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"AIS 2.0": Technological changes, implications and policy recommendations

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ABSTRACT
Space-based detection of Automatic Identification System (AIS) transmissions is increasingly being used as a means of collating vessel information for building Maritime Domain Awareness (MDA). With the introduction of "Long-Range AIS" through a specific AIS message (Message 27), designed for reception from space, some of the existing problems with space-based vessel detection would be obviated. Nonetheless, the system cannot replace terrestrial detection. In some cases, interaction between the two segments – space and ground based – of the system may even render one segment totally ineffective. From the user-perspective, an examination of the underlying technical issues will help understand the capabilities and limitations of the system as an aid to global vessel tracking. Designing future sub-systems to optimally exploit the changes is important.

KEYWORDS
Long-range AIS; space; vessel-tracking; message 27

Automatic identification system for tracking vessels at sea

The Automatic Identification System (AIS) was adopted by the Maritime Safety Committee of the International Maritime Organisation (IMO) in 1998.[1] Carriage for specified categories of vessels was made mandatory, in 2000, through an amendment to the SOLAS (Safety of Life at Sea) regulations.[2] The technical characteristics of the system are specified by the ITU (International Telecommunications Union) and have been revised from time to time.[3]

The AIS was essentially designed as an anti-collision system, even though other uses such as "Electronic Aid to Navigation" and tracking of ships from shore were also envisaged. The use of the system for enhancing security and compiling MDA was not, however, a part of the initial envisaged use. The system therefore has many limitations in that role.[4]

Over the years, the system has undergone some changes. Specifically, incorporation of "Long-Range AIS" through a dedicated AIS message (Message 27), designed for reception from space would have implications on how ships can be tracked when away from shore. This paper examines the genesis of the system as a security tool, its limitations in that role and recommends measures for effective exploitation of the technical changes that have been recently incorporated in the system.

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Limitations of AIS

The primary limitations of AIS as a security tool pertain to incorrect information (deliberately or inadvertently fed), the limited availability of time slots under the SOTDMA (Self Organised Time Division Multiple Access) architecture;[5] and, limited range (when used from terrestrial receivers).

Incorrect information

Issues of incorrect information being accidently or even intentionally being fed into the system by a user (the latter often called "AIS spoofing") and the fact that correct implementation is not formally "policed", are well documented.[6] As per some observers, this puts a question-mark over the system's efficacy as a security tool.[7] One commentator has opined that "There are reasons to believe that purposeful deceptions have been carried out by North Korean and Chinese ships and by Vietnamese ships, possibly under Chinese ownership".[8]

Even without "purposeful deception", inadvertent mistakes often lead to incorrect data being fed to the system, leading to the possibility of incorrect deductions being made. Although it has been estimated that "upwards of 30%" of AIS data is incorrect[9], the situation may not be as alarming as that figure portends. Information that is transmitted by AIS can be placed for consideration in one of two groups: (1) information that is automatically fed into the system, and (2) data that the user manually enters at various stages of the voyage. Information that is automatically fed into the system, for example the positional data that is picked up from the GNSS (a Global Navigation Satellite System[10] such as GPS) receiver integrated with the AIS may be relied upon much more strongly than data fed manually by the user, even though the former, too, can potentially be manipulated.[11] Data, such as the next port-of-call, may often be incorrect or outdated depending on timeliness of data-entry by the user. Some data, such as the length of the ship, which is also fed by the user but does not need to be changed as frequently would fall somewhere in between the two cases just discussed. One therefore needs to be aware of the inherent limitations imposed by the system-design, and also about the reliance that ought to be placed on the data obtained[12], so that wrong assessments are not made.

