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Proposed Minimum Luminous Range for Existing Lighthouses in This Age of Global Navigation Satellite Systems by Using the Correlation between Light Intensity and Luminous Range ☆

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Abstract

Long-range visual marine aids to navigation are not required for current marine navigational practices. Therefore, the objective of this study was to develop a minimum luminous range for major lighthouses that are still in existence to sustain the operation of the lighthouses in the future. Two steps were involved in the determination of the minimum luminous range, namely the modification of the existing geographical range formula, and the finding of a strong linear correlation between the light intensity and the luminous range with the lowest gradient possible in a graph. The application of the minimum luminous range would eliminate the loom of light beyond the geographical range of the lighthouse. This approach was applied to seven major lighthouses in Peninsular Malaysia, which resulted in a minimum luminous range of between 12 nm to 14 nm, which was a reduction from the existing range of 18 nm to 25 nm. The validation of the minimum luminous range was performed in two ways; using a Full Mission Ship Simulator (FMSS), and matching the proposed minimum luminous range with the lighting system available. The results of the validation by using the FMSS between the luminous range of 25 nm and 14 nm showed that the light could be sighted and identified at 58.7 nm and 58.6 nm, respectively, which was, therefore, not significant. The validation by matching with the lighting equipment available in the market showed that the eight-tier VLB-44, which has replaced the rotating lighting system in the US since 2008, was highly matched with the proposed minimum luminous range. This further validated the minimum luminous range. The minimum luminous range is sufficient for current navigational uses and may reduce the costs for procuring and maintaining lighting systems, and will be able to sustain the operations of lighthouses in this GNSS age.

Keywords: Lighthouse, Luminous range, Marine navigation

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1. Introduction

A lighthouse is a large conspicuous structure on land close to the shoreline or in water, which acts as a daymark and provides a platform for a higher range of marine Aids to Navigation (AtoN) signal lights (IALA, 2014). Among the functions of a lighthouse are to mark the landfall position, mark an obstruction, and provide a reference for mariners to take their bearing or line of position (IALA, 2014). This study focused on the role of a lighthouse as a landfall light. Landfall is defined as "the first sighting of land when approaching from seaward" and a landfall light is defined as "the first light to be seen by the observer approaching the coast from the open sea. It is so situated and has a luminous range and geographical range that are so great that it can be identified at a great range" (Hooff, 1982). During the era before the introduction of a Global Navigation Satellite System (GNSS), mariners used to navigate in the open sea by using celestial navigation and approached the coast by following the guidance from the landfall light. This marked a change in the phase of navigation from open sea navigation using a celestial body to coastal navigation using references on land. In order to ensure that vessels navigating in the open sea sighted the landfall light, with a certain error of position from the distance as far as possible, the landfall light was built to deliver a luminous range in order to create a window with as large a radius as possible.

GNSS was introduced widely to marine commercial users in the 1990s. GNSS, or widely known as Global Positioning System (GPS), has changed the navigational practices of mariners (Theiss, Yen, & Ku, 2005). For instance, GPS has eliminated the change in phase from open sea navigation to coastal navigation by using the same method to fix the position in both areas and to achieve the same level of accuracy. To make life easier, GPS has been integrated with a radar, Electronic Chart Display and Information System (ECDIS), Automatic Identification System, and autopilot, which enable many inputs into a single screen. The current navigational practice of using GPS as the primary means of navigation has caused long-range marine aids to navigation, such as lighthouses, to play a secondary role in navigation. In the event of GPS failure, the radar can still be used to fix the position of the ship, thereby further reducing the dependence of mariners on lighthouses. Despite the fact that the introduction of GPS has changed the navigational practices of mariners, the luminous range of lighthouses in Malaysia has remained unchanged.

The current luminous range for lighthouses in Malaysia was set during the 70s, prior to the GPS era (Hooff, 1982; Hooff & Sirks, 1979). During that period, lighthouses were manned and the lighting system was powered either by using an engine generator or domestic power supply. Starting from the 90s, the obsolete lighting system was changed to a more advanced lighting system that was unmanned (automatic). This system was more reliable and consumed relatively little energy as the system was powered by renewable energy such as solar energy. However, the luminous range of the light from the lighthouses remained the same. Hitherto, the luminous range for major lighthouses in Malaysia has not been reviewed by the relevant authority, unlike in other countries such as the United Kingdom (UK).

