MEASURES TO ENHANCE MARITIME SECURITY

Satellite-based AIS Long-Range Identification and Tracking (LRIT)

Submitted by Norway

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Introduction

1 The annex to this document presents the possibility of establishing long-range identification and tracking (LRIT) by means of satellite-based AIS.

2 Reception of AIS signals by satellites will make AIS become a LRIT system, operating beyond the intended ship-to-ship and ship-to-shore communications.

3 With a sufficient number of satellites able to receive signals from AIS, together with shore-based AIS infrastructure, the AIS could provide LRIT with global coverage.

4 The annexed paper “Maritime Traffic Monitoring using a Space-based AIS Receiver” may be useful in the development of LRIT standards. The paper was first presented at the 55th International Astronautical Congress (held in Vancouver, Canada, 4 to 8 October 2004) by the Norwegian Defence Research Establishment.

Action requested of the Sub-Committee

5 The Sub-Committee is invited to note the annexed information and decide accordingly.

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ANNEX

MARITIME TRAFFIC MONITORING USING A SPACE-BASED AIS RECEIVER

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ABSTRACT

The Automatic Identification System (AIS) is a maritime safety and vessel traffic system imposed by the International Maritime Organisation (IMO). The system broadcasts position reports and short messages with information about the ship and the voyage. Using frequencies in the maritime VHF band, the coverage is similar to other VHF applications, and is essentially dependent on the altitude of the antenna. For ship-to-ship communications the range is typically 20 nautical miles and for ship-to-shore up to 40 nm. A space-based AIS receiver in low earth orbit will have a range to the horizon of more than 1000 nm, giving an excellent opportunity for large-area ocean surveillance. The Norwegian Defence Research Establishment (FFI) has performed a feasibility study on reception of AIS messages from space. The results show that a ship detection probability of near 100% can be obtained for up to 1000 ships within the coverage area, and that for a standard AIS receiver a signal power margin of 10 to 20 dB can be achieved. On this background, swath-width analyses for European scenarios are done. It is argued that space-based reception of AIS messages is a promising way of achieving long-range identification and tracking services at marginal cost.

1 INTRODUCTION

Norwegian waters amount to more than 1.2 million square miles, comprising the 200 miles economic zone, the fishery protection zone around Svalbard and the fishery zone around Jan Mayen. Fishing, shipping, and export of oil and natural gas are some of Norway’s largest industries. To ensure a sustainable development, the safety of people and installations as well as national sovereignty, a control system must be in place. Since 1991 radar satellite images have been used as an aid to surveillance of remote areas. A feasibility study at the Norwegian Defence Research Establishment (FFI) shows that space-based reception of messages from the cooperative Automatic Identification System (AIS) for ships gives an excellent opportunity to contribute further to the monitoring of remote areas [10].

The universal shipborne Automatic Identification System (AIS), as outlined by the International Maritime Organisation (IMO) in the International Convention for the Safety of Life at Sea (SOLAS)[1], is a shipborne transponder broadcasting ship, voyage, and safety-related reports.

The coverage of the system is similar to other VHF applications, and is mainly dependent on the range to the horizon from the position of the VHF antenna. A typical value at sea is 20 nm. In Norway, and several other nations, a network of AIS base stations is being built along the coast. This network will have a range of typically 40 nm and is expected to give significant improvements to the shore-side Vessel Traffic Services (VTS).

Nationally and internationally there also is an urge for long-range identification and tracking (LRIT) services. The AIS standard has an option for long-range applications. However, the IMO Sub-Committee on Radiocommunications and Search and Rescue (COMSAR) has stated that “considerable work need to be done before the Sub-Committee will be in a position to advise the Maritime Safety Committee on LRIT” [9].

From a satellite in 600 km altitude orbit, the range to the horizon is 1440 nm. The possibility of space-based reception of AIS messages from the existing VHF system could be part of the work to take into consideration, as a space-based receiver can provide long-range data at marginal cost.
This paper gives a brief introduction to the AIS system in section 2. On this background space-based message reception is treated and swath width analyses are made for two European scenarios in section 3. Fig. 1.1 shows a European scenario where the satellite is descending across Europe, with markers representing vessels at a ratio of 100:1. Coverage areas of diameter 800, 1200, 1900 and 2880 nm are used in the analysis. Some system considerations are made in section 4, and the conclusions are presented in section 5.

2 THE AIS-SYSTEM

2.1 Background

According to the International Association of Maritime Aids to Navigation and Lighthouse Authorities (IALA), the purpose of AIS is “to improve the maritime safety and efficiency of navigation, safety of life at sea and the protection of the marine environment” [5]. IALA presented the first proposal for AIS to IMO in the early 1990’s. The original motivation for the system was to get means to identify vessels on the radar screen.

