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# FFI RAPPORT

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8) ABSTRACT

There is an increasing requirement for global tracking of sea-going vessels. This report investigates the possibility of optimising the existing Universal Shipborne Automatic Identification System (AIS) for long-range AIS (LRAIS), and suggests to do so by implementing; 1) a separate VHF channel for LRAIS, 2) short LRAIS messages, and 3) longer ship reporting interval.

The analyses show that the suggested system could be suitable for LRAIS, and that such an LRAIS system could be optimised to handle more than 10 000 ships with a ship detection probability of 99% or better.

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# Ship detection probability analysis for a possible long-range AIS system

## 1 INTRODUCTION

Internationally, there is a growing need to develop a global maritime surveillance capability. This stems from increased levels of hazardous cargo transports, smuggling of goods and humans, and growth in global terrorism. New cooperative systems for ship reporting are now being implemented to meet emerging requirements for detection, identification, and tracking.

One such system is the recently introduced Universal Shipborne Automatic Identification System (AIS). AIS is a ship-to-ship and ship-to-shore reporting system based on broadcasting of messages in the maritime VHF band. The AIS messages could also be received from space (1), and two previous reports (2), (3) have studied the ship detection probability for space-based AIS reception. The ship detection probability was found to be better than 99% for up to 900 ships within the AIS sensor's field of view.

There is an increasing requirement for global tracking of sea-going vessels. This report investigates the possibility of optimising the existing AIS system for long-range AIS (LRAIS). The parameters to optimise are the ship reporting interval and corresponding observation time. The optimising of these parameters is done with respect to required ship detection probability and the number of ships that the system must be able to handle. In principle, the system could be optimised to handle 10 000 ships or more with a ship detection probability of better than 99%.

Chapter 2 gives a brief overview of the AIS system. Chapter 3 discusses problems related to the space-based AIS concept, and Chapter 4 presents a possible LRAIS system. The ship detection probability equation is given in Chapter 5, and Chapter 6 presents the results from the optimisation process, followed by a discussion in Chapter 7. Finally, a summary is given in Chapter 8.

## 2 THE AIS SYSTEM

AIS is a new element under the United Nation's SOLAS convention (5). It is a ship-to-ship and ship-to-shore reporting system that operates on two channels in the maritime VHF band. Ships send reports every 2-10 seconds with detailed information about vessel identity, position, heading, nature of cargo, etc. The range is typically 20 nautical miles for ship-to-ship communication and somewhat larger for ship-to-shore communications in coastal waters. Figure 2.1 illustrates the concept.

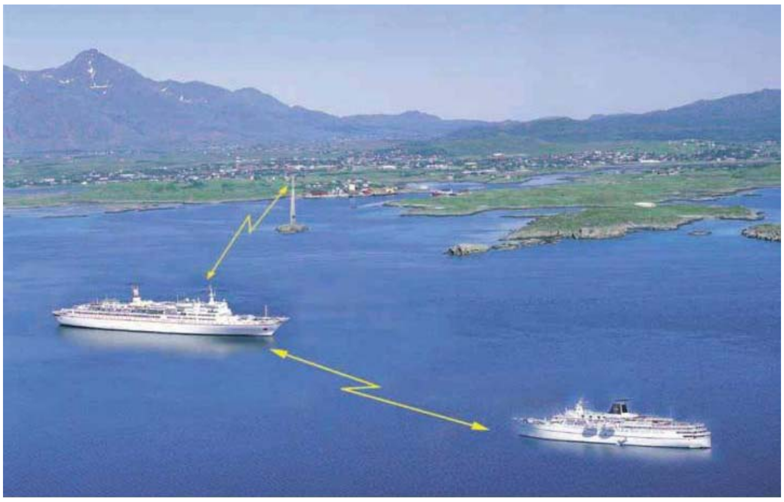

*Figure 2.1 The AIS ship-to ship and ship-to-shore concept (Courtesy of Kongsberg Seatex).*

The AIS reporting system is based on the broadcasting of digital messages that are entered into a 1 minute long message frame of 2250 message slots (6). The message entry is synchronized to the universal time coordinated (UTC), and the length of each message is limited to 256 bits. The two VHF maritime mobile channels 87B (AIS1) and 88B (AIS2) are allocated to AIS. Messages are broadcasted alternately on the two channels giving the system a total capacity of 4500 message slots per minute. The reporting between ships within communication range (~20 nm) is organized by a Self-Organizing Time Division Multiple Access (SOTDMA)-algorithm to avoid coinciding transmissions, see Figure 2.2.

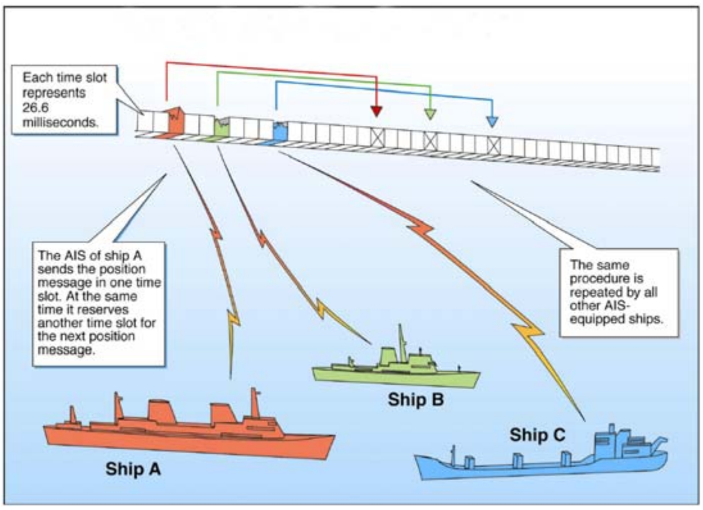


*Figure 2.2 The AIS SOTDMA principle.*

## 3 SPACE-BASED AIS

AIS signals can be detected from space by a standard AIS receiver for altitudes up to at least 1000 km. However, an AIS sensor in space would cover a much larger area on the ground than the AIS system was originally designed for. The reporting between ships within communication range (~20 nm) is organized by the SOTDMA-algorithm to avoid coinciding transmissions, but from space the AIS sensor will see more than one such organized area as illustrated in Figure 3.1. With many ships within the field of view interference problems will occur, and the AIS messages from some of the ships may not be detected.

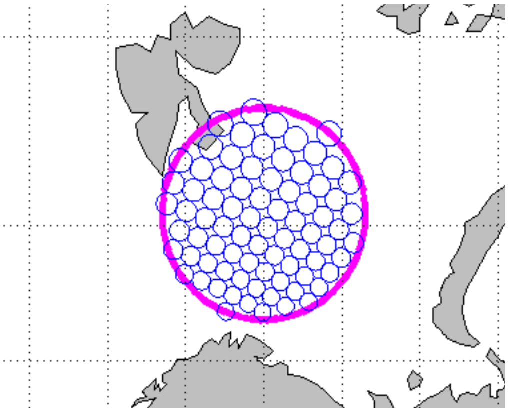

*Figure 3.1 AIS sensor's field of view (big red circle) with several organized areas (small blue circles).*

There are two possible mechanisms for coinciding transmissions:

1) AIS messages from different ships are sent in the same message slot.
2) AIS messages from different ships are sent in different message slots, but are received simultaneously by the AIS sensor in space due to different signal path lengths.