Insofar as the reporting-interval is concerned, the original designed-purpose of the system, viz., anti-collision, comes into play. The time-interval between successive transmissions of "dynamic" data may vary from three minutes for a ship at anchor to two seconds for a ship that is moving faster than 23 knots or is manoeuvring.[13] "Static" information, such as the name of the ship, ETA, length *et cetera*, which is of limited utility in collision avoidance – but can be important from the MDA perspective – is transmitted either once every six minutes or on request.[14]

Slot-management under SOTDMA

Slot-management for transmissions is controlled by SOTDMA multiplexing. The AIS system has 2250 time-slots per minute in each of two assigned frequencies. This limits the number of messages, and thereby, the number of ships that can be tracked. If the limit is exceeded, ships are prioritised based on range, with the closer ones being given a higher priority – a basic requirement for collision-avoidance. In this manner, tracks of ships that are located further away may even be dropped altogether, especially in areas of heavy traffic-density.[15]

Range limitations

The only major limiting factor continues to be the limited range of a "line-of-sight" system. Transmissions from receivers fitted on tall structures such as masts or atop hills are received at longer ranges. Similarly, receivers fitted on aircraft have enhanced coverage. In instances where Anomalous Propagation (Anaprop) conditions prevail, the range of reception can be very significantly enhanced.[16] All this notwithstanding, the limitation on the number of available slots means that many messages can be dropped, due to message collisions. When receiving AIS transmissions from aircraft, for example, two vessels that were not "in-sight" of each other, could not negotiate slots. An aircraft, which by virtue of its height could "see" both such ships, could possibly receive simultaneous transmissions from both – thereby resulting in none of the messages being successfully demodulated thanks to mutual interference.

Despite these limitations, AIS has proved to be an invaluable tool for collating MDA, ever since it began to be used for that purpose.

Long range Identification and tracking – the solution that wasn't!

As the limitations of the AIS as a security tool were realised, a need was felt to introduce a system specifically covering beyond-line-of-sight vessels and in which integrity of information could be assured. This led to the "Long Range Identification and Tracking" (LRIT) system being internationally mandated.

Unlike AIS which is a "broadcast" that any user with a receiver can monitor, LRIT is a "point-to-point" signal that is controlled by the Flag State of the concerned vessel and is coordinated through internationally accepted agreements. Based upon the experience with AIS, IMO member-States had come to realise that if LRIT was to work, it needed to be: (1) satellite-based; (2) not an open broadcast network; (3) have restrictions on information-distribution; and (4) based on existing equipment so as to obviate the incurring of additional costs on procuring equipment and imparting training.[17]

Although there was broad consensus on how the proposed system should differ from existing ones, as the deliberations proceeded differences amongst IMO member States arose on the actual modalities of implementation. Most States had reservations about introducing a new system – so soon after implementation of the AIS – and were concerned about the costs. It was, therefore, decided that existing INMARSAT[18] (or equivalent) terminals that were already available aboard ships as a part of the GMDSS (Global Maritime Distress and Safety System) would be used. Accordingly, in January 2003, the IMO Sub-Committee on Radio communications and Search-and-Rescue (COMSAR) promulgated detailed guidelines for the "harmonization of GMDSS requirements for radio installations".[19] This was an attempt to solve the problem within the given limitations of existing equipment, so that no additional equipment would need to be installed.

Even so, as the discussions on the LRIT system progressed, changes were made to the characteristics originally envisaged. Eventually the system was adopted to provide only the ship's identity, position, and the date and time of that "position". Other parameters, such as the ship's course and speed, were dropped. This was justified as being logical, as both these parameters could change "immediately before, during, or after transmissions" rendering them of little use.[20] This logic is correct, especially if a four-hourly position report is received. Economic criteria may, therefore, have been an important factor in the system-design. In fact, in 2008, discussions were also held on the feasibility of increasing the default reporting-interval to 12 h, so as to further reduce implementation costs. As far as the position is concerned, the LRIT system does permit any authorised user to seek more frequent updates, but such a user would need to pay the cost of the satellite transmissions.