The IALA Technical Clarifications on ITU Recommendation ITU-R M.1371-1 [5] says further: “It was long been realized that an automatic reporting device fitted to a ship would have the potential to increase significantly the safety of navigation and would allow the improved control and monitoring of the maritime events. Taking up this challenge, IMO together with the International Telecommunications Union (ITU) and the International Electrotechnical Commission (IEC) developed a new navigation system called the Automatic Identification System (AIS).”

The implementation plan and requirements for AIS are outlined in Subparagraph 2.4 of Regulation 19 of Chapter V of the International Convention for the Safety of Life at Sea (SOLAS) [1]. The system has been mandatory on all new ships in international traffic since 1 July 2002, and will by the end of 2004 include all passenger ships, tankers and other ships of 300 tons engaged in international voyages. Fully implemented in 2008, the system will also cover all ships of 500 tons or more in national voyages. The requirements state that:

“AIS shall:
1. provide automatically to appropriately equipped shore stations, other ships and aircraft information, including the ship’s identity, type, position, course, speed, navigational status and other safety-related information;
2. receive automatically such information from similarly fitted ships;”

Fig. 1.1: Illustration of a European scenario with targets representing vessels and the satellite in a descending pass, shown as a dotted black line. Swath widths of 800, 1200, 1900 and 2880 nm are shown in white.
3. monitor and track ships; and
4. exchange data with shore-based facilities.

AIS shall be operated taking into account the guidelines adopted by the Organization. Ships fitted with AIS shall maintain AIS in operation at all times except where international agreements, rules or standards provide for the protection of navigational information.”

Ships covered by regulation 19 are defined as SOLAS Class A ships, and a mobile AIS station is mandatory on these ships. Work is also under way at IEC to develop an equipment recommendation for SOLAS Class B ships [8], but AIS on these ships is at present not mandatory.

Long-range applications are described in Annex 4 of ITU Recommendation M.1371-1 [6]. The Annex states that “the AIS equipment provides for two-way long-range communications, and that the reporting rate will be 2-4 times per hour.” COMSAR has expressed the view that “a cost benefit analysis and study need to be undertaken before the issue of LRIT can be pushed further” [9]. At present, there is no plan for mandatory long-range reporting.

Standards, guidelines and clarifications for AIS and its implementation have been developed by IMO [3] together with IALA [4], [5], the International Telecommunications Union (ITU) [6], and the International Electrotechnical Commission (IEC) [7].

2.2 Operational characteristics

AIS is developed as a ship-to-ship and ship-to-shore reporting system. AIS-equipped ships periodically broadcast position reports and ship, voyage, and safety-related messages that are received by other ships and shore-based stations.

The mobile AIS station onboard the ship consists of VHF radio equipment connected to the ship’s sensor and display systems. Position and timing information is normally derived from a satellite navigation system (e.g. GPS). The reporting system is based on broadcasting of fixed-length digital messages. A position report from an AIS station fits into one of 2250 time slots entered into a frame established every 60 sec. Messages are broadcasted alternately on two VHF channels giving a total capacity of 4500 message slots per minute.

AIS uses Time Division Multiple Access (TDMA) access schemes to allocate time slots and avoid overlap of transmissions within the AIS station’s coverage area. When a message is sent, the station also pre-announces its next transmission slot. Fig. 2.1 illustrates the access scheme.

Fig. 2.1: The AIS access scheme.

2.2.1 AIS messages

There are 22 message types, which can be grouped into the categories of Table 2.1. All messages uses the Maritime Mobile Service Identities (MMSI) number as source ID.

<table>
<thead>
<tr>
<th>Message type</th>
<th>Description</th>
<th>Reporting interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>ship IMO number, call sign &amp; name, length &amp; beam, etc.</td>
<td>6 min</td>
</tr>
<tr>
<td>Dynamic</td>
<td>position, time, course over ground, speed over ground, heading, etc.</td>
<td>2 sec to 3 min depending on dynamic conditions, see Table 2.2.</td>
</tr>
<tr>
<td>Voyage</td>
<td>destination, cargo type, waypoints, etc.</td>
<td>6 min</td>
</tr>
<tr>
<td>Safety</td>
<td>safety related text</td>
<td>as required</td>
</tr>
<tr>
<td>Control</td>
<td>UTC, synchronisation</td>
<td>as required</td>
</tr>
</tbody>
</table>

Table 2.1: Class A shipborne mobile equipment massage types.

The dynamic messages are of particular interest to large-area ocean surveillance, as they are reported often and contain a ship’s identity and position. Reporting intervals for dynamic messages from
Class A ships are shown in Table 2.2. Class B messages have longer reporting intervals [6].