The AIS system uses a distance delay buffer to prevent overlap between messages that are sent in adjacent timeslots as long as the difference in the signal path length is less than about 200 nm. For an AIS sensor at 1000 km altitude with field of view to the horizon (3630 nm wide swath) the difference in signal path length is about 1400 nm for messages sent from the centre of the observation area compared to messages sent from areas close to the horizon. The distance delay buffer is therefore not sufficient in this case, and both mechanisms for coinciding transmissions must be included in the analyses. Ship detection probability analyses for a space-based AIS system, taking both mechanisms for coinciding transmissions into account, have been performed in a previous report (3).

# 4 A POSSIBLE LRAIS SYSTEM

It has been shown in a previous report (3) that a space-based AIS system could handle up to about 900 ships. The LRAIS system should, however, be able to handle higher numbers of ships. This could be obtained by implementing the following:

1) Separate VHF channel for LRAIS
2) Short LRAIS messages
3) Longer ship reporting interval

An explanation for these suggestions follows below.

## 4.1 Separate VHF channel for LRAIS

In order not to interfere with the existing AIS system, a separate VHF channel could be used for LRAIS. The messages transmitted on this channel could then be adapted for LRAIS.

All analyses in this report are based on the assumption that a separate VHF channel is used for LRAIS.

## 4.2 Short LRAIS messages

Short LRAIS messages that contain only identity and position (±185 m) could be used instead of standard AIS messages. The content of such short LRAIS messages is described in Appendix A.

The main difference between the short LRAIS message and the standard AIS message is that the short LRAIS message contains a much longer distance delay buffer, allowing signal path differences of up to 1550 nm. This would prevent overlap between adjacent messages for AIS sensor altitudes up to about 1000 km (see Appendix A). The ship detection probability would therefore increase compared to when using standard AIS messages.

We will in this report optimise both for an LRAIS system that uses standard AIS messages and for an LRAIS system that uses short LRAIS messages.

## 4.3 Longer ship reporting interval

Increasing the ship reporting interval, decreases the number of messages received by the AIS sensor in space and thereby increases the ship detection probability.

We will in this report optimise the ship reporting interval for different numbers of ships and different ship detection probabilities.

## 5 THE SHIP DETECTION PROBABILITY EQUATION

The equation for the ship detection probability $P$ has been derived in a previous report (3) and is given by

$$P = 1 - \left[ 1 - \exp\left( -\frac{(1+s)\cdot N_{tot}}{37.5 \cdot n_{ch} \cdot \Delta T} \right) \right]^{\frac{T_{obs}}{\Delta T}} \tag{5.1}$$

where $N_{tot}$ is the total number of ships within the field of view, $\Delta T$ is the ship reporting interval, $T_{obs}$ is the observation time, and $n_{ch} = 1$ is the number of channels. The overlap factor $s$ describes the overlap that occurs when AIS messages that are sent in adjacent time slots from ships in different parts of the observation area partly overlap due to differences in the signal path lengths between each of the ships and the AIS sensor. The overlap factor depends on the AIS sensor's altitude and field of view and has the value $s = 0.7$ for an AIS sensor at 1000 km altitude with field of view to the horizon (3).

When optimising for an LRAIS system that uses standard AIS messages, we will then use the following value for the overlap factor

$$s_{AIS} = 0.7 \tag{5.2}$$

For an LRAIS system that uses short LRAIS messages the overlap factor is zero, i.e.,

$$s_{LRIT} = 0 \tag{5.3}$$

since in this case the messages are sufficiently short that no overlap will occur between messages that are sent in adjacent time slots from ships in different parts of the observation area.

# 6 RESULTS

We have optimised both for an LRAIS system that uses standard AIS messages and for an LRAIS system that uses short LRAIS messages. Section 6.1 presents the results for standard AIS messages, and Section 6.2 for short LRAIS messages. Section 6.3 compares the results for standard AIS messages and short LRAIS messages.

## 6.1 The LRAIS system that uses standard AIS messages

We have calculated the ship detection probability for the LRAIS system that uses standard AIS messages as a function of number of ships for up to 20 000 ships within the field of view. Observation times of $T_{obs}$ =5, 10, 15, 20, 30, 40, 50, and 60 min were used in the calculations. For each choice of observation time, the ship detection probability was calculated for five different ship reporting intervals $\Delta T_n = T_{obs} / n$, where $n$ =1, 2, 5, 10, and 20 is the number of reports transmitted by the ship during the observation period. Results from the calculations are presented in Figure 6.1-Figure 6.8 and Table 6.1-Table 6.8.

Based on the results, we have determined optimum ship reporting intervals with corresponding observation times for given numbers of ships within the field of view. Ship detection probabilities of better than 99% and 90% respectively were required.

Criteria when choosing the optimum ship reporting intervals were:

1) Keep the observation time as short as possible.
2) If more than one ship reporting interval can be used (for a given number of ships, ship detection probability, and observation time), choose the ship reporting interval that gives the slowest decline in the ship detection probability curve.

Recommended ship reporting intervals with corresponding observation times are given in Table 6.9 and Table 6.10 for different number of ships within the field of view. The corresponding ship detection probability curves are shown in Figure 6.9 and Figure 6.10.

The calculations were done for an AIS sensor at altitude $H_{sat}$ =1000 km with field of view to the horizon. The calculations assume an even ship distribution.

