] Crumey, A 2014, *Human contrast threshold and astronomical visibility*, Monthly Notices of the Royal Astronomical Society, vol. 442, no. 3, pp. 2600–2619. https://doi.org/10.1093/mnras/stu992.

[7] Davies, TW, Bennie, J, Inger, R, & Gaston, KJ 2013, 'Artificial light alters natural regimes of night-time sky brightness', *Scientific Reports*, vol. 3, pp. 1722. https://doi.org/10.1038/srep01722.

[8] Department of Physics, & Florida Atlantic University 2014, *Light Pollution Hurts the Environment, Hides the Night Sky*, viewed on 6 January 2019, http://cescos.fau.edu/observatory/lightpol.html.

[9] EIA 2018, *Electric Sales, Revenue, and Average Price - Energy Information Administration*, viewed on 6 January 2019, https://www.eia.gov/electricity/sales_revenue_price/

[10] Faid, MS, Shariff, NNM, Hamidi, ZS, Husien, N, Ali, MO, Zainol, NH, & Sabri, SNU 2016, 'Monitoring the level of Light Pollution and its Impact on Astronomical Bodies Naked-Eye Visibility Range in Selected Areas in Malaysia using Sky Quality Meter', *Journal of Industrial Engineering and Management Science*, vol. 1, pp. 1–18.

[11] Faid, MS, Shariff, NNM, Hamidi, ZS, Kadir, N, Ahmad, N, & Wahab, RA 2018, 'Semi empirical modelling of light polluted twilight sky brightness', *Jurnal Fizik Malaysia*, vol. 39, no. 2,

pp. 30059–30067.

[12] Falchi, F, Cinzano, P, Duriscoe, D, Kyba, CCM, Elvidge, CD, Baugh, K, … Furgoni, R 2016, 'The new world atlas of artificial night sky brightness', *Science Advances*, vol. 2, no. 6, pp. e1600377–e1600377. https://doi.org/10.1126/sciadv.1600377.

[13] Farrington, DP, & Welsh, BC 2008, *Effects of improved street lighting on crime : a systematic review*, Home Office. https://doi.org/10.4073/csr.2008.13.

[14] Frank, K 2006, 'Effects of artificial night lighting on moths', in *Ecological Consequences of Artificial Night Lighting*, retrieved from http://books.google.com/books?hl=en&lr=&id=dEEGtAtR1NcC&pgis=1%5Cnhttp://books.google.com/books?hl=en&lr=&id=dEEGtAtR1NcC&oi=fnd&pg=PA305&dq=Effects+of+Artificial+Night+Lighting+on+Moths&ots=82_8j687jI&sig=OcVL2Sp2PBaJoMTWDq8CYiFuKQ0

[15] Gallaway, T 2010, 'On Light Pollution, Passive Pleasures, and the Instrumental Value of Beauty', *Journal of Economic Issues*, vol. 44, no. 1, pp. 71–88. https://doi.org/10.2753/JEI0021-3624440104.

[16] Gallaway, T, Olsen, RN, & Mitchell, DM 2010, 'The economics of global light pollution', *Ecological Economics*, vol. 69, no. 3, pp. 658–665. https://doi.org/10.1016/j.ecolecon.2009.10.003.

[17] Haans, A, & de Kort, YAW 2012, 'Light distribution in dynamic street lighting: Two experimental studies on its effects on perceived safety, prospect, concealment, and escape', *Journal of Environmental Psychology*. https://doi.org/10.1016/j.jenvp.2012.05.006.

[18] Hamidi, ZS, Abidin, ZZ, Ibrahim, ZA, & Shariff, NNM 2011, 'Effect of light pollution on night sky limiting magnitude and sky quality in selected areas in Malaysia', in *Sustainable Energy Environment (ISESEE), 2011 3rd International Symposium Exhibition, June 2011*, pp. 233–235. https://doi.org/10.1109/ISESEE.2011.5977095.

[19] Hölker, F, Moss, T, Griefahn, B, Kloas, W, & Voigt, CC 2010, 'The Dark Side of Light : A Transdisciplinary Research Agenda for Light', *Ecology and Society*, vol. 15, no. 4, pp. 13. https://doi.org/10.1890/080129.

[20] Hölker, F, Wolter, C, Perkin, EK, & Tockner, K 2010, 'Light pollution as a biodiversity threat', *Trends in Ecology and Evolution*, vol. 25, no. 12, pp. 681–682. https://doi.org/10.1016/j.tree.2010.09.007

[21] Hunter, T, & Crawford, D 1991, 'The Economics of Light Pollution. Light Pollution, Radio Interference, and Space Debris', in *ASP Conference Series, 17(IAU Colloquium 112)*, vol. 89.

[22] Kamrowski, RL, Sutton, SG, Tobin, RC, & Hamann, M 2014, *Potential applicability of persuasive communication to light-glow reduction efforts: A case study of marine turtle conservation*, Environmental Management. https://doi.org/10.1007/s00267-014-0308-9.

[23] Kloog, I, Haim, A, Stevens, RG, & Portnov, BA 2009, 'Global co-distribution of light at night (LAN) and cancers of prostate, colon, and lung in men', *Chronobiology International*, vol. 26, no. 1, pp. 108–125. https://doi.org/10.1080/07420520802694020.

[24] Kloog, I, Portnov, BA, Rennert, HS, & Haim, A 2011, 'Does the modern urbanized sleeping habitat pose a breast cancer risk?', *Chronobiology International*. https://doi.org/10.3109/07420528.2010.531490.

[25] Kloog, I, Stevens, RG, Haim, A, & Portnov, B A. 2010, 'Nighttime light level co-distributes with breast cancer incidence worldwide', *Cancer Causes Control*, vol. 21, no. 12, pp. 2059–2068.

[26] Kubo, T, Ozasa, K, Mikami, K, Wakai, K, Fujino, Y, Watanabe, Y, … Tamakoshi, A 2006, 'Prospective cohort study of the risk of prostate cancer among rotating-shift workers: Findings from the Japan Collaborative Cohort Study', *American Journal of Epidemiology*. https://doi.org/10.1093/aje/kwj232

[27] Kuijper, D, Schut, J., Dullemen, D van, Hanne, T, Noreen, G, Janne, O, & Limpens, H 2008, 'Experimental evidence of light disturbance along the commuting routes of pond bats (Myotis dasycneme)', *Lutra*. https://doi.org/2.

[28] Kyba, CCM, Ruhtz, T, Fischer, J, & Hölker, F

2011, 'Lunar skylight polarization signal polluted by urban lighting', *Journal of Geophysical Research: Atmospheres*, vol. 116, pp. 1–7. https://doi.org/10.1029/2011JD016698

[29] Lacoeuilhe, A, Machon, N, Julien, JF, Le Bocq, A, & Kerbiriou, C 2014, 'The influence of low intensities of light pollution on bat communities in a semi-natural context', *PLoS ONE*. https://doi.org/10.1371/journal.pone.0103042

[30] Lewanzik, D, & Voigt, CC 2014, 'Artificial light puts ecosystem services of frugivorous bats at risk', *Journal of Applied Ecology*. https://doi.org/10.1111/1365-2664.12206.

[31] Lyytimäki, J, & Rinne, J 2013, 'Voices for the darkness: online survey on public perceptions on light pollution as an environmental problem', *Journal of Integrative Environmental Sciences*, vol. 10, no. 2, pp. 127–139. https://doi.org/10.1080/1943815X.2013.824487.

[32] Macgregor, CJ, Pocock, MJO, Fox, R, & Evans, DM 2015, 'Pollination by nocturnal Lepidoptera, and the effects of light pollution: A review', *Ecological Entomology*. https://doi.org/10.1111/een.12174.

[33] Merkel, FR, & Johansen, KL 2011, 'Light-induced bird strikes on vessels in Southwest Greenland', *Marine Pollution Bulletin*, vol. 62, no. 11, pp. 2330–2336. https://doi.org/10.1016/j.marpolbul.2011.08.040 .

[34] Mizon, B 2002, *Light pollution – responses and remedies (B, M. (200)*, London: Springer.

[35] Molenaar, JG De, Sanders, ME, & Jonkers, DA 2006, 'Road lighting and grassland birds: local influence of road lighting on a black-Tailed godwit population', in *Ecological consequences of artificial night lighting*.

[36] Navara, KJ, & Nelson, RJ 2007, 'The dark side of light at night: Physiological, epidemiological, and ecological consequences', *Journal of Pineal Research*, vol. 43, pp. 215–224. https://doi.org/10.1111/j.1600-079X.2007.00473.x.

[37] Pendoley, K, & Kamrowski, RL 2016, 'Sea-finding in marine turtle hatchlings: What is an appropriate exclusion zone to limit disruptive impacts of industrial light at night?', *Journal for Nature Conservation*. https://doi.org/10.1016/j.jnc.2015.12.005.

[38] Poot, H, Ens, BJ, de Vries, H, Donners, MAH, Wernand, MR, & Marquenie, JM 2008, 'Green light for nocturnally migrating birds', *Ecology and Society*. https://doi.org/10.5751/ES-02720-130247.

[39] Potts, SG, Biesmeijer, JC, Kremen, C, Neumann, P, Schweiger, O, & Kunin, WE 2010, 'Global pollinator declines: Trends, impacts and drivers', *Trends in Ecology and Evolution*. https://doi.org/10.1016/j.tree.2010.01.007.

[40] Raap, T, Pinxten, R, & Eens, M 2015, 'Light pollution disrupts sleep in free-living animals', *Scientific Reports*. https://doi.org/10.1038/srep13557

[41] Rodríguez, A, Rodríguez, B, & Negro, JJ 2015, 'GPS tracking for mapping seabird mortality induced by light pollution', *Scientific Reports*. https://doi.org/10.1038/srep10670.

[42] Russ, A, Rüger, A, & Klenke, R 2015, 'Seize the night: European Blackbirds (*Turdus merula*) extend their foraging activity under artificial illumination', *Journal of Ornithology*. https://doi.org/10.1007/s10336-014-1105-1.

[43] Rydell, J, & Baagoe, HJ 1996, 'Street lamps increase bat predation on moths', *Entomologisk Tidskrift*, vol. 117, no. 4, pp. 129-135.

[44] Salmon, M 2003, 'Artificial night lighting and sea turtles', *Biologist*, vol. 50, pp. 163-168.

[45] Salmon, M, & Witherington, BE 1995, 'Artificial Lighting and Seafinding by Loggerhead Hatchlings: Evidence for Lunar Modulation', *Copeia*. https://doi.org/10.2307/1447042.

[46] Schaefer, B 1993, 'Astronomy and the limits of vision', *Vistas in Astronomy*, vol. 36, pp. 311–361.

[47] Schwartz, H 2003, *Light pollution control: world-wide effects of and efforts to reduce light pollution. In Organizations and strategies in astronomy*, Dordrecht: Kluwer.

[48] Shariff, NNM, Faid, MS, Hamidi, ZS, Osman, MR, Sabri, SNU, Zainol, NH, ... Ali, MO 2016, 'Creating Awareness on Light Pollution' (CALP) Project: Essential requirement for school-

university collaboration', in *International Conference on Industrial Engineering, Management Science and Application*. Jeju, South Korea: IEEE.

[49] Shariff, NNM, Hamidi, ZS, & Faid, MS 2017, 'The Impact of Light Pollution on Islamic New Moon (hilal) Observation', *International Journal of Sustainable Lighting*, vol. 19, no. 1, pp. 10–14.

[50] Sigurdardottir, LG, Markt, SC, Rider, JR, Haneuse, S, Fall, K, Schernhammer, ES, ... Mucci, LA 2015, 'Urinary melatonin levels, sleep disruption, and risk of prostate cancer in elderly men', *European Urology*. https://doi.org/10.1016/j.eururo.2014.07.008.

[51] Silva, A Da, Samplonius, JM, Schlicht, E, Valcu, M, & Kempenaers, B 2014, 'Artificial night lighting rather than traffic noise affects the daily timing of dawn and dusk singing in common European songbirds', *Behavioral Ecology*. https://doi.org/10.1093/beheco/aru103.

[52] Smolensky, M 2013, 'Review of Light pollution as a new risk factor for human breast and prostate cancers', *Chronobiology International*, vol. 30. https://doi.org/10.3109/07420528.2013.834173.

[53] Steinbach, R, Perkins, C, Tompson, L, Johnson, S, Armstrong, B, Green, J, ... Edwards, P 2015, 'The effect of reduced street lighting on road casualties and crime in England and Wales: controlled interrupted time series analysis', *Journal of Epidemiology and Community Health*, vol. 69, no. 11, pp. 1118-1124. https://doi.org/10.1136/jech-2015-206012.

[54] Steinmeyer, C, Schielzeth, H, Mueller, JC, & Kempenaers, B 2010, 'Variation in sleep behaviour in free-living blue tits, *Cyanistes caeruleus*: Effects of sex, age and environment', *Animal Behaviour*. https://doi.org/10.1016/j.anbehav.2010.08.005.

[55] Stevens, RG 2006, 'Artificial lighting in the industrialized world: Circadian disruption and breast cancer', *Cancer Causes and Control*. https://doi.org/10.1007/s10552-005-9001-x.

[56] Stone, EL, Jones, G, & Harris, S 2009, 'Street Lighting Disturbs Commuting Bats', *Current Biology*. https://doi.org/10.1016/j.cub.2009.05.058.

[57] Tousey, R, & Hulburt, EO 1948, 'The Visibility of Stars in the Daylight Sky', *Journal of Optical Society of America*, vol. 38, no. 10, pp. 886–896.

[58] van Langevelde, F, Ettema, JA, Donners, M, Wallis De Vries, MF, & Groenendijk, D 2011, 'Effect of spectral composition of artificial light on the attraction of moths', *Biological Conservation*. https://doi.org/10.1016/j.biocon.2011.06.004.

[59] Walker, MF 1977, 'Effects of Urban Lighting on the Brightness of the Night Sky', *Astronomy Society of The Pacific*, vol. 89, pp. 405–409. https://doi.org/10.1086/130142.

[60] Witherington, BE, & Bjorndal, KA 1991, 'Influences of artificial lighting on the seaward orientation of hatchling loggerhead turtles *Caretta caretta*', *Biological Conservation*. https://doi.org/10.1016/0006-3207(91)90053-C.

[61] Witherington, BE, & Martin, RE 1996, *Understanding, Assessing, and Resolving Light-Pollution Problems on Sea Turtle Nesting Beaches*, Fl. Mar. Res. Inst. Tech. Rep. TR-2.

Assessment of Satellite Altimeter's Dual Frequency Ionospheric Delay in Tropical Regions Compared to Global Ionospheric Models

Aiman Syahmi Mohamad Atrash[1], Ami Hassan Md Din[1,2,3*], Mat Nizam Uti[1]

[1]*Geomatic Innovation Research Group (GnG),* [2]*Geoscience and Digital Earth Centre (INSTEG), Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia*

[3]*Associate Fellow, Institute of Oceanography and Environment (INOS), Universiti Malaysia Terengganu, Kuala Terengganu, Terengganu, Malaysia*

The rapid development of satellite altimeters has brought about a remarkable feat of innovation in the field of ionosphere studies as they can measure the ionosphere using an on-board instrument called dual frequency sensor. Some methods that can be used to measure the ionosphere are by using satellite altimeters, Global Positioning Systems (GPS), and Ionosondes. Most of the well-known agencies such as NASA and ESA are working hard to study the ionosphere by producing their own Global Ionospheric Models (GIMs). However, factors like point based monitoring techniques and the scarcity of monitoring stations in tropical regions could deteriorate the quality of these GIMs. This study aimed to assess the performance of the satellite altimeter derived ionospheric delay compared to GIMs over tropical regions especially in Malaysian Seas. Three GIMs were used for the purpose of this study namely the IRI2007, Jet Propulsion Lab (JPL) GIM and the NOAA Ionosphere Climatology 2009 (NIC09). This study used the Radar Altimeter Database System (RADS) to extract ionospheric corrections from Malaysian seas. The expected result was to evaluate the ionospheric delay pattern in marine areas in tropical regions from 2009 until 2016. It was found that the performance of the satellite altimeter's ionospheric delay works best with the IRI2007 with a root mean square error (RMSE) value of 1.1115cm. Furthermore, the data from satellite altimeter was in a good understanding with the latitudinal variation of the ionosphere since the study area's ionosphere is characterized by the presence of the Equatorial Ionospheric Anomaly (EIA) and a strong amplitude magnetic signature of the equatorial electrojet (EEJ). In conclusion, satellite altimetry could be a useful data source for the under observed areas such as the tropical regions.

Keywords: Satellite altimeter; ionospheric delay; tropical regions

I. INTRODUCTION

The ionosphere is a layer of electrons and electrically charged atoms and molecules that surround the earth from an altitude of about 50km to more than 1000km. This layer is a result of the sun's ultraviolet radiation. Studies have shown that the sun is the main source of radiation on earth, which is why the electrons in the ionosphere are highly influenced by the sun. The ionosphere can be classified into three regions, polar region, mid-latitudes region and equatorial region. The study area of this study lies well within the equatorial region or also known as the

*Corresponding author's e-mail: amihassan@utm.my

tropical region. The benefit of studying the ionosphere is that we can help improve in GPS positioning as the ionosphere is one of the major sources of errors and also in helping the communication companies as their satellites are also affected by the same error, and the power companies since the ionosphere is highly influenced by solar activities and solar flares have been known to disrupt power plants (Tim Fuller-Rowell 2007). There are many methods used to study the ionosphere. The first method is by using the GNSS tool. Though able to provide accurate estimations of the ionosphere, it is more a "point-based" tool. The second method is by using ionosondes which is used to study the ionosphere. The problem is the reliability and availability of data as there is no agency or institution that is responsible for managing the equipment. The third method is by relying on the global ionosphere models such as the Klobuchar model, NeQuick model and the IRI model. The final method is by using dual-frequency satellite altimeter measurements that maintained the required precision and reliability of data with altimeter missions dating back to the 1990's such as the Jason mission and Topex/Poseidon mission.

II. DATA AND METHODS

The dual-frequency ionospheric delay, IRI-2007, JPL GIM and NIC09 were all downloaded via the RADS system. The downloaded parameters from RADS were in ionospheric delay and were in the unit meter (m). The data were acquired in the same manner as in the RADS system from latitude from 0° until 14° and from longitude 95° until 126°. The data were extracted point by point with a .25° separation. The following table shows the points selected on each Malaysian sea: Malacca Straits, South China Sea, Celebes Sea and Sulu Sea to study the condition of the ionosphere. The latitudes and longitudes for all points are as in Table 1.

Table 1. The geographical coordinates of the selected points over Malaysian Seas

Sea	Points Name	Latitudes (N)	Longitudes (E)	Distance from Coast (km)
Celebes Sea	cbs05	3.32	120.25	215
	cbs08	3.82	122.27	400
South China Sea	scs18	5.88	109.10	460
	scs20	4.99	105.96	285
Sulu Sea	sus22	6.32	118.93	105
	sus23	8.77	119.64	140
Malacca Straits	mcs25	3.89	99.70	70
	mcs26	5.39	98.59	95

A. Dual-frequency altimeter ionospheric delay

Dual-frequency ionospheric delay is the correction which takes into account the path delay in the radar signal due to electron content in the atmosphere. The delay is calculated by combining radar altimeter measurements acquired at two separate frequencies, for example the C-band and Ku-band. The ionospheric correction is obtained by the assumption of $1/f^2$ frequency- dependence of the range (Imel, 1994)

$$R_{Ku} = R_o + \alpha_{Ku}/f_{Ku}^2 + b_{Ku} + C \quad (1)$$

$$R_C = R_o + \alpha_C/f_C^2 + b_C + C \quad (2)$$

where, R_o is the true range, R_{Ku} and , R_C are the ranges measured by the Ku-band and C-band respectively, α_{Ku} and α_C are the corresponding ionosphere correction coefficients which are proportional to the integrated electron density along the signal's path, b_{Ku} and b_C are all the other frequency-dependent corrections and C represents all the frequency-independent corrections such as the orbit correction and the tides. Provided measurements for b_{Ku} and b_C and assuming $\alpha = \alpha_{Ku} = UC$ (neglecting the effects of higher than second order frequency dispersion, the R_{Ku} and R_C may be used to eliminate α in the above equations and estimate the ionosphere corrections (Imel, 1994)

$$\Delta R_{ion} \equiv (R_{Ku} - b_{Ku}) - (R_O + C) = \delta_f[(R_C - b_C) - (R_{Ku} - b_{Ku})] \quad (3)$$

where $$\delta_f = \frac{f_C^2}{f_{Ku}^2 - f_C^2} \quad (4)$$

However, as a consequence of having a range measurement from a second altimeter to obtain the ionosphere correction, the noise of the range estimate is increased. The range estimate is given in terms of the two range measurements by solving (1) and (2) for R_o which yields (Imel, 1994)

$$R_o = (1 + \delta_f)(R_{Ku} + b_{Ku}) - \delta_f(R_C + b_C) - C \quad (5)$$

One may propagate the error in R_o from the errors in the individual terms of (3) and subtract the contributions due to all other sources of error (Ku-band altimeter noise, other frequency-dependent correction estimates and frequency independent corrections) to obtain the noise contributed to the range estimate by the dual-frequency ionosphere correction (Imel,1994)

$$(\triangle R_{ion})^2 = \left[(1 \pm \delta_f)^2 - 1\right](\triangle R_{Ku})^2 i\, \delta_f^2 (\triangle R_C)^2 \quad (6)$$

where $\triangle R_{Ku}$ and $\triangle R_C$ are the noise errors of the two altimeter frequencies.

B. Global Ionospheric Models (GIMs)

Basically, there are two types of global ionospheric models (GIMs), which are empirical models and semi-empirical models. Empirical models are created by a complex statistical analysis of a long history of measured data (Bilitza, 2014), based on their climatology, representing seasonal or monthly average conditions and measured at a specific time and location. Semi empirical models are models established depending on the assumptions of an evolving theory. A large number of empirical models provide more reliable information of the northern hemisphere than the southern hemisphere due to the global distribution of the ground observation stations (Bilitza, 2014). Ionospheric parameters at equatorial and at high latitudes suffer the most from the station scarcity in these regions. Taking the main international standard for ionospheric studies into account, which is the International Reference Ionosphere (IRI) GIM, even their global data network is fewer representatives of the equatorial and low latitude regions. Only 11 are present in the equatorial region and that number drops to only one in the South East Asian (SEA) region.

C. International Reference Ionosphere 2007 (IRI2007)

The International Reference Ionosphere (IRI) is an international project funded by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). These organizations formed a Working Group in the late sixties to produce an empirical standard model of the ionosphere based on all the available data sources. Several steadily improved editions of the model have been released. IRI is able to provide monthly averages of the electron density, electron temperature, ion temperature, and ion composition in the altitude range from 50km to 2000km. Other parameters given by IRI include the Total Electron Content (TEC), the occurrence probability for Spread-F and the F1-region, and the equatorial vertical ion drift. Basically, IRI2007 is one of the ionosphere models that has been used in the Radar Altimeter Database System (RADS) for ionosphere estimation.

D. Jet Propulsion Laboratory GIM (JPL GIM)

NASA's Jet Propulsion Laboratory (JPL) produces maps of 2 hour intervals of TEC based on the global constellation of GPS satellites and IGS GPS receivers. There are more than 100 continuously operating GPS receivers which were used to produce the global ionospheric maps. Besides, the laboratory also produces a comprehensive tool to monitor the global ionosphere known as GIMs. GIMs are being used for global ionospheric delay calibrations, scientific research of the upper atmosphere and as data source for weather predictions. Figure 1 shows an example of the GIMs produce by the laboratory.