<table>
<thead>
<tr>
<th>Ship’s dynamic conditions</th>
<th>Reporting interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship at anchor or moored and not moving faster than 3 knots</td>
<td>3 min</td>
</tr>
<tr>
<td>Ship at anchor or moored and moving faster than 3 knots</td>
<td>10 s</td>
</tr>
<tr>
<td>Ship 0-14 knots</td>
<td>10 s</td>
</tr>
<tr>
<td>Ship 0-14 knots and changing course</td>
<td>3 1/3 s</td>
</tr>
<tr>
<td>Ship 14-23 knots</td>
<td>6 s</td>
</tr>
<tr>
<td>Ship &gt;23 knots and changing course</td>
<td>2 s</td>
</tr>
<tr>
<td>Ship &gt;23 knots</td>
<td>2 s</td>
</tr>
</tbody>
</table>

Table 2.2: Class A shipborne mobile equipment reporting intervals for dynamic messages.

2.3 Technical characteristics

A space-based AIS receiver is dependent on the performance and characteristics of the physical layer and the link layer of the AIS system. A short summary of their specification is presented.

2.3.1 Physical layer

The physical layer is responsible for the transfer of a bit-stream out on the data link. A summary of performance requirements for the physical layer is given in Table 2.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequencies</td>
<td>161.975 and 162.025 MHz (channel 87B and 88B)</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1.85 m</td>
</tr>
<tr>
<td>Transmitter power</td>
<td>2 and 12.5 W</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>12.5 and 25.0 kHz</td>
</tr>
<tr>
<td>Modulation</td>
<td>Gaussian Minimum Shift Keying (GMSK)</td>
</tr>
<tr>
<td>Modulation index</td>
<td>0.25 for 12.5 kHz and 0.5 for 25 kHz</td>
</tr>
<tr>
<td>Receiver sensitivity</td>
<td>-107 dBm for 25 kHz and -98 dBm for 12.5 kHz bandwidth</td>
</tr>
<tr>
<td>Bit rate</td>
<td>9600 bit/s</td>
</tr>
</tbody>
</table>

Table 2.3: Extract of AIS physical layer requirements.

By default, an AIS station broadcasts alternately on channels 87B and 88B. Other channels can be applied in some regions. Transmitter power of 12.5 W and bandwidth of 25 kHz are default settings for the open oceans.

2.3.2 Link layer

The link layer specifies how data is packaged, how access to the link is managed, how the system is synchronized, as well as message types and descriptions.

The system uses the concept of a frame that is 1 minute long and divided into 2250 slots, giving a slot length of 26.7 ms or 256 bits at 9.6 kbps. Synchronization is achieved using one of four Time Division Multiple Access (TDMA) access schemes (see Table 2.4) that can operate autonomously.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronization</td>
<td>UTC</td>
</tr>
<tr>
<td>Message length</td>
<td>26.7 ms (256 bits)</td>
</tr>
<tr>
<td>Frame length</td>
<td>1 minute (2250 messages)</td>
</tr>
<tr>
<td>Capacity</td>
<td>4500 messages/min (for the two AIS channels)</td>
</tr>
<tr>
<td>Distance delay</td>
<td>12 bits, equivalent to 202 nm</td>
</tr>
<tr>
<td>Access schemes</td>
<td>SOTDMA, ITDMA, RATDMA, FATDMA</td>
</tr>
<tr>
<td>Message types</td>
<td>See Table 2.1 and Table 2.2 above.</td>
</tr>
</tbody>
</table>

Table 2.4: Extract of AIS link layer requirements.

The message entry is synchronized to the universal time coordinated (UTC). The distance delay bits prevent problems with overlapping messages due to different signal path lengths up to a range of 202 nm. This is useful also for the space-based application.

Self-Organizing TDMA (SOTDMA) is the basic access scheme used for scheduled repetitive transmissions from an autonomous station. The access scheme allocates time slots and resolves potential conflicts autonomously. Fig. 2.2 shows a simplified illustration of the access scheme.
At power on, a station monitors the TDMA channels for 1 minute to determine channel activity, other participating member IDs, current slot assignments and reported positions of other users. The station then enters the network and starts to transmit reports according to its own schedule.

The first slot used by a station to announce itself on the data link is called the Nominal Start Slot (NSS). Other repeatable transmissions are generally selected with the NSS as reference.

The Nominal Slot (NS) is used as the centre around which slots are selected for transmission of position reports. For the first transmission in a frame, the NSS and NS are equal. The NS is given by

\[ NS = NSS + n \cdot NI, \quad (0 < n < Rr) \]  

where \( n \) is an integer, \( Rr \) is the Report rate, i.e., the number of position reports per frame, and \( NI \) is the Nominal Increment.