The 2010 Marine Aids to Navigation (AtoN) Review in the UK resulted in the decommissioning of 20 lighthouses and the transfer of another 14 lighthouses to local authorities (ATKINS Ltd., 2010). A recent review conducted by the General Lighthouse Authority UK for the period 2010 to 2015 resulted in the following: reduced luminous range for 41 lighthouses, discontinuance of operation for 6 lighthouses, transfer of 14 lighthouses to local authorities, replacement of 1 lighthouse with Port Entry Light (PEL), increased range of light for 1 lighthouse, reduced fog signal range for 1 lighthouse, establishment of AIS for 1 lighthouse, and no changes for 76 lighthouses (Commissioners of Northern Lighthouses, Trinity House, & Commissioners of Irish Lights, 2010). The majority of the 76 unchanged lighthouses had a range of light that was below 18 nm, which was assumed to have been reviewed during the period 2005 to 2009. The results of this review showed that the dependence of mariners on lighthouses was gradually decreasing, thereby resulting in a reduction in the luminous range of lighthouses and even in the discontinuation of lighthouse operations.

However, the review did not mention the use of any specific method to reduce the luminous range of existing lighthouses. Therefore, to address this issue, this research proposed a new method for determining the minimum luminous range for lighthouses based on the height of the existing structure and the linear correlation between the intensity of the light and the luminous range achieved. The lighthouse authority can apply the concept of the minimum luminous range by choosing the lighting system that produces such an output using the least possible power and as compact a size as possible to facilitate the installation. This approach may reduce the costs for procuring and maintaining a lighting system.

2. Methodology

The flowchart of the research activities is shown in Figure 1 below.

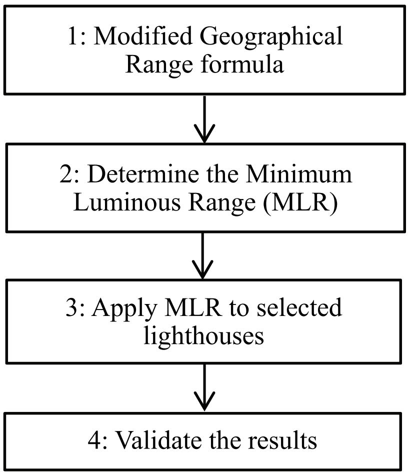

Figure 1. Flowchart of research activities

The first step was to derive a geographical formula for the lighthouse based on the existing geographical range formula (International Hydrographic Bureau, 2004), which is shown in Eq. 1. The objective of this study was to determine the geographical range of a lighthouse according to its elevation above sea level and to eliminate the loom of the lighthouse beyond its geographical range. Therefore, Eq. 1 was modified by deleting the height of the observer. As a result, Eq. 2 was derived, and was referred to as the geographical range of a lighthouse.

$$Range\ (nm) = 2.03\ A?\ \sqrt{e\ + h} \quad (1)$$

where:

e = elevation, in metres, of the object

h = height, in metres, of the observer's eye.

$$Range\ (nm) = 2.03\ A?\ \sqrt{e} \quad (2)$$

The second step was to determine the minimum luminous range of a lighthouse. In order to do this, a graph of the light intensity according to the luminous range was developed by using the IALA luminous range (in nautical miles) table for 7 nm to 28 nm. The graph was plotted using Microsoft Excel software. Based on the trend of the line plotted in the graph, the exponential trend was the best fit and resulted in the highest correlation coefficient (R^2) that was close to one compared to other trends. The software also derived the exponential formula of the trend. The formula was then used to derive the data that perfectly matched the exponential trend and was eventually used to develop a new exponential graph. A range of between 10 nm to 25 nm was selected in the graph to determine the best linear trend. A starting value of 10 nm was selected because it was assumed to be the lowest luminous range for major lighthouses (Commissioners of Northern Lighthouses et al., 2010). The best linear trend was determined by testing the different ranges starting from 10 nm until R^2 = 0.95 was achieved. When an R^2 of 0.95 was achieved, the maximum value for the range was accepted as the minimum luminous range.