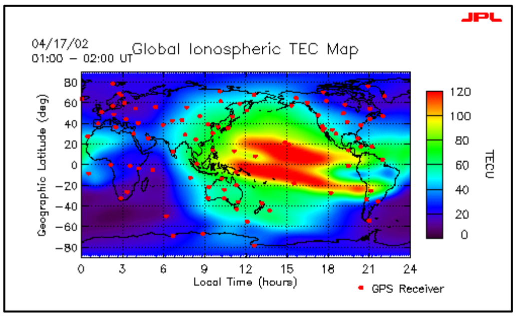


Figure 1. Global Ionospheric TEC Map (NASA, 2016)

E. NOAA Ionospheric Climatology 2009 (NIC09)

The NOAA Ionospheric Climatology 2009 (NIC09) GIM is based on 12 years of JPL GIM maps and can be extended as far back as the 1950s or extrapolated using predicted solar flux values (Scharroo & Smith, 2010). This model is particularly useful for studies which include periods prior to August 1998 (before the availability of iono_gim in the RADS system).

F. The Sun's Effect on the Ionosphere

As mentioned earlier in 1.0, during the sun's activities such as flares and other big events, the sun produces increased ultraviolet, x-ray and gamma-ray photons towards the earth. This would greatly increase the ionization that occurs in the atmosphere. There are two ways we can study this. First is by studying the number of the sun's sunspots. Sunspots are temporary phenomena occurring on the sun that appear to be darker than the surrounding areas. Sunspots are regions of reduced surface temperature caused by concentrations of magnetic field flux that inhibit convection. Their numbers vary according to the approximately 11-year solar cycle (Clette *et al.*, 2014). Second, we can study the ionosphere delay during the occurrence of solar flares. Solar flares are able to release a broad amount of energy, energy of 10^{20} joules is considered to be the median for a well-observed event, while a major event can emit up to 20^{25} joules. Solar flares are classified according to four letters, B, C, M and X according to their strength. Each letter represents a tenfold increase in energy output. Within each letter, there is a finer scale from 1 to 9. The most powerful flare recorded was in November 2003 during the last solar maximum. It was an X17 solar flare and it overloaded the sensors measuring it.

III. RESULTS AND DISCUSSION

A. Data Comparison

By calculating the RMSE value of the satellite altimeter derived ionospheric delay, we can evaluate the performance of the satellite altimeter's ionospheric delay compared to the GIMs. It was found that the ionospheric delay from the satellite altimeter was best suited with the IRI2007 with an RMSE of 0.214852cm and a mean difference of 1.24cm between the satellite altimeter and IRI2007 and JPL was the second best and NIC09 was the least suitable with RMSE values of 1.024137cm and 1.206753cm, respectively.

Table 2. Statistical analysis for each model with satellite altimeter derived ionospheric delay

Model	Minimum (cm)	Maximum (cm)	Mean (cm)	RMSE(cm)	Rank
IRI2007	0.21	1.96	1.24	1.111542	1
NIC09	0.84	2.29	1.64	1.280974	2
JPL	0.77	2.40	1.65	1.286019	3

This study showed that the ionospheric delay derived using satellite altimeter was usually lower than those from the other GIMs. This could be due to the scarce data source for the GIMs in this region.

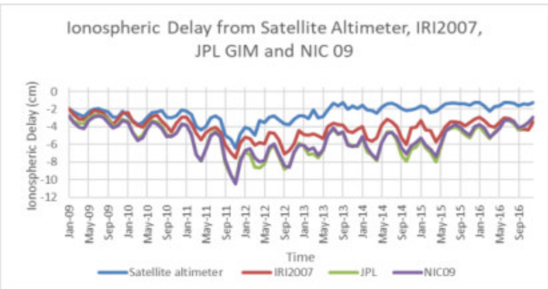


Figure 2. Ionospheric delay trend from January 2009 until December 2016

B. Ionospheric Delay over Malaysian Seas

The data from satellite altimeter was verified with the GIMs which were IRI2007, NIC09 and JPL. The data verification was viewed from four different seas; Malacca Straits, South China Sea, Celebes Sea and Sulu Sea. These data represented the marine areas and the intention was to see the trend of the mean ionospheric delay for each sea. In Table 3 is presented the calculated RMSE values. It shows that for most of the selected points, satellite altimeter's ionospheric delay was more suited with IRI2007 over the Malacca Straits and the Sulu Sea except for over the South China Sea and the Celebes Sea, where points SCS18 and SCS20 over the South China Sea showed better performance by the JPL GIM and point CBS08 at the Celebes Sea showed that NIC09 had the best performance. Figure 4 shows the ionospheric delay from satellite altimeter and GIMs over the Malaysian seas.

C. Ionospheric Delay with Response to Solar Events

First, we took into account the relationship between the sun's number of sunspots with the magnitude of the ionospheric delay derived from satellite altimeter (as shown in Figure 4).

It could be seen that the magnitude of the ionospheric delay changed with the number of sunspots. For the purpose of this study, the real magnitude of the sunspot such as its magnetic field, size of sunspot etc. of each sunspot was ignored and was treated as

Table 3. RMSE (cm) for each global ionospheric model with satellite altimeter derived ionospheric delay over each Malaysian Sea

Point Name	**Model Name**			**Point Location**
	IRI2007	**JPL**	**NIC09**	
MCS25	0.01012	0.06124	0.06124	Malacca Straits
MCS26	0.01021	0.07144	0.09186	Malacca Straits
SUS22	0.01118	0.07144	0.07144	Sulu Sea
SUS23	0.01369	0.09186	0.13268	Sulu Sea
SCS18	0.05103	0.03004	0.03062	South China Sea
SCS20	0.05021	0.03094	0.03751	South China Sea
CBS08	0.05124	0.04132	0.04082	Celebes Sea
CBS05	0.03062	0.05103	0.04227	Celebes Sea

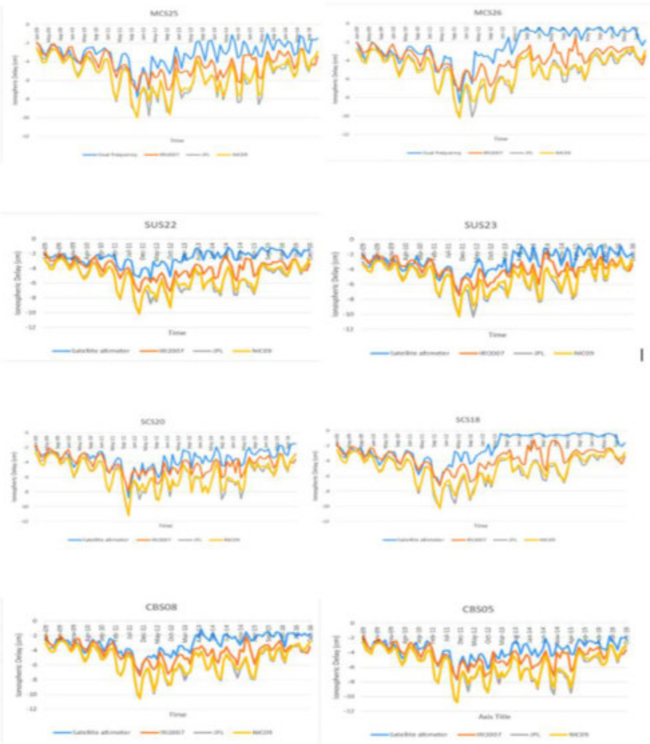


Figure 3. Ionospheric delay (cm) over selected points across Malaysian Seas

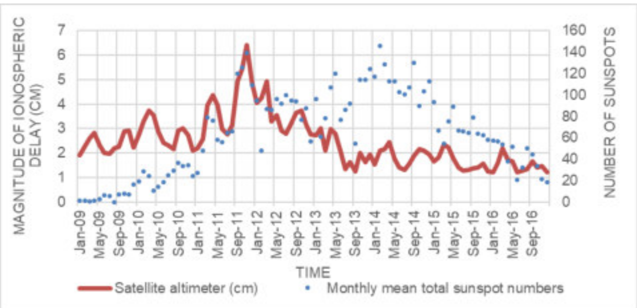


Figure 4. Satellite altimeter ionospheric delay in relationship to the number of sunspots present

equal. Then we could find the rate of change of the ionospheric delay per sunspot, where satellite altimeter gave us a value of 0.038661cm of ionospheric delay per sunspot. For IRI2007, it was 1.68425cm of ionospheric delay per sunspot. This meant that for every sunspot present on the sun, IRI2007 would measure the ionosphere as much as 1.64559cm more than the satellite altimeter. Another contributing factor to the ionosphere was the sun's solar flares. From 2009 to 2010, there were a low number of solar flares occurring and the numbers began to rise starting from 2011. Table 4 shows the occurrences of solar flares from 2011 to 2014. Figure 5 shows the Ionospheric delay from satellite altimeter and GIMs during each of the solar flares and Table 5 is the statistical analysis for each global ionospheric model with satellite altimeter derived ionospheric delay.

Taking into account the low solar year of 2009 and also the solar flares that occurred, we could see that the different sources of ionospheric delay produced different ionospheric results. For the 2009 low solar year, the satellite altimeter data were much closer to the IRI2007 which were within the range of -3cm until -2.5cm. However, the satellite altimeter data were very different from those of JPL and NIC09 especially in marine areas far away from the coastal regions. In areas where satellite altimeter provided ionospheric delay of -2.5cm, JPL gave ionospheric delay of -3.25cm in the same area and it was even worse for NIC09, where ionospheric delay of less than -3.5cm was measured. Figure 6 shows the ionospheric delay from satellite altimeter and the GIMs during the 2009 low solar year with a box focusing the area of interest.

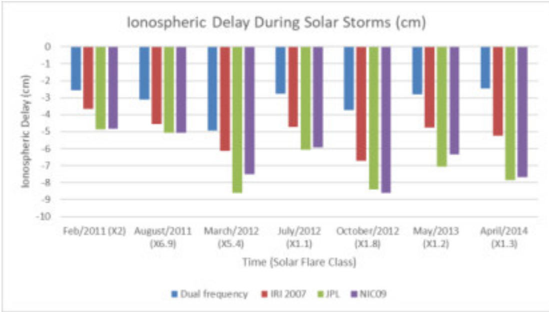


Figure 5. Ionospheric delay from satellite altimeter and GIMs during each of the solar flares

Table 4. Occurrences of solar flares from 2011 until 2014

Date	Solar Flare Class
Feb 2011	X2
August 2011	X6.9
March 2012	X5.4
July 2012	X1.1, X1.4
October 2012	X1.8
May 2013	4 occurrences of X class storms ranging from X1.2 – X3.2
April 2014	X1.3 (causing high frequency communications blackout on earth)
September 2017	X9.3

Table 5. Statistical analysis for each model with satellite altimeter derived ionospheric delay

Model	Min (cm)	Max (cm)	Median (cm)	RMSE (cm)	Rank
IRI2007	1.070905	2.963916	1.90799	1.3813	1
NIC09	1.952856	5.238975	3.366793	1.834882	2
JPL	1.955733	5.410204	3.644371	1.909024	3

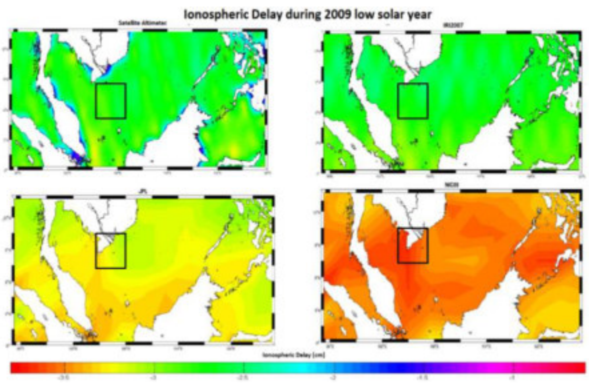


Figure 6 Ionospheric delay during the 2009 low solar year

D. Mission-by-mission Analysis

A major advantage of this project was that it used multi satellite altimeter missions as its data source. However, this could only be fully utilized if and only if the sensors on the separate satellites were working in sync with each other. The purpose of this analysis was to study the system biases between the sensors on board each satellite and what were their differences with each other. This was to ensure that the sensors were synchronous and harmonious with each other. Figures 7(a) (b) and (c) show the sensors were all following the same trend with each other, whereas Table 6 shows the root mean square difference to show the performance of the sensors with each other.

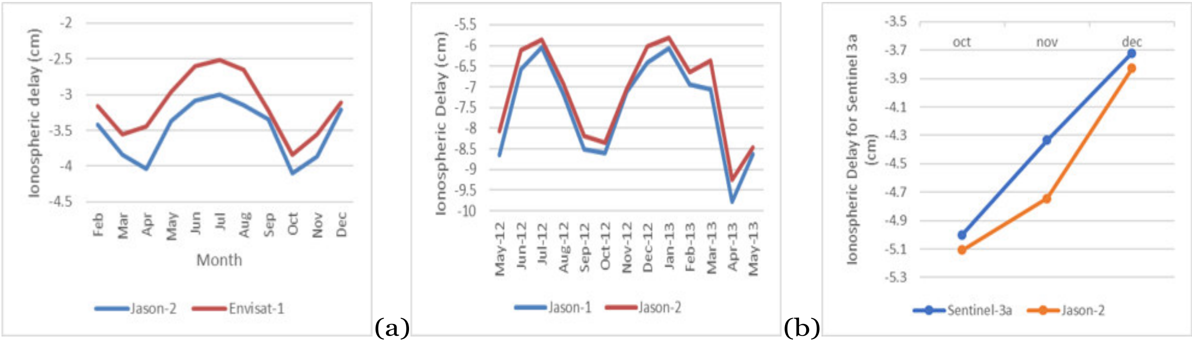


Figure 7. Mission by mission analysis for Jason 1 and Envisat 1 from Feb 2009 until Dec 2009 (a); Jason 1 and Jason 2 from May 2012 until May 2013(b); and (c) for Jason 2 and Sentinel 3a from October 2016 until Dec 2016

Table 6. Root mean square difference (RMSD) between satellite altimeter missions

Mission pair	Duration	RMSD (cm)
Jason 1 and Envisat 1	Feb 2009 – Dec 2009	0.378232
Jason 1 and Jason 2	May 2012 – May 2013	0.379855
Jason 2 and Sentinel 3a	Oct 2016 – Dec 2016	0.548667

IV. CONCLUSION

Global ionosphere models such as IRI2007, JPL GIM and NIC09 had been quite extensively used in studying the ionosphere's parameter. When looked at from a long-term perspective, the satellite altimeter's ionospheric delay seemed to be in sync with the global ionospheric models with IRI2007 being the best performing GIM with satellite altimeter's ionospheric delay with an RMSE of 1.111542cm and residual average of just 1.24cm. However, when we looked closer into specific events such as during the occurrence of solar flares, even with the IRI2007, the RMSE value was 1.38130cm, a 0.26cm increase from its long term RMSE. The case was even worse for JPL which had an RMSE value of 1.909024cm during solar flare occurrences, a 0.62cm increment from its long term RMSE value. With that being said, the satellite altimeter's ionospheric delay was best suited with IRI2007 for the ionospheric conditions in tropical regions for the long term. Even when in the presence of a high number of sunspots or during occurrences of solar flares, satellite altimeter's ionospheric delay with IRI2007 was still best suited for the ionosphere in tropical regions especially over Malaysian seas. In conclusion, satellite altimeter could provide a good data source as the pattern of ionospheric delay derived from satellite altimeter matched those of the existing GIMs. It would also be beneficial to determine the ionospheric delay in Malaysian seas for marine environmental planning and marine engineering.

V. ACKNOWLEDGMENTS

Sincere thanks to the GNSS and the Geodynamic (G&G) Lab, Faculty of Geoinformation and Real Estate, (FGHT) Universiti Teknologi Malaysia (UTM) for their support and assistance during the data collection for this research. The authors are grateful to TU Delft, NOAA, Altimetrics Llc for providing the altimetry data. We are grateful to the Ministry of Education Malaysia and Universiti Teknologi Malaysia for funding this research under Research University Grant (VOTE number: Q.J130000.2527.19H83).

VI. REFERENCES

[1] Bilitza, D, Altadill, D, Zhang, Y, Mertens, C, Truhlik, V, Richards, P & Reinisch, B 2014, 'The International Reference Ionosphere 2012–a model of international collaboration', *Journal of Space Weather and Space Climate*, vol. 4, no. A07.

[2] Clette, F, Svalgaard, L, Vaquero, JM & Cliver EW 2014, 'Revisiting the sunspot number: A 400 year perspective on the solar cycle', *Space Sci. Rev*, vol. 186, no. 1-4, pp. 35-103.

[3] Imel, DA 1994, 'Evaluation of the TOPEX/POSEIDON dual-frequency ionosphere correction', *Journal of Geophysical Research: Oceans*, vol. 99, no. C12, pp. 24895-24906.

[4] Pajares, M, Dollase, DR, Krankowski, A, Rigo, AG & Orús Pérez, R 2017, 'Methodology and consistency of slant and vertical assessments for ionospheric electron content models', *Journal of Geodesy*, vol. 91, no. 12, pp. 1405-1414.

[5] Povero, G, Pini, Marco, Alfonsi, L, Spogli, L, Mauro, DD, Dovis, F, Romero, R, Minh, LH, Abadi, P, Vinh, LT & Floury, N 2015, 'Ionosphere monitoring in South East Asia: Activities in GINESTRA and ERICA projects', in *2015 International Association of Institutes of Navigation World Congress (IAIN), 20-23 October 2015*, Prague, Czech Republic.

[6] Scharroo, R & Smith, WHF 2010, 'A global positioning system- Based climatology for total electron content in the ionosphere', *Journal of Geophysical Research Atmosphere*, vol. 115, no. A10.

[7] Wang, N, Yuan, Y, Li, Z, Montenbruck, O & Tan, B 2015, 'Determination of differential code biases with multi-GNSS observations', *Journal of Geodesy*, vol. 90, no. 3, pp. 209-228.

[8] Wielgosz, P, Grejner-Brzezinska, D & Kashani, I 2003, 'Regional Ionosphere Mapping with Kriging and Multiquadric Methods', *Journal of Global Positioning System*, vol. 2, no. 1, pp. 48-55.

[9] Xiang, Y, Yaun, Y, Li, Z & Wang, N 2015, 'Analysis and validation of different global ionospheric maps (GIMs) over China', *Advances in Space Research*, vol. 55, no. 1, pp. 199-210.

[10] Ya'acob, N, Abdullah, M, Ismail, M, Ibrahim, M & Zakaria, Z 2010, 'Total Electron Content (TEC) and Estimation of Positioning Error Using Malaysia Data', in *Proceedings of the World Congress on Engineering 2010, 30 June-2 July 2010*, London, United Kingdom.

ASM Sc. J., 12, Special Issue 2, 2019 for Malaysia in Space, 152-161

Interpretation of Atmospheric Wet Delay in the Tropical Region Using Space-Based Radiometer System

Muhammad Saiful Baharudin[1], Ami Hassan Md Din[1,2*], Mat Nizam Uti[1], Tajul Ariffin Musa[1] and Suhaila Salihin[1]

[1]*Geomatic Innovation Research Group (GIG),* [2]*Geoscience and Digital Earth Centre (INSTEG),*
Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia,
81310 Johor Bahru, Johor, Malaysia

Due to the inherent advantages of monitoring from space, and developments in sensor technology, satellite altimeters have brought about a revolution in the field of weather forecasting as they can measure atmospheric conditions using an onboard instrument called a passive microwave radiometer over the ocean areas. Since tropospheric wet delay in the atmosphere is one of the limiting factors to satellite altimeter measurement range, it is important for weather and climate predictions. The methods that can be used to measure wet delay are satellite altimeter, Global Positioning Systems (GPS), and Radiosonde. Weather satellites offer some potential advantages over conventional methods as they can cover marine areas, whereas conventional weather networks cover only about 20% of the globe, which are land areas using point-based solutions. A combination of these methods will improve tropospheric wet delay studies. The focus of this study was to evaluate wet delay data using radiometer measurements for tropical regions. The 10 altimeter missions used for this study consisted of ERS-1, ERS-2, Envisat, Jason-1, Jason-2, Jason-3, SARAL, Sentinel, TOPEX, and Poseidon. This study used the Radar Altimeter Database System or RADS to extract wet tropospheric corrections from radiometer measurements in the Malaysian region. The expected result was to evaluate the wet delay pattern in marine areas in tropical regions during the monsoon season. This study would also verify wet delay data from satellite altimeters with GPS-derived data at 12 GPS MyRTKnet Stations in Malaysia and the European Centre for Medium-Range Weather Forecast (ECMWF) Global Tropospheric model. The verification results showed that the RMSE between altimetry-derived wet delay with GPS-derived wet delay and the ECMWF model were both about 1cm to 15cm. The observed data also gave reasonable values for the wet and dry seasons because the MyRTKnet and the ECMWF model from satellite altimeters only had slight differences. Altimetry-derived wet delay studies are very important to climate and weather forecasting and many kinds of research in marine areas and tropical regions.

Keywords: Atmospheric humidity; microwave radiometer; wet delay pattern

I. INTRODUCTION

Water vapour is the Earth's most abundant greenhouse gas, but the extent of its contribution to global warming has been debated. Using recent NASA satellite data, researchers have more precisely estimated the heat-trapping effects of water in the air, validating the role of the gas as a critical component of climate change (Elegered *et. al.,* 1991; Bevis *et. al.,* 1994; Chen, 2004; Fernandes *et. al.,* 2013; Wang and Li, 2016). Water vapour consists of two components, dry and wet delay. This study highlighted wet delay as dry delay could be easily modelled. The use of satellites for weather forecasting and the prediction of related phenomena have become indispensable. Some

*Corresponding author's e-mail: amihassan@utm.my

current practices used to measure wet delay such as Radiosonde and Global Positioning Systems (GPS) have their limitations (Mousa *et. al.,* 2016; Mohd Azman *et. al.,* 2019). For example, they are point based solutions that only are available for certain land areas. Meanwhile, the radiosonde methods need to be launched twice daily and every single launch is expensive. On the other hand, the satellite altimeter has its own limitation which is the grid measurements are affected by the presence of land-mass (Uti *et al.*, 2017). Wet delay in the atmosphere needs to be monitored for land and marine areas, especially in the tropical region, which is known as a challenging area for weather and climate prediction due the high variability of humidity and the complexity of the water cycle at all spatial and time scales. However, since we already know that the wet delay of marine areas would be higher than those of land areas, and due to a lack of information, this study focussed on marine areas in tropical regions. The aim of this research was to evaluate wet delay patterns using radiometer measurements from multi-mission satellite altimeters for tropical regions, specifically in Malaysia. In pursuit of this aim, some of the objectives of this study were to extract wet delay data from 25 years of radiometer measurements, to evaluate the wet delay pattern in the tropical region, and to verify altimetry-derived wet delay with GPS-derived wet delay and the ECMWF model. The advantage of using satellite altimeters rather than the GPS MyRTKnet stations was that satellite altimeters could retrieve wet delay data over marine areas. A combination of both methods, GPS and Satellite Altimeters, could improve climate studies and other related activities.