The Report rate relates to the reporting interval \( \Delta T \) as follows

\[ Rr = \frac{60}{\Delta T} \]  

The Nominal Increment is given in number of slots and is found from

\[ NI = \frac{2250}{Rr} \]  

where 2250 is the number of slots per frame.

The Selection Interval (SI) is the collection of slots that can be candidates for position reports. It is centred around the Nominal Slot, and covers the interval

\[ SI = \{NS - 0.1NI, NS + 0.1NI\} \]  

Finally, the Nominal Transmission Slot (NTS) is the slot used for the transmission. The Nominal Transmission Slot is chosen applying randomisation within the Selection Interval.

A summary of the parameters is given in Table 2.5.

### 3 SPACE-BASED AIS CONCEPT

#### 3.1 Space-based surveillance

FFI continues the development of operational ship detection services. Requested data products are position reports containing vessel identification, as well as more timely information. A system for passive detection of navigation radars was presented at the 8th International Symposium on Re-

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Symbol Description</th>
<th>Equation</th>
<th>Min val</th>
<th>Max val</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Start Slot</td>
<td>NSS</td>
<td>The first slot used by a station to announce itself on the data link.</td>
<td>-</td>
<td>0</td>
<td>2249</td>
</tr>
<tr>
<td>Nominal Slot</td>
<td>NS</td>
<td>The centre around which slots are selected for transmission of position reports.</td>
<td>(2.1)</td>
<td>0</td>
<td>2249</td>
</tr>
<tr>
<td>Report Rate</td>
<td>Rr</td>
<td>Number of position reports per frame.</td>
<td>(2.2)</td>
<td>1/3</td>
<td>30</td>
</tr>
<tr>
<td>Nominal Increment</td>
<td>NI</td>
<td>The distance (number of slots) between two Nominal Slots.</td>
<td>(2.3)</td>
<td>75</td>
<td>6750</td>
</tr>
<tr>
<td>Selection Interval</td>
<td>SI</td>
<td>The collection of candidate slots for position reports.</td>
<td>(2.4)</td>
<td>0.2*NI</td>
<td>0.2*NI</td>
</tr>
<tr>
<td>Nominal Transmission Slot</td>
<td>NTS</td>
<td>The slot used for transmission.</td>
<td>-</td>
<td>0</td>
<td>2249</td>
</tr>
</tbody>
</table>

Table 2.5: The SOTDMA parameters.
mote Sensing in 2001 [11]. At the 4th IAA Symposium on Small Satellites for Earth Observation in April 2003 [12], ideas for fusion of data from radar and passive sources were presented, as well as the possibility of using a space-based AIS receiver. A spin-off of this activity is the student satellite project NCUBE currently under development [13].

The feasibility of a space-based AIS system for long-range identification and tracking of ships is discussed with focus on the following subjects:

1. Signal power in space.
2. Detection probability from space.
3. Scenarios for coverage of Europe.
4. Considerations for space-based system.

3.2 Glossary

The terms used in this paper are in compliance with the ITU Recommendation [6] and the corresponding IALA Clarifications [5]. However, when going beyond the intended range of the AIS specification, properties of the system change and new behaviour emerges. The following terms are defined to handle such properties:

**Space-based AIS receiver**: The receiver part of an AIS station on a satellite, receiving simultaneously on both AIS channels.

**Organized area**: The area within communications range of an AIS station on a ship. Within this area the slot allocation is organized by the TDMA-algorithm, in order to avoid coinciding transmissions.

**Coverage area**: The instantaneous footprint of the receiver’s field of view on the earth, consisting of several organized areas.

**Swath**: The area on the earth swept by the coverage area as the satellite moves.

**Simultaneous arrival**: Ships in different organized areas transmit messages independently of each other. Simultaneous arrival is when two or more messages coincide at the receiver. Messages arriving simultaneously will be lost.

**Detection probability**: The probability of detecting one or more position report from a vessel.

For coverage area and swath considerations, a near-polar 600 km altitude orbit and a nadir pointing AIS receiver is anticipated. Fig. 3.1 shows an example of a coverage area with diameter 400 nm containing several organized areas.

Fig. 3.1: Illustration showing the coverage area containing several organized areas.

3.3 Signal power in space

For the ship-to-satellite link the received signal power $P_r$ can be calculated using Friis transmission equation

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2$$  \hspace{1cm} (3.1)

where $P_t$ is the transmitted power, $G_t$ the transmitter gain, and $G_r$ the receiver gain. The term $\left(\frac{\lambda}{4\pi d}\right)^2$ is the path loss, where $d$ is the path length and $\lambda$ the wavelength.