From the security perspective, of course, a longer reporting-interval, and the absence of kinematic parameters, placed severe constraints upon the utility of the LRIT system. As per the United States Coast Guard this would have "little, if any, adverse impact on the Maritime Domain Awareness benefits to be derived from LRIT," but it could degrade significantly the ability of agencies to conduct effective "track analysis".[21]

Although the LRIT system remains the only internationally mandated Vessel Tracking System designed *ab initio* from the security perspective, economic factors have resulted in very few States actually seeking the information that they are entitled to – such as positional information about all ships up to 1000 nm from their coasts – due to the prohibitive costs involved.[22]

Even for administrations such as the United States of America, which do seek information as per the maximum permitted entitlement, the LRIT is increasingly being seen as an "additional" source of information rather than a "primary" one. The final MDA would be compiled by using a number of systems, each contributing to a part of the solution to the puzzle. As per the US Coast Guard, "AIS satellite technologies improve US tracking capabilities and LRIT will continue to provide an *additional* tracking source of information"[23] (emphasis added).

Space based AIS – a midway solution

As the AIS system became mandatory in 2004, interest in the detection of AIS signals from space gained momentum[24] and many papers, proposing use of satellite based receivers, were written.[25] Even with the existing limitations of AIS, long-range detection at affordable costs seemed a particularly attractive proposition. Detection of AIS signals from aircraft was the first step, with space-based detection being the next logical extension.

Difficulties in space-based AIS

Space-based AIS, however, suffers from many problems. To begin with, the AIS antennae on board ships are designed for terrestrial communication – primarily in the horizontal plane. While many different types of antennae are in use, the most common is the static rod antenna.[26] Although AIS signals can, indeed, be received from space even when such an antenna is employed, it must be borne in mind that the system was never designed for this purpose and will therefore have limitations.

The difficulties related to the Space-AIS are well-known and have been adequately described.[27] Several of these difficulties have been progressively overcome, albeit to varying extents. The first experimental AIS satellite was launched in 2006 and numerous technical challenges soon became apparent.[28] Not all of these were unexpected, and some, indeed, had been predicted through modelling and some had even been catered-for. Prominent amongst the difficulties were the Doppler Shift due to the speed of the satellite; overlapping messages due to the larger Field of View (FoV) of the satellite vis-à-vis the SOTDMA cell; Faraday Rotation and attendant signal attenuation due to signals passing through the Earth's ionosphere; and, attenuation due to the longer range. Due to a combination of all these factors, demodulation of overlapped AIS messages proved to be a great challenge.[29]

Demodulation[30] of messages from space, especially in high-traffic zones, became difficult due to message collisions.[31] Some collisions were due to multiple simultaneous transmissions within the same time-slot, as had also been experienced (albeit to a lesser extent) by aircraft. A further source of collisions was due to "path delay", as signals, even when transmitted in distinct slots, could arrive simultaneously at the satellite receiver based on the difference in range from the satellite. This was the result of longer time delays in reception by the satellite vis-à-vis the maximum that the system had been designed for. AIS messages incorporate an extra 12 bits as a "buffer" for supporting path-delays. This is the interval in which no transmission takes place and there is, therefore, a "gap" between one transmission ending and transmission in the next slot commencing. No successive messages, therefore, overlap when received. This buffer caters for a relative transmission distance of approximately 375 km. Larger distances between two transmissions in adjoining slots, can lead to a rise in message-overlaps due to different propagation times. This is because a message from a distant ship, with a longer propagation time, can arrive at the receiver overlapping with a later message from a ship located closer.

A number of approaches, based on both, software and hardware, have been attempted to improve the demodulation capabilities of satellite-based receivers. Some of these are enumerated below:-

- Interference-Cancellation. This may be undertaken through repeated demodulation of received signals. In the first step, the successfully demodulated signal is subtracted from the initial (mixed) signal and the demodulation algorithm applied once again. This is termed "CSC" (Consecutive Signal Cancellation)[32] or, the Remod-Demod method.[33]
- Directional Suppression/ Isolation of Signals. Signals from different directions may be isolated using Phased Array antennas[34] or, through the use of varied Faraday rotation-angles to suppress certain signals.[35]
- Bandwidth-Separation through Doppler Shift. The received signal bandwidth would be spread across the central frequency with both positive and negative Doppler Shifts, depending on whether the satellite was approaching or receding from a ship. A process called "Zonal-Demodulation" gainfully utilises this.[36]

As per one estimate only about 60%–80% of AIS messages are tracked using space-based AIS (depending on the demodulation schemes in use)[37], with the problem being the worst in high traffic-density areas.