II. DATA AND METHODS

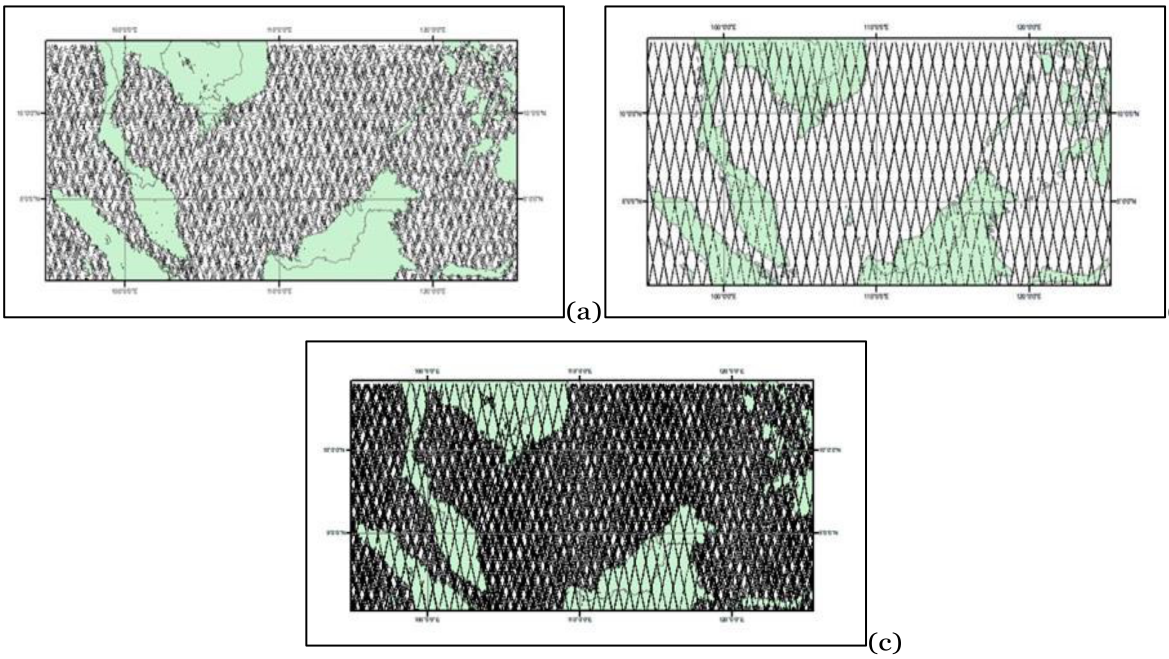
The study area was bounded between latitude 0° to 14° and longitude 95° to 126°. The study area focused on Malaysian seas; the Malacca Straits, South China Sea, Celebes Sea and Sulu Sea. GPS data from MyRTKnet Stations were retrieved for the ground truth data which were in the form of point-based solutions. GPS-derived wet delay data from MyRTKnet Stations were point-based data sets controlled by the Control Centre at the JUPEM Head Quarters, Kuala Lumpur, Malaysia. The MyRTKnet Stations used in this study were located at coastal regions in Peninsular Malaysia. This study used data from 10 satellite altimeters, which were ERS-1, ERS-2, Envisat, Jason-1, Jason-2, Jason-3, SARAL, Sentinel, TOPEX, and Poseidon from 1993 to 2017. This data were extracted using RADS to obtain the wet delay troposphere. We extracted wet delay data for a 25-year period from 1st January 1993 to 31st December 2017 using ten satellite altimeters, the process continued with data gridding using three solutions which were daily, monthly, and climatology. Satellite altimeters' temporal and spatial characteristics are as shown in Table 1. For validation, only altimeter missions near to MyRTKnet stations were selected. Information on the distance between the satellite altimeter track and the GPS MyRTKnet stations are shown in Table 2. The satellite track plots are as shown in Figure 1, which were from Jason-1 and SARAL. As shown in Figure 1, the Malacca Straits, South China Sea, Celebes Sea, and Sulu Sea were covered by both missions, but only the SARAL mission covered land areas. Meanwhile, Jason-1 only covered the nearest coastline of Malaysia. However, the Jason-1 altimeter had a denser spatial resolution than the SARAL altimeter, which meant that the Jason-1 altimeter mission provided more data for the stated period than SARAL. However, by combining these two satellite missions, the spatial and temporal resolution of the data could be improved in the area of interest.

Table 1. The satellite altimeter's temporal and spatial characteristics (Aviso, 2018)

Satellite Mission	Agency	Life span	Temporal resolution	Track spacing	Orbit Accuracy
ERS-1	ESA	Jul 1991 – Mar 2000	3, 35, 168 days	80 km	7-8 cm
ERS-2	ESA	Apr 1995 – Jul 2011	35 days	80km	7-8 cm
Envisat	ESA	Mar 2002 – Jun 2012	30-35 days	80km	~10 cm
Jason-1	CNES/NASA	Dis 2001 - Jul 2013	10 days	315km	2-3 cm
Jason-2	CNES/NASA	Jun 2008 - current	10 days	315km	2-3 cm
Jason-3	CNES/NASA/	Jan 2016 – current	10 days	315 km	2-3 cm
SARAL	ESA & ISRO	Feb 2013 - current	35 days	75 km	~2 cm
Sentinel	ESA	Feb - 2016	27 days	104 km	2-3 cm
TOPEX/		Aug 1992 – Jan 2006	10 days	315km	2-3 cm

Table 2. Distance between satellite altimeter tracks and GPS MyRTKnet stations

No.	Cors Station Selected	Nearest Mission	Distance (km)
1.	BABH	SARAL	4.588
2.	BANT	SARAL	0.954
3.	JUML	Jason-1 Phase C	4.852
4.	KROM	SARAL	1.544
5.	MERS	SARAL	3.733
6.	MERU	SARAL	3.830
7.	PDIC	Envisat	1.084
8.	PEKN	Jason-1 Phase C	1.132



(a) (b) (c)

Figure 1. Satellite altimeter's tracks for Jason-1 (a) and SARAL (b) and the multi-mission altimeter track: combination of Jason-1 and SARAL (c).

III. RESULTS AND DISCUSSION

A. Data Verification: Altimetry-derived wet delay vs GPS-derived wet delay

For data verification, the accuracy of the altimetry-derived wet delay was validated with GPS-derived wet delay data using Root Mean Square Error (RMSE). A graph was plotted to determine the correlation coefficient, R^2. Meanwhile, the validation of marine area data was based on the Global Tropospheric Model, which was an ECMWF model. GPS MyRTKnet stations were used as reference values to evaluate measurement of wet delay from the satellite altimeter. Figure 2 shows the wet delay patterns between the GPS MyRTKnet and the satellite altimeters for the chosen areas, which were coastal regions around Peninsular Malaysia such as BABH, BANT, JUML, KROM, MERS, MERU, PDIC, and PEKN.

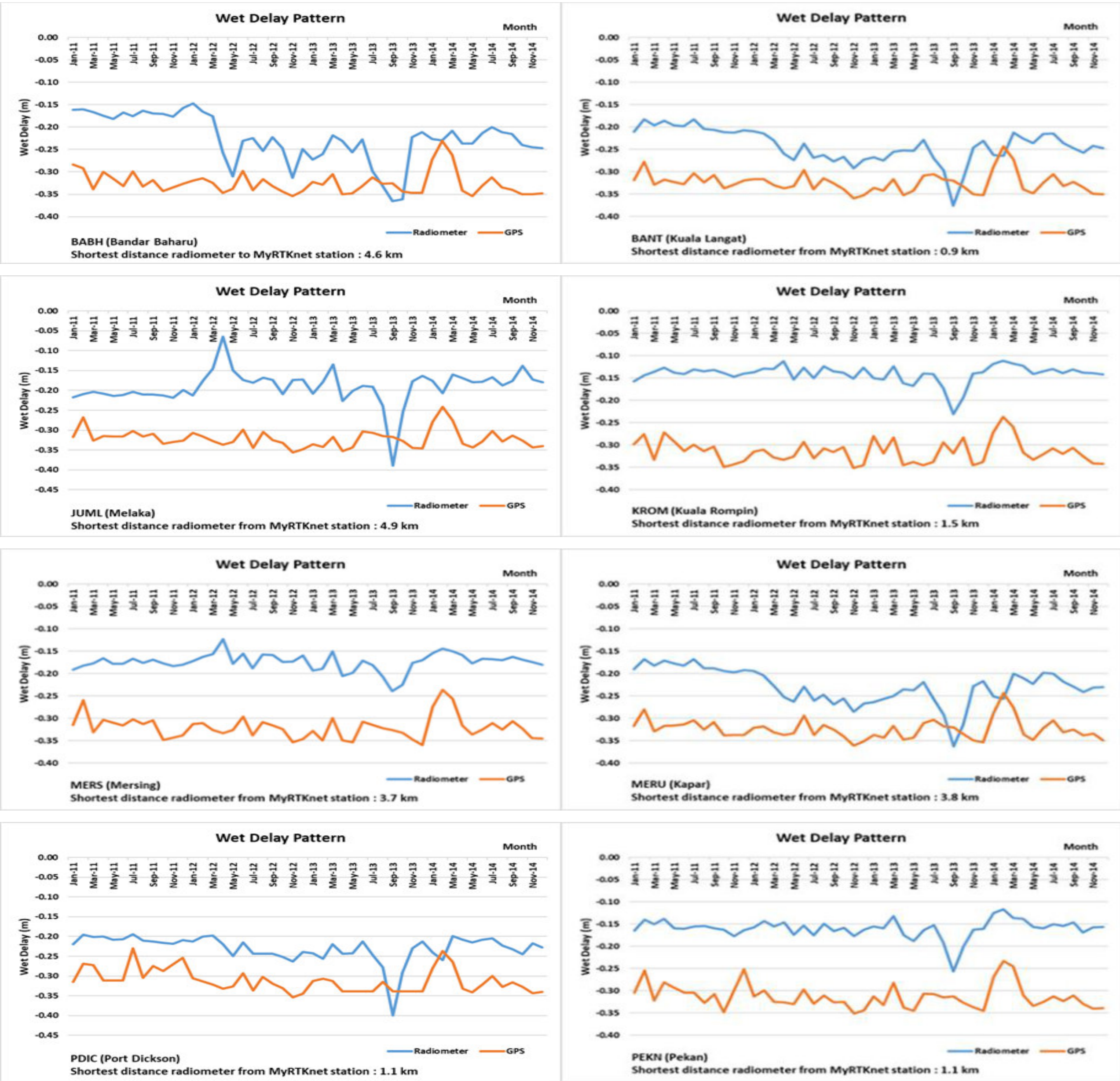


Figure 2. Wet Delay Patterns for the Year 2011 until 2014 at chosen areas for both altimetry and GPS

Figure 3 shows the correlation and RMSE for the chosen stations. All of these stations were located along the coastline of Peninsular Malaysia. The graphs from both Figures 2 and 3 show that the data shapes for both the altimetry and the GPS-derived wet delay had the same trend and the RMSE varied between 0.05m and 0.15m. The distances between the GPS MyRTKnet stations and the altimeter tracks were calculated and sorted into average ranges of 0-5km, 5-30km, 30-50km, and 50-200km. In our understanding, the best data correlation should be produced for the 0-5km average range between the satellite track and the MyRTKnet station location. The patterns showed that the highest derived wet delay values from both techniques occurred between November and December and the lowest were in between February and March. The graphs showed that the data shape for both the altimetry and the GPS-derived wet delay were not similar as the correlation coefficients R^2 for all the chosen areas were less than 0.6. This was due to the extrapolation of the multi-mission satellite altimetry along-track data, which degraded the comparison.

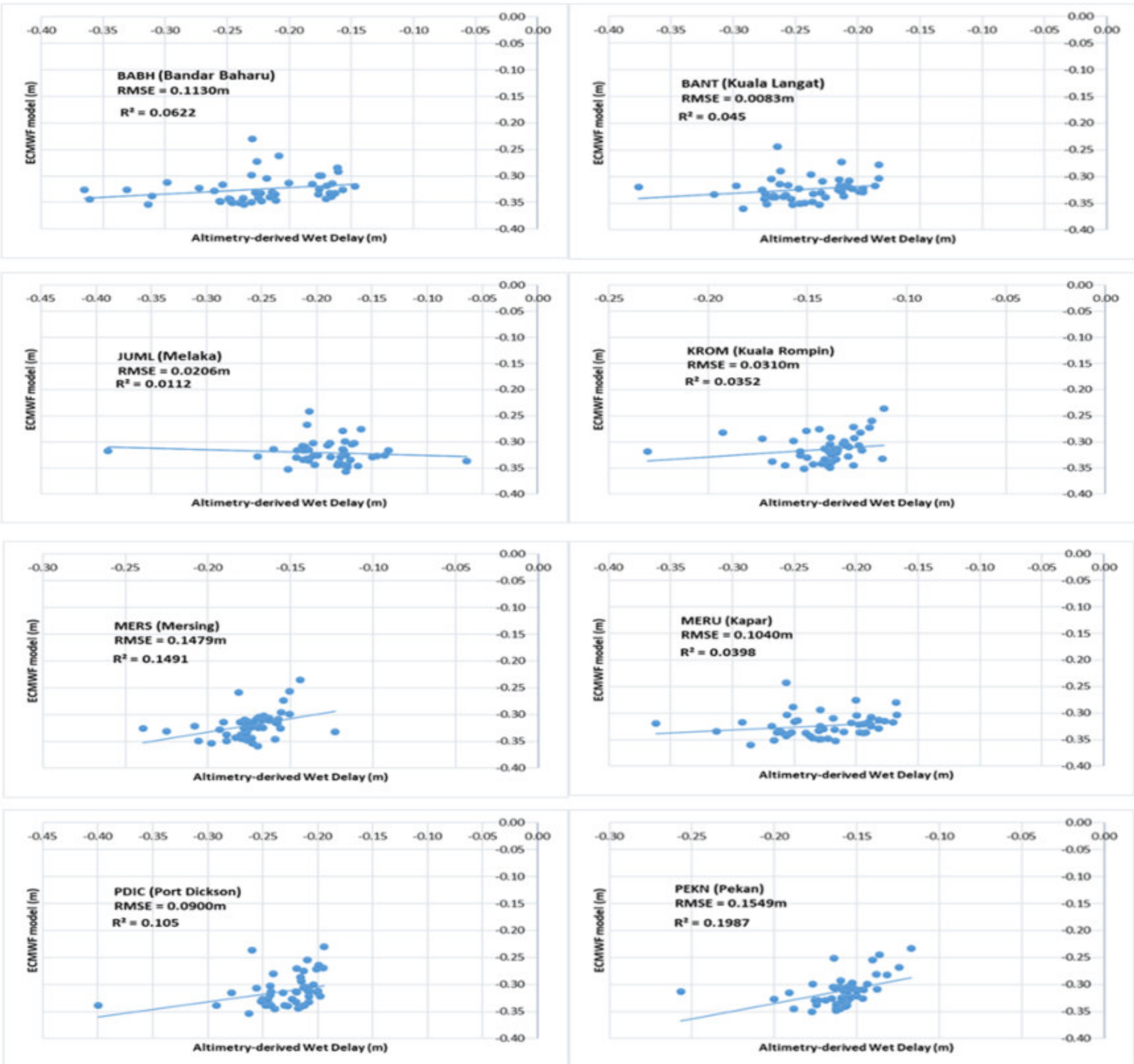


Figure 3. The altimetry and GPS correlation analysis at chosen areas

1. Altimetry-derived wet delay vs ECMWF

For marine areas, data from satellite altimeters were verified by the ECMWF wet tropospheric model. Data verifications were conducted for the Malacca Straits (mcs25), South China Sea (scs18), Celebes Sea (cbs05), and Sulu Sea (sus22). For the Celebes Sea, the climatology mean was -0.327m and for the South China Sea it was -0.320m. Meanwhile, the climatology mean for the Sulu Sea was at -0.327m and the Malacca Straits at -0.326m. Figure 4 shows the wet delay pattern between the ECMWF model and satellite altimeters for the chosen areas. From Figure 4, we could see that the altimetry-derived wet delay data for each sea were similar to the wet delay data from the ECMWF model for all four sea points. Figure 5 shows the correlation coefficient, R^2, and RMSE for the chosen points in the Celebes Sea (cbs05), South China Sea (scs18), Sulu Sea (sus22), and Malacca Straits (mcs25). The graphs showed the altimetry and ECMWF wet delay values were similar and in good relationship as the correlation coefficients, R^2, for all the chosen areas were more than 0.6 and the RMSE varied between 1 - 2cm.

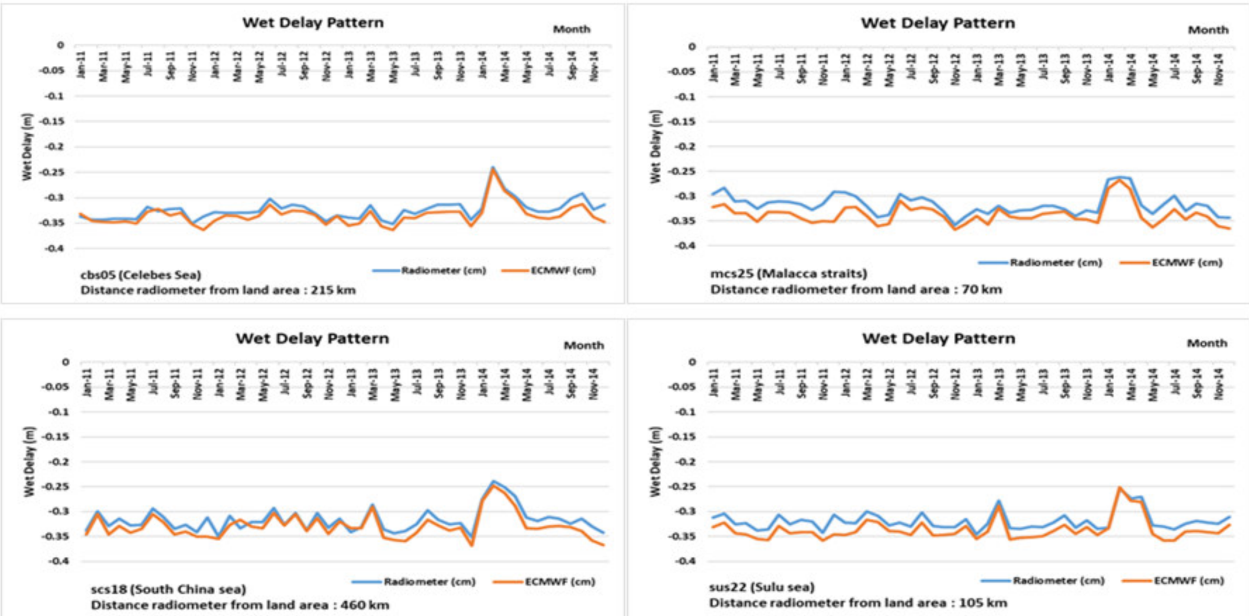


Figure 4. Wet Delay Patterns for the Year 2011 until 2014 at chosen areas

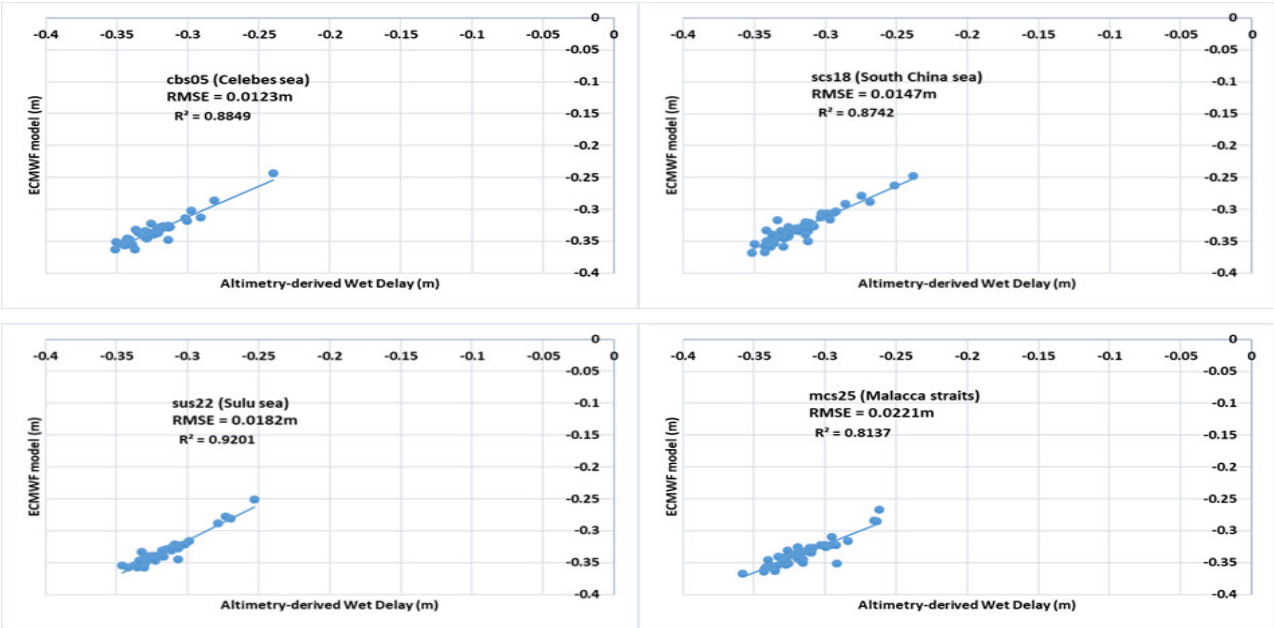


Figure 5. The altimetry and ECMWF correlation analysis at four different seas

2. Comparisons between Mean Wet Delays on Land and Marine Areas

In this section the mean wet delays for land and marine areas were investigated for differences. From the graphs shown in Figure 6a (land areas) and Figure 6b (marine areas), we could see the differences between the highest and mean value of the wet delay for both land and marine areas. Based on Figure 6(a) and Figure 6(b), the wet delay values were similar for the marine and land areas. For the mean wet delay of each Malaysian sea, the average climatology meanwet delay over four years for the Malacca Straits was 33cm to 37cm. Climatology mean wet delay varied from 32cm to 36cm for the South China Sea, 33cm to 37cm for the Celebes Sea, and 33cm to 36cm for the Sulu Sea. Therefore, we could see that all Malaysian seas had similar mean wet delays of about 32cm to 37cm from 2011 to 2014. Meanwhile, for land area mean wet delay, the average climatology mean wet delay over four years was about 32cm to 36cm. In conclusion, this information is important as it can be used by the public or authorities who need to travel around Malaysian seas in the future.

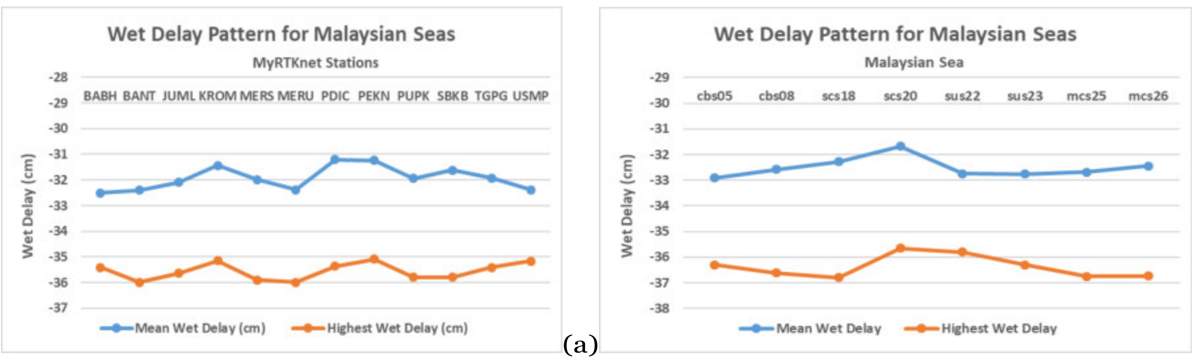


Figure 6. (a) time series of highest and mean wet delay for four years on land areas; (b) is time series of highest and mean wet delay for four years on marine areas

B. Wet Delay Pattern using Time-series Analysis

1. Long Term Mean Wet Delay

This study highlighted the altimeter mean wet delay trend over 25 years from 1993 to 2017, which was extracted using RADS. For annual mean wet delay, data were sorted by month for year. A graph was plotted to see trends in yearly mean wet delay for 25 different years. Figure 7 shows the climatology mean wet delay pattern for each sea, which was the average of the annual mean over 25 years. It could be seen that the Malacca Straits had the lowest mean wet delay due to its small area near the coastline region. Meanwhile, the highest mean wet delay was at the Celebes Sea due to its nature as a large open sea. Hence, the rate of evaporation over the open sea was higher rather than at the coastline region, leading to a higher wet delay value in the atmosphere.