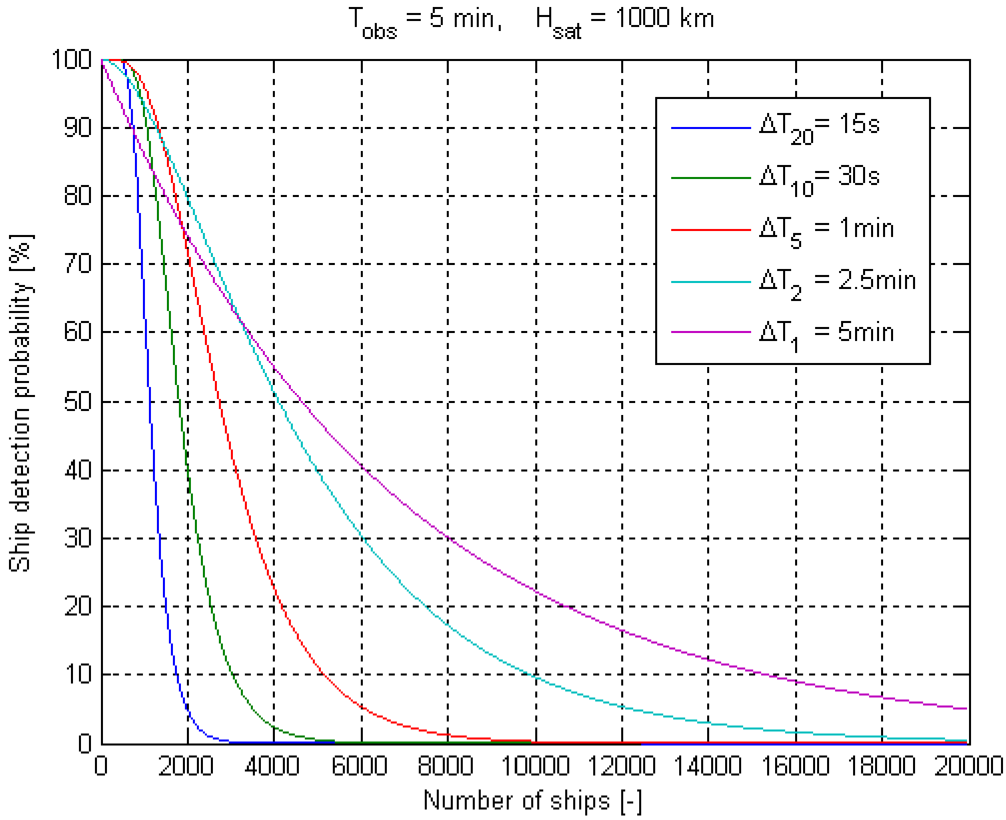


*Figure 6.1* *Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals* $\Delta T$ *. The observation time is* $T_{obs}$ *=5 min. Standard AIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=15s** | **$\Delta T_{10}$=30s** | **$\Delta T_5$=1min** | **$\Delta T_2$=2.5min** | **$\Delta T_1$=5min** |
| 1000 | 64.0 | 92.0 | 95.9 | 93.3 | 86.1 |
| 2000 | 4.8 | 40.1 | 71.8 | 79.7 | 74.1 |
| 3000 | 0.2 | 10.6 | 42.8 | 64.8 | 63.8 |
| 4000 | <0.1 | 2.5 | 22.6 | 51.2 | 54.9 |
| 5000 | <0.1 | 0.6 | 11.3 | 39.7 | 47.3 |
| 6000 | <0.1 | 0.1 | 5.5 | 30.4 | 40.7 |
| 7000 | <0.1 | <0.1 | 2.6 | 23.0 | 35.0 |
| 8000 | <0.1 | <0.1 | 1.2 | 17.4 | 30.2 |
| 9000 | <0.1 | <0.1 | 0.6 | 13.0 | 26.0 |
| 10 000 | <0.1 | <0.1 | 0.3 | 9.7 | 22.4 |
| 12 000 | <0.1 | <0.1 | <0.1 | 5.4 | 16.6 |
| 14 000 | <0.1 | <0.1 | <0.1 | 3.0 | 12.3 |
| 16 000 | <0.1 | <0.1 | <0.1 | 1.6 | 9.1 |
| 18 000 | <0.1 | <0.1 | <0.1 | 0.9 | 6.7 |
| 20 000 | <0.1 | <0.1 | <0.1 | 0.5 | 5.0 |

*Table 6.1* *Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals* $\Delta T$ *. The observation time is* $T_{obs}$ *=5 min. Standard AIS messages are used.*

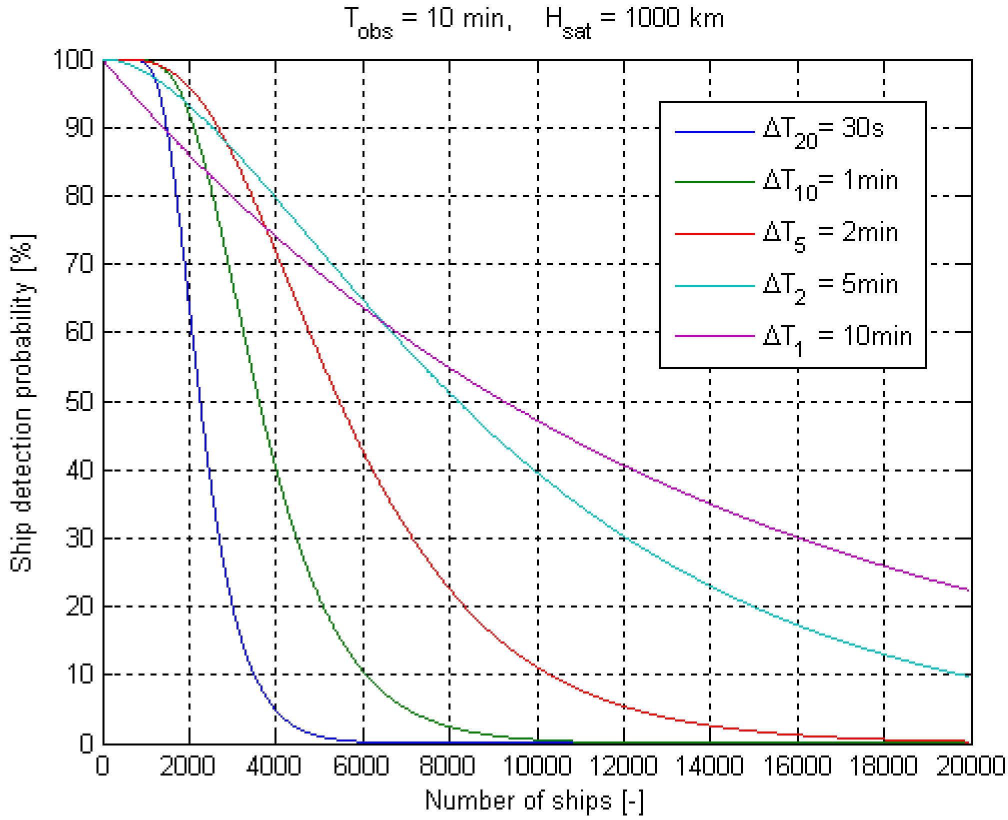


*Figure 6.2 Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =10 min. Standard AIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=30s** | **$\Delta T_{10}$=1min** | **$\Delta T_5$=2min** | **$\Delta T_2$=5min** | **$\Delta T_1$=10min** |
| **1000** | 99.4 | 99.8 | 99.7 | 98.0 | 92.8 |
| 2000 | 64.1 | 92.0 | 95.9 | 93.3 | 86.1 |
| 3000 | 20.1 | 67.3 | 86.0 | 86.9 | 79.9 |
| 4000 | 4.9 | 40.1 | 71.8 | 79.7 | 74.1 |
| 5000 | 1.1 | 21.3 | 56.6 | 72.2 | 68.8 |
| 6000 | 0.2 | 10.6 | 42.8 | 64.8 | 63.8 |
| 7000 | <0.1 | 5.1 | 31.4 | 57.8 | 59.2 |
| 8000 | <0.1 | 2.5 | 22.6 | 51.2 | 54.9 |
| 9000 | <0.1 | 1.2 | 16.0 | 45.2 | 50.9 |
| 10 000 | <0.1 | 0.6 | 11.3 | 39.7 | 47.3 |
| 12 000 | <0.1 | 0.1 | 5.5 | 30.4 | 40.7 |
| 14 000 | <0.1 | <0.1 | 2.6 | 23.0 | 35.0 |
| 16 000 | <0.1 | <0.1 | 1.2 | 17.4 | 30.2 |
| 18 000 | <0.1 | <0.1 | 0.6 | 13.0 | 26.0 |
| 20 000 | <0.1 | <0.1 | 0.3 | 9.7 | 22.4 |