Existing space-AIS – not "ideal" but certainly "good"

Despite the limitations described earlier, the current space-based AIS receivers have contributed significantly to MDA. Receiving AIS messages from space[38] using the existing system, has become increasingly common and a number of satellites have been launched. Space-based AIS is also commercially available. This has enabled many data centres to compile global MDA. For example, the Centre for Maritime Research and Experimentation[39] (CMRE) reportedly received, as of 2012, an average of 600 million AIS messages per month from multiple sources.[40] Information that was hitherto virtually impossible to collate, except by the most advanced nations, is now available to everyone. Technology has become an enabler to use the system for a purpose for which it was never intended. Integrating space-based data with terrestrial data throws up additional issues with variable frequency update, coverage and persistence.[41] Data picked up by a satellite may be available at the MDA centre only after considerable delay. Correlation with terrestrial data, therefore, becomes important.

Despite various solutions, high traffic-density areas continue to pose difficulties. If the volume of received data is high, demodulation may still fail or only partially succeed. The only option available to reduce message-collisions is to reduce the AIS channel-load. The transmission interval may be made longer to achieve this. The only major consideration for transmission-interval would be that the signal from every ship should be transmitted during the "pass" of a satellite. This is the primary logic underpinning the new space-based AIS.[42]

Long range AIS – the next step

Even though space-based detection of AIS signals is fairly well-established, the introduction of a specific message designed for detection from space has the potential to transform the way vessels are tracked, especially when at a distance from land.

Work on a new Space-AIS standard to improve reception from space is proceeding apace. In 2009, the ITU undertook a detailed study on improving space-based detection of AIS.[43] Subsequently, technical documents promulgated by the ITU, including ITU-R M-1371-4 (2010) and ITU-R M.1084-5 (2012), defined the proposed technical characteristics of the space-AIS technology.

A new message type – the Long Range AIS Message (Message 27) was introduced. The transmitting-interval was fixed at three minutes. Given the limitations of slot-availability on the two existing AIS frequencies, two additional frequencies were exclusively allocated for Message 27. These new channels, called AIS3 and AIS4, at 156.775 and 156.825 MHz, respectively, correspond to Maritime Mobile Band (MMB) channels 75 and 76. Since ships would be geographically dispersed, slot-management may not be feasible through SOTDMA. Random Access TDMA (RATDMA) is therefore used. To further reduce the channel-congestion, smaller vessels, that use Class B AIS[44], are excluded from the new architecture.

Structurally, Message 27 very closely resembles the position-report rendered by the existing Message 1.[45] The most important change is that there are fewer data-bits per message (96 bits in Message 27 as compared to 168 bits in Message 1), which is achieved through a lower position-resolution and the exclusion of SOTDMA channel-status. This permits a large 96-bit buffer for each time-slot, which is now able to address the problem of overlap. This propagation delay-time ensures the avoidance of consecutive message-overlaps for range differences up to 1467 nm. A satellite antenna possessing a field of view of 90 degrees, would result in the available propagation delay being suitable for satellites at altitudes of up to approximately 1600 km. Since current AIS satellites are normally at an altitude lower than this, a larger field of view may be employed as well (a complete earth-horizon view corresponds to a 134-degree conical antenna opening, in the case of a satellite operating at an altitude of 560 km, and 128 degrees for a satellite operating at an altitude of 700 km).[46]

To further reduce the messages being transmitted to space, a greater cooperative opportunity between terrestrial and space AIS networks was also explored. The reporting of Message 27 can be suppressed in the proximity of coastal Base Stations. Since 2010, the "Ground Station Report" (AIS Message 4) contains a switching bit. This can be used to command an AIS transmitter on board a ship to cease space-AIS transmission. This is based on the logic that the particular ship would have been detected by the Base Station ashore (being within the line-of-sight of the latter) and this would free the satellites to monitor ships beyond this range without any interference. Dense shipping-areas, especially around harbours, can thus be prevented from interfering with space-AIS. This can, however, also have unintended consequences – especially in ANAPROP (anomalous propagation) conditions.