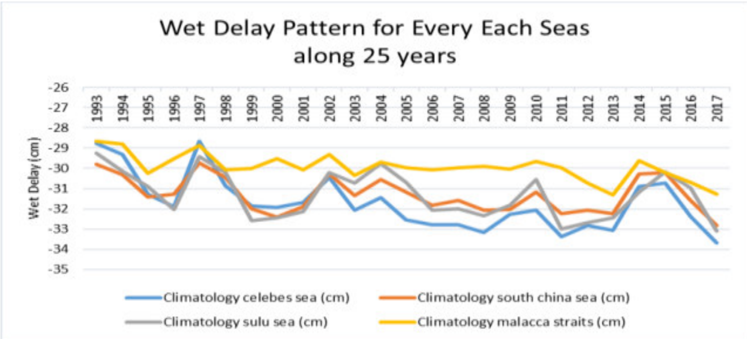
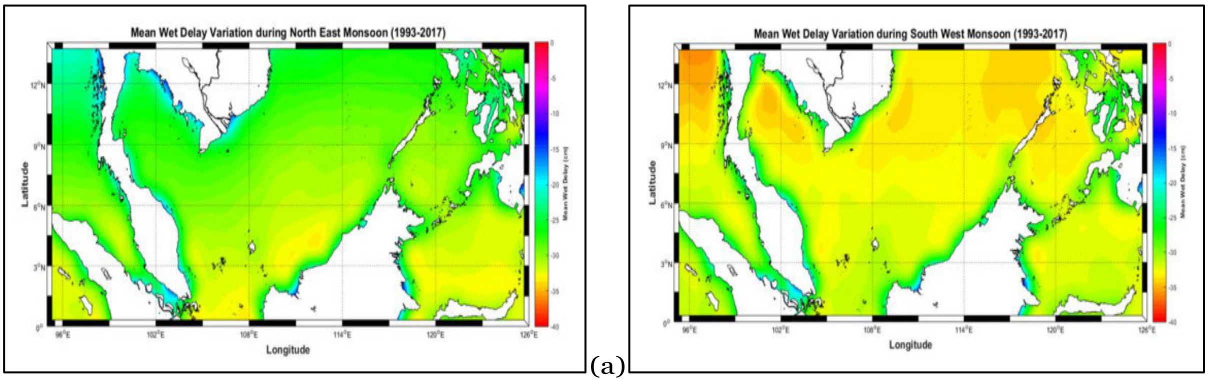


Figure 7. The climatology mean wet delay patterns over 25 years

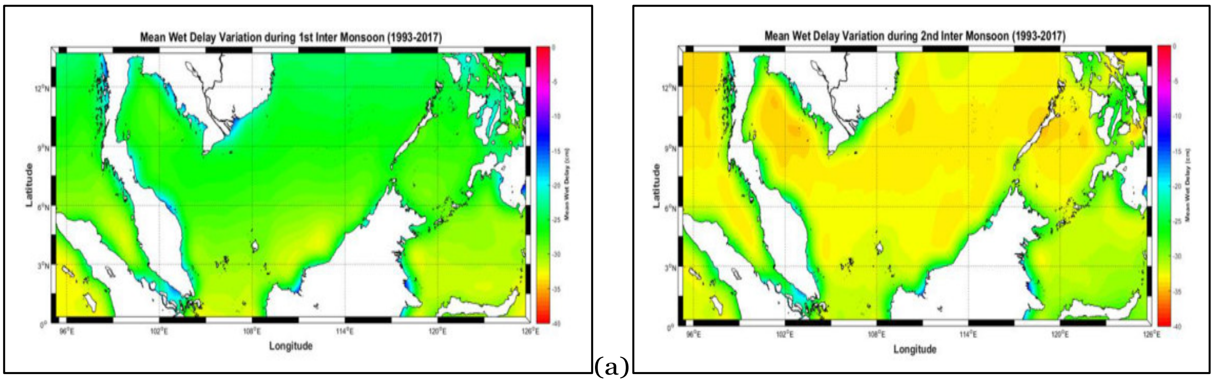
2. Wet Delay Variations due to Seasonal Effects (Monsoon Season)

In this study, seasonal variation was categorized into four categories namely Northeast monsoon, Southwest monsoon, First-inter and Second-inter monsoon. The significance of this assessment was to highlight the interchange of wet delays during each season. Figure 8 shows the wet delay map during the Northeast monsoon and Southwest Monsoon, while Figure 15 shows the wet delay map during the First and Second Inter-Monsoon. Based on Figure 8, the highest wet delay reading recorded for the Northeast monsoon was -34cm and the lowest was 4cm. The average value of this season was -24cm. Meanwhile, for the Southwest monsoon the average recorded wet delay value was -27cm and the highest value was -36cm. From Figure 9, the highest monthly mean wet delay occurred from May to October while the lowest monthly wet delay mean occurred from March to April. The Southwest monsoon was the wettest season because the wet delay recorded from May to August was highest in the year. The map pattern also showed how the monsoon seasons affected the amount of the atmospheric wet delay over marine areas.



(a) (b)

Figure 8. Altimetry-derived wet delay during the Northeast Monsoon (a); and the Southwest Monsoon (b)



(a) (b)

Figure 9.Altimetry-derived wet delay during the First Inter-Monsoon (a); and the Second Inter-Monsoon (b)

IV. CONCLUSION

Accurate tropospheric wet delay data over an extended period are vital for precise GNSS applications and to provide reliable spatial and temporal data for the study of troposphere wet delay in tropical regions. The wet delay patterns for Malaysian land and marine areas were evaluated, which would help the study of short-term weather forecasting and long-term climate changes as they were affected by water vapour content in the atmosphere. Thus, this study proposed a technique for wet delay studies using satellite altimetry to help improve, in terms of spatial and temporal coverage, understanding of wet delay. For data verification, GPS data from MyRTKnet stations were used as a reference for altimetry-derived wet delay data. The results of this study showed that the Root Mean Square Error (RMSE) between the altimetry-derived wet delay and GPS-derived wet delay was 5cm to 15cm. and the RMSE between altimetry-derived wet delay and the ECMWF model was 1cm to 2cm. Furthermore, data from satellite altimeters were in accordance with the seasonal variations in precipitation according to regional climatic classifications. This study's observed data gave reasonable values for the wet and dry seasons because the values from MyRTKnet, ECMWF, and satellite altimeters only had slight differences. It showed a correlation between wet delay behaviour from different techniques. From this study's results, the wet delay figures derived from satellite altimeters could be used to study the inconsistency of atmospheric content in a regional or global area over the short or long term. The assessment of wet delay climatology data could support weather forecasting in Malaysia in terms of providing continuous data to authorities such as government agencies, non-government agencies, researchers, and university students. In conclusion, the contribution of this study was the provision of wet delay information for marine areas in the Malaysian region with promising applications for climate and weather predictions.

V. ACKNOWLEDGEMENT

The authors would like to acknowledge the GNSS and Geodynamic (G&G) Lab, Faculty of Geoinformation and Real Estate, (FGHT) Universiti Teknologi Malaysia (UTM) for their support and assistance with data collection. The authors are grateful to TU Delft, NOAA, and AltimetricsLlc for providing altimetry data. The authors are grateful to the Ministry of Education Malaysia and Universiti Teknologi Malaysia for funding this research under Research University Grant (VOTE number: Q.J130000.2527.19H83).

VI. REFERENCES

[1] Bevis, M, S, Businger, S, Chriswell, TA, Herring, RA, Anthes, C, Rocken, & RH, Ware 1994 'GPS meteorology: Mapping zenith wet delays onto precipitable water', *J. Appl. Meteor.*, vol. 33, no. 3, pp. 379–386.

[2] Chen G 2004, 'A 10-Yr Climatology of Oceanic Water Vapor Derived from the TOPEX using Microwave Radiometer', *Journal of Climate*, vol. 17, no. 13, pp. 2541-2557.

[3] Elegered, G, Davis, JL, Herring, TA, Shapiro, II 1991, 'Geodesy by Radio Interferometry: Water Vapor Radiometry for Estimation of the Wet Delay', *Journal of Geophysical Research*, VOL. 96, PP. 6541-6555.

[4] Fernandes, MJ, Nunes, AL & Lazaro, C 2013, 'Analysis and Inter-calibration of wet path delay datasets to compute the wet tropospheric correction for Cryosat-2 over ocean', *Journal of Remote Sensing*, vol. 5, no. 10, pp. 4977-5005.

[5] Mohd Azman, MA, Din, AHM, Musa, TA, Salihin, S, Omar, AH 2019, 'Assessing the Reliability and Validity of Satellite Altimetry-Derived Wet Delay in Peninsular Malaysia', in *Pradhan B. (eds) GCEC 2017, GCEC 2017, Lecture Notes in Civil Engineering, vol 9*, Springer, Singapore.

[6] Mousa, AEL-K, Aboualy, N, Sharaf, M, Zahra, H, Darrag, M 2016, *Tropospheric Wet Delay Estimation using GNSS: Case Study of a Permanent Network in Egypt*, National Research Institute of Astronomy and Geophysics. DOI: 10.1016.

[7] Uti, MN, Din, AHM & Omar, AH 2017, 'Reliability of Wind Speed Data from Satellite Altimeter to Support Wind Turbine Energy.The Int. Archives of the Photogrammetry', *Remote Sensing and Spatial Sciences*, Vol XLII-4/W5, pp. 215-224.

[8] Wang, M, & Li, B 2016, 'Evaluation of Empirical Tropospheric Models using Satellite-Tracking Tropospheric Wet Delays with Water Vapor Radiometer at Tongji, China', *Sensors*, vol. 16, no. 2, pp. 186-186. DOI: 10.3390.

Possible Malaysian Contributions to Future Space Food during Long-Duration Space Mission

Hadi Akbar Dahlan[1*]

[1]*Department of Biotechnology, Graduate School of Engineering, Osaka University,*

2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

Food is one of the most important logistic preparations during a space mission. From human nutrition in space to payload delivery, each step was analysed and simulated in detail on earth before the actual mission took place. However, the current strategy of delivering payload containing food to the space station is not feasible for long-duration space mission such as space exploration to the moon and beyond. Thus, a food supply strategy for such mission requires plans on how to develop sustainable food supply in space. This paper intended to suggest possible Malaysian contributions toward plans for food during long-duration space mission as well as their limitations and further recommendations toward this effort.

Keywords: Space food; Malaysia; palm oil milk; tempeh; nutrition

I. INTRODUCTION

Throughout the six-decades of human spaceflight, people collectively had completed remarkable achievements. These achievements ranged from sending the first human to orbit the earth in 1961 to sending a robotic space probe to Mars in 2012. In 2017, the American government reinstated the National Space Council (NSC) and had formally directed the National Aeronautical Space Agency (NASA) to focus on returning humans to the moon. The space policy which was signed by President Trump hoped to be a foundation for a future mission on Mars exploration and many worlds beyond (Jen Rae Wang, 2017).

Although space exploration was initiated from rivalries between the then Soviet Union (now Russia) and the United States during the cold war era (Launius, 2010), developments only accelerated significantly when it became a collaborative effort (Ansdell, Ehrenfreund, & McKay, 2011). From space probes to robotic explorers (Mateo Sanguino, 2017), collaboration between nations have accelerated the development of space exploration technology. However, there are still many logistical issues that require further research. One of the major issues is nutrition of humans in space. This includes providing basic nutrients for basic human physiological functions and sufficient calories for humans to work in space. However, currently food for humans in space is based on pre-packaged food from earth.

II. FOOD AND NUTRITION IN SPACE

Food for human spaceflight was first developed in the Soviet Union and the United States. Although Yuri Gargarin was the first Soviet cosmonaut and the first human to eat in space (pureed meat and chocolate in tube paste), but it was Gherman Titov, the second cosmonaut

*Corresponding author’s e-mail: hadiakbar1591@rocketmail.com

(and the fourth person to space) that prompt the need for space nutrition research (Lane & Feeback, 2002). This was because Gherman Titov vomited his food during a space mission due to "space sickness".

During the early phase of human flights to space, basic physiology experiments were conducted such as drinking water in space. This was done because human physiology in space was relatively unknown at the time. Once it was determined that humans can conduct normal physiological activities in space, research on human food and nutrition in space began to accelerate. Most of the nutritional research was based on ground-based research and was replicated in space missions. To reduce the risk of nutrition deficiency of travelling in space, NASA developed a roadmap detailing possible conditions, risks, and consequences during space travel habitation (Vodovotz, Bourland, Kloeris, Lane, & Smith, 1999). Some of the questions regarding the consequences of space habitation are still being studied today (Lane, Smith, & Kloeris, 2016).

Physiological factors are important because they affect the overall status of humans. Impaired physiological status will affect the adaptability of humans during space travel and habitation and this can easily affect other factors such as the neurosensors and nutrition. Therefore, it is imperative that intervention and preparation steps be taken on these factors to ensure prolonged space habitation (Doarn, Williams, Schneider, & Polk, 2016; Smith & Zwart, 2008). Losing one of these functions will gradually lead to increased stressed, debilitation and death. As a preparation step, many space programs had comprehensive training protocols to enable fast adaptation to space conditions such as performance evaluation of astronaut candidates using 20G centrifuge as well as psychological support to reduce stress such as frequent family visitation and food request during space missions (Lane & Feeback, 2002).

Food in space is usually in the forms of (1) thermostabilized, (2) irradiated, (3) rehydratable, (4) natural form (but with reduced water content), (5) extended shelf life bread products, (6) fresh foods (for short duration space missions) and (7) beverages (Figure 1) (Cooper, Douglas, & Perchonok, 2011). All of the planned space food must undergo the rigorous Hazard Analysis Critical Control System (HACCP) (Ross-Nazzal, 2007). Besides safety, food in space must also fulfil human micronutrients which are usually lacking since the food in space is limited and rationed. Thus, every meal taken in space must fulfil the minimal human nutritional requirements based on ground-based Dietary Reference Intakes for micronutrients and WHO recommendations (Smith & Zwart, 2008).

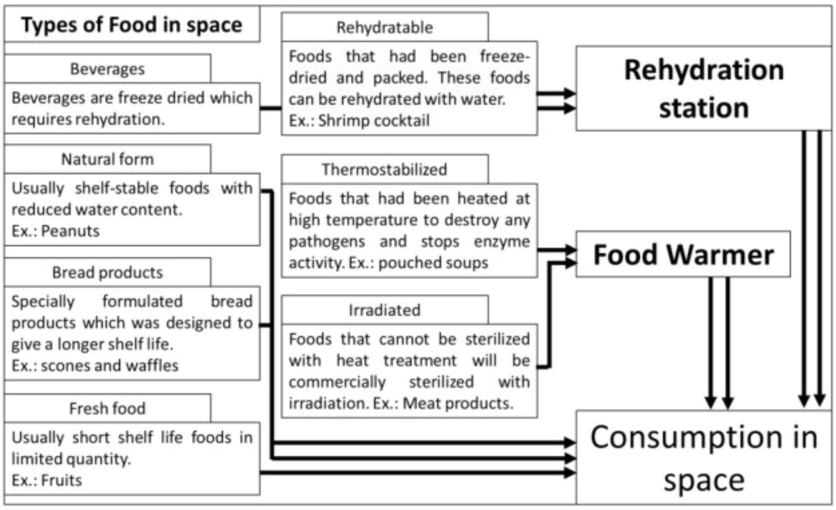


Figure 1. Types of food in space. Adapted from (Cooper *et al.*, 2011)

However, astronauts or national space agencies are able to bring special food requests during space missions. Such foods usually represent the countries that the astronauts came from. Some notable examples included Japan Aerospace Exploration Agency (JAXA) registering ramen from Nissin Food Products Co. as a Japanese Space food (Azusa Ushio, 2017) and Mexican Astronaut Rodolfo Neri Vela requesting to bring Tortillas during the STS-61-B space mission (Casaburri & Gardner, 1999). In 2007, Malaysian foods such as sate Ayam (chicken satay), rendang daging (beef rendang) and kuih bangkit (tapioca cookies) were also brought to space (Adham Shadan, 2008).

III. MALAYSIA IN SPACE

The Government of Malaysia signed a Contract for the performance of scientific research activities and experiments with the Russian Federal Space Agency in 2005. The project was named ANGKASA MSM Project where the project was conducted by Angkasawan Sheikh Muszaphar Shukor Al Masrie at the International Space Station (ISS) in 2007. He conducted eight experiments one of which involved Malaysian food. The Malaysian food experiment was named FIS experiment and the objective of the experiment was to compare sensory evaluations of nine types of Malaysian food in the ISS under near-zero gravity ("ANGKASA MSM Project "FIS EXPERIMENT"," 2005). This research heralded Malaysia's own contribution to global space research and exploration. This was because the FIS experiment utilized Malaysian culture and resources and its outcome contributed to the food sensory perception of humans in space.

Aside from the Angkasawan program (which was a cooperation from an offset agreement with Russia), Malaysia had also collaborated with JAXA in several space research missions. One of the early collaborations was the Space Seeds for Asian Future (AstroSeed) program organized by the Asian "KIBO" Mission Planning Task Force in 2010 ("Space Seeds for Asian Future Program (AstroSeed)," 2012). One of the objectives of this program was based on the Malaysia Space Seed Education Module which aimed to inspire prospective students and citizens on microgravity and agricultural research in space. This involved distributing *Capsicum annum* (cv M11) that had undergone microgravity conditions in the ISS to Malaysian secondary school students for cultivation ("Space Seeds for Asian Future Program (AstroSeed)," 2012). Another JAXA-ANGKASA collaboration was the Asian Herbs in Space (AHiS) program which studied the effects of microgravity on two local herbs; "Hempedu Bumi" (*Andrographis paniculate*) and "Holy Basil" (*Oscimum sanctum*). This program also debuted the first Malaysia space hardware experiment which was a prototype Automated Cultivation System (ACS) (Mohd Helmy Hashim, 2015).

This collaboration and achievement showed that Malaysia had some preliminary experience in collaboration in food and agricultural research in space. To align with the current international space exploration theme, it was imperative that Malaysia and the National Space Agency (ANGKASA) also focused on ground-based research to develop Malaysian or ASEAN food for a long-duration space mission.

IV. CURRENT SPACE TECHNOLOGY FOR FOOD PRODUCTION AND PROCESSING

Sustainable food production for a long-duration space mission is currently one of the major focuses for space science research. Many space agencies had organized specific groups or departments that focused solely on long-duration food production in space (Wheeler, 2017). The subsequent agricultural and food processing technology discussed shortly would be of major interest for researchers to develop our own national research on food production during a long-duration space mission.

At the ISS, “Veggie”; vegetable production system (VEG-01) is one of the current technologies that has been developed and validated for planting vegetables for food in space. The timeframe from designing to prototype and finally validation in ISS took around 10 years when Astronaut Steve Swanson finally harvested the space lettuce on June 10th, 2014 (Massa Gioia *et al.*, 2017; Stutte, Wheeler, Morrow, & Newsham, 2004).

The Veggie unit consisted of three main subsystems, a LED light cap (imitating sunlight for photosynthesis), a bellows enclosure (for shoot growth) and a root mat with a water reservoir underneath. The portable vegetable hardware had been tested and was able to grow various small salad vegetables on earth before it was sent to the ISS (Massa *et al.*, 2013).

The VEG-01 in ISS was tested to grow two crops; red romaine lettuce (*Lactucasativa* cv. ‘Outredgeous’) on two units of VEG-01 (VEG-01A and VEG-01B) and zinnia (*Zinnia hybrida* cv. ‘Profusion’) on VEG-01C. The test was a success and the data and samples of the vegetables were sent back to earth for safety analysis (they successfully passed food safety tests) and further improvements were made (Massa Gioia *et al.*, 2017).

Besides growing vegetables in space, food processing capability was also required for a long-duration space mission. However, common food processing (such as heating and rehydration) had already been installed in ISS. More complex food processing capabilities such as fermenting would be ideal for producing more types of food for a long-duration space mission.

The PAO S. P. Korolev Rocket and Space Corporation “Energia”; one of the companies that was in charge of the Russian manned spaceflight program had developed a kit for making probiotic yogurt onboard ISS. The experiment was named the Probiovit Experiment and one of its objectives was to determine the feasibility of making probiotic yogurts in space in order to maintain cosmonaut health for a long-duration space mission ("Probiovit Experiment ", 2013).

The method of fermentation in the Probiovit experiment was by inoculating “seeds” containing probiotic strains into powdered freeze-dried drinking milk. The powdered milk would be rehydrated and fermented into a fermented milk product ("Probiovit Experiment", 2013). The Probiovit experiments started in 2013 but there was a delay in conducting the experiments due to a failure to deliver one of the Probiovit kit payloads in 2016 (Zak, 2016). In 2017, the experiment was still ongoing in ISS (Keeter, 2017).

V. POSSIBLE MALAYSIAN AND ASEAN CONTRIBUTIONS TO LONG-DURATION SPACE NUTRITION

The current food production research for a long-duration space mission is generally based on global population diets, which are usually based on western food preferences. In order for Malaysia to become a more active member in future space ventures; it is imperative that Malaysia contributes Malaysian and ASEAN food culture to the space venture. In doing so, Malaysia could also become a medium for other ASEAN countries to contribute knowledge and ideas for the space food (Noichim, 2008).

Another advantage of Malaysia and ASEAN is our bioresources. It is possible to make new types of food by using these bioresources. An uncommon bioresource could become the food for space exploration. This perspective is imperative because such a perspective is also being utilized in research to solve the current global food shortage. In doing so, some scientists had developed cultured meat and other scientists had also introduced the idea of insect farming as a meat alternative to tackle the global food shortage (Alexander *et al.*, 2017). In this context, producing new food using alternative resources could contribute to developing a strategy for long-duration space nutrition.

Our food culture is considered “exotic” from the western perspective. But when the knowledge of our food culture was studied, the whole body of science gained critical insights, especially in terms of ingredients, fermentation technology and health benefits (Astuti, 2015; Marina & Nurul Azizah, 2014). However, this will only happen if we took the effort to catalogue and disseminate our ideas to the major space exploration players (Kwon, 2017). The following are two suggestions for food production in long-duration space mission based on Malaysian and ASEAN resources and food culture.

One of Malaysia’s strength is our palm oil bioresource. The Malaysian Palm oil board (MPOB) is the governing agency for the management of the palm oil bioresources in Malaysia. This includes research on diversifying palm oil products. One of the palm oil products is Palm oil milk which is sold and marketed as a healthier coconut milk replacement (Zaida Zainal, Mohd Suria Affandi Yusoff, Noor Lida Habi, Muhammad Nor Omar, & Burhanuddin Abd Salam, 1997).

The palm oil milk is a Malaysian bioresource and it has the potential to become a food resource during a space mission. Due to its milk-like appearance and texture, palm oil milk had been utilized in a study to produce palm oil milk yogurt (Hadi Akbar Dahlan, Abdullah Sani, & Dahlan, 2017). The palm oil milk yogurt’s nutritional content should be able to support the macronutrient nutritional requirements of humans in space as shown in Table 1 (Hadi Akbar Dahlan, 2017).

Table 1. Comparison of daily nutritional requirements in space with the nutritional content of tempeh and palm oil milk yogurt.

Nutrient	Requirement in space** per day	Tempeh per 100g	Palm oil milk yogurt per 100g
Energy*	7920 kJ	1971.2kJ/100g	2274kJ/100g
Protein	55 – 70 g	37.10g	2.35g
Carbohydrate	233 g	37.68g	46.9g
Lipid	64 – 75 g	19.41g	29.26g
Moisture	2000 ml	10.09 ml	15.1 ml

*The individual energy requirement of an astronaut/cosmonaut was calculated with the WHO equation. Therefore, there was no average value since each astronaut/cosmonaut had his own energy requirement. However, the average percentage of protein, carbohydrate and lipid of humans in space had been published and were used in this table using a replacement value of energy. The replacement value of energy shown here was based on the Daily average energy requirement for men aged 18 to 30 years old with a mean weight of 80 kg (FAO/WHO/UNU, 2004).

**This table excluded the nutrient requirement of micronutrients due to limited information of other micronutrients in both tempeh (Astuti, 2015) and palm oil milk yogurt (Hadi Akbar Dahlan, 2017).

The method to process the palm oil milk yogurt could be done in a similar process as described in the Probiovit experiment. This was because the palm oil milk yogurt was inoculated with the probiotic *Lactobacillus* strain (Hadi Akbar Dahlan et al., 2017), similar to the probiotic seed used in the Probiovit experiment. The palm oil milk could be brought to space in a powdered freeze-dried form. A possible strategy for producing palm oil milk yogurt in space is described in Figure 2.