*Table 6.2 Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =10 min. Standard AIS messages are used.*

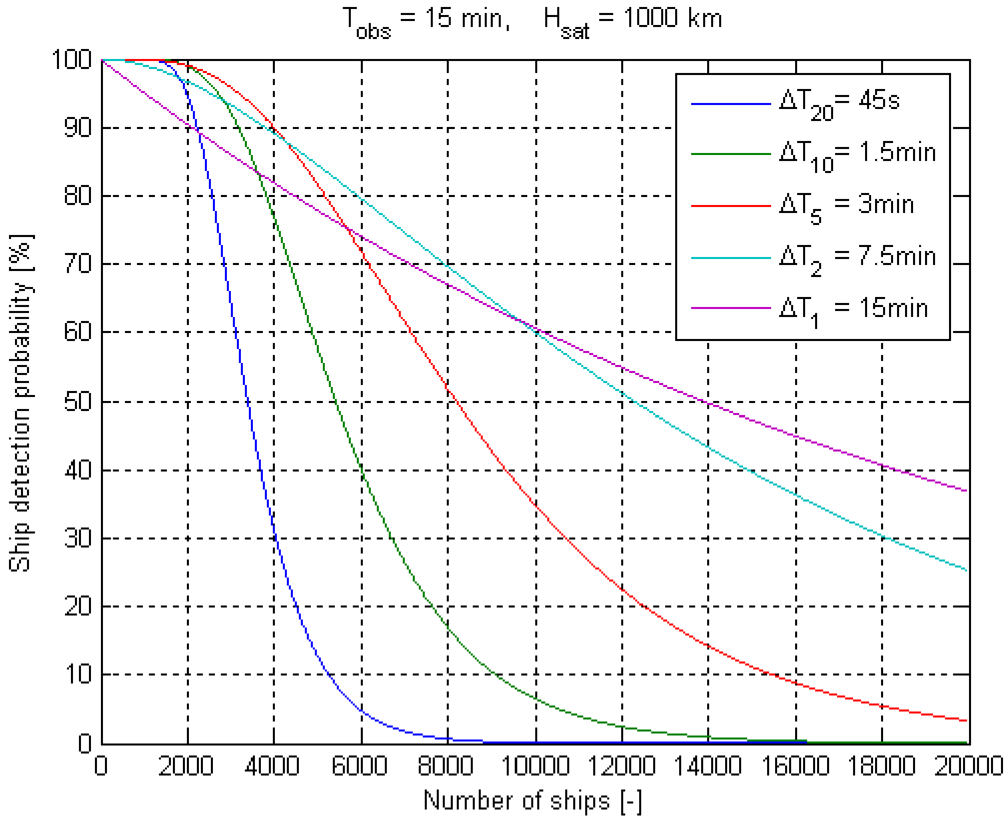


*Figure 6.3 Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =15 min. Standard AIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=45s** | **$\Delta T_{10}$=1.5min** | **$\Delta T_5$=3min** | **$\Delta T_2$=7.5min** | **$\Delta T_1$=15min** |
| **1000** | >99.9 | >99.9 | 99.9 | 99.1 | 95.1 |
| **2000** | 94.6 | 99.0 | 99.1 | 96.7 | 90.5 |
| 3000 | 64.1 | 92.0 | 95.9 | 93.3 | 86.1 |
| 4000 | 31.0 | 76.7 | 89.9 | 89.2 | 81.9 |
| 5000 | 12.7 | 57.7 | 81.6 | 84.6 | 77.9 |
| 6000 | 4.9 | 40.1 | 71.8 | 79.7 | 74.1 |
| 7000 | 1.8 | 26.5 | 61.6 | 74.7 | 70.5 |
| 8000 | 0.7 | 17.0 | 51.8 | 69.7 | 67.1 |
| 9000 | 0.2 | 10.6 | 42.8 | 64.8 | 63.8 |
| 10 000 | <0.1 | 6.6 | 34.9 | 60.1 | 60.7 |
| 12 000 | <0.1 | 2.5 | 22.6 | 51.2 | 54.9 |
| 14 000 | <0.1 | 0.9 | 14.3 | 43.3 | 49.7 |
| 16 000 | <0.1 | 0.3 | 8.9 | 36.4 | 45.0 |
| 18 000 | <0.1 | 0.1 | 5.5 | 30.4 | 40.7 |
| 20 000 | <0.1 | <0.1 | 3.3 | 25.3 | 36.8 |

*Table 6.3 Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =15 min. Standard AIS messages are used.*