3.3.1 High AIS settings

The high AIS settings are default on the open oceans. The transmitter power is 12.5 W, and the channel spacing is 25 kHz. Both carrier frequencies correspond to a wavelength of 1.85 m.

For the shipborne VHF transmitter antenna an omnidirectional radiation pattern is anticipated. An on-axis gain of 3 dB horizontally and a simple cosine elevation pattern is anticipated.

For the satellite receiver antenna a gain of 3 dB is used for a coverage area to the horizon. Fig. 3.2 shows the computed signal power vs. ground range for an orbit altitude of 600 km.
The variation in signal power vs. ground range is due to the angular dependency of the antenna gain and the range dependency of the path loss. The calculated signal peaks to a value of -89 dBm at a ground range of 200 nm. The signal received from a transmitter close to the horizon is -99 dBm. For shorter ground ranges the received signal is stronger except for a small “hole” around nadir, caused by the null of the transmitter antenna diagram at 90°. The “hole” is, however, less than 20 nm (-99 dBm level), and detection of ships passing through the centre of the coverage area is made before and after.

Anticipating a standard AIS receiver with sensitivity of -107 dBm, the signal power at the peak is 18 dB above the receiver sensitivity, and 8 dB above the sensitivity at the horizon. This indicates adequate margin for space-based reception of AIS messages when default operating settings apply.

### 3.3.2 Low AIS settings

The low AIS settings should only be used by assignment from the appropriate authority in territorial waters. When the low channel spacing setting of 12.5 kHz is applied, the sensitivity specification is -98 dBm. The peak signal power in the calculation is 9 dB above this value. If the low transmitter power setting of 2 W is also applied the signal power falls to -96 dBm, which is at the lower limit of the specification. If detection of messages sent with low power and bandwidth settings is desired, a more sensitive receiver should be considered.

However, as important as the power level vs. the sensitivity, is the 7 dB decrease in signal power relative to the power level of 12.5 W. Signals transmitted at 2 W will be closer to the threshold limit, and the swath width will be narrower if a directional receiver antenna is applied.

On the other hand, reducing the power in coastal waters makes these vessels less visible from space. This is favourable for detection of vessels on the open oceans because it reduces the probability of simultaneous arrival of messages.

### 3.3.3 Signal power vs. satellite altitude

For orbit altitude selection, the signal power variation vs. altitude has been studied. The sensitivity of the received signal power to a variation in distance is approximately -1 dB/100 km. It seems reasonable to assume that the AIS signals can be received for orbits up to 1000 km altitude under the given assumptions.

### 3.4 Detection probability from space

#### 3.4.1 Simultaneous arrival of messages

The allocation of message slots is coordinated only within each organized area. When observing several organized areas, two mechanisms can cause simultaneous arrival of messages:

1. AIS messages are sent in the same time slot from different organized areas.
2. AIS messages are sent in adjacent time slots from different organized areas, but overlap partly at the receiver due to different path lengths.

The AIS standard has a buffer of 12 delay bits, equivalent to a path length of 202 nm, to avoid overlap of messages sent in adjacent timeslots. From 600 km altitude, the 202 nm difference in path length is equivalent to a ground range of 394 nm, or a swath width of almost 800 nm, see Fig. 3.3.

The statistical analyses of ship detection probability in section 3.4.2 have been restricted to coverage areas of up to 800 nm (corresponding to a FOV of 96°). In section 3.4.3 the statistical analyses have been extended to also deal with the second mechanism for simultaneous arrival of messages for swath widths greater than 800 nm.
3.4.2 Detection probability within 800 nm

Detailed analyses of the ship detection probability from space have been performed [14]. The analytical analyses were based on the following assumptions:

1. The coverage area is a square.
2. The size of each organized area is 40x40 nm.
3. The ships are evenly distributed within the coverage area.
4. All ships transmit with the same reporting interval, $\Delta T = 10$ s.

The reporting interval of 10 s reflects an assumption that the typical ship travels at a speed of less than 14 knots.

The system has been modelled in accordance with the SOTDMA access scheme used by the AIS system.

The detection probability $P$ for a given ship within the coverage area can be written

$$P = 1 - \left[ 1 - \left( 1 - \frac{N}{75 \cdot M \cdot \Delta T} \right)^{M - 1} \right]^{\frac{T_{obs}}{\Delta T}} \quad (3.2)$$

where $M$ is the number of organized areas, $N$ is the number of ships, $\Delta T$ is the reporting interval, and $T_{obs}$ is the observation time.