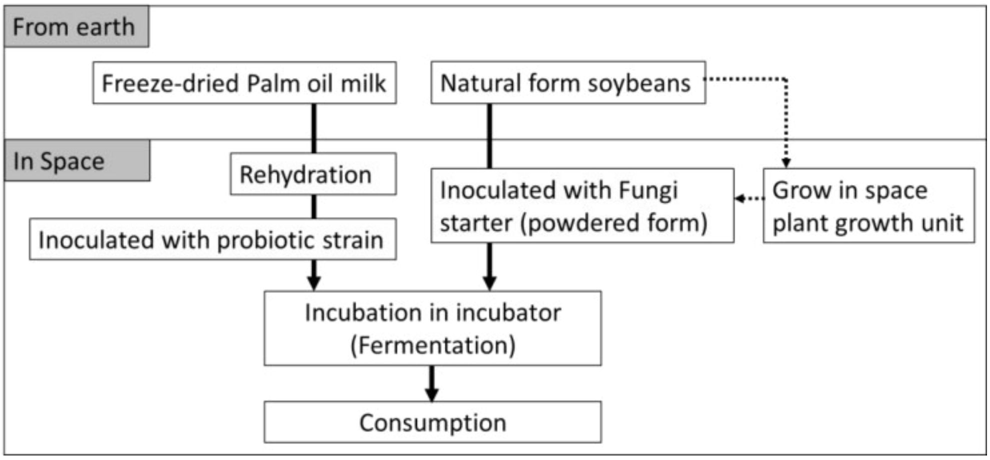


Figure 2. Strategy to produce palm oil milk yogurt and tempeh in space

Palm oil milk could be a replacement for dairy milk due to possible long-duration health effects in space. Recently, NASA found that astronauts contracted ophthalmic syndrome after a space mission (Zwart *et al.*, 2015). Although the reason was still unclear, they hypothesized that space conditions had affected the subarachnoid space in the brain which could lead to a possible polymorphism that affected astronauts' vision (Zwart *et al.*, 2017). From this perspective, it was possible that lactose intolerance might also occur due to space-condition induced polymorphism. This was because sudden lactose intolerance status could also occur due to polymorphisms (Ponte *et al.*, 2016). As a method of the prevention for sudden lactose intolerance in space, Malaysia can suggest palm oil milk as replacement milk in space missions.

Aside from palm oil milk, tempeh can also become a food for a long-duration space mission. Tempeh is a mycelium coated soybean that had undergone solid-state fermentation with *Rhizopus* sp. Tempeh originates from Indonesia, but it is popular globally due to its complete amino acid nutrient as well as its meat-like texture. It is a low-cost meat substitute not just for the poor, but also for the vegetarian community (Nout & Kiers, 2005). Due to its simple production requirements and nutritive value, tempeh can also become a source of protein for a long-duration space mission.

Tempeh is made by inoculating *Rhizopus* sp. starter into dried soybeans or other types of beans. The commercial *Rhizopus* sp. tempeh starter is safe to be consumed and only require an incubator to start the fermentation. The incubating temperature of making tempeh is between 28°C to 35°C for 24 to 48 hours. The nutritive value of tempeh will increase due to the fermentation. The increase of amino acid content and variety from tempeh comes from the proteolytic activity of the *Rhizopus* sp. (Bujang & Taib, 2014).

The method to produce tempeh in space can be done by storing both components (the soybean and the *Rhizopus* sp. starter) in a single pouch separately. Figure 2 illustrates the possible strategy to bring tempeh to space. Processing tempeh for consumption can be easily done in space using microwave cooking. Tempeh can also support the macronutrient requirement of humans especially in terms of protein requirement in space as shown in Table 1 (Astuti, 2015).

As a summary, Figure 3 shows the possible Malaysian contributions to long-duration space nutrition. Malaysia can contribute by becoming a Medium for ASEAN to contribute local knowledge & strategy to space food. Introducing Tempeh is an example of a contribution in this category. Another possible contribution is by developing new and sustainable food types using local bioresources. Palm oil milk yogurt discussed in this section is an example for this category.

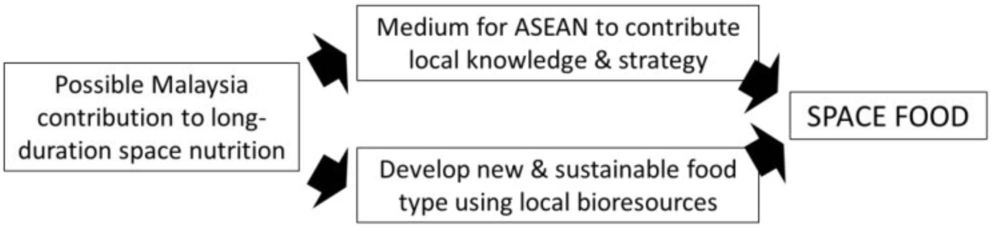


Figure 3. Possible Malaysian contributions to long-duration space nutrition

VI. LIMITATION AND CHALLENGES

Soybean and freeze-dried palm oil milk can be brought to space in huge amounts by volume. Although both requires a starter (starter culture of bacteria or fungi), the food production can still continue in a long-duration space mission with the back slopping method. However, further research should be pursued especially on the efficacy of the back slopping method in producing these foods under microgravity conditions.

Soybean crops had been tested to be able to grow in space, but the experiment was done with an earlier plant growth unit (Advanced Astroculture plant growth unit). One of the major findings from the experiment was that managing soybean crops was labour intensive (Wheeler & Sager, 2006). Thus, it is recommended that VEG-01 or a future plant growth unit should be equipped with automation to manage and harvest the crops in space.

Tempeh production and soybean crops will produce dust and debris in space. Future studies should also focus on cleaning the environment inside a space station when producing tempeh or growing soybean crops. Palm oil milk yogurt health effects should also be further investigated. The non-dairy yogurt has high-fat content which could lead to increased blood lipid content and possible various detrimental health effects during a long-duration space mission. This was because cosmic radiation had been shown to hasten the formation of atherosclerosis in mice and it was possible that this effect applied to humans as well (White *et al.*, 2015).

VII. CONCLUSION

This paper summarized the need for space food and nutrition research as well as the current food production system in space. Malaysia, as one of the space actors in the global space exploration effort, should also contribute in this field since our food culture is unique and could provide some new insights for plans to develop food for a long-duration space mission. The objective of this paper was to introduce possible Malaysian contributions in the field of space food for a long-duration space mission. The possible Malaysian solutions described in this paper are Palm oil milk yogurt and Tempeh. Both foods should be able to support the human nutritional requirements and are feasible to be brought and sustained in space using the current space technology. Palm oil milk yogurt is a good replacement for dairy milk and it can also become an alternative ingredient when an incident of lactose intolerance occurs during a space mission. Tempeh is a good protein source and can be developed further to become a sustainable source of food a during long-duration space mission. However, further studies should be conducted especially in terms of a continuous production strategy for tempeh and the health effects of palm oil milk yogurt on humans in space.

VIII. REFERENCES

[1] Adham Shadan 2008, *10 October 2008 Memori beraya di angkasa*, Kosmo, retrieved from http://ww1.kosmo.com.my/kosmo/content.asp?y=2008&dt=1010&pub=Kosmo&sec=Rencana_Utama&pg=ru_01.htm.

[2] Alexander, P, Brown, C, Arneth, A, Dias, C, Finnigan, J, Moran, D, & Rounsevell, MDA 2017, *Could consumption of insects, cultured meat or imitation meat reduce global agricultural land use?*, Global Food Security. doi:https://doi.org/10.1016/j.gfs.2017.04.001.

[3] ANGKASA MSM Project "FIS EXPERIMENT" 2005, *Science research on ISS RUSSIAN segment, Human Life Research*, retrieved from https://www.energia.ru/eng/iss/researches/medic-85.html

[4] Ansdell, M, Ehrenfreund, P, & McKay, C 2011, 'Stepping stones toward global space exploration', *Acta Astronautica*, vol. 68, no. 11-12, pp. 2098-2113. doi:10.1016/j.actaastro.2010.10.025.

[5] Astuti, M 2015, *Health benefits of tempe*, Health Benefits of Fermented Foods, pp. 371-394.

[6] Azusa Ushio 2017, *Food companies in space race to beef up menu for astronauts*, retrieved from http://www.asahi.com/ajw/articles/AJ201712040001.html.

[7] Bujang, A, & Taib, NA 2014, 'Changes on amino acids content in soybean, garbanzo bean and groundnut during pre-treatments and tempe making', *Sains Malaysiana*, vol. 43, no. 4, pp. 551-557.

[8] Casaburri, AA, & Gardner, CA 1999, *Space Food and Nutrition: An Educator's Guide with Activities in Science and Mathematics*, (EG-1999-02-115-HQ), Washington: NASA.

[9] Cooper, M, Douglas, G, & Perchonok, M 2011, 'Developing the NASA food system for long-duration missions', *J Food Sci*, vol. 76, no. 2, pp. R40-48. doi:10.1111/j.1750-3841.2010.01982.x.

[10] Doarn, CR, Williams, RS, Schneider, VS, & Polk, JD 2016, 'Principles of Crew Health Monitoring and Care', in *Space Physiology and Medicine: From Evidence to Practice*, eds New York, NY: Springer New York, pp. 393-421.

[11] FAO/WHO/UNU 2004, *Human energy requirements*, Report of a Joint FAO/WHO/UNU Expert Consultation, Rome, 17-24 October 2001.

[12] Hadi Akbar Dahlan 2017, 'Perbandingan ciri-ciri fizikal, proksimat dan tumbesaran kultur pemula yogurt bukan tenusu (Comparison of non dairy yogurt physical characteristic, proximate and starter culture growth)', Master thesis, Universiti Kebangsaan Malaysia, Malaysia.

[13] Hadi Akbar Dahlan, Abdullah Sani, N, & Dahlan, I 2017, 'Logistic-like Growth Model of *Lactobacillus acidophilus*, *Lactobacillus delbrueckii* subsp. bulgaricus and *Streptococcus thermophilus* in Palm Oil Santan', *Japan Journal of Food Engineering*, vol. 18, no. 3, pp. 155-159. doi:10.11301/jsfe.16474.

[14] Jen Rae Wang 2017, *New Space Policy Directive Calls for Human Expansion Across Solar System*, retrieved from https://www.nasa.gov/pressrelease/new-space-policy-directive-calls-for-human-expansion-across-solarsystem.

[15] Keeter., B 2017, *ISS Daily Summary Report – 8/24/2017*, retrieved from https://blogs.nasa.gov/stationreport/2017/08/24/iss-daily-summary-report-

8242017/.

[16] Kwon, DY 2017, 'Why data creation is important for ethnic foods', *Journal of Ethnic Foods*, vol. 4, no. 4, pp. 211-212. doi:10.1016/j.jef.2017.11.004.

[17] Lane, HW, & Feeback, DL 2002, 'History of nutrition in space flight: Overview', *Nutrition*, vol. 18, no. 10, pp. 797-804. doi:https://doi.org/10.1016/S0899-9007(02)00946-2.

[18] Lane, HW, Smith, SM, & Kloeris, VL 2016, 'Metabolism and Nutrition', in Space Physiology and Medicine: From Evidence to Practice, Eds New York, NY: Springer New York, pp. 307-321.

[19] Launius, RD 2010, 'An unintended consequence of the IGY: Eisenhower, Sputnik, the Founding of NASA', *Acta Astronautica*, vol. 67, no. 1-2, pp. 254-263. doi:10.1016/j.actaastro.2009.10.019.

[20] Marina, AM, & Nurul Azizah, S 2014, 'Use of Coconut Versus Dairy Milk Products in Malaysian Dishes: Comparison of Nutritional Composition and Sensory Evaluation', *Journal of Food and Nutrition Research*, vol. 2, no. 4, pp. 204-208. doi:10.12691/jfnr-2-4-12.

[21] Massa, GD, Newsham, G, Hummerick, ME, Caro, JL, Stutte, GW, Morrow, RC, & Wheeler, RM 2013, 'Preliminary species and media selection for the Veggie space hardware', *Gravitational and Space Research*, vol. 1, no. 1.

[22] Massa Gioia, D, Dufour Nicole, F, Carver John, A, Hummerick Mary, E, Wheeler Raymond, M, Morrow Robert, C, & Smith Trent, M 2017, *VEG-01: Veggie Hardware Validation Testing on the International Space Station Open Agriculture*, vol. 2, pp. 33.

[23] Mateo Sanguino, Tomás de J 2017, '50 years of rovers for planetary exploration: A retrospective review for future directions', *Robotics and Autonomous Systems*, vol. 94, pp. 172-185. doi:10.1016/j.robot.2017.04.020.

[24] Mohd Helmy Hashim 2015, *Malaysia KIBO Activity 2015*, retrieved from http://iss.jaxa.jp/en/kuoa/news/pdf/04_KIBO_Meeting_APRSAF-22.pdf

[25] Noichim, C 2008, 'Promoting ASEAN space cooperation', *Space Policy*, vol. 24, no. 1, pp. 10-12. doi:10.1016/j.spacepol.2007.11.008.

[26] Nout, MJ, & Kiers, JL 2005, 'Tempe fermentation, innovation and functionality: Update into the third millenium', *Journal of applied microbiology*, vol. 98, pp. 789-805. doi:10.1111/j.1365-2672.2004.02471.x.

[27] Ponte, PR, Medeiros, PH, Havt, A, Caetano, JA, Cid, DA, Prata, MM., ... Lima, AA 2016, 'Clinical evaluation, biochemistry and genetic polymorphism analysis for the diagnosis of lactose intolerance in a population from northeastern Brazil', *Clinics*, vol. 70, no. 2, pp. 82-89. doi:10.6061/clinics/2016(02)06.

[28] Probiovit Experiment 2013, *Space biology and biotechnology*, Retrieved from https://www.energia.ru/en/iss/researches/biology/28.html.

[29] Ross-Nazzal, J 2007, *From farm to fork: How space food standards impacted the food industry and changed food safety standards*, Societal Impact of Spaceflight, NASA, Washington, DC, 219-236.

[30] Smith, SM, & Zwart, SR 2008, 'Nutrition issues for space exploration', *Acta Astronautica*, vol. 63, no. 5-6, pp. 609-613. doi:10.1016/j.actaastro.2008.04.010.

[31] 2012, *Space Seeds for Asian Future Program (AstroSeed)*, retrieved from http://iss.jaxa.jp/en/kuoa/pdf/ssaf_2012.pdf

[32] Stutte, G, Wheeler, R, Morrow, R, & Newsham, G 2004, 'Concept for Sustained Plant Production on ISS Using VEGGIE Capillary Mat Rooting System', in *41st International Conference on Environmental Systems*.

[33] Vodovotz, Y, Bourland, C, Kloeris, V, Lane, H, & Smith, SM 1999, *Critical path plan for food and nutrition research required for planetary exploration missions (0148-7191)*.

[34] Wheeler, R, & Sager, J 2006, *Crop production for advanced life support systems*.

[35] Wheeler, RM 2017, 'Agriculture for Space: People and Places Paving the Way', *Open Agriculture*, vol. 2, no. 1. doi:10.1515/opag-2017-0002.

[36] White, CR, Yu, T, Gupta, K, Babitz, SK, Black, LL, Kabarowski, JH, & Kucik, DF 2015, 'Early changes in vascular reactivity in response to 56Fe irradiation in ApoE−/− mice', *Acta Astronautica*, vol. 108, pp. 40-45. doi:https://doi.org/10.1016/j.actaastro. 2014.10.010.

[37] Zaida Zainal, Mohd Suria Affandi Yusoff, Noor Lida Habi, Muhammad Nor Omar, & Burhanuddin Abd Salam 1997, *Production and caharacterization of Palm-based Santan Powder*, PORIM Information Series, PORIM TT No.45.

[38] Zak., A 2016, *Progress MS-04 fails to reach orbit*, retrieved from http://www.russianspaceweb.com/progress-ms-04.html.

[39] Zwart, SR, Gibson, CR, Gregory, JF, Mader, TH, Stover, PJ, Zeisel, SH, & Smith, SM 2017, 'Astronaut ophthalmic syndrome', *The FASEB Journal*, vol. 31, no. 9, 3746-3756.

[40] Zwart, SR, Gregory, JF, Zeisel, SH, Gibson, CR, Mader, TH, Kinchen, JM, ... Smith, SM 2015, 'Genotype, B-vitamin status, and androgens affect spaceflight-induced ophthalmic changes', *The FASEB Journal*, vol. 30, no. 1, pp. 141-148.

Space Science Education in Malaysia: A Review Based on Performance Improvement Framework in Complex Systems

Zainuddin, M.Z. [1], Mohamad, N.S.[2*], Assilam, M.F.[3], Mastor, M.Z.S.[4], Hashim, M.H.[5] and Radzi, Z.[5]

[1]*Department of Physics, Faculty of Science, University of Malaya*

[2]*Pusat PERMATApintar® Negara, Universiti Kebangsaan Malaysia*

[3]*Perdana School of Science, Technology and Innovation Policy, UTM*

[4]*Planetarium Negara, Ministry of Energy, Science, Technology, Environment and Climate Change (MESTECC)*

[5]*National Space Agency of Malaysia (ANGKASA), Ministry of Energy, Science, Technology, Environment and Climate Change (MESTECC)*

This paper focused on reviewing space science education in Malaysia based on the performance improvement framework in complex systems. Therefore, not all articles were reviewed but only randomly selected ones to find the pattern by analyzing activities commenced and compared to the performance improvement framework in complex systems. The data were then analyzed by using the continuous comparison method. The findings from this study implied that to improve space science education for the younger generation, it was important to view the direction of education and to understand in depth the complex systems of education as a whole. The direction of the younger generation's education system should enable them to solve complex problems efficiently. Space science education could be set as an example of how to move forward in this direction. This is due to the nature of space science education itself which is multidisciplinary. Transdisciplinary methods could be used in space science education and might act as a case of an integrated STEM model for the Malaysian Education System. Other implications of the transdisciplinary method implementation are exposure to systems thinking among scientists, teachers, educators, administrators, authorities, students and the public. The changes will take effect only if more people are aware of the importance of systems thinking as the basis in life so as to be able to understand that all the elements are interconnected in the complex systems as a whole.

Keywords: Space science education; complex systems; systems thinking; performance improvement; transdisciplinary

I. INTRODUCTION

Students should be prepared to confront many issues or challenges such as climate change, natural hazards, ozone, mineral, water depletion and others that urgently need multi-discipline knowledge. Recently, a declaration emphasized on the importance of space science education in future scientific progress and reinforcing the link between the scientific

*Corresponding author's e-mail: sakinah@ukm.edu.my

community, national governments, and the public to contribute to sustainable development of society through scientific awareness and actions related to challenging problems in society (IUGG, 2015).The declaration was adopted on 1 December 2015 by the participants of the International Conference "Future Earth and Space Science and Education" held in Italy on 2-6 November 2015. Among the statements in this declaration is an urgent need to improve the education of the young generation of tomorrow, not only through innovative teaching and learning but also through facilities and research opportunities for all young people so that the best of them can help to solve some of the world's most complex problems.

Therefore, Malaysia needs to review her education system from time to time and also observe how space science education and the relevant space science activities progress so that she can find a coherent framework for all agencies on space science and education in Malaysia to work upon. Thus, space science education activities were reviewed via a performance improvement framework (Mohamad, 2012) and discussed for further recommendations.

II. PERFORMANCE IMPROVEMENT FRAMEWORK IN COMPLEX SYSTEMS

One way to approach fundamental questions about education is from the perspective of complex systems. In the past two decades, this perspective had been advocated more and more in the field of education as an approach to better understand the processes of learning and teaching (Stamovlasis, 2016). However, most research on teaching and learning involved only one dimension or component, and thus issues in education could not be entirely solved (Rueda, 2011). Performance improvement should be seen as a whole and contextually (Brethower, 2006) not compartmentalized in order to understand the whole process in education fully. By this approach, efforts in performance improvement could be implemented effectively (Thornton *et al.*, 2004)

As education itself is complex and non-linear, the performance improvement system model in the systems of teaching and learning (Mohamad, 2012) was used. This complex model comprises of five components; orientation, process, support, feedback and output. Hence understanding the complex systems became a priority in all educational reform towards performance improvement. This kind of study in complex systems that required systems thinking towards performance improvement was hopefully beneficial to find the real underlying cause so that we could find the best recommendations for space science education.

III. OBSERVATORIES AS CATALYST FOR THE DEVELOPMENT OF SPACE SCIENCE EDUCATION IN MALAYSIA

In Malaysia, for now, there are ten observatories. This number might change because there are many new observatories built in schools out of interest in observing the sky via co-curricular activities. Some of these observatories are situated at Universiti Sultan Zainal Abidin (UniSZA) in Terengganu, University of Malaya, PERMATApintar National gifted school in Universiti Kebangsaan Malaysia (UKM), Sheikh Tahir Falak Centre in Penang, The National Planetarium Observatory in Kuala Lumpur, Al-Khawarizmi Falak Complex in Malacca, The Al-biruni Observatory in Sabah, Langkawi National Observatory, the Selangor Observatory and the Teluk Kemang Baitulhilal Complex. Through the institutionalization of these observatories, studies of astronomy are done widely and shared with the public (Mohd Hafiz Safiai *et al.*, 2014). The National Planetarium Observatory was officially opened by the fourth Prime Minister of Malaysia, Tun Dr. Mahathir Mohamad on the 7th of February, 1994.

The stellar and solar observatory complex in the University of Malaya was completed in 2006. It has two smaller observatories named Al-Najam and As-Shams. The purposes of these two small observatories are to educate and train students in the field of astronomy and astrophysics. The focus here is training for astrometry, photometry and spectroscopy techniques in the field of astronomy and astrophysics by observing celestial objects including the sun. The complex is operated by the Space Physics research group in the Department of Physics, Faculty of Science, at the University of Malaya. The Langkawi National Observatory (LNO) was built in 2006, and it is now known internationally for space science research and education. To sum up, the existence of these observatories is the catalyst for the development of space science education in Malaysia. Based on the performance improvement model in the systems of learning and teaching (Mohamad, 2012), these observatories are items under the component of support. However, there are issues on the high cost of observatory maintenance and the risk of sustainability in securing the limited numbers of skilled workers. These issues are items under the component of feedback.

IV. SPACE SCIENCE CURRICULUM DEVELOPMENT AND IMPLEMENTATION IN MALAYSIA

At the lower secondary school, the science curriculum in Malaysia is organized into six content areas and one of these is astronomy and space exploration. The content topics are solar, stars, galaxies and space exploration. The solar topic describes the characteristics and structures of the sun and how its energy affects the earth. For the topic of stars and galaxies in the universe, the students are asked to compare the stars based on certain characteristics; describe the formation and death of stars; describe types of galaxies; identify the position of the Solar System in the universe, and appreciate the uniqueness, order, beauty and harmony in the universe as a sign of the glory of God. Furthermore, for the topic of space exploration, the students are exposed to developments in the fields of astronomy and space exploration. The objectives for this topic are (i) Describe the developments in the field of astronomy and space exploration, (ii) Explain the application of technology to space exploration and astronomy, giving examples and (iii) Explain the need to continue space exploration (Mullis, 2016).

Most teachers did not major in space science, and hence they might not deliver up to standard and they are likely to lose interest if there is no active support in training (Fraknoi, 2007). Without this expertise in Space Science, teachers might fail to inculcate a good understanding of space science in their students.

There are many learning modules on space science education, and also space application education developed for either primary or secondary students and teachers or higher education students. For example, the division in charge of teacher education in the Ministry of Education collaborated with the National Space Agency to produce a space science module in conjunction with the International Year of Astronomy (IYA 2009). The purpose of this module is to supplement and enrich learning about concepts in astronomy. It also aims to create awareness and appreciation for the importance and contributions of astronomy in daily lives. The main purpose of this module is to assists and support teachers in primary schools in delivering the existing astronomy curriculum in Malaysia. This module consists of seven main topics followed by a number of subtopics. Each subtopic has a number of activities with the following features: learning outcomes, introduction, materials, procedures, resources and teacher's notes which would be highlighted. There are seven topics covering the universe, galaxies, stars and constellation, solar system, the Earth, Moon and the Sun, astronomical instrumentation and methods, and space exploration. Thirteen lecturers from the Ministry of Education, two lecturers from the University, and two officers from the National Space Agency were assigned to do each topic (Mohd Zambri, 2013). The teaching module was completed and adopted by the Ministry of Education of Malaysia to be used in teaching astronomy to future teachers that enrolled in the Institute of Teacher Education (IPG).