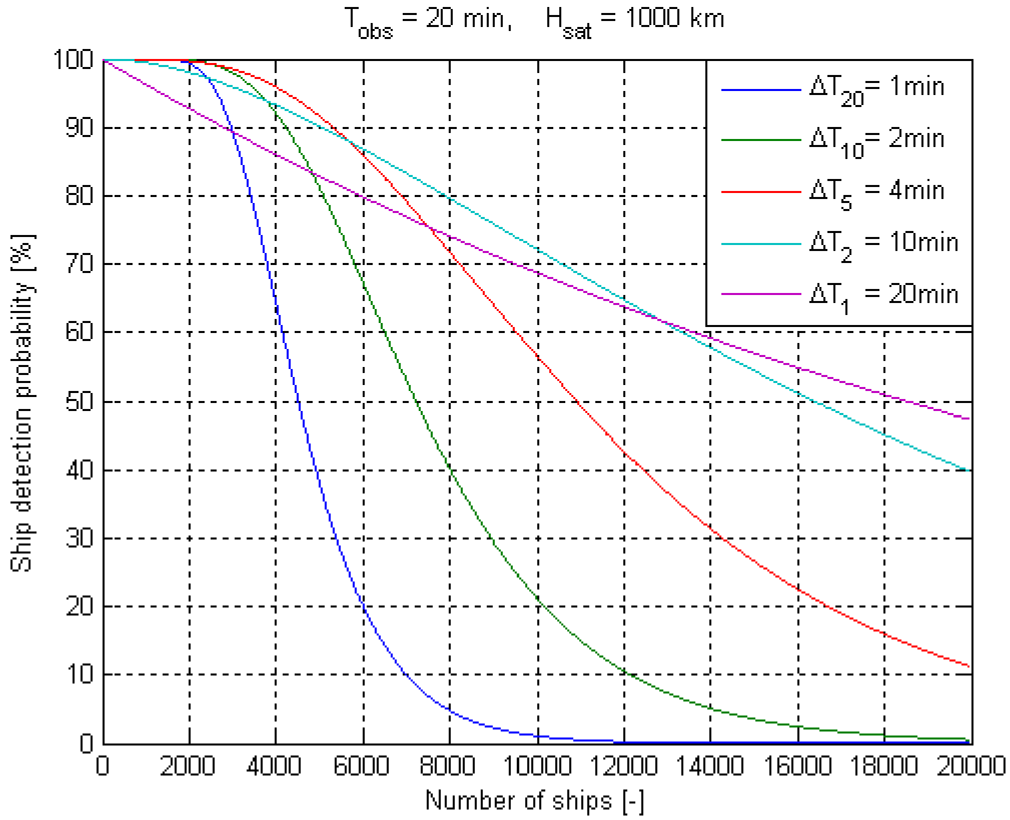


*Figure 6.4* *Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals* $\Delta T$ *. The observation time is* $T_{obs}$ *=20 min. Standard AIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=1min** | **$\Delta T_{10}$=2min** | **$\Delta T_5$=4min** | **$\Delta T_2$=10min** | **$\Delta T_1$=20min** |
| **1000** | >99.9 | >99.9 | >99.9 | 99.5 | 96.3 |
| **2000** | 99.4 | 99.8 | 99.7 | 98.0 | 92.8 |
| 3000 | 89.3 | 98.0 | 98.5 | 96.0 | 89.4 |
| 4000 | 64.1 | 92.0 | 95.9 | 93.3 | 86.1 |
| 5000 | 38.0 | 81.2 | 91.7 | 90.2 | 82.9 |
| 6000 | 20.1 | 67.3 | 86.0 | 86.9 | 79.9 |
| 7000 | 10.0 | 53.0 | 79.2 | 83.4 | 76.9 |
| 8000 | 4.9 | 40.1 | 71.8 | 79.7 | 74.1 |
| 9000 | 2.3 | 29.5 | 64.1 | 76.0 | 71.4 |
| 10 000 | 1.1 | 21.3 | 56.6 | 72.2 | 68.8 |
| 12 000 | 0.2 | 10.6 | 42.8 | 64.8 | 63.8 |
| 14 000 | <0.1 | 5.2 | 31.4 | 57.8 | 59.2 |
| 16 000 | <0.1 | 2.5 | 22.6 | 51.2 | 54.9 |
| 18 000 | <0.1 | 1.2 | 16.0 | 45.2 | 51.0 |
| 20 000 | <0.1 | 0.6 | 11.3 | 39.7 | 47.3 |

*Table 6.4* *Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals* $\Delta T$ *. The observation time is* $T_{obs}$ *=20 min. Standard AIS messages are used.*

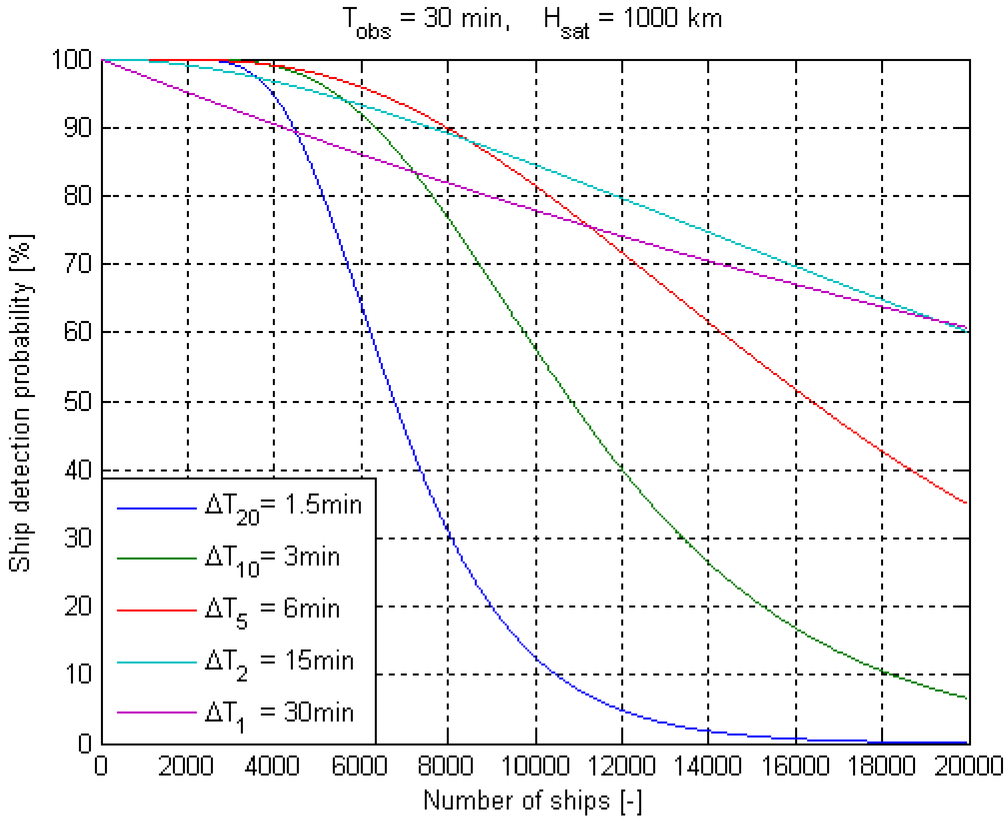


*Figure 6.5* *Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =30 min. Standard AIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=1.5min** | **$\Delta T_{10}$=3min** | **$\Delta T_5$=6min** | **$\Delta T_2$=15min** | **$\Delta T_1$=30min** |
| **1000** | >99.9 | >99.9 | >99.9 | 99.8 | 97.5 |
| **2000** | >99.9 | >99.9 | >99.9 | 99.1 | 95.1 |
| **3000** | 99.4 | 99.8 | 99.7 | 98.1 | 92.8 |
| **4000** | 94.6 | 99.0 | 99.1 | 96.7 | 90.5 |
| 5000 | 82.1 | 96.6 | 97.8 | 95.1 | 88.3 |
| 6000 | 64.1 | 92.0 | 95.9 | 93.3 | 86.1 |
| 7000 | 46.0 | 85.2 | 93.3 | 91.3 | 84.0 |
| 8000 | 31.0 | 76.7 | 89.9 | 89.2 | 81.9 |
| 9000 | 20.1 | 67.3 | 86.0 | 86.9 | 79.9 |
| 10 000 | 12.7 | 57.7 | 81.6 | 84.6 | 77.9 |
| 12 000 | 4.9 | 40.1 | 71.8 | 79.7 | 74.1 |
| 14 000 | 1.8 | 26.5 | 61.6 | 74.7 | 70.5 |
| 16 000 | 0.7 | 17.0 | 51.8 | 69.7 | 67.1 |
| 18 000 | 0.3 | 10.6 | 42.8 | 64.8 | 63.8 |
| 20 000 | <0.1 | 6.6 | 34.9 | 60.1 | 60.7 |

*Table 6.5* *Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =30 min. Standard AIS messages are used.*