Atmospheric propagation conditions

Radio-wave propagation conditions, based on atmospheric conditions, will have an effect on AIS reception.[47] This aspect has, unfortunately, not received the attention that it deserves. With the suppression of Message 27 by Message 4, however, it may become critical in the years to come. As per one research[48] on the effect of atmospheric conditions on coastal radars and AIS systems in the North Sea, at the start of the research, only "two studies were found to analyse the impact of the atmospheric conditions on AIS performance; a 2011 study by Green et al.[49], which analyses such facets as could theoretically influence AIS performances, and, a 2007 report by the International Telecommunications Union (ITU)[50], which models the impact of some general propagation mechanisms on AIS, so as to analyse extended detection-ranges, but without looking at the atmospheric conditions behind it."[51] The detailed North Sea study, while being a pioneering effort, did not consider the effects on Space-AIS and Message 27.

ANAPROP conditions and their effect on AIS are important from the Indian viewpoint, as such conditions are prevalent in the North Arabian Sea for extended durations of the year, especially in the post-monsoon period. While the extension of the terrestrial AIS range from ashore was (and is) a welcome prospect, the adverse effects on space-AIS need to be catered-for as well.

Of the five common radio-wave propagation conditions (standard atmosphere, evaporation ducts, standard surface ducts, surface-based ducts, and elevated ducts) two (elevated and surface ducts) extend both AIS and radar detection ranges, whereas evaporation ducts extend only radar detection ranges. Theoretical "Standard" atmospheric conditions[52] lead to minimum detection ranges, for both radar and AIS.

The extended AIS range during ANAPROP conditions could mean that Message 27 is suppressed. Corresponding high radar-ranges could also imply that the same ship is picked up on radar, thereby being confused for a "dark ship" (i.e. one that is not transmitting on AIS).

The fact that Base-Station messages can suppress space-AIS detection on AIS3 and AIS4 frequencies over a large area during ANAPROP conditions implies that there may be an additional need to monitor the two primary frequencies. Also, the need for nations to collaborate with one another while collating MDA is apparent, as the Base Station operated by one country may well be receiving data, but access to this data may not be available to other nations without collaboration or data-exchange agreements.

Other problems with the reception of Message 27 include: (1) a fewer number of ships transmitting on this frequency as of date (this number will, however, increase with time as the system becomes more prevalent); (2) exclusion of Class B AIS from the architecture; (3) interference from land-based transmissions on the two frequencies designated for Message 27; and, (4) most shore-based receivers are not full-fledged Base Stations, but only passive receivers that are incapable of transmitting Message 4.[53]

These problems notwithstanding, the performance of one receiver on AIS channels designed for space-reception was found to be better, even in high density areas, than nominal AIS channels.[54] It is important to note that the receivers used in this study for quantifying the efficacy of space-AIS (including on nominal channels) were deployed in space and, therefore, have had their algorithms upgraded in-situ. Since refinements to algorithms are continually being devised, the satellites themselves need to have the capability of in-orbit upgrades. This is especially true when processing is done on board the satellite itself, rather than at a ground-station.