Many other agencies or universities were also involved in developing modules in space science education. For instance, the National Space Agency (NSA) of Malaysia, Malaysia Centre for Remote Sensing (MACRES) and universities jointly organized the development of a space science module and awareness program for the public (Zambri, 2007). The Education Ground Receiving System module (EGRS) introduced broader spectrums of space science education content to primary and secondary schools and tertiary level students who would become future innovative Malaysians. EGRS is proposed to be introduced at the secondary level, as the technology requires basic knowledge in multidiscipline such as physics, mathematics and related science subjects. However, this did not stop the primary scholars at a much younger age from enjoying the system, but with the right guidance from teachers. To create interest in innovation and the scientific environment at the school level, the EGRS introduced the gizmo in kits form to provide a hands-on experience for teachers and students to setup some parts of the receiving system of which the antenna required minimal supervision for installation by the developer. The students learn the system and automatically gain interest to learn other space technologies better. The EGRS learning kits are cheap and affordable to all (Norhan *et al.*, 2008).

The UKM-SID teaching module was developed at UKM with the collaboration of Stanford University under the ISWI program. This module is capable of detecting solar flares using the VLF technique. This module has been deployed to selected high schools in Selangor to expose and educate them on space science. It is hoped that the skills and knowledge gained from the project will cultivate students' interest in space science (Mardina Abdullah *et al.*, 2013).

Dr. Norilmi Amilia Ismail and team also developed a learning module known as CanSat Kit for Education. There were also Rocketry Workshops throughout Malaysia. Mohd Harridonbin Mohamed Suffian along with members of the Astronautical Association of Malaysia (AAM) organized Advanced Rocketry Workshops throughout Malaysia in the year 2014. The workshops taught high school students about solid fuel and the aerodynamics of rockets. At the end of the workshops, students got the opportunity to launch their own rockets (SGAC, 2015). To spread knowledge of Solid Fuel during the World Space Week 2014, the National Planetarium of Malaysia in collaboration with the Astronautical Association of Malaysia organized a Solid Fuel Workshop that taught high school students the composition of Solid Fuel and its usage in the field of Rocket Science. Mohd Harridon bin Mohamed Suffian taught the students how to measure the thrust produced by the Solid Fuel (SGAC, 2015).

A. Astronaut Program on the International Space Station

The interest of these students for the astronomy courses is because of the various programs related to the astronomy phenomena organized by the National Space Agency. One such program was the Malaysian astronaut program. The Malaysian government embarked on the astronaut program with the first Malaysian astronaut on board the International Space Station (ISS), Dr. Sheikh Muszaphar Shukor, on 12th October 2007. Malaysia had successfully sent an astronaut to the International Space Station to conduct scientific experiments in the microgravity environment. This program rekindled the interest and enthusiasm of the Malaysian society regardless of age (Mohd Zambri, 2013).

Space Seeds for Asian Future (SSAF) was one of the educational programs of the KIBO-ABC Initiative, which was a sample return mission of plant seeds to and from JEM. The participants were provided with the opportunities to grow the plant seeds returned from JEM. More than one thousand students from Indonesia, Malaysia, Thailand, and Vietnam participated in the first SSAF in 2010 and 2011. The second SSAF was implemented in 2013 using AZUKI, a popular bean in Asia. Astronaut Wakata supported the experiment in orbit. The students from Australia, Indonesia, Japan, Malaysia, New Zealand, Thailand, and Vietnam conducted the experiments on earth and issued their reports on their results (Kikuchi *et al.*, 2016).The Malaysia space seed program (2010-2012) was a combination of research and education programs between MARDI, JAXA, ANGKASA, MOE and the Department of Agriculture, Malaysia. The objectives were to promote microgravity science – space awareness; b) to develop student interest and skill in scientific space experiments and research; and c) to compare, analyse and come up with a hypothesis about the growth of microgravity environment – exposed seeds compared to earth – grown seeds (Mhd Fairos Asillam, 2011).

The Malaysia Education Programme, in commemoration of the national astronaut program (Mhd Fairos Asillam, 2011), decided to design and implement the education program for microgravity. A coordinating committee was formed by ANGKASA, MOE, and UKM. The program was meant to be used by teachers as members of the core group who understood the concepts on microgravity for teaching in classrooms and conducting live video sessions with the Angkasawan in the ISS. The preparation of the module took three stages: i) exploring possible types of experiments and demonstrations in ISS, ii) testing of experiments and documenting the plan for the lesson and iii) completing and refining the educational module in ISS. The main topics of the module represented basic concepts in physics: i) twisted orbital platform (gasing), ii) fluid behaviour and iii) Newton's law.

Among other activities in the Malaysian Microgravity Program were the National Astronaut Program in 2007 and the Post-national Astronaut program that ran from 2008 till 2011. Among the activities for the Post-national Astronaut program in Malaysia were the utilization of high quality protein crystal growth experiments on board the Japanese Experimental Module "Kibo" (2009-2012), biosatellite program (2013-2015), MARS500 (2009-2012), Space Science Educational Portal (2011), Space Science Educational Module (2009), dialogue with parliamentary members on Microgravity Sciences (2010), Asian Students' Parabolic Flight (2007-2011), Malaysian Space Seed Program (2010-2012) and Microgravity Workshop 1 (2008) & II (2009) (Mhd Fairos Asillam, 2011). The motivation for Malaysia's involvement in microgravity sciences is to build local capacity, basic infrastructure, spacelab, equipment, research mechanisms, and identify national priority needs and development goals as well as estimate the national readiness.

However, space science is not taught officially in schools as a subject but as a section in the science curriculum either in primary or secondary schools. Therefore, space science education is not emphasized as a subject in the Malaysian education system. This is also reflected in the tertiary education either at the diploma or degree level. There are neither colleges nor universities that offer astronomy courses for a degree in astronomy or multidiscipline courses in space science. However, the Physics Department from the Faculty of Science do offer astronomy courses as elective subjects (Mohd Zambri, 2013).

Malaysia is not only interested in the astronaut program in space but, also in microsatellites. The Malaysia Microsatellite Program was first launched by the Prime Minister YAB Tun Dr. Mahatihir Mohamad on 13 January 2004 (Angkasa, 2004). Cabinet approved the microsatellite project in partnership with Surrey Satellite Technology Limited (SSTL) from the UK. In 1997, Astronautic Technolgy (M) Sdn Bhd (known then as Parallel Knowledge) was established as a Ministry of Finance Incorporated Company to implement the microsatellite program. The launch of the Malaysian Experiment on the SUNSAT satellite by the University of Stellenbosch, South Africa, collaborating with the National University of Malaysia (UKM) produced an experiment to test the performance of glassy carbon from local palm tree frond and superconducting material in the space environment on board SUNSAT which was launched in October 1997. TiungSAT-1 was officially named by the cabinet on 19 February 1997. With miniaturization of technology and new trends for practical space science education, new opportunities arise for students and universities to become involved with practical space education.

B. Public Outreach

The National Planetarium also has an interactive exhibition gallery to give greater exposure and entertaining experiences to the public while they wait for the Planetarium shows to start. It is also in line with the initiative to enculture Science, Technology, Engineering and Mathematics (STEM) activities among the visitors. The National Planetarium is also providing outdoor exhibits within its compound including the ancient observatory monument park and a special picnic area. The National Planetarium is conducting regular star gazing activities including during any important astronomical phenomena or events. It also organizes planetarium talks, space-related seminars and workshops such as the Telescope Seminar in 1996 and 1998 and and many others in Malaysia. For example, ASTROcon in 2016 brought together professionals and amateurs from all walks of life on the theme of the convention. The scope of the convention was astronomical research, astronomical folklore, education and awareness, light pollution and archeoastronomy / astrotourism. The planetarium celebrates international events such as World Space Week during October every year. Furthermore, an outreach program is also organized throughout the country every year.

In the effort to enhance the participation of the nation in space education activities, a nationwide competition, the National Space Challenge for the Prime Minister's trophy, is organized for primary school students. The National Water Rocket Championship is organized for secondary school students. Malaysia is also participating in the Asia Pacific Regional Space Agency Forum (APRSAF) Water Rocket Competition organized yearly at the regional level. Furthermore, in the year 2003, the National Space Agency (NSA) introduced a pilot project for Rocket technology launching competition for secondary schools in Malaysia. This competition attracted more than 45 secondary schools in the Klang Valley. In 2013, the competition attracted more than 300 secondary schools in Malaysia (Mohd Zambri, 2013). Other competitions include the National level rocket technology competition (Angkasa, 2004).

C. Summary of Space Science Curriculum Development and Implementation

Only a few themes were highlighted in this section of the space science curriculum development and implementation. However, a few implications could be derived for improvement in space science development and implementation. Overall, there were many activities in the space education program for students, teachers and the public throughout the year either nationally or internationally. To have a long term effect of sustainable change, space science education should match the challenges faced by students. Therefore, a plan is needed for space science education in the Malaysian education system.

Offering an astronomy course as an elective subject is not effective for human capacity building. The academic space science program in Malaysia can be improved at all levels, especially in the universities. The authorities should find ways and means to help universities cope with the challenges and either maintain existing space science programs or create new related academic programs in specific disciplines and multidiscipline or interdisciplinary needs. Synergistic collaboration among amateurs as well as professional astronomers, scientists, college students, and teachers should become a priority. A lot of hard work needs to be done to encourage teamwork in developing hands-on astronomy or space science activity modules in the classroom. Over the years, it has been found that students are highly motivated when they are assigned responsibilities within a project with real impact (Avsar *et al.*, 2014). More incentives should also be given to professional societies, industry associations and educational association's joint undertakings with universities with regard to recruitment and curriculum development.

There is a need for improvement in early space science education among the younger generation especially those of the lower age either at the primary or at the secondary level. A significant factor in the declining Malaysian educational performance in the fields of science, technology, engineering and math (STEM) is the lack of qualified teachers. Thus, efforts to upgrade teachers' skills, educational backgrounds, and general capabilities must be of high priority. Many institutions have begun to address sustainability challenges through curricular and pedagogical innovations and significant changes to facilities and operations are needed (Evans, 2015).

Finally, the world of space will become increasingly interdisciplinary and the involvement of private/public partnerships will give rise to new educational and training needs. For space science activities such as the astronaut program in ISS, national and international space science competitions among others, more expertise from diverse disciplines are needed. These concerns are related to the implications mentioned before which are, support for higher education by maintaining existing or creating new space science programs, leveraging efforts on space science module development and improving space science programs in the primary or secondary level, especially by upgrading teachers' skills.

V. DISCUSSION

Therefore, a new paradigm should be embraced to improve space science education holistically. Students will also need to confront complex challenges in their future. Consequently, the students need a new direction in the Malaysian education system. Space science education could become an example on how to go about integrating all disciplines in STEM. Integration of disciplines within the curriculum is needed. We may redesign the curriculum either around a common theme or phenomenon. A transdisciplinary approach in education is required to educate future generations on how to deal with the complex problems of the world. Most of the complex scientific issues exist in the domain of multi scientific disciplines (Güvenen, 2016). The learning processes are becoming more complex, and students must, therefore, be offered possibilities to develop skills and competencies necessary to become self-directed life-long and not least interdisciplinary learners (Stentoft, 2017). According to Ertas (2013), a transdisciplinary approach in education will change paradigms and form new frontiers. Mohamad (2012) recommended that the application of systems thinking for all should be learned as early as possible in education. Furthermore, more creative ideas could be derived to improve the education system for the younger generation.

In a performance improvement framework, the component of orientation also has a big influence on other components directly or indirectly (Mohamad, 2012). For instance, teachers are prevented from implementing innovations in classroom teaching and learning that need more time because they are expected to achieve the target of high achievements among students. Therefore, all teachers practice examination-based orientation in the classroom. In short, there is a misalignment between the component of orientation in the systems of education and the components of activities/teaching and learning.

Therefore, the elements in the component of orientation need to be aligned with the process components in the systems of teaching and learning if long term changes in space science education are to take place. There is more evidence on the misalignment between the component of orientation and the component of process in teaching and learning from the national level to schools (Blackmore, 2004). Therefore, the right educational policies are needed to develop a conducive environment for the education system (Mangiante, 2011).

VI. CONCLUSION

Implementing changes is not easy because smaller systems are influenced by bigger systems. Thus, smaller systems cannot be changed unless all systems from small to big are systematically changed. Therefore, the component of orientation should be considered seriously because it directly influences other components in the systems of teaching and learning directly. In other words, all components in the systems of teaching and learning should be addressed simultaneously to ensure that efforts in performance improvement in space science education would eventually succeed.

Direction needs a shared vision or philosophy. Muhammad Abd Hadi Bunyamin & Finley (2016) found that the crucial thing is to revise the national science philosophy of Malaysia since the philosophy drives the whole direction for science education in the Malaysian context. A new philosophy is required which explicitly mentions STEM phrases. Whenever there is a shared vision or a national science philosophy, everyone has a target to achieve and this builds trust that encourages continued collaboration. For a long term vision, patience is an asset not least because interdisciplinary collaboration requires much time. Becoming familiar with a foreign terminology, preparing plans for radically new conceptions, and communicating with specialists from other fields are all likely to demand a greater amount of time and effort than disciplinary work (Evans, 2015). This future action in creating a shared vision is important to get a better view for policymakers to form a comprehensive STEM curriculum.

The paradigm shift is necessary from a simple to a more comprehensive framework in space science education. Therefore, an integrated education paradigm is called for the students of tomorrow, and this change of paradigm will cause implications on new ways of instructional design for teaching and learning, curriculum development, assessment, evaluation, teacher training and so forth. In other words, all these changes need an integrated instructional design consisting of various dimensions to meet the diverse needs in the systems of teaching and learning space science education. An integrated instructional design needs to comprise all dimensions mentioned in the systems of teaching and learning space science education. Among those which need to be considered are systems of knowledge taxonomy, systems of value and culture, systems of belief, systems of assessment and evaluation and so forth. A shared vision will encourage all agencies to work harmoniously to achieve new frontiers; a transdisciplinary approach in space science curriculum development and implementation.

VII. REFERENCES

[1] Angkasa 2004, *Sedekad angkasa 1994-2004*, Putrajaya: MESTECC.

[2] Avsar, C, Frese, W, Meschede, T, Brieß, K 2014, 'Developing a Planetary Rover with Students: Space Education at TU Berlin', *Journal of Automation Mobile Robotics and Intelligent Systems*, vol. 8, no. 1, pp. 20-29.

[3] Blackmore, J 2004, 'Leading as Emotional Management Work in High Risk Time: The Counterintuitive Impulses of Perfomativity and Passion', *School Leadership & Management*, vol. 24, no. 4, pp. 439-459.

[4] Brethower, DM 2006, 'Systemic Issues', in *Handbook of Human Performance Technology: Principles, Practices & Potential*, eds J.A. Pershing, San Francisco, CA: Pfeiffer, pp. 111-137.

[5] Ertas, A 2013, 'Integrating Transdisciplinary in Undergraduate Education', in *Transdisciplinary Theory & Practice*, eds ATLAS Publishing, 4, pp. 17-19.

[6] Evans, TL 2015, 'Transdisciplinary Collaborations for Sustainability Education: Institutional and Intragroup Challenges and Opportunities', *Policy Futures in Education*, vol. 13, no. 1, pp. 70-96. http://doi.org/10.1177/1478210314566731.

[7] Fraknoi, A 2007, 'Space Science Education in the United States: The Good, Bad, and the Ugly', in *Societal Impact of Spaceflight*, eds Washington DC: NASA Office of External Relations History Division, pp. 407 - 419.

[8] Güvenen, O 2016, 'Transdisciplinary Science Methodology as a Necessary Condition in Research and Education', *Transdisciplinary Journal of Engineering & Science*, vol. 7, pp. 69-78. http://doi.org/10.22545/2016/0008.

[9] International Union of Geodesy and Geophysics (IUGG) 2015, 'Declaration Future Earth and Space Science Education', *The IUGG Electric Journal*, vol. 15, no. 12, pp. 3-5.

[10] Ibrahim, IA, Safiai, MH, Jamsari, EA Ahmad, MY, Mohd Nor, AH, Mohd Nasir, B 2017, 'Observatories in Malaysia: Descendants of Islamic Civilization superiority', *International Journal of Civil Engineering and Technology*, vol. 8, no. 12, pp. 782-795.

[11] Kikuchi, K, Yamanaka, R & Yamaguchi, K 2016, 'JAXA's Educational Activities through JEM Utilization', *Int. J. Microgravity Sci. Appl.*, vol. 33, no. 2, pp. 330210(1-3).

[12] Krippendorff, K 2004, *Content anaysis: An introduction to its methodology*, CA, Sage Publications.

[13] Mangiante, EMS 2011, 'Teachers matter: Measures of Teacher Effectiveness in Low-Income Minority Schools', *Educ Asse Eval Acc*, vol. 23, no. 1, pp. 41-63.

[14] Mardina Abdullah, Badariah Bais, Alina Marie Hasbi, Rosadah Abd Majid, Baharudin Yatim, Mohd Aluddin Mohd Ali, Siti Aminah Bahari, Noridawaty Mat Daud, Mohd Hezri Mokhtar, Ahmad Faizal Mohd Zain & Mhd Fairos Asillam 2013, 'Development of UKM-SID teaching module for space science

education', *Procedia – Social and Behavioural Sciences*, vol. 102, pp. 80-85. https//doi.org/10.1016/j.sbspro.2013.10.716.

[15] Mhd Fairos Asillam 2011, 'Malaysia Education Program in Commemoration of National "Angkasawan" Program', in *United Nations/Malaysia expert meeting on Human Space Technology, 15 November 2011*, Putrajaya, Malaysia.

[16] Mohamad, NS 2012, 'Analisis Sistem Pengajaran dan Pembelajaran Sekolah Menengah daripada Perspekstif Teknologi Prestasi Manusia', Tesis PhD, Universiti Putra Malaysia.

[17] Mohd Hafiz Safiai, Ezad Azraai Jamsari & Ibnor Azli Ibrahim 2014, 'Malaysian Observatories and those of the Islamic Civilization era: General similarities', *Middle-East Journal of Scientific Research*, vol. 20, no. 12, pp. 2164-2171.

[18] Mohd Zambri, Z 2007, 'Perspective of Space Science Education and Awareness in Malaysia', in *Thai National Astronomy Meeting 2007, 22-24 March, 2007*, Nakorn Pathom. http://www.narit.or.th/tnam2007/paper/Zainuddin-Zambri.pdf.

[19] Mohd Zambri Zainuddin (Ed.) 2009, *Space Science Educational Module for Primary School (Teacher Training Version)*, Putrajaya, ANGKASA & BPG.

[20] Mohd Zambri, Z 2013, 'Astronomy Educational Module for primary school in Malaysia', in *The 11th Asian-Pacific Regional IAU Meeting 2011 NARIT Conference Series*, Vol. 1, c 2013 S, Komonjinda, YY, Kovalev, and D, Ruffolo, eds.

[21] Muhammad Abd Hadi Bunyamin & Finley, FN 2016, *STEM education in Malaysia: Reviewing the current Physics Curriculum*, https//www.researchgate.net/publication/294722510.

[22] Mullis, IVS, Martin, MO, Goh, S & Cotter, K 2016, *TIMSS 2015 Encyclopedia: Education Policy and Curriculum in Mathematics and Science*, Boston: Boston College, TIMSS & PIRLS International Study Center.

[23] Norhan Mat Yusoff, Helmi Zulhaidi Mohd Shafri & Ahmad Razlan Mohamed 2008, 'Remote Sensing Educational Ground Receiving System for interest creation in space science and technology in education', *International Journal of Education and Development using Information and Communication Technology*, vol. 4, no. 4, pp. 171-182.

[24] Planetarium 2016, *Resolusi Konvesyen Astronomi Nasional ASTROcon2016, 5 December 2016*, Kuala Lumpur.

[25] Rasi, P, Ruokamo, H and Maasiita, M 2017, 'Towards a Culturally Inclusive, Integrated, and Transdisciplinary Media Education Curriculum: Case study of an International MA Program at the University of Lapland', *Journal of Media Literacy Education*, vol. 9, no. 1, pp. 22-35.

[26] Rueda, R 2011, *The 3 dimensions of improving student performance: Finding the right solutions to the right problems*, New York, Teachers College Press.

[27] Space Generation Advisory Council 2015, *Annual Report Space Generation Advisory Council*, Vienna, Austria, European Space Policy Institute.

[28] Stamovlasis, D 2016, *Catastrophe theory: Methodology, epistemology and applications in learning science*, in *Complex Dynamical Systems in Education: Concepts, Methods and Applications*, Switzerland, Springer Academic Publishing, pp. 141-175.

[29] Stentoft, D 2017, 'From Saying to Doing Interdisciplinary Learning: Is Problem-Based Learning the Answer?', *Active Learning in Higher Education*, vol. 18,

no. 1, pp. 51-61.

[30] Thornton, B, Peltier, G & Perreault, G 2004, 'Systems Thinking: A Skill to Improve Student Achievement', *The Clearing House*, vol. 77, no. 5, pp. 222-227.

Report: Meteorological Assessment for the Malaysian Annular Solar Eclipse on 26 December 2019

Asillam, M.F.[1*] and Othman, M.[2]

[1]*Perdana School of Science, Technology & Innovation Policy Center,*

Universiti Teknologi Malaysia

[2]*International Science Council, Regional Office for Asia and the Pacific*

The annular solar eclipse phenomenon will occur on 26 December 2019. Its shadow in Malaysia falls on two interesting areas: Tanjung Piai, Johor and Batang Ai, Sarawak. The quality of viewing of the eclipse is not only determined by the optics of the telescope or any other sensor, but also by the meteorological conditions of the area of viewing. The aim of this paper was to assess the meteorological data, i.e. rainfall, rainday and cloud cover, and the accessibility and logistics of these two locations.

Keywords: Solar eclipse; meteorology; wet delay

I. INTRODUCTION

An annular solar eclipse will occur on 26 December 2019. The last annular solar eclipse experienced by Malaysia was on 21 August 1998. The National Planetarium at that time organized a premiere public viewing at Mersing, Johor, which got excellent response from the general public. Jay Pasachoff, a prominent figure in solar eclipse, was also present and some photos by the National Planetarium team are shown in Figures 1 and 2.

Figure 1. The crowds during the annular solar eclipse at Mersing in August 1998 (National Planetarium, 1998)

*Corresponding author's e-mail: mhdfairos@gmail.com

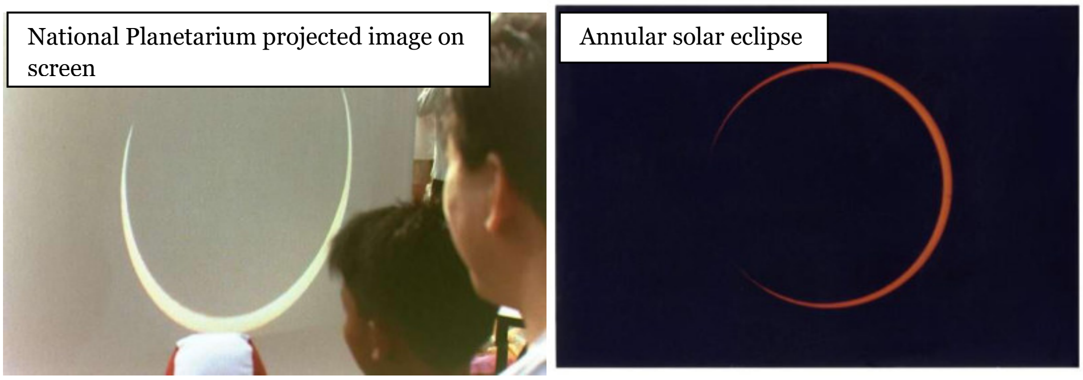


Figure 2. The 21 August 1998 annular solar eclipse (National Planetarium, 1998)

The next annular solar eclipse in Malaysia will occur on 26 December 2019, while the next total solar eclipse will occur on 24 August 2082 as shown in Table1.