The third step was to apply the geographical range for a lighthouse and the minimum luminous range to the major lighthouses in Peninsular Malaysia. The application of either the lighthouse geographical range or minimum luminous range depends on the following rule: If the luminous range is more than the geographical range, then the luminous range is limited to match the geographical range. If the geographical range is more than the minimum luminous range, then the minimum luminous range is applied.

The fourth step was to validate the minimum luminous range result by using a Full Mission Ship Simulator (FMSS). The first test was to determine the maximum range of the existing lighthouse light that could be seen and identified by observers on board a small vessel. The second test was to determine the maximum range of the minimum luminous light range of the lighthouse that could be seen and identified by observers on board a small vessel and to compare it with the existing light. The observers in the tests were persons with a background in sailing and marine aids to navigation.

3. Results and Discussion

The geographical ranges of seven major lighthouses in Peninsular Malaysia were calculated using Eq. 2. The results are shown in Table 1.

Table 1: Geographical ranges of selected lighthouses

Lighthouse	Elev. (m)	Existing Luminous Range (nm)	Lighthouse Geographical Range (nm)
Muka Head	242	25	31.6
One Fathom Bank	43	23	13.3
Cape Rachado	118	23	22.1
Pulau Angsa	36	22	12.2
Pulau Rimau	39	22	12.7
Kuala Selangor	73	18	17.3
Tanjung Gelang	85	25	18.7

Source: Marine Department Malaysia (2012)

The geographical ranges of the lighthouses in Table 1 were calculated based on the elevation of each lighthouse structure above the mean sea level (MSL). The lighthouse geographical range was used as the first limit for the luminous range of the lighthouse. This was to utilise the heights of the existing lighthouses. The purpose of limiting the luminous range according to the geographical range of the lighthouse was to eliminate the loom of light beyond the geographical range, which is not necessary for current navigational practices. Among the seven lighthouses, the geographical range of the Muka Head lighthouse was more than its existing luminous range, while the luminous ranges of the remaining lighthouses were more than their geographical ranges. These luminous ranges were further limited by the minimum luminous range, which was a balance between the increment of light intensity and the corresponding luminous range. The breaking point of this balance was when the requirement of light intensity was drastically increased to gain a similar distance as previously. To determine the minimum luminous range, the graph in Figure 2 was developed based on the IALA table for the darkness luminous range in nautical miles.

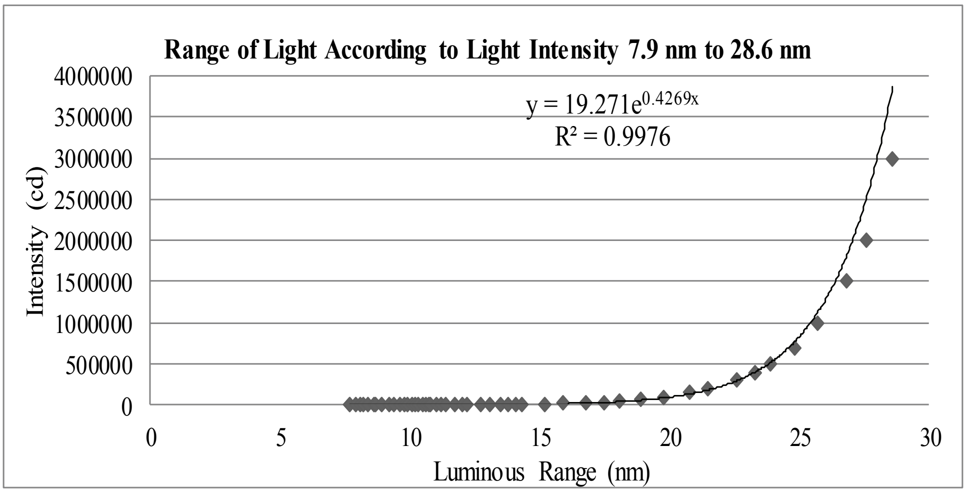

Figure 2: Luminous range of lighthouse according to light intensity for 7 nm to 28 nm

Based on the trend plotted by using Microsoft Excel, an exponential formula with R^2 close to one (1.0) was developed in Figure 2. The exponential trend was selected because it closely fitted the plotted curve and the correlation coefficient was close to one compared to the other trends.