Implications and policy recommendations

Consequent upon ongoing changes in technology, a number of policy implications emerge – both technical and procedural. A few of these are summarised below:-

- AIS Satellites should ideally be designed for monitoring all four AIS frequencies. Monitoring only space-AIS frequencies may prove inadequate, especially in ANAPROP conditions.
- If limitations of satellite-design preclude the monitoring of four frequencies, preference should be given to monitoring one each of the space and terrestrial frequencies. This may provide better results under certain conditions, especially in North Arabian Sea.
- Monitoring of nominal AIS channels will continue to be important, especially if smaller vessels that use Class B receivers are also to be tracked.
- Since space-based AIS technology is still evolving, changes need to be incorporated over time and as experience grows. Similarly, newer and better algorithms for detection are being continually developed. The design of satellites should permit changes to be effected while in orbit. The use of Software Defined Radio is preferable to permit in-orbit reconfiguration.
- Atmospheric propagation prediction-software, which is commonly used for predicting radar-ranges, may also be used to predict AIS ranges. A dedicated study on the effects in the North Arabian Sea could be undertaken and would be useful.

- The need for data-sharing amongst entities and nations will become increasingly pronounced. Base Stations located in one country may render data unavailable to others (through Message 27) unless agreements for "white shipping" information-exchange are in place.

Conclusion

Technical solutions for tracking ships away from the coast so as to achieve global MDA are continuously evolving. Recent changes are bound to provide an unprecedented leap in this capability. There would, however, continue to be limitations, and a user should be aware of the basic technical details so as to understand these limitations.

Finally, there is a growing realisation that any Self Reporting System (SRS), such as the AIS, will necessarily have a strong "human element" in all stages of its exploitation. This "human element" is relevant, from the perspective of ship-board operators, as well as MDA-compilers. At the ship end, the human element can influence AIS by deliberate or inadvertent reporting of incorrect data. At the shore end, data received from AIS can be incorrectly interpreted, thereby providing wrong deductions, unless the functioning and the limitations of the systems are understood.

Defence Research and Development, Canada, had undertaken a study (in 2006) on the importance of trained manpower for optimal exploitation of any MDA system. They concluded that "understanding an SRS (Self-Reporting System such as AIS or LRIT) is less about physics and engineering than it is about social psychology, public relations and law. In short, there is a strong human element to SRS. Security centres should respond by hiring or developing more expertise in these areas".[55]

Notes

1. Resolution MSC.74(69), "Adoption of New and Amended Performance Standards," International Maritime Organisation, 1998.
2. International Convention for the Safety of Life at Sea (SOLAS), Chapter V, "Carriage Requirements for Shipborne Navigational Systems and Equipment".
3. Recommendation ITU-R M.1371-4, "Technical Characteristics for an Automatic Identification System Using Time-Division Multiple Access in the VHF Maritime Mobile Band," Radiocommunication Sector of International Telecommunication Union, 2010.
4. Arun Pratap Golaya, "Maritime Domain Awareness: Challenges and Effective Exploitation," in *Indian and American Perspectives on Technical Developments in the Maritime Domain and Their Strategic implications in the Indian Ocean Region*, ed. Pradeep Kaushiva and K.K Agnihotri (New Delhi: KW Publishers, 2013), 107.
5. In the SOTDMA multiplexing system, time is divided into slots, with each ship that is transmitting in a particular slot also "reserving" a subsequent vacant slot for itself. Other ships in the vicinity are free to transmit in the slots that are vacant and have not been reserved. In this way, two ships would not transmit at the same time. The AIS system has 2250 time slots per minute.
6. Ibid.
7. "Reliability of Ship-Identification System in Doubt," *Tradewinds*, September 7, 2007, 42.
8. Martin N. Murphy, "Lifeline or Pipedream? Origins, Purposes, and Benefits of Automatic Identification System, Long-Range Identification and Tracking, and Maritime Domain Awareness," in *Lloyd's MIU Handbook of Maritime Security*, ed. Rupert Herbert-Burns