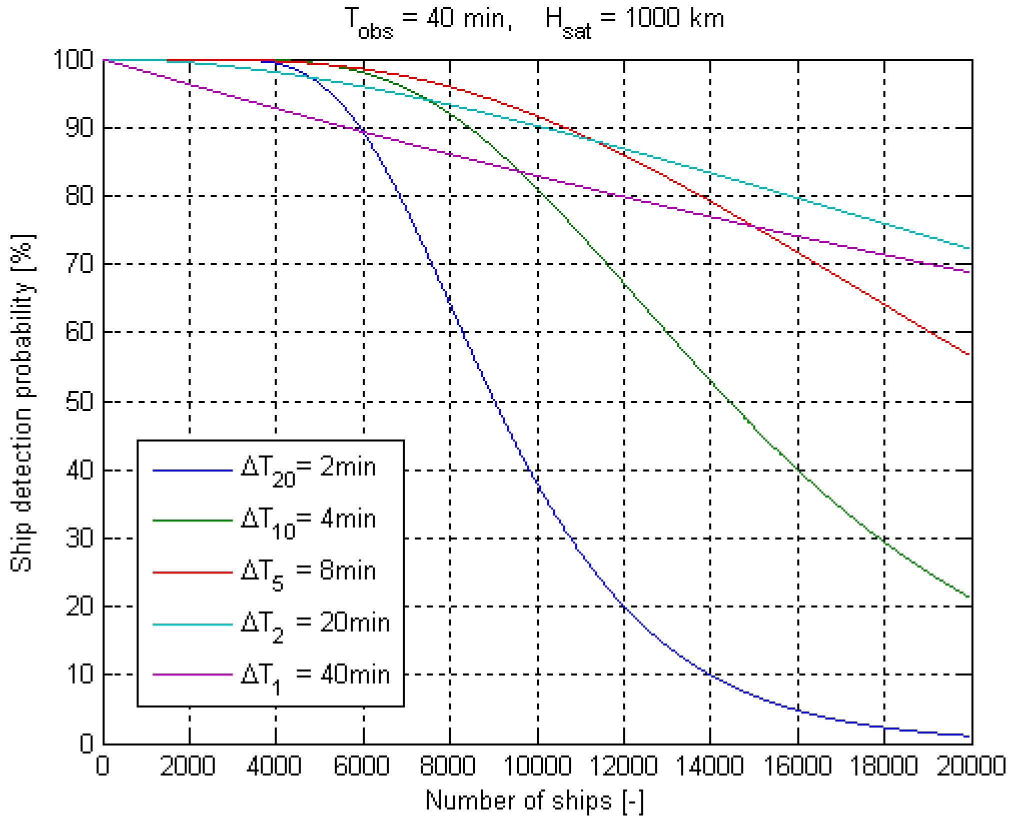


*Figure 6.6* *Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals* $\Delta T$ *. The observation time is* $T_{obs}$ *=40 min. Standard AIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=2min** | **$\Delta T_{10}$=4min** | **$\Delta T_5$=8min** | **$\Delta T_2$=20min** | **$\Delta T_1$=40min** |
| **1000** | >99.9 | >99.9 | >99.9 | 99.9 | 98.1 |
| **2000** | >99.9 | >99.9 | >99.9 | 99.5 | 96.3 |
| **3000** | >99.9 | >99.9 | 99.9 | 98.9 | 94.5 |
| **4000** | 99.4 | 99.8 | 99.7 | 98.1 | 92.8 |
| **5000** | 96.4 | 99.3 | 99.3 | 97.1 | 91.1 |
| 6000 | 89.3 | 98.0 | 98.5 | 96.0 | 89.4 |
| 7000 | 77.9 | 95.7 | 97.4 | 94.7 | 87.7 |
| 8000 | 64.1 | 92.0 | 95.9 | 93.3 | 86.1 |
| 9000 | 50.3 | 87.1 | 94.0 | 91.8 | 84.5 |
| 10 000 | 38.0 | 81.2 | 91.7 | 90.2 | 82.9 |
| 12 000 | 20.1 | 67.3 | 86.0 | 86.9 | 79.8 |
| 14 000 | 10.0 | 53.0 | 79.2 | 83.4 | 76.9 |
| 16 000 | 4.9 | 40.1 | 71.8 | 79.7 | 74.1 |
| 18 000 | 2.3 | 29.5 | 64.1 | 76.0 | 71.4 |
| 20 000 | 1.1 | 21.3 | 56.6 | 72.2 | 68.8 |

*Table 6.6* *Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals* $\Delta T$ *. The observation time is* $T_{obs}$ *=40 min. Standard AIS messages are used.*