The graph in Figure 3 was derived from the exponential formula developed in Figure 2, where the data followed exactly the exponential line. Based on the exponential formula in Figure 3, the selected data were plotted to develop the graph in Figure 4.

The purpose of developing the graph in Figure 4 was to determine the breaking point from the linear to the exponential trend in the graph, which is roughly shown in the graph in Figure 3. By testing different ranges from 10 nm to 25 nm in the graph, a range 10 nm to 14 nm yielded an R^2 of 0.9, which showed a high correlation factor for the linear trend.

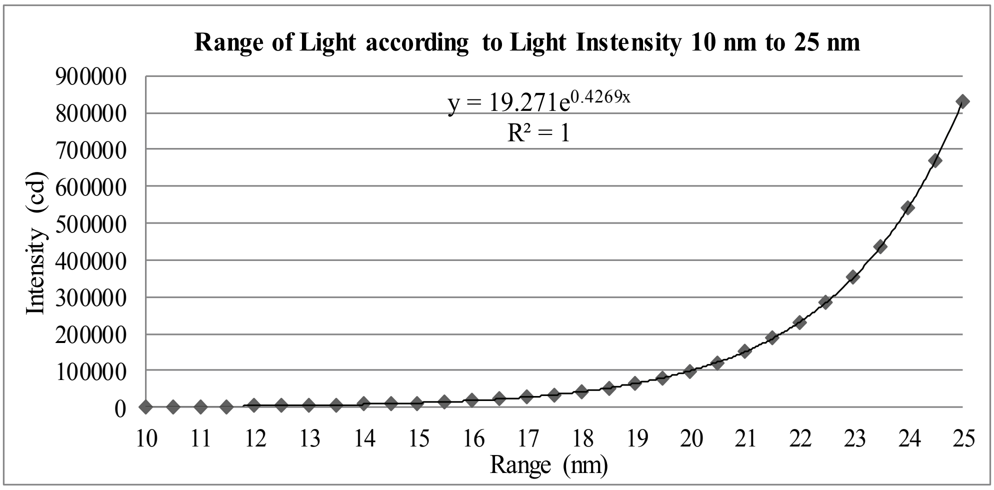

Figure 3: Luminous range of lighthouse for 10 nm to 25 nm according to light intensity

This indicated that 14 nm was the breaking point before the graph switched to an exponential trend. This range (10 nm to 14 nm) also produced the least gradient compared to the other ranges that were tested. The least gradient indicated that the least increase of light intensity was required to increase the luminous range between 10 nm to 25 nm. The least increase of light intensity was assumed using the least power required for the lighting system to increase the luminous range. The least power required to run the lighting system corresponded to less equipment needed to power the system, such as solar panels and battery banks, especially at remote locations. This would reduce the cost for the procurement and maintenance of the lighting system.