et al. (Boca Raton Florida: CRC Press, 2009), 13–25. (Quoting a 2007 interview with an unnamed "maritime official").
9. Steve Carmel (Senior Vice President, Maritime Services for Maersk Line) as quoted by Matt Hilburn, "Broader Picture," *Sea Power* 50, no. 12 (2007): 33.
10. GNSS is a generic term covering satellite-based navigation systems with global coverage such as the Global Positioning System or GLONASS. Any of these can be used to provide positional information about the ship to the AIS. The position so received is then transmitted to other ships by the AIS.
11. Arun Pratap Golaya, "Maritime Domain Awareness: Challenges and Effective Exploitation," note 4, 111.
12. M. Baldauf, K. Benedict, and F. Motz, "Aspects of Technical Reliability of Navigation Systems and Human Element in Case of Collision Avoidance" (paper presented at Navigation Conference and Exhibition, London, UK, October 28–30, 2008).
13. Recommendation ITU-R M.1371-4, "Technical Characteristics for an Automatic Identification System Using Time-Division Multiple Access in the VHF Maritime Mobile Band," note 3.
14. Ibid.
15. Mariusz Kościelski, Ryszard K. Miler, and Mariusz Zieliński, "Automatic Identification System (AIS) as a Main Tool of NCAGS ADP Systems," 2007, https://www.amw.gdynia.pl/images/AMW/Menu-zakladki/Nauka/Zeszyty_naukowe/Numery_archiwalne/2007/Koscielski,_Miler,_Zielinski.pdf (accessed July 10, 2018).
16. ANAPROP conditions are said to exist when extended ranges are obtained due to radio waves travelling in "ducts", which are formed due to specific atmospheric conditions.
17. Martin N. Murphy, "Lifeline or Pipedream? Origins, Purposes, and Benefits of Automatic Identification System, Long-Range Identification and Tracking, and Maritime Domain Awareness", note 8.
18. INMARSAT terminals are satellite communication terminals provided commercially by a number of companies.
19. COMSAR/Circ.32 dated August 16, 2004, "Harmonization of GMDSS Requirements for Radio Installations on board SOLAS Ships".
20. Alice Lipowicz, "Coast Guard Plans Data Center to Monitor Vessels," *Washington Technology*, May 1, 2008.
21. Ibid.
22. The cost of each report is 25 cents thereby entailing a cost of 1 USD per ship tracked per day for six-hourly reports.
23. U.S. Coast Guard. "LRIT Frequently Asked Questions," https://www.navcen.uscg.gov/?pageName=lritFaq (accessed July 18, 2018).
24. G. Hoye, "Observation Modelling and Detection Probability for Space-Based AIS Reception – Extended Observation Area," Norwegian Defense Research Establishment, FFI/RAPPORT-2004/04390, 2004.
25. For example, see T. Eriksen et al., "Maritime Traffic Monitoring Using a Space-based AIS Receiver," *Acta Astronautica* 58 (2006): 537–49 and O.F.H. Dahl, "Space-based AIS Receiver for Maritime Traffic Monitoring Using Interference Cancellation" (M.S. thesis, Norwegian University of Science and Technology, Department of Electronics and Telecommunications, 2006).
26. Technical Report ITU-R M.2123, "Long Range Detection of Automatic Identification System (AIS) Messages Under Various Tropospheric Propagation Conditions," International Telecommunications Union, 2007.
27. For example, see M.A. Cervera, A. Ginesi, and K. Eckstein, "Satellite-based Vessel Automatic Identification System: A Feasibility and Performance Analysis," *International Journal of Satellite Communications and Networking* 29 (2011): 117–42; F. Hennepe et al., "Space-based Detection of AIS Signals" (5th Advanced Satellite Multimedia Systems Conference (ASMA) and the 11th Signal Processing for Space Communications Workshop (SPSC), 2010), 17–24; and, P. Burzigotti, A. Ginesi, and G. Colavolpe, "Advanced Receiver Design

for Satellite-Based AIS Signal Detection" (5th Advanced satellite multimedia systems conference (ASMA) and the 11th signal processing for space communications workshop (SPSC), 2010), 1–8.