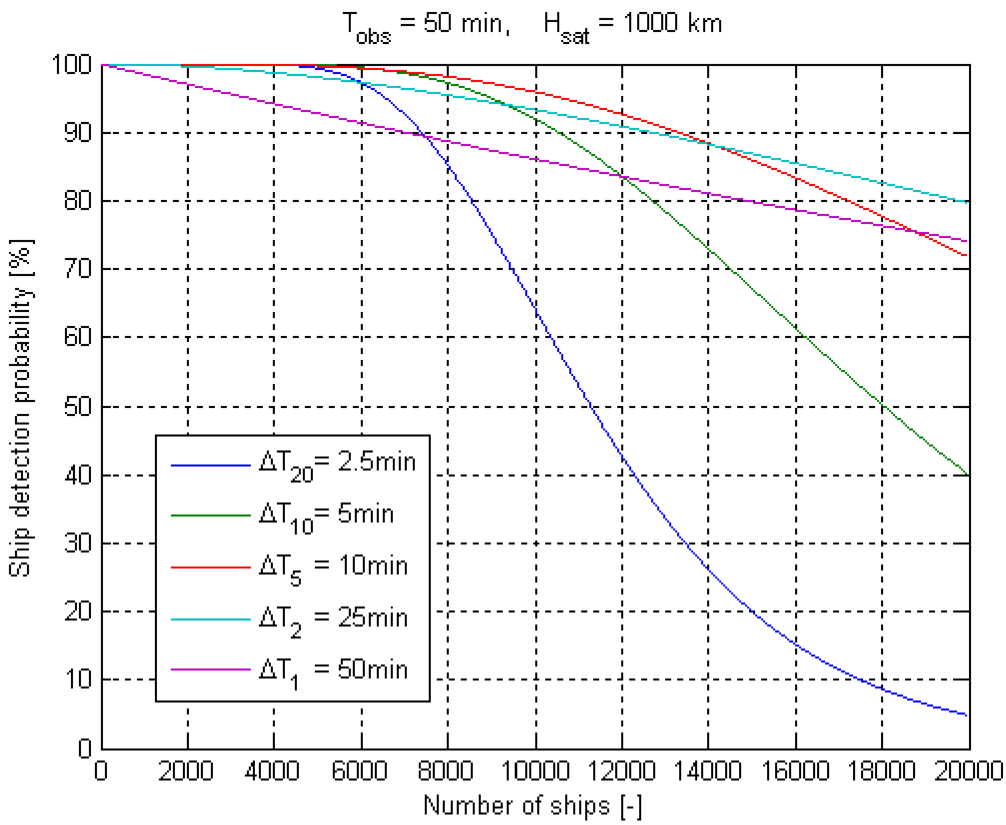


*Figure 6.7* *Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals* $\Delta T$ *. The observation time is* $T_{obs}$ *=50 min. Standard AIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=2.5min** | **$\Delta T_{10}$=5min** | **$\Delta T_5$=10min** | **$\Delta T_2$=25min** | **$\Delta T_1$=50min** |
| **1000** | >99.9 | >99.9 | >99.9 | 99.9 | 98.5 |
| **2000** | >99.9 | >99.9 | >99.9 | 99.7 | 97.0 |
| **3000** | >99.9 | >99.9 | >99.9 | 99.3 | 95.6 |
| **4000** | 99.9 | >99.9 | 99.9 | 98.7 | 94.2 |
| **5000** | 99.4 | 99.8 | 99.7 | 98.1 | 92.8 |
| **6000** | 97.3 | 99.5 | 99.4 | 97.3 | 91.4 |
| 7000 | 92.7 | 98.7 | 98.9 | 96.4 | 90.0 |
| 8000 | 85.2 | 97.2 | 98.1 | 95.5 | 88.7 |
| 9000 | 75.3 | 95.1 | 97.2 | 94.4 | 87.4 |
| 10 000 | 64.1 | 92.0 | 95.9 | 93.3 | 86.1 |
| 12 000 | 42.7 | 83.7 | 92.7 | 90.9 | 83.5 |
| 14 000 | 26.2 | 73.0 | 88.4 | 88.3 | 81.1 |
| 16 000 | 15.3 | 61.5 | 83.4 | 85.5 | 78.7 |
| 18 000 | 8.7 | 50.3 | 77.8 | 82.6 | 76.4 |
| 20 000 | 4.9 | 40.1 | 71.8 | 79.7 | 74.1 |

*Table 6.7* *Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals* $\Delta T$ *. The observation time is* $T_{obs}$ *=50 min. Standard AIS messages are used.*

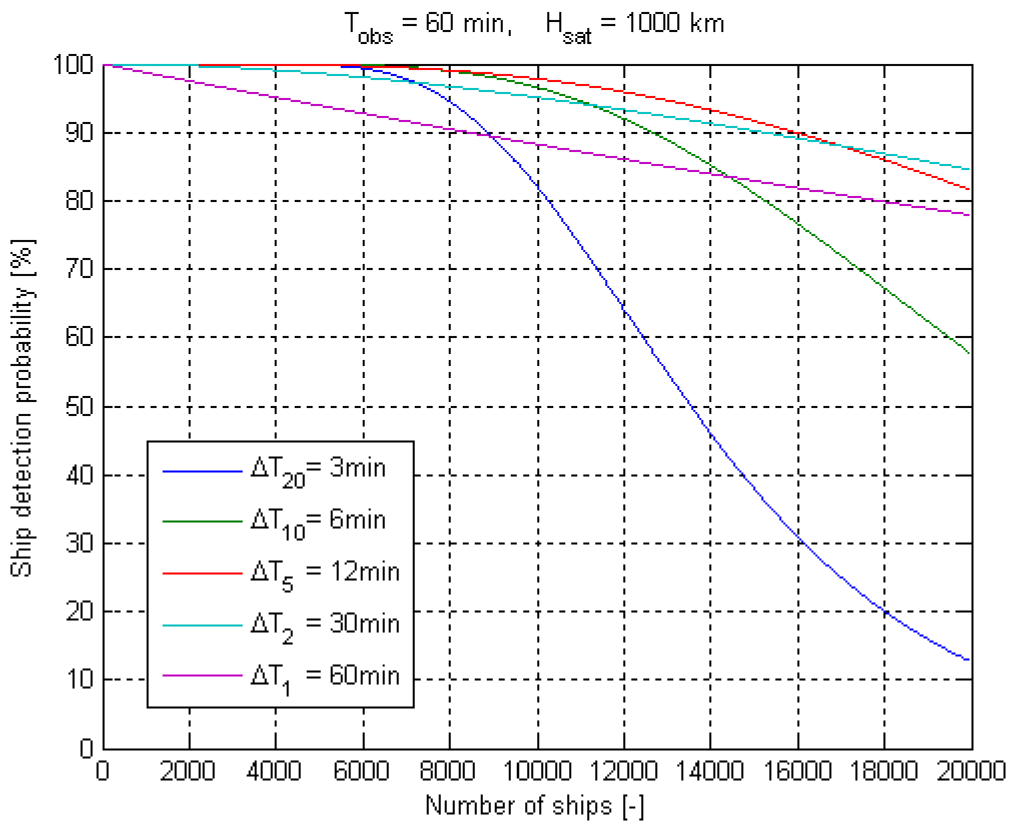


*Figure 6.8* *Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =60 min. Standard AIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=3min** | **$\Delta T_{10}$=6min** | **$\Delta T_5$=12min** | **$\Delta T_2$=30min** | **$\Delta T_1$=60min** |
| **1000** | >99.9 | >99.9 | >99.9 | 99.9 | 98.8 |
| **2000** | >99.9 | >99.9 | >99.9 | 99.8 | 97.5 |
| **3000** | >99.9 | >99.9 | >99.9 | 99.5 | 96.3 |
| **4000** | >99.9 | >99.9 | 99.9 | 99.1 | 95.1 |
| **5000** | 99.9 | >99.9 | 99.9 | 98.6 | 94.0 |
| **6000** | 99.4 | 99.8 | 99.7 | 98.1 | 92.8 |
| **7000** | 97.8 | 99.5 | 99.4 | 97.4 | 91.6 |
| **8000** | 94.6 | 99.0 | 99.1 | 96.7 | 90.5 |
| 9000 | 89.3 | 98.0 | 98.5 | 96.0 | 89.4 |
| 10 000 | 82.1 | 96.6 | 97.8 | 95.1 | 88.3 |
| 12 000 | 64.1 | 92.0 | 95.9 | 93.3 | 86.1 |
| 14 000 | 46.0 | 85.2 | 93.3 | 91.3 | 84.0 |
| 16 000 | 31.0 | 76.7 | 89.9 | 89.2 | 81.9 |
| 18 000 | 20.1 | 67.3 | 86.0 | 86.9 | 79.9 |
| 20 000 | 12.7 | 57.7 | 81.6 | 84.6 | 77.9 |

*Table 6.8* *Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =60 min. Standard AIS messages are used.*

| Number of ships | Observation time, $T_{obs}$ | Reporting interval, ΔT | n = $T_{obs}$ /ΔT |
|---|---|---|---|
| 1000 | 10 min | 2 min | 5 |
| 2000 | 15 min | 3 min | 5 |
| 3000 | 30 min | 6 min | 5 |
| 4000 | 30 min | 6 min | 5 |
| 5000 | 40 min | 8 min | 5 |
| 6000 | 50 min | 10 min | 5 |
| 7000 | 60 min | 12 min | 5 |
| 8000 | 60 min | 12 min | 5 |
| 9000 | - | - | - |
| 10 000 | - | - | - |
| 12 000 | - | - | - |