Table 1. Previous and future solar eclipse phenomena in Malaysia

PREVIOUS SOLAR ECLIPSES	FUTURE SOLAR ECLIPSES
24 October 1995 (Total)	26 December 2019 (Annular)
21 August 1998 (Annular)	21 June 2020 (Partial)
16 February 1999 (Annular)	20 April 2023 (Partial)
10 June 2002 (Partial)	2 August 2027 (Partial)
1 August 2008 (Partial)	27 July 2028 (Partial)
26 January 2009 (Partial)	13 July 2037 (Partial)
22 July 2009 (Partial)	26 December 2038 (Partial)
15 January 2010 (Partial)	20 September 2052 (Partial)
20 May 2012 (Partial)	20 March 2053 (Partial)
10 May 2013 (Partial)	12 September 2053 (Partial)
9 March 2016 (Partial)	5 January 2057 (partial)
	3 September 2062 (Partial)
	28 February 2063 (Annular)
	17 February 2064 (Partial)
	24 August 2082 (Total)

II. 26 DECEMBER 2019 ANNULAR ECLIPSE PATH AND PARAMETERS

A solar eclipse occurs when the Moon passes between the Earth and the Sun, thereby totally or partly obscuring the image of the Sun for a viewer on Earth. Unfortunately, not every eclipse of the Sun is a total eclipse. Sometimes, the Moon's apparent diameter is smaller than the Sun's, blocking most but not all of the Sun's light, causing the Sun to look like an annulus (ring). An annular eclipse appears as a partial eclipse over a region of the Earth thousands of kilometres wide.

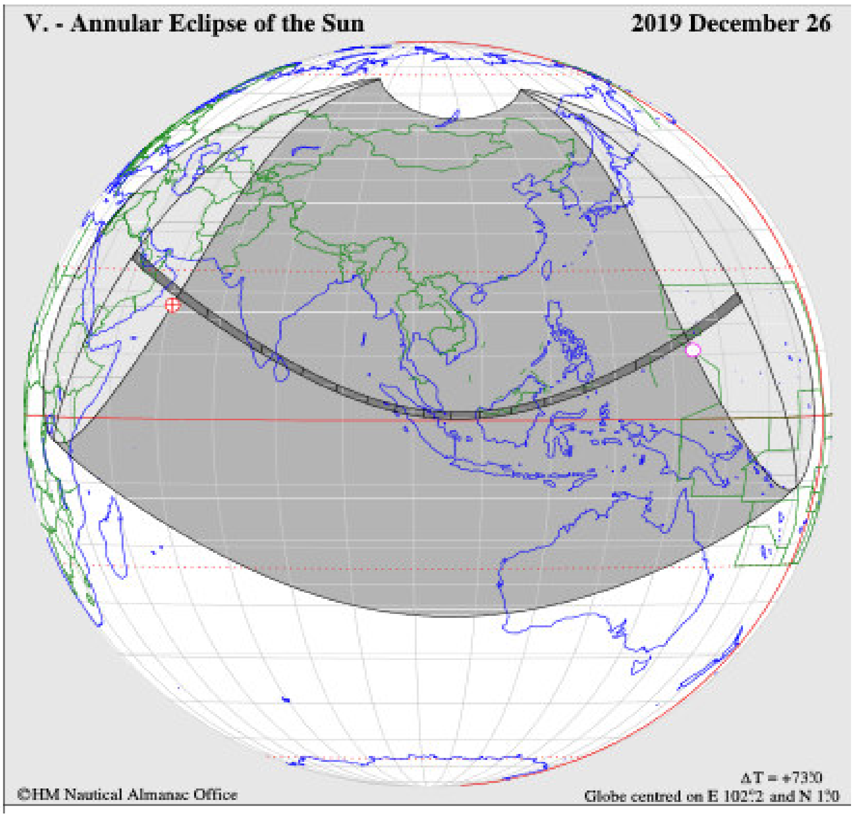


Figure 3. The global visibility of this solar eclipse (Almanac, 2018)

Table 2. Circumstances of the annular solar eclipse on 26 December 2019 (Espanak 1987)

CIRCUMSTANCES	TIME (UT)	LONGTITUDE	LATITUDE
Eclipse begins, first contact with Earth	2 hours 29.8 minutes	E 60° 34.9’	N 17° 47.1’
Central eclipse at apparent noon	5 hours 14.5 minutes	E 101° 26.5’	N 1° 07.0’
Eclipse ends; last contact with Earth	8 hours 05.7 minutes	E 144° 00.9’	N 10° 37.1’

Geocentric conjunction	05:14:26.7 UT
Greatest eclipse	05:17:36.0 UT
Eclipse magnitude	0.9701
Saros series	132

Magnitude	0.9701
Maximum duration of eclipse	03 minutes 40 seconds
Location at maximum duration	1°N 102.3°E
Greatest eclipse time (UT)	5 hours 18 minutes 53 seconds
Maximum width of eclipse path (km)	118

III. GENERAL CLIMATE OF MALAYSIA

Malaysia occupies a region within the equatorial belt and enjoys warm weather with consistent rainy periods and sunshine throughout the year. Generally, the humidity is high, ranging from 70% – 90% and the average temperatures range from 25-35°C (Peng, 1998). Being surrounded by the sea, the climate in Malaysia is very much affected by land-sea circulation and their interactions with the monsoons and global scale motions. The Malaysian weather is generally governed by two main monsoon seasons: North East Monsoon from November to March and South West Monsoon from May to September (Peng, 1998).

The Malaysia Meteorological Department (MMD) has 44 climate stations distributed throughout the country (Bahari, 2016) which make observations at specific times during the day. A typical meteorological station makes observations of pressure, wind speed and direction, temperature and dew point, rainfall, visibility, weather, clouds and sunshine duration.

In recent years, the issue of extreme weather and climate has become a concern to the public throughout the world. There has been an increase in occurrences of weather and climate extremes, such as the heat waves in Europe and the Middle East, long dry periods in Central America and parts of Southeast Asia, and unusually heavy rainfall over Malawi and Zimbabwe (Bahari, 2016). This phenomenon is also apparent in Malaysia where the present trends on rainfall have become very hard to predict as they are not in conformity with past records. Nevertheless, records indicate that, heavy rainfall should occur during the North East Monsoon period, i.e. from November until March 2019, especially on the east of Peninsular Malaysia and West Sarawak (Pusat Iklim Nasional, 2018). Several places, such as the South of Pahang, East Johor and North of Terengganu, are predicted to receive rain up to 400mm, while Bahagian Sri Aman, Betong and Sibu are are predicted to receive rain of between 300 to 450mm. This trend is expected to continue until the end of 2019 and early 2020.

IV. ANALYSIS OF LOCATIONS IN MALAYSIA

The best two locations in Malaysia which will have the longest duration for the annular solar eclipse are Tanjung Piai, Johor and Batang AI, Sarawak as shown in Figures 4, 5 & 6.They are the most suitable because of the amenities available near them.

Table 3 shows that the eclipse durations for Tanung Piai and Batang Ai will be 2 minutes 31.8 seconds and 3 minutes 36.6 seconds, respectively. The annular eclipse will begin at Tanjung Piai at 13:21:03.7, and 13:51:20.9 at Batang Ai (Malaysia standard time). Meanwhile, the time for maximum eclipse will be 13:22:19.5 and 13:53:09.2 for Tanjung Piai and Batang Ai, respectively. In addition, the altitude and azimuth for the beginning and ending of the annular solar eclipse at Tanjung Piai will be (+65.6°, 182.6°) and (+65.5°, 184.6°), respectively, and at Batang Ai will be (+58.8°, 216.7°) and (58.3°, 218.0°), respectively.

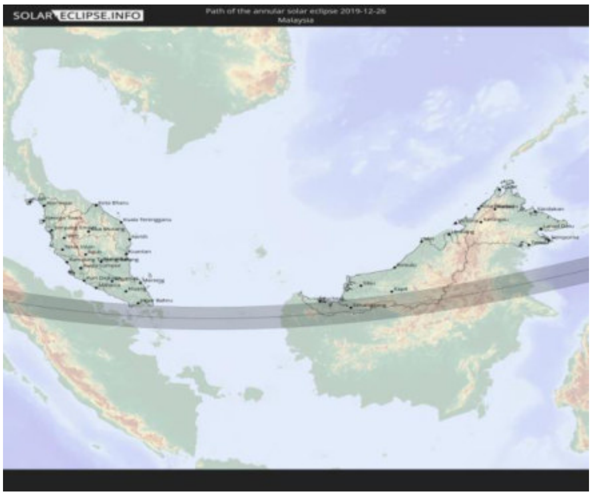


Figure 4. General outlook of the eclipse path near Malaysia (Thorsen, 2018)

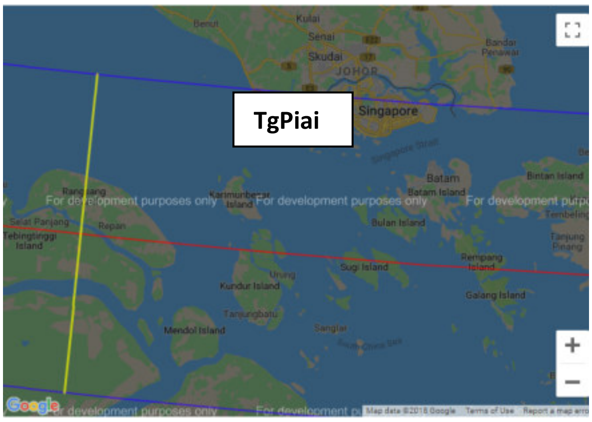


Figure 5. Focus at observation point, Tanjung Piai, Johor (Espanak, 2016)

Figure 6. Focus at observation point, Batang Ai, Sarawak (Espanak, 2016)

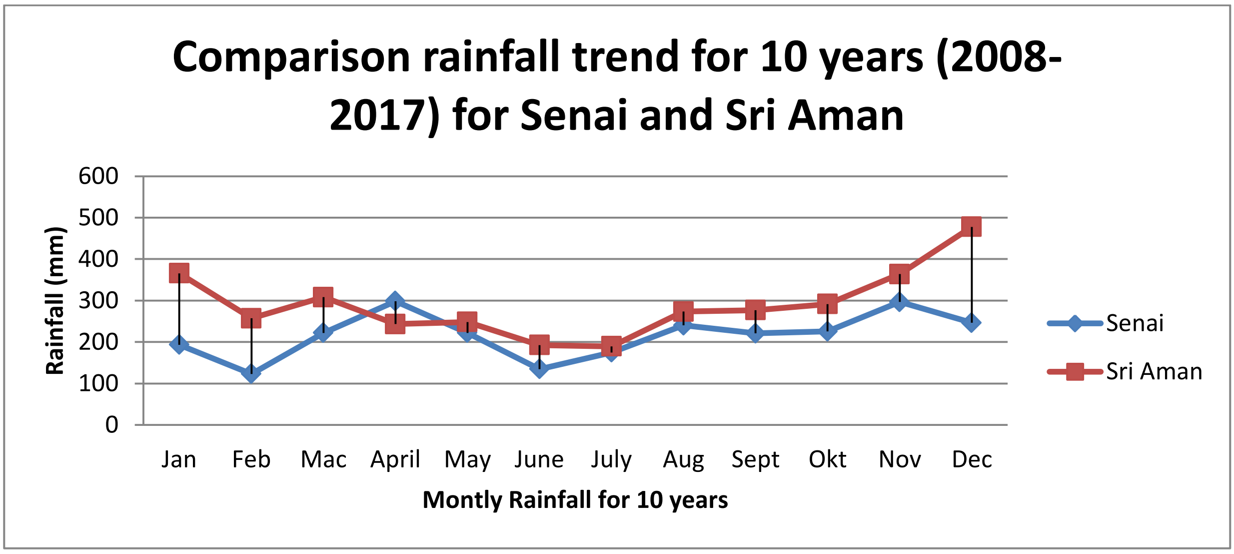
Table 3. Eclipse contacts at Tanjung Piai and Batang Ai

	GREATEST ECLIPSE POINT - SUMATERA LAT: N 01° 0.53' LONG: E 102° 14' 36.6"	**NATIONAL PARK TANJUNG PIAI JOHOR** LAT: N 01° 16' 05.27" LONG: E 103° 30' 31.39"	**NATIONAL PARK BATANG AI SARAWAK** LAT: N 01° 10' 41.52" LONG: E 111° 57' 32.12"
Annular Duration	3 minutes 39.5 seconds	2 minutes 31.8 seconds	3 minutes 36.6 seconds
Time Annulus Begin (Malaysia Time)	13:15:54.2	13:21:03.7	13:51:20.9
Altitude, Azimuth For Begin Annular Eclipse	+65.6°, 182.6°	+65.1°, 188.1°	+58.8°, 216.7°
Time Partial Begin (Malaysia Time)	11:22:38.3	11:26:02.4	11:54:01.2

Altitude, Azimuth For Partial Eclipse	+54.1°, 134.5°	+55.4°, 136.9°	+63.7°, 159.8°
Time Maximum Eclipse (Malaysia Time)	13:17:43.9	13:22:19.5	13:53:09.2
Time Annulus End (Malaysia Time)	13:19:33.7	13:23:35.5	13:55:00.3
Altitude, Azimuth For End Annulus Eclipse	+65.5°, 184.6°	+65.0°, 189.5°	+58.3°, 218.0°

V. ANALYSIS OF CLIMATIC CONDITIONS AND LOGISTICS

For this study, two MMD meteorological stations were chosen, located at Senai, Johor and Sri Aman, Sarawak (Table 4). These are the nearest stations available to Tanjung Piai and Batang Ai, respectively. The distance between the Senai meteorological station to Tanjung Piai is approximately 68km, whereas the distance between the Sri Aman Meteorological Station to Batang Ai is approximately 60 km. For this study, ten years of meteorological data had been used as shown in Figures 7 – 10.



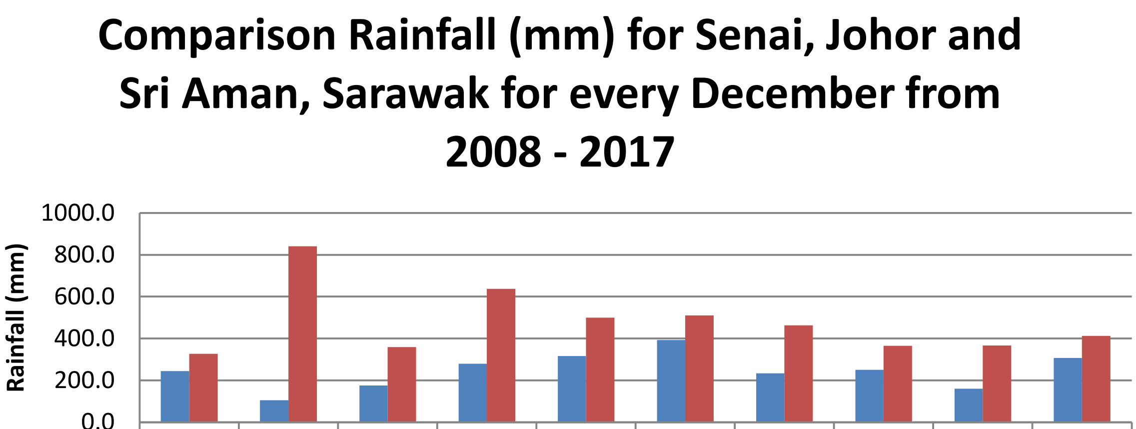
	Jan	Feb	Mac	April	May	June	July	Aug	Sept	Okt	Nov	Dec
Senai	193.3	122.9	222.2	298.7	222	134.6	174.7	240	221	225.6	296.7	246.2
Sri Aman	365.8	257.1	308.1	243.2	248.4	192.8	189.7	273.5	277	291.4	363.7	477.9

Figure 7. Comparison of rainfall trends for 10 years (2008-2017) for Senai and Sri Aman (MMD 2018)

Table 4. Information on meteorology stations

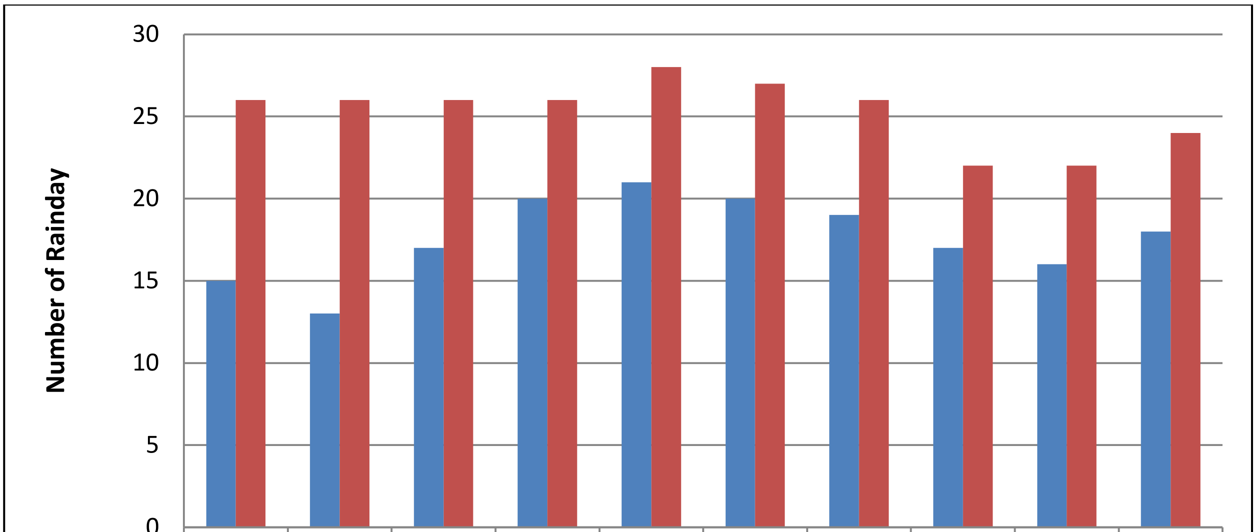
	SENAI METEOROLOGY STATION	SRI AMAN METEOROLOGY STATION
Latitude	N 1° 38'	N 1° 13'
Longitude	E 103° 40'	E 111° 27'
Elevation (meter)	37.8	9.6

Figure 7 exhibits the trend of rainfall for every month based on ten years data for both locations. The Senai station shows a much lower rainfall rate of 193.3mm and 246.2mm for January and December, respectively, compared to Sri Aman which shows 365.8mm for January and 477.9mm for December. Figure 8 shows the comparison on rainfall in December for 10 years for both locations. Consistently every year, the rainfall rate is lower at Senai. Figure 9 shows the comparison on rainday in December for 10 years for both locations. Consistently every year, the numbers of raindays is lower at Senai. Figure 10 shows consistently, every year; the cloud cover is less at Senai, except for 2017.



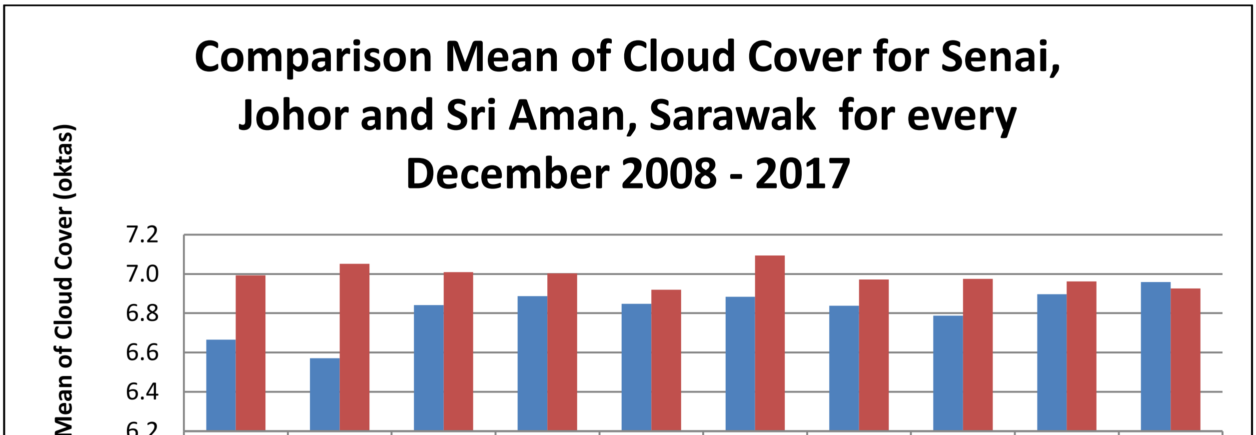
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Senai	244.2	104.6	175.6	279.0	315.6	393.1	232.6	249.6	160.4	307.4
Sri Aman	326.2	841.2	359.4	636.8	499.8	509.6	462.4	364.6	366.6	412.2

Figure 8. Rainfall (mm) for Senai, Johor and Sri Aman, Sarawak for every December 2008 - 2017 (MMD 2018)



	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Senai	15	13	17	20	21	20	19	17	16	18
Sri Aman	26	26	26	26	28	27	26	22	22	24

Figure 9. Number of Raindays for Senai, Johor and Sri Aman, Sarawak for every December 2008 – 2017 (MMD 2018)



	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Senai	6.7	6.6	6.8	6.9	6.8	6.9	6.8	6.8	6.9	7.0
Sri Aman	7.0	7.1	7.0	7.0	6.9	7.1	7.0	7.0	7.0	6.9

Figure 10. Mean Cloud Cover for Senai, Johor and Sri Aman, Sarawak for every December 2008 - 2017 (MMD 2018)

Table 5 demonstrates that Tanjung Piai is a better location in terms of accessibility and logistics. The Tanjung Piai venue is next to the beach while Batang Ai is a remote inland site. Tanjung Piai is accessible from the Senai International Airport, Johor and the Changi International Airport, Singapore, which are 69.3km and 106km away, respectively (Google Map, 2019). Tanjung Piai is easily accessible by road from all the surrounding areas, whereas Batang Ai is only accessible via the Kuching International airport and requires another 235km by road to reach the site (Google Map, 2019).

In addition, there are 98 hotels near Tanjung Piai on the eclipse day compared to only two hotels that are available at Batang Ai and Sri Aman (Expedia.my, 2019). Most of the hotels at Batang Ai and Sri Aman are already fully booked at the time of writing.

Table 5. Location accessibility and logistics of Tanjung Piai and Batang Ai

CRITERIA	**TANJUNG PIAI**	**BATANG AI**
Duration	2 min 31.8 sec	3 min 36.6 sec
Accessibility (distance from airport)	Close to airport *Senai International Airport, Johor to Tanjung Piai is 69.3km and Changi International Airport, Singapore to Tanjung Piai is 106 km, which takes 80 minute and 122 minutes, respectively, by car* (Google Map, 2019)	Remote area. Closest city - Sri Aman *Kuching International Airport to Sri Aman is 183km which takes 198 minute by car* (Google Map, 2019) *and from Sri Aman to Batang Ai National Park is 52 km and requires 60 minute driving by car* (DistanceBetween, 2019)
Logistics Based (Expedia.my, 2019) official site search on 19 December 2018. Criteria of search: i) Check-in: 25 December 2019; check-out: 27 Dec 2019 ii) One room for two adults	98 hotels Convenient with good accommodation (hotel) and internet connection	Two hotel: i) Aiman Batang Ai Resort & Retreat at Lubok Antu ii) Sri Simanggang at Bandar Sri Aman
Others	Close to sea	Inland remote area

VI. CONCLUSION

An analysis of the rainfall, cloud cover and number of raindays had been carried out for Tanjung Piai and Batang Ai. Generally, the trends show that at the end of December and early January the rainfall is heavy at both sites. Nevertheless, Tanjung Piai is a better venue compared to Batang Ai in terms of overall meteorological assessment. In addition, Tanjung Piai is a better choice in terms of accessibility. It is close to two international airports and has better road access. Tanjung Piai has a good network of hotels compared to Batang Ai. Several activities such as the Astronomy Festival and ASEAN Astronomy Teachers Workshop, are planned at the Tanjung Piai area by the National Planetarium, National Space Agency of Malaysia (ANGKASA), International Science Council and Universiti Teknologi Malaysia (UTM)(IAU100, 2018) during the eclipse period.