28. T. Eriksen et al., "Tracking Ship Traffic with Space-Based AIS: Experience Gained in First Months of Operations" (paper presented at International Waterside Security Conference (WSS), Carrara, Italy, November 3–5, 2010).
29. Andis Dembovskis, "AIS Message Extraction From Overlapped AIS Signals for SAT-AIS Applications" (PhD dissertation, University of Bremen, 2015).
30. Demodulation is simply the process of "extracting" information embedded in a radio signal.
31. Collision could occur when two messages are received simultaneously at the receiver, possibly resulting in neither of them being demodulated.
32. O.F.H. Dahl, "Space-Based AIS Receiver for Maritime Traffic Monitoring Using Interference Cancellation" (M.S. thesis, Norwegian University of Science and Technology, Department of Electronics and Telecommunications, 2006).
33. A. Burzigotti et al., "Advanced Receiver Design for Satellite-Based AIS Signal Detection," note 27.
34. M. Zhou, A.J. Veen and R. Leuken, "Multi-User LEO-Satellite Receiver for Robust Space Detection of AIS Messages" (paper presented at IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Kyoto, Japan, March 25–30, 2012).
35. F. Hennepe et al., "Space-Based Detection of AIS Signals," note 27.
36. A. Burzigotti et al., "Advanced Receiver Design for Satellite-Based AIS Signal Detection," note 27.
37. Presentation made during the Workshop on International Standardisation of Next Generation AIS (VDE) organised by the Japanese Coast Guard at Tokyo, Japan 3–7 December 2017, http://www.sjofartsverket.se/pages/41996/e-NAV13-38%20Tokyo%20workshop%20report.pdf (accessed August 12, 2018).
38. G.K. Høye et al., "Space-Based AIS for Global Maritime Traffic Monitoring," *Acta Astronaut* 62 (2008): 240–5.
39. CMRE, earlier known as NATO Undersea Research Center, based in La Spezia, Italy is the executive body of NATO's Science and Technology Organisation which conducts research focused on technology development for the maritime domain.
40. G. Cimino et al., "Sensor Data Management to Achieve Information Superiority in Maritime Situational Awareness" (CMRE Formal Report, NATO, Brussels, Belgium, 2013).
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43. ITU Report ITU-R M.2169, "Improved Satellite Detection of AIS," Radiocommunication Sector of International Telecommunication Union, 2009.
44. "Class B" AIS can be used by vessels such as pleasure craft and yacht on which the system is not mandatory but which may want to install the system to reap its benefits. The specifications for this are less stringent.
45. Message 1 is the standard position report message used by AIS.
46. Andis Dembovskis, "AIS Message Extraction From Overlapped AIS Signals for SAT-AIS Applications," note 29.
47. E.R. Bruin, "On Propagation Effects in Maritime Situation Awareness: Modelling the Impact of North Sea Weather Conditions on the Performance of AIS and Coastal Radar Systems" (Utrecht University Master's Thesis, 2016).
48. Ibid.
49. D. Green et al., "VHF Propagation Study," Contractor report DRDC-ATLANTIC-CR-2011-152, Defence R&D Canada, 2012.

50. Technical Report ITU-R M.2123, "Long Range Detection of Automatic Identification System (AIS) Messages Under Various Tropospheric Propagation Conditions," note 26.
51. Ibid.
52. The International Standard Atmosphere is an atmospheric model (established to provide a common reference) to describe how pressure, temperature, density and viscosity of the Earth's atmosphere change over altitude. At Mean Sea Level (MSL), the values are 15 degrees centigrade temperature, 1013.25 hpa pressure and a lapse rate of −1.98 degrees centigrade per 1000 feet gain in altitude.
53. Andreas Nordmo Skauen, "Quantifying the Tracking Capability of Space-Based AIS Systems,"*Advances in Space Research* 57 (2016): 527–42.
54. Ibid.
55. Defence R&D Canada Technical Memorandum, 2006–32. "The Implications of Self-Reporting Systems for Maritime Domain Awareness," http://pubs.drdc.gc.ca/inbasket/hammond.061031_1017TM%202006-232.pdf (accessed April 21, 2012).

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