Three parameters in equation (3.2) relates directly to the swath width; $M$, $N$, and $T_{obs}$. Analyses in [14] have shown that the number of organized areas $M$ within the coverage area does not affect the detection probability significantly.

Two parameters then remain that are important for the detection probability:

1. The number of ships within the coverage area, $N$.
2. The observation time, $T_{obs}$.

Increasing the swath width increases the observation time$^1$, and thereby the detection probability for a given number of ships within the coverage area. This can be seen from Fig. 3.4, which shows the detection probability as a function of number of ships for coverage areas with diameter of 80, 200, 400, 600, and 800 nm. However, increasing the swath width also increases the number of ships within the coverage area, thereby lowering the detection probability. Which of these two factors that dominate depends on the scenario, and the optimum swath width will therefore be scenario dependent.

![Fig. 3.4: Ship detection probability as a function of number of ships for different swath widths assuming the ships are evenly distributed within the coverage area.](image)

A model of the space-based observation system has been developed and applied to two scenarios representing realistic ship distributions in Norwegian waters. Assumptions 1, 2, and 4 from the analytical approach have been applied, but the simulations have been used to investigate the detection probability for uneven vessel distributions. The first scenario is a typical scenario with respect to number of vessels in open oceans, having 196 vessels in the Barents Sea. The second scenario is a worst-case scenario having high numbers of

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$^1$ For a square coverage area an increase in swath width is equivalent to an increase in the length (along track) of the coverage area, which gives a longer observation time.
vessels on the oceans as well as high coastal traffic, giving totally 1110 vessels in Norwegian waters.

The results show that the typical scenario from open oceans is so sparsely populated that the ship detection probability is 100% for all swath widths. For the worst-case scenario the detection probability is better than 99% for all swath widths up to 800 nm.

The ship detection probabilities found through modelling of the observation system and simulating different swath widths for the scenarios show the same trend as the results from equation (3.2) for even ship distribution. Equation (3.2) can therefore be used as a good approximation for realistic ship distributions.

Note that the worst-case scenario assumes high-density ship traffic only in parts of the coverage area. For scenarios with high ship densities over large areas the results from the analyses will be different.

### 3.4.3 Detection probability beyond 800 nm

Equation (3.2) has been developed further to also include simultaneous arrival of messages sent in adjacent time slots. Swath widths larger than 800 nm can then also be considered.

The same four assumptions as in the previous section have been used, except that the reporting interval is decreased to 6 s, which indicates that the typical ship travels at a speed of more than 14 knots. The detection probabilities versus number of vessels and swath width in Fig. 3.5 show a small reduction of detection probability when increasing the swath beyond 800 nm. A more important characteristic is that the roll-off of the probability occurs at the same number of vessels for all the swaths, and that one must go down to low probabilities before the swath width makes a significant difference.

Again, in the real world the ship distribution will not be even. However, we do expect that the results calculated for even ship distributions can be used as a good approximation for realistic ship distributions. In fact, uneven distributions are expected to increase the detection probability for a given number of ships, because the organisation within the high-density areas will reduce the number of simultaneous transmissions.

The analyses shows that the ship detection probability is 99% at about 1200 ships for 800 nm swath and \( \Delta T = 10 \, \text{s} \), whereas the 99% level is reached at about 900 ships for swaths wider than 800 nm and \( \Delta T = 6 \, \text{s} \).

### 3.5 Scenarios for coverage of Europe

To treat large-area space-based AIS reception, scenarios for European waters have been used. The vessel distribution is based on the worst-case number of 1110 for Norwegian waters and on the web site aislive.com for the southern North Sea, which typically shows between 600 and 700 vessels. For the rest of Europe and the Atlantic, as well as at the boundary to Africa, Asia, and America, estimates are made. The total number of vessels is 9500. Fig. 1.1 and 3.7 show the vessel distribution, with one marker on the map for each 100th vessel, and the satellite in two passes. The first is a pass over entire Europe, the second is a pass favourable to northern Europe.

Although the scene is populated using estimates, the analyses should be appropriate to capture the essential characteristics with respect to detection probability vs. swath width. In the simulations, a 600 km sun synchronous orbit, inclination 98°, making almost 15 complete revolutions per day, is used.

The coverage is simulated for 24 hours, and the access times are recorded for all markers, as illus-
Fig. 3.6: The visibility of markers during a day for 2880 nm swath.

For the 2880 nm swath the number of vessels exceeds 2000 in 10 passes, and peaks to values greater than 5000 in 5 of the passes. The access time is 150-160 min for the Barents Sea, about 70 min for the English Channel, and 50-60 min in the Mediterranean. The average observation time per pass with access is 10 min.