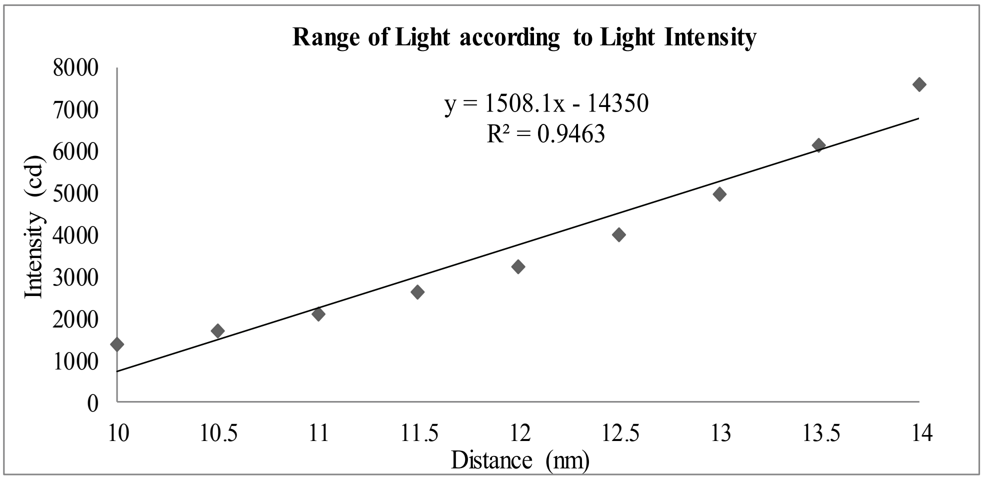

Figure 4: Range of lighthouse light for 10 nm to 14 nm according to light intensity

The lighthouse geographical range and the minimum luminous range approaches were applied to seven lighthouses in Peninsular Malaysia, as shown in Table 2.

The new luminous range for the lighthouses ranged from 12 nm to 14 nm, which was lower than the existing range of 12.2 nm to 31.6 nm. This new luminous range would ensure that the loom of light of each lighthouse would not go beyond its horizon as this is not necessary for current navigational practices.

The first validation of the minimum luminous range was conducted by using the Full Mission Ship Simulator (FMSS) at Universiti Malaysia Terengganu (UMT). The test subject was the Muka Head lighthouse. The tests were conducted by two faculty members, namely a deck officer with more than 5 years of working experience, and a former marine Aids to Navigation manager with more than eight years of working experience in the field. A tug boat with an overall length of 30 m and height of an observer of 4.6 m above water was selected as an observation platform because it was the smallest vessel with the lowest height of an observer available in the UMT FMSS, which also had the lowest geographical range.

Table 2: Proposed new minimum luminous range of selected lighthouses

Lighthouse	Elevation (m)	Existing Luminous Range (nm)	Geographical Range (nm)	New Luminous Range (nm)
Muka Head	242	25	31.6	14
One Fathom Bank	43	23	13.3	13
Cape Rachado	118	23	22.1	14
Pulau Angsa	36	22	12.2	12
Pulau Rimau	39	22	12.7	13
Kuala Selangor	73	18	17.3	14
Tanjung Gelang	85	25	18.7	14

The first series of tests was to evaluate the performance of the lighthouse light with the existing luminous range (25 nm) from the sea adjacent to the lighthouse at various distances. The second series of tests was conducted with the luminous range of the lighthouse set at 14 nm. Good weather conditions, with good visibility of at least 10 nm over the horizon, were set for the first and second series of tests. The distance observed from the lighthouse was initially at 36 nm and this was increased by 5 nm each time until the light could not be sighted. The distance of 36 nm, which was selected as the first distance for the observation, was determined from the calculation of the geographical range using Eq. 1, based on the height of the lighthouse above mean sea level and the height of the observer above water. The results are shown in Table 3.

Table 3: Results of observation on 14 and 25 nm luminous range at various distances

Distance Observed (nm)	Luminous Range of 25 nm	Luminous Range of 14 nm
36	Easily sighted and identified.	Easily sighted and identified.
41	Easily sighted and identified. Horizon height lower than 36 nm.	Easily sighted and identified. Horizon height lower than 36 nm.
46	Easily sighted and identified. Horizon height lower than 41 nm.	Easily sighted and identified. Horizon height lower than 41 nm.
51	Easily sighted and identified. Horizon height lower than 46 nm.	Easily sighted and identified. Horizon height lower than 46 nm.
56	Easily sighted and identified. Horizon height lower than 51 nm.	Easily sighted and identified. Horizon height lower than 51 nm.
58.6	Poorly sighted and identified.	Barely sighted and identified. Horizon height lower than 51 nm.
58.7	Barely sighted and identified.	Not sighted.
61	Not sighted.	Not sighted.