VII. REFERENCES

[1] Almanac, HN 2018, *HM Nautical Almanac Office: On-line Data*, HM Nautical Almanac Office.

[2] Bahari, A 2016, *Malaysian Meteorological Department (MMD) Annual Report 2016*, Petaling Jaya.

[3] Espanak, F 1987, *Fifty Year Canon of Solar Eclipses: 1986-2035*.

[4] Espanak, F 2016, *Annular Solar Eclipse of 2019 Dec 26*, NASA Goddard Space Flight Center.

[5] Expedia.my 2019, viewed on 2 January 2019, https://www.expedia.com.my.

[6] Google Map 2019, viewed on 2 January 2019, https://www.google.com/maps.

[7] IAU100, M 2018, *Minute of the Meeting Malaysia IAU100 Programme*, Kuala Lumpur.

[8] Peng, LC 1998, *Current Weather Trends in Malaysia for Astronomical Observation Activities*, Space Science Studies Division (BAKSA), MOSTE.

[9] Pusat Iklim Nasional 2018, *Tinjauan Cuaca Bagi Tempoh Desember 2018 hingga Mei 2019*, Petaling Jaya.

[10] Thorsen, S 2018, *26 December 2019 — Annular Solar Eclipse*, timeanddate.com.

ALAM SEKITAR DAN PERUBAHAN IKLIM
MINISTRY OF ENERGY, SCIENCE, TECHNOLOGY, ENVIRONMENT, & CLIMATE CHANGE

Timeline

NATIONAL PLANETARIUM

1989

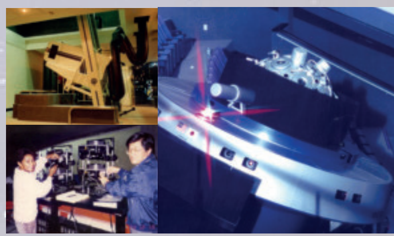
Planetarium Division established under the Prime Minister's Department.

1990

Construction of NATIONAL PLANETARIUM begins.

1992

Construction of NATIONAL PLANETARIUM building completed. Installation of tilted dome and star and large format movie projectors begins.



1993

The NATIONAL PLANETARIUM complex fully operational and opened to public.

1994

Official opening of NATIONAL PLANETARIUM by Prime Minister Dato' Seri Dr Mahathir Mohamad 7 February

Premier Lecture "Is Physics Predictable?" By Professor Stephen Hawking September 18.

1995

Launch of National Microsatellite Programme by Prime Minister Dato' Seri Dr Mahathir Mohamad 13 January.

1997

First Interschool National Space Challenge Quiz for the Prime Minister's trophy.

Merdeka Sundial relocated from Merdeka Stadium to the National Planetarium grounds.

1998

Establishment of the AMATEUR RADIO SATELLITE STATION (ARSS).

Visitors to the National Planetarium reached 1,000,000.

2000

First celebration of WORLD SPACE WEEK.

2002

Establishment of the National Space Agency (ANGKASA) and NATIONAL PLANETARIUM is placed under ANGKASA.

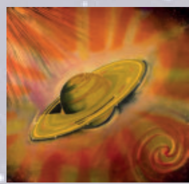
Digital Planetarium Mini Exhibition.

2003

Pilot Water Rocket Launch Competition.

2004

Batik Painting Competition: "Inspired by Space".



2007

Direct communication with Malaysia's first Angkasawan at the International Space Station (ISS) from ARSS October 14.

2008

Entered Malaysian Book of Records for the largest planetarium in Malaysia.

2010

Opening of Full Digital Dome System 9 February.

2012

First Try Zero G Programme (Science Experiment) at the International Space Station February.

Exhibition - A Tribute To Neil Armstrong

2016

National Astronomical Convention (AstroCON) October.

Opening Ceremony of new exhibition 22 August.

NATIONAL PLANETARIUM absorbed under the Science and Technology Division of the Ministry of Science, Technology and Innovation October 3.

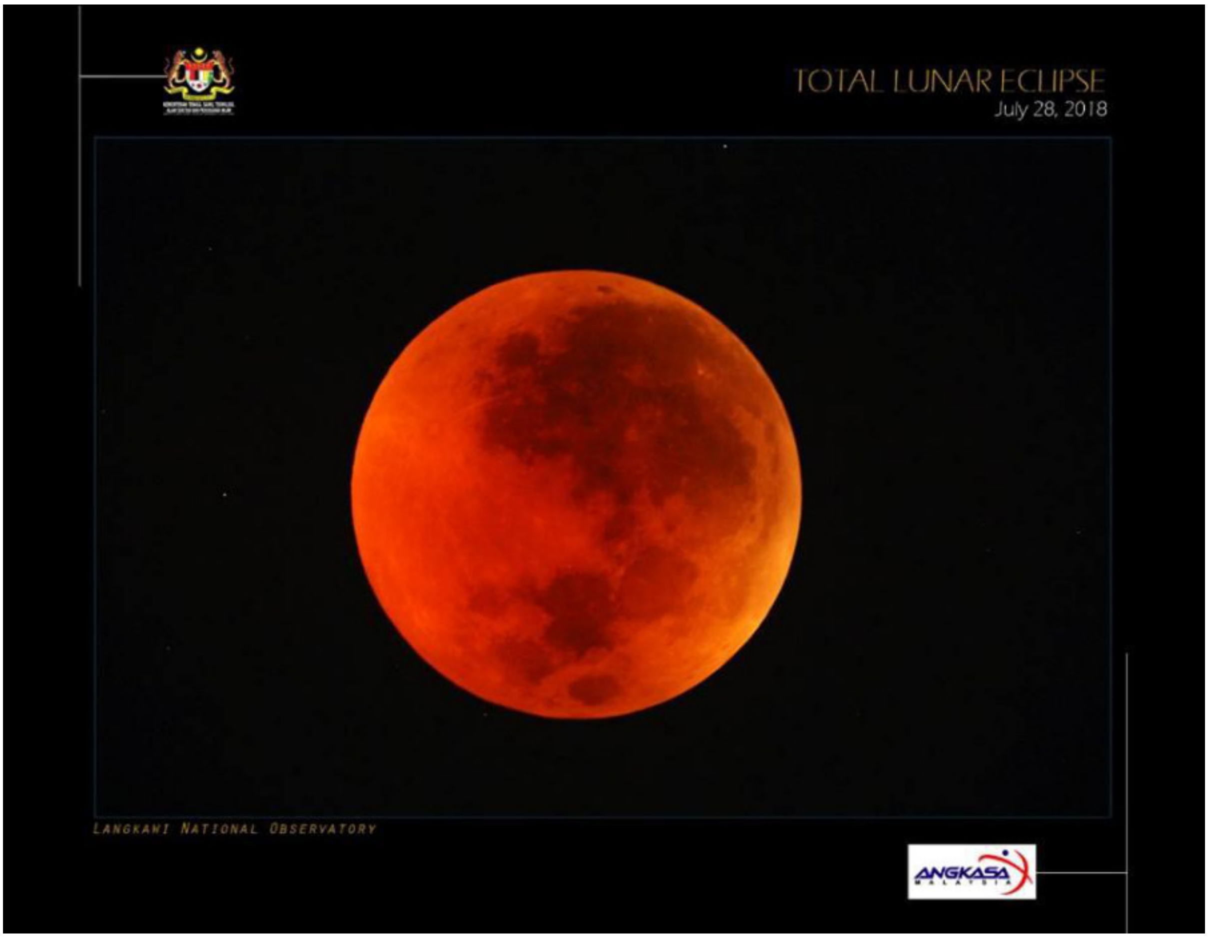
2018

Establishment of Mini Library July 2.

Establishment of National Planetarium Club (K-Planet) June 21.

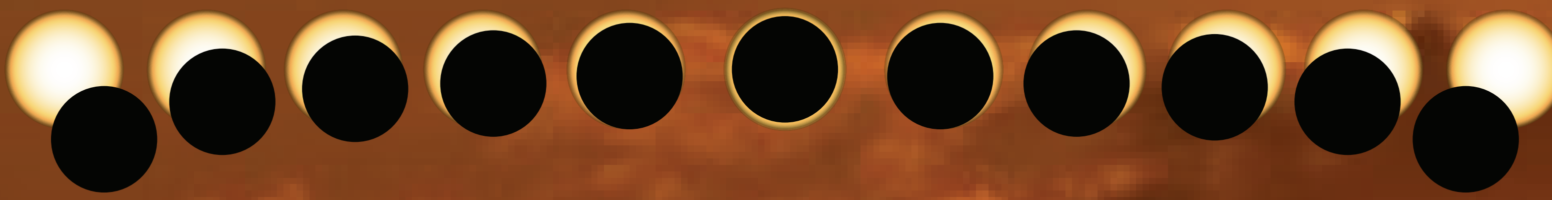
Note: Longest Lunar Eclipse in this Century (2001-2100)

National Space Agency of Malaysia



This image is recorded during the second lunar eclipse in 2018 which is the longest lunar eclipse in this century (2001-2100). The totality lasted for 1 hour 42 minutes and 57 seconds while the longest possible duration for totality is 1 hour 47 minutes.
This image was taken on 28 July 2018 at 05:13 am.

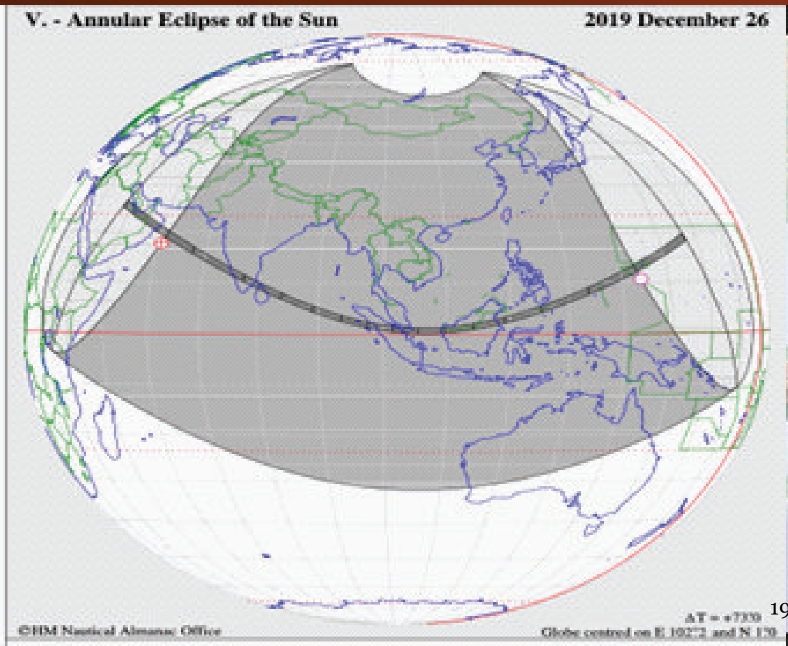
The camera used was Nikon D40X with ISO 1600 and 30 seconds exposure attached to a Skywatcher ED120 with objective mirror diameter 120mm, focal length 900mm and F-ratio of f/7.5.

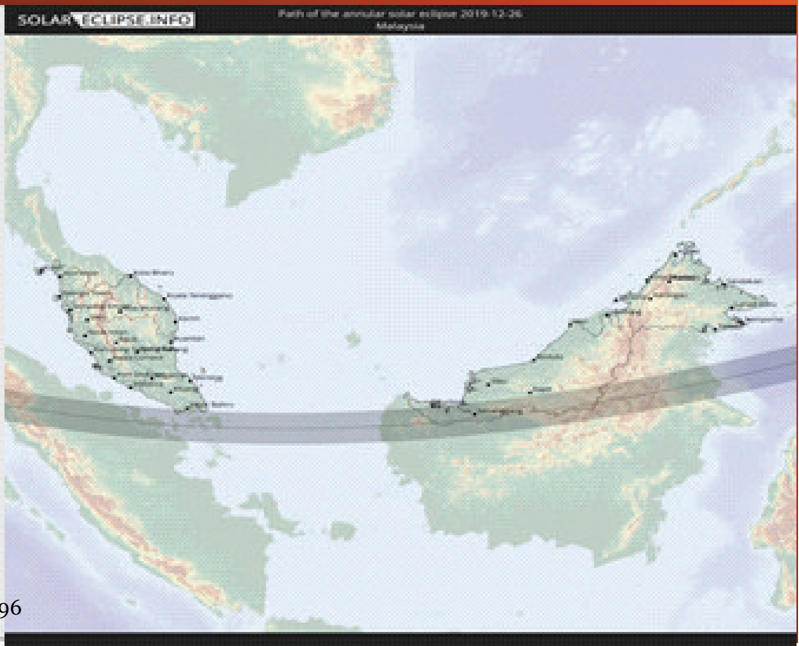


ANNULAR SOLAR ECLIPSE

26 December 2019

Location	GREATEST ECLIPSE POINT - SUMATERA LAT: 1.0089°N LONG: 102.2435°E	NATIONAL PARK TANJUNG PIAI, JOHOR LAT: N 01° 16’ 05.27” LONG: E 103° 30’ 31.39”	NATIONAL PARK BATANG AI, SARAWAK LAT: N 01° 10’ 41.52” LONG: E 111° 57’ 32.12”
Annular Duration	3 minutes 39.5 seconds	2 minutes 31.8 seconds	3 minutes 36.6 seconds
Time Annulus Begin (Malaysia Time)	13:15:54.2	13:21:03.7	13:51:20.9
Altitude, Azimuth For Begin Annular Eclipse	+65.6°, 182.6°	+65.1°, 188.1°	+58.8°, 216.7°
Time Partial Begin (Malaysia Time)	11:22:38.3	11:26:02.4	11:54:01.2
Altitude, Azimuth For Partial Eclipse	+54.1°, 134.5°	+55.4°, 136.9°	+63.7°, 159.8°
Time Maximum Eclipse (Malaysia Time)	13:17:43.9	13:22:19.5	13:53:09.2
Time Annulus End (Malaysia Time)	13:19:33.7	13:23:35.5	13:55:00.3
Altitude, Azimuth For End Annulus Eclipse	+65.5°, 184.6°	+65.0°, 189.5°	+58.3°, 218.0°





ANNOUNCEMENT

MALAYSIA IAU100 GLOBAL PROGRAMME

Uniting our World to Explore the Universe

In 2019, the International Astronomical Union (IAU) is celebrating its 100th anniversary. To commemorate this milestone, the IAU is organising a year-long celebration to increase awareness of a century of astronomical discoveries as well as to support and improve the use of astronomy as a tool for education, development and diplomacy under the central theme "Under One Sky". The centennial celebrations will stimulate worldwide interest in astronomy and science and will reach out to the global astronomical community, national science organisations, societies, policy-makers, students, families and the general public.

The IAU100 activities will take place at global and regional levels, including in Malaysia. To coordinate the initiative, the Malaysia IAU Committee has set up the IAU100 Task Force as well as secretariat based in National Planetarium, Kuala Lumpur The task force has prepared a comprehensive programme to reach targeted audiences nationwide through the IAU National Outreach Coordinators and partners.

Malaysia names Exoworld
Date: April 2019
Venue: National Planetarium
Contact: En.Muhammad Hafez bin Amat Murtza
- unawemy@gmail.com
Category: Competition to primary and secondary school

Malaysia IAU100 Exhibition
Date: TBD
Venue: National Planetarium
Contact: En. Mohd Zamri Shah Mastor
- zamri@planet.gov.my
Category: Physical and virtual exhibition

100 Hours of Astronomy
Date: 11-13 January 2019
Venue: Langkawi National Observatory and nationwide
Contact: Pn Farahana Kamarudin
- farahana@angkasa.gov.my
Category: Star parties nationwide for 100 hours

Moon Landing 50th Anniversary
Date: July 2019
Venue: National Planetarium
Contact : En. Mohd Zamri Shah Mastor
- zamri@planet.gov.my
Category: Exhibition

Astronomy Society of Penang (ASP) Astronomy Conference
Date: 21 – 22 June 2019 (TBD)
Venue: Penang
Contact: Daim Harizan
- daim_har@yahoo.com
Category: Conference, exhibition and star parties

Malaysia Einstein School
Date: 1 March 2019 - 30 September 2019
Venue: National Planetarium
Contact: En. Mohd Zamri Shah Mastor
- zamri@planet.gov.my
Category: Activities in school for primary and secondary school

Celebrating Dark Sky Sabah & Penang
Date: May until mid September 2019
Venue: Sabah & Penang
Contact (Sabah): Pn. Emma Zulaikha Zulkifli
- emmazulaiha@gmail.com
Contact (Penang): Dr Chong Hon Yew
- pearl_of_orion@yahoo.com
Category: Night observation and campaign on preservation of dark sky as a new source of astrotourism in Sabah and Penang

Observation of Apollo Moon Landing Sites through Telescope in conjunction with Moon Landing 50th Anniversary
Date: A day from the Feb, Apr, Jul, Nov & Dec of 2019
Venue: Various spot all over Malaysia - TBD
Contact : William Chin
- universe24@hotmail.com
Category: Public moon observation

IAU Women and Girls in Astronomy Day
Date: February 2019
Venue: Pusat PERMATA Pintar Negara UKM, Universiti Kebangsaan Malaysia
Contact: Dr Nor Sakinah Mohammad
- sakinah@ukm.my
Category: Talks

MALAYSIA IAU100 GLOBAL PROGRAMME

ASEAN Astronomy Workshop for Teachers (AAWT)

Date: 26 - 28 December 2019
Venue: Universiti Teknologi Malaysia
Contact: Prof Emeritus Datuk Dr Mazlan Othman
- mazlan.vienna@gmail.com
Category: Teachers workshop

TV documentary entitle "Cinta Alam Cakerawala"

Date: 4 - 10 October 2019
Venue: 13 episode TV shows in RTM
Contact : En Foo Danson
- danson@eugenetek.com.my
Category: 13 episode TV shows in RTM

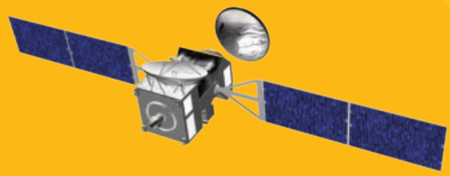
25th Anniversary of National Planetarium

Date: April 2019 (TBD)
Venue: National Planetarium
Contact: En. Mohd Zamri Shah Mastor
- zamri@planet.gov.my
Category: Exhibition, activities

CALL FOR PAPERS

IconSpace2019

Pulai Springs Resort, Johor Bahru,
Johor, Malaysia
28-30 July 2019



2019 6th International Conference on Space Science and Communication

"Advancing Space Science for Societal Sustainability"

Important Dates:

Full paper submission: **31 January 2019**
Acceptance notification: **15 April 2019**
Early bird payment: **31 May 2019**
Camera-ready with payment: **28 June 2019**
Conference day: **28-30 July 2019**

Topics:

Track 1: Astronomy and Astrophysics
Track 2: Atmospheric and Magnetospheric Sciences
Track 3: Geosciences and Remote Sensing
Track 4: Satellite & Communication Technology
Track 5: Interdisciplinary Space Science
Track 6: Others

International Advisory Committee:

1. Prof. Dr. Babatunde Rabiu (National Space Research & Development Agency (NASRDA), Nigeria)
2. Prof. Dr. Moses Oludare Ajewole (The Federal University of Technology, Nigeria)
3. Prof. Dr. Akira Kadokura (National Institute of Polar Research, Japan)
4. Dr. Maria Cecilia D. Galvez (De La Salle University, Philippines)
5. Dr. Zahra Bouya (Australian Bureau of Meteorology, Australia)
6. Dr. Tirthankar Banerjee (Banaras Hindu University, India)
7. Dr. Robert Cahill (The Queen's University Belfast, UK)
8. Prof. Dieter Bilitza (George Mason University, USA)
9. Dr. Mark Moldwin (University of Michigan, USA)
10. Dr. Kirpa Ram (Banaras Hindu University, India)
11. Dr. Simon Wing (Johns Hopkins University, USA)
12. Prof. Dr. Kazuo Shiokawa (Nagoya University, Japan)
13. Assoc. Prof. Dr. Huixin Liu (Kyushu University, Japan)
14. Prof. Dr. Jann-Yenq Liu (National Central University, Taiwan)
15. Dr. Claudio Ricci (The Pontifical Catholic University of Chile, Chile)
16. Prof. Sr. Dr. Mazlan Hashim (Universiti Teknologi Malaysia, Malaysia)
17. Prof. Dr. Mastura Mahmud (Universiti Kebangsaan Malaysia, Malaysia)
18. Prof. Minh Young-Chol (Korea Astronomy and Space Science Institute, South Korea)
19. Prof. Dato' Dr. Sharifah Mastura Syed Abdullah (Universiti Kebangsaan Malaysia, Malaysia)
20. Prof. Dr. Craig J. Rodger (University of Otago, New Zealand)
21. Dr. Andrew Thomas Hudak (USDA Forest Service, USA)
22. Prof. Dr. Mengu Cho (Kyushu Institute of Technology, Japan)

Committee:

Patron
Prof. Dato' Dr. Sharifah Mastura Syed Abdullah

General Chair
Prof. Ir. Dr. Mardina Abdullah

Secretariat
Assoc. Prof. Dr. Badariah Bais (Chair)

Treasurer
Muhamad Roszaini Roslan

Technical Program Committee (TPC)
Prof. Dr. Mohammad Tariqul Islam (Chair)

Logistic
Dr. Sabirin Abdullah (Chair)

Organised by

Universiti Kebangsaan Malaysia
The National University of Malaysia

ANGKASA
PUSAT SAINS ANGKASA

Supported by

CENTRE OF ADVANCED ELECTRONIC AND COMMUNICATION ENGINEERING
Pusat Kejuruteraan Elektronik dan Komunikasi Terkehadapan (PAKET)
Faculty of Engineering and Built Environment
Universiti Kebangsaan Malaysia

www.ukm.my/iconspace

Email: iconspace@ukm.edu.my
Phone: +603-8911 8033/8497

Do you teach astronomy or plan to use astronomy as an educational tool?

Join us at the

ASEAN ASTRONOMY WORKSHOP FOR TEACHERS (AAWT)

HOOKED ON THE SHADOW

26-28 December 2019 . University Teknologi Malaysia (UTM)

AAWT is a regional workshop designed to promote teaching of astronomy for primary and secondary school teachers in ASEAN countries and to bring basic observational tools of astronomy closer to them. This workshop is unique as it will be held in conjunction with the Annular Solar Eclipse which will take place on 26 December 2019. The 2-day workshop of 30 participants will feature talks and hands-on activities such as telescope demonstrations and observations (day and night). Apart from that, this workshop will also introduce and demonstrate opportunities to use robotic observatories in this region. Teachers will experience hands-on training aimed at upgrading the skills, teaching tools and aids equipping them with innovative and simple methods of teaching and learning.

SUPPORT TO QUALIFIED APPLICANTS

Applicants and their nominating organisations are strongly encouraged to find their own sources of sponsorship to participate in the Workshop. However, within the limited financial resources available, a number of qualified applicants from developing and emerging economies expressing the need for financial support will be offered financial support to attend the Workshop.

IMPORTANTS DATES

Application Open: **February 2019**

Application Dateline: **April 2019**

Acceptance Notification: **June 2019**

Workshop: **26 – 28 December 2019**

International Science Council

IAU 100 Years: Under One Sky

INTERNATIONAL ASTRONOMICAL UNION 1919 - 2019

Table of content

ASM Sc. J.
Volume 12, Special Issue 2, 2019

Continued on the inside of the back cover

ISSN 1823-6782
9 771823 678004