Applying the results of the previous sections along with a requirement for a ship detection probability of 99%, about 1000 vessels could be in the swath at any time. To find the appropriate swath width, the satellite is modelled with four sensors giving swath widths of 800, 1200, 1900, and 2880 nm, the last being the local horizon. Table 3.1 gives the results of simulation for the four sensors.

<table>
<thead>
<tr>
<th>Swath width (nm)</th>
<th>FOV (deg)</th>
<th>Area (1000 nm²)</th>
<th>Relative area (-)</th>
<th>Obs time (s)</th>
<th>Num vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>96</td>
<td>457</td>
<td>0,07</td>
<td>153</td>
<td>1240</td>
</tr>
<tr>
<td>1200</td>
<td>116</td>
<td>1120</td>
<td>0,17</td>
<td>254</td>
<td>2090</td>
</tr>
<tr>
<td>1900</td>
<td>128</td>
<td>2750</td>
<td>0,43</td>
<td>435</td>
<td>3660</td>
</tr>
<tr>
<td>2880</td>
<td>132</td>
<td>6424</td>
<td>1,00</td>
<td>599</td>
<td>5400</td>
</tr>
</tbody>
</table>

Table 3.1: Observation modelling of different swaths.

For each swath width the corresponding field of view (FOV) is given. The coverage area of the sensor is in thousand square nautical miles, and the relative area is relative to coverage to the horizon. The observation time is the average observation time for all markers and all accesses. The number of vessels is the peak instantaneous number of vessels averaged over the observation time, occurring during the first of the passes in Fig. 3.7.

The observation time and the number of ships within the field of view are both essential for the ship detection probability. Relevant representations for these figures are the mean coverage time and the mean number of vessels. These values are listed in Table 3.1. The time variation of the number of vessels is plotted for some passes and swath widths in Fig. 3.7.

Fig. 3.7: Average number of vessels during four passes over Europe.

Note that the plot shows the mean number of vessels, averaged over the mean observation time, because this is the relevant figure. The instantaneous number of vessels can be about 20% higher at the peak. The deviation gets larger the more tapered the curve is, and the longer interval the averaging is made for. That is, the deviation is largest for the 2880 nm swath, for the narrower swaths the deviations tend to get smaller as the averaging time gets shorter.

Two different scenarios are studied with respect to the number of vessels in the coverage area.

**Scenario 1**

Optimum pass for Norway and Europe: descending pass across the Barents Sea, the Baltic Sea and the Mediterranean.

For coverage to the horizon, the Norwegian Sea, the North Sea, Bay of Biscay and large parts of the North Atlantic is covered. Coverage is shown...
on the map in Fig. 1.1. The number of vessels for different swaths is the first pass at 12:00 in Fig. 3.7.

Requiring 99% ship detection, the swath width should be 800 nm.

**Scenario 2**
Optimum pass for the Barents Sea and Northern Atlantic: ascending over Siberia and descending over Greenland.

For coverage to the horizon, the Baltic Sea and the North Sea is also covered. Coverage is shown on the map in Fig. 2.8. The number of vessels for different swaths is the last pass in Fig. 3.7.

Requiring 99% ship detection probability, the swath width should be 1900 nm.

### 3.5.1 Coverage vs. orbit altitude

The shortening of the range to the horizon vs. orbit altitude is 233 nm going from 600 km to 400 km, and an elongation of the range of 203 nm occurs when increasing to 800 km.

Considering the results from the analyses of swath widths, the low sensitivity of the horizon range to the orbit altitude does not imply restrictions on the selection of orbit.

### 3.6 Discussion

The ship detection probability and swath width analyses are based on two reporting rates. The results for 800 nm swath and wider show that the detection probability is 99% at about 1200 ships for $\Delta T = 10$ s, whereas 99% level is reached at about 900 ships for $\Delta T = 6$ s. The actual distribution of reporting rates has not been modelled, but it seems reliable to recommend that the coverage area can contain a number of 1000 vessels.

In the European scenarios the number of vessels are based on sources for Norwegian waters and the southern North Sea, whereas the rest is a best guess estimate. The total number, including the boundaries, is 9500 vessels. The simulations are used to capture the essential characteristics of the detection probability for different swath widths and vessel densities. Requiring 99% ship detection probability, a swath of 1900 nm can be applied in remote ocean areas in the north, whereas 800 nm is appropriate when dense traffic in Europe is within the coverage area.

The new equation applied for the ship detection probability for swaths wider than 800 nm is not verified against an observation model yet, and the results should be considered preliminary.