By comparing the results between the lighthouse with a luminous range of 25 nm and 14 nm, the maximum distance at which the light was sighted for 25 nm was 58.7 nm and for 14 nm was 58.6 nm. This result showed that the difference in the performance of the light with different luminous ranges was very small and insignificant. However, the difference in the light intensity between 14 nm and 25 nm, which was 9,000 cd and 700,000 cd, respectively, was huge. The validation in the field by using the real lighthouse to compare the results between the real lighthouse and the FMSS was not possible because the lighting system could not be manipulated to deliver the light intensity other than for a luminous range of 25 nm. Furthermore, the lighthouse authority would not give its permission to alter the lighting system. Therefore, based on the limitation on using a real lighthouse as the validation tool, the result produced by using the FMSS was used to validate the luminous range developed in this study.

The second validation was conducted by comparing the proposed luminous range with the lighting systems currently offered by three leading manufacturers, as shown in Table 4. For comparison, items 2 and 4 were offered in the early 2000s but are currently not available on the website of the respective manufacturers. This may be due to the reduced demand in the market because the systems are cumbersome and consume a lot of power. The systems also use incandescent bulbs, unlike the other systems that use LED bulbs. Out of the 13 items of lighting equipment presented in Table 4, the eight-tier VLB-44 was found to be the most suitable match for the minimum luminous range (14 nm using certain flash characters) proposed in this study and it consumed the least power (80 watt) compared to the other models. This selection was based on the limited information provided by the respective manufacturers on their websites, namely luminous range, weight and power consumption, without taking into account other factors such as cost and reliability. By using the VLB-44 instead of the PRB-24 or PRB-21, which are no longer offered, the lighthouse authorities may be able to reduce their procurement cost by buying a relatively compact lighting system that uses less power generating equipment (solar panels and battery banks) and is easier to mobilise and install. The lighthouse authorities may also reduce their operational cost as the number of scheduled visits can be reduced as there will be no faulty bulbs (using LED) to be replaced at the site. This particular model, the eight-tier VLB-44 made by Vega, has been replacing the rotating type of lighting system, the VRB-25, from the same manufacturer of lighthouses in the US since 2008, thereby showing a steady decrease in the number of rotating type of lighting systems in the US in favour of relatively low-powered flashing type of lighting systems (Trapani, 2012). This trend further validated the proposed luminous range in this study. This was also parallel with the general principle of review of AtoN in the UK, which states that rotating optics are no longer a requirement (Commissioners of Northern Lighthouses et al., 2010).

Table 4: Lighting system for lighthouses from three leading AtoN manufacturers

Equipment	Range (nm) at T=0.74	Weight (kg)	Maximum Power Require -ment	Manu -facturer
APRB-252 Rotating Beacon	22	15	1.5-200 watt	Pharos Marine AP
APRB-288 Rotating Beacon	23	20	201.5	Pharos Marine AP
FA-250HA LED LR	18	20	690 watt (3 tier)	Pharos Marine AP
FA-410 LED LR	20	41	300 watt	Pharos Marine AP
Nova-65 HI	10	0.77-1.97	10 watt	Tideland
Nova-250	15 -18	12-32.5	230 watt (2 tier) 15 nm, 390 watt (3 tier) 18 nm	Tideland
PRB-24 Parabolic Reflector Array	25.1	560	91 watt (2 lamps per beam and motor)	Pharos Marine AP
TRB-220 Rotating Beacon	20	20.5	5.5 -112.5 watt	Tideland
TRB-400 Rotating Beacon	24	110	12.5-112.5 watt	Tideland
PRB-21 Sealed beam lamp array	23.3	More than 500	1446 watt (4 lamps per panel and motor) 2 panels	Pharos Marine AP
VRB-25 Rotating Beacon	15-26	43-87	50 watt (6 panels & 2 tier) 22 nm	Vega
VLB-44 (Tier 1-8)	6-14	10-27.5	10-80 watt (tier 1–tier 8)	Vega
VLB-92 (Tier 1-3)	13-22	38-47	1200 watt (3 tier) for 22 nm	Vega

Source: Pharos Marine Automatic Power (2004, 2016a, 2016b, 2016c, 2016d), Tideland Signal Corporation (2015a, 2015b, 2015c, 2016), Vega Industries Ltd (2015a, 2015b, 2015c, 2015a)