The requirement for 99% percent detection prob-

![Fig. 3.8: A European scenario with targets representing vessels and the satellite passing over the Arctic region. Swath widths are 800, 1200, 2000 and 2880 nm.](image-url)
ability is applied to provide high reliability on operational services. A demonstration satellite for the open oceans and the Arctic regions may have coverage to the horizon. This will give good experience with the signal environment from low earth orbit.

Two features of the AIS system are not analysed here:

1. The use of other frequencies than the default channels.
2. The use of the low power settings in waters with dense traffic.

Both may cause fewer signals that can interfere in the messages reception (earlier referred to as simultaneous arrival). Hence, a higher number of vessels can be in the coverage area.

4 | SYSTEM CONSIDERATIONS

The AIS system is expected to give significant improvements on the safety at sea and on shore-side vessel traffic services. With the AIS system implemented on vessels and in coastal networks, data sources and infrastructure that can provide long-range identification and tracking data from a possible future space-based receiver already exist.

Link-budget calculations show that the AIS signals can be detected with a margin of more than 10 dB relative to the sensitivity specification of a standard AIS receiver. Standard AIS equipment can be utilized in the satellite, maybe with some enhancements due to the launch and space environment, but the performance is proven.

Statistical detection probability analyses show that for swath widths up to 800 nm the detection capacity increases with swath width. For swath widths greater than 800 nm, the capacity for a detection probability of 99% is about 1000 vessels.

The appropriate swath width to obtain 99% detection probability is dependent on the number of vessels on the scene. For the European scenarios, a swath width of 1900 nm is appropriate for Northern Europe, while 800 nm should be used to avoid saturation for coverage of all of Europe. Even applying the narrowest swath of 800 nm will give frequent and timely information from most ocean areas.

The analyses calls for a directional antenna, the swaths above are equivalent to a field of view of 128° and 96°. The swath width must be defined by the antenna pattern of the receiver. The AIS standard calls for an in-band signal suppression of 10 dB to avoid interference.

The link-budget calculations used an antenna gain of 3 dB, which should be easily obtained when a directional antenna is required from a detection probability field of view. Further, the in-band signal suppression imposes a side-lobe level of between -5 and -10 dB, dependent on the swath width chosen.

The on-board data storage requirement, assuming that one position report from each of 10,000 vessels should be stored and forwarded, is about 2 Mbyte. Assuming a downlink time of 600 s, the required downlink rate becomes 34 kbit per second. The on-board data-handling capacity must also be specified, larger amounts of data and shorter downlink times may be requested, but the requirements will be well within the performance of state-of-the-art systems.

A space-based AIS receiver may be suitable for a micro-satellite mission. The specifications of a standard AIS receiver unit are well within typical micro-satellite specifications. The pointing and stability requirements are expected to be of the order of 1°, mainly dependent on the swath width and the antenna pattern chosen. If a directional antenna is chosen, the main challenge will be that a directional VHF antenna will be 3.7 m long, assuming a helical antenna of length 2λ. Antenna design and deployment mechanisms should be studied to make a suitable selection of coverage area with respect to antenna design.

The satellite, or constellation, requires one control station and one or more downlink stations as gateways to the AIS data network. The number is dependent on the area of operation, but for timely delivery of messages, gateways should be located so that data can be downlinked directly for areas of permanent interest.

Small, if any, modifications are necessary at the user end. The VTS are already including AIS messages. The data correlation and display system
must, however, handle messages that are not repeated continuously, and may propagate the vessels according to their reported speed and course.

5 CONCLUSION

The proposed space-based AIS receiver makes use of the AIS system beyond the intended ship-to-ship and ship-to-shore communications. Requiring only small additions to the system, the concept extends the operational range of AIS to the open oceans.

The analyses show that space-based message reception is possible. In terms of signal power a margin of 10 to 20 dB relative to the sensitivity of a standard receiver can be achieved. The detection probability can be as high as 99% for approximately 1000 vessels.

The swath width must be considered with respect to relevant scenarios. The simulations for European waters show that for remote ocean areas, a swath width of 1900 nm is found suitable, whereas for European waters with high traffic density 800 nm seems more appropriate.

For concept development and experimentation, a satellite with coverage to the horizon can give reliable services in sparsely trafficked waters, and real numbers for the ship detection rate. Such experience with the signal environment can be crucial for specification of operational satellites with global coverage.

IALA’s original motivation for the AIS system was the identification of ships on the radars. Space-based AIS can give more than that, and may be considered as one alternative in the cost benefit analysis on long-range applications requested by IMO’s COMSAR sub-committee.

The installation of AIS on ships is going on, the infrastructure and the services in the vessel traffic centres are being developed. A satellite with an AIS receiver and a gateway to the existing infrastructure can add long-range identification and tracking services to the system.

A small investment can extend the range of the vessel traffic services across the ocean.

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