5. Conclusion

The luminous range of lighthouses should be reduced as mariners are relying less on lighthouses for navigation. The minimum luminous range for lighthouses proposed in this study was 14 nm, which was determined by two steps, namely by modifying the existing geographical range formula, and obtaining a strong linear correlation between the light intensity and the luminous range. These approaches eliminated the loom of light beyond the geographical range of the lighthouse structure and ensured that the luminous range achieved was in accordance with the linear correlation obtained between the light intensity and luminous range. The proposed minimum luminous range was applied in two ways: first, the minimum luminous range was applied when the luminous range was less than the geographical range; second, the geographical range was applied when the minimum luminous range was more than the geographical range. Validation by using FMSS to compare the performance of light between the existing and the minimum luminous range of a lighthouse showed that the difference in terms of range of light detected and identified was not significant. The minimum luminous range proposed in this study was referred to a list of lighting equipment that are currently available in the market, and it matched the eight-tier VLB-44 model, which is currently gaining popularity and is replacing the rotating type of light that is being used in lighthouses in the US. This further validated the proposed minimum luminous range. The minimum luminous range proposed in this study is sufficient for mariners who rely primarily on GNSS for navigation, and it is able to reduce the operational cost of marine Aids to Navigation authorities. Therefore, the application of this new minimum luminous range may sustain the operation of lighthouses in the future.

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References

ATKINS Ltd. (2010), *Assessment of the Provision of Marine Aids to Navigation around the United Kingdom & Ireland*, London.

Commissioners of Northern Lighthouses, Trinity House, & Commissioners of Irish Lights (2010), *Aids to Navigation Review 2010 - 2015*, London.

Hooff, J. F. D. van. (1982), *Aids to Marine Navigation*, Wageningen.

Hooff, J. F. D. van, & Sirks, J. C. (1979), Lights for Landfall, *Journal of Navigation*, *28*, 168–192.

IALA (2014), *Aid to Navigation Manual* (Vol. 7th), St Germain En Laye, Retrieved from http://www.iala-aism.org

International Hydrographic Bureau (2004), *Standardization of List of Lights and Fog Signals* (No. S-12), Monaco.

Marine Department Malaysia (2012), Aids to Navigation Equipment, Retrieved June 19, 2012, from http://www.marine.gov.my

Pharos Marine Automatic Power (2004), PRB - 21 Sealed Beam Lamp Array, Retrieved January 6, 2004, from www.pharosmarine.com

Pharos Marine Automatic Power (2016a), APRB-252 Marine Rotating Beacon, Retrieved June 6, 2016, from www.automaticpower.com

Pharos Marine Automatic Power (2016b), APRB-288 Rotating Beacon, Retrieved June 6, 2016, from www.automaticpower.com

Pharos Marine Automatic Power (2016c), FA-250HA LED LR Series, Retrieved June 6, 2016, from www.automaticpower.com

Pharos Marine Automatic Power (2016d), FA-410 LED LR, Retrieved June 6, 2016, from www.automaticpower.com

Theiss, A., Yen, D. C., & Ku, C.-Y. (2005), Global Positioning Systems: an analysis of applications, current development and future implementations, *Computer Standards & Interfaces*, *27*(2), 89–100. http://doi.org/10.1016/j.csi.2004.06.003

Tideland Signal Corporation (2015a), NOVA-250, Retrieved June 6, 2016, from http://www.tidelandsignal.com/

Tideland Signal Corporation (2015b), TRB-220, Retrieved June 6, 2016, from http://www.tidelandsignal.com/

Tideland Signal Corporation (2015c), TRB-400, Retrieved June 6, 2016, from http://www.tidelandsignal.com/

Tideland Signal Corporation (2016), Nova-65.

Trapani, B. (2012), Vega VRB-25 Last of the Lighthouse Rotating Beacons as We Know Them, Retrieved July 8, 2012, from http://www.stormheroes.com/aton/vrb25_200904.htm

Vega Industries Ltd. (2015a), VLB-44, Retrieved June 6, 2016, from http://www.vega.co.nz/

Vega Industries Ltd. (2015b), VLB-92, Retrieved June 6, 2016, from http://www.vega.co.nz/

Vega Industries Ltd. (2015c), VRB-25, Retrieved June 6, 2016, from http://www.vega.co.nz/