*Table 6.9* *Best choice of observation time $T_{obs}$ and ship reporting interval $\Delta T$ for different numbers of ships within the field of view when requiring a ship detection probability of better than 99%. Standard AIS messages are used.*

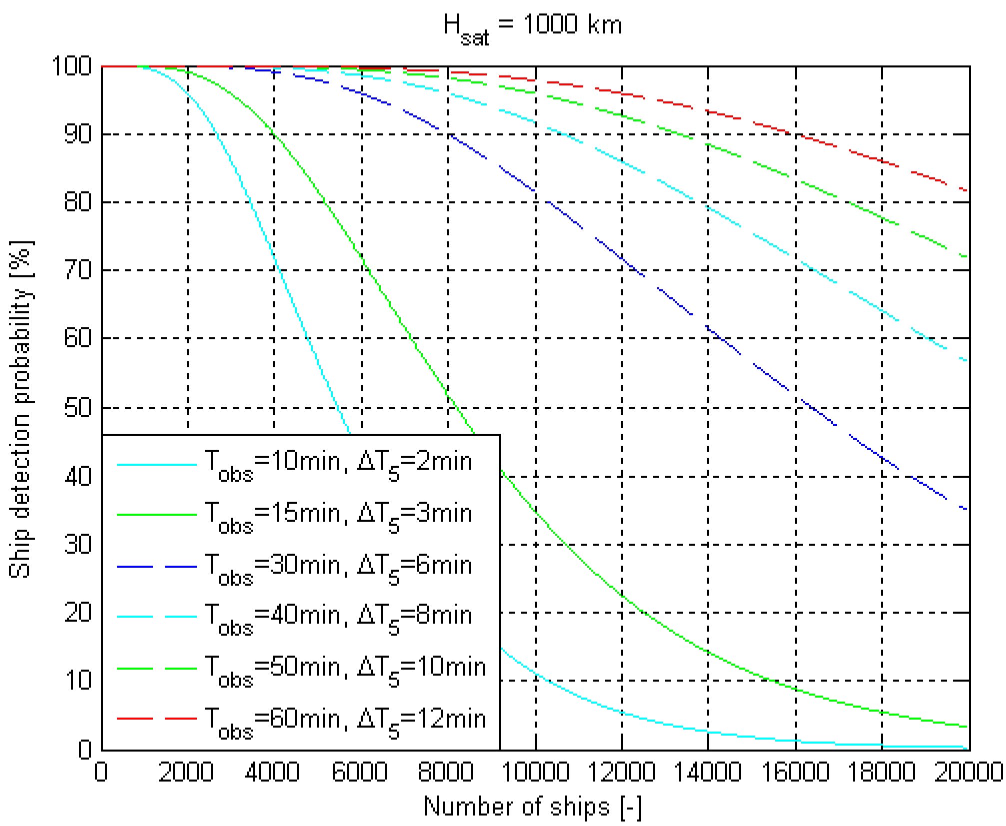


*Figure 6.9* *Ship detection probability curves for optimal combinations of ship reporting interval $\Delta T$ and observation time $T_{obs}$ when requiring a ship detection probability of better than 99%. Standard AIS messages are used.*

| Number of ships | Observation time, $T_{obs}$ | Reporting interval, ΔT | $n = T_{obs} / \Delta T$ |
|---|---|---|---|
| 1000 | 5 min | 2.5 min | 2 |
| 2000 | 10 min | 5 min | 2 |
| 3000 | 15 min | 7.5 min | 2 |
| 4000 | 20 min | 10 min | 2 |
| 5000 | 20 min | 10 min | 2 |
| 6000 | 30 min | 15 min | 2 |
| 7000 | 30 min | 15 min | 2 |
| 8000 | 40 min | 20 min | 2 |
| 9000 | 40 min | 20 min | 2 |
| 10 000 | 40 min | 20 min | 2 |
| 12 000 | 50 min | 25 min | 2 |
| 14 000 | 60 min | 30 min | 2 |
| 16 000 | - | - | - |
| 18 000 | - | - | - |
| 20 000 | - | - | - |

*Table 6.10 Best choice of observation time $T_{obs}$ and ship reporting interval $\Delta T$ for different numbers of ships within the field of view when requiring a ship detection probability of better than 90%. Standard AIS messages are used.*

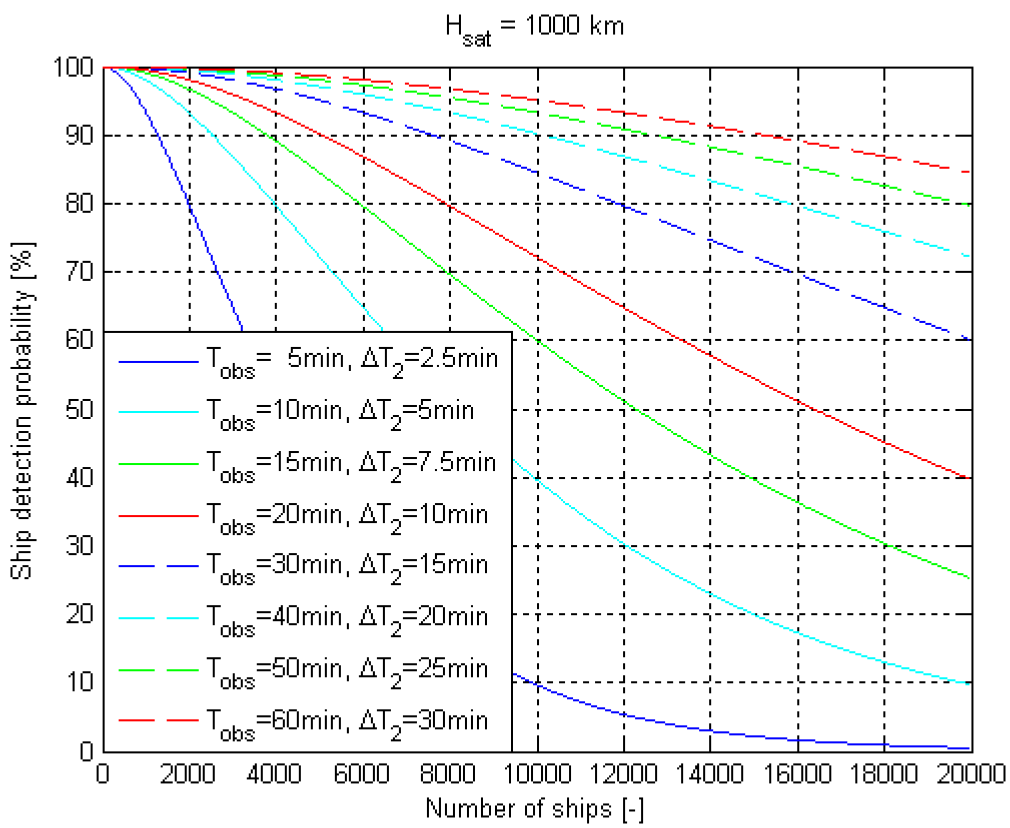


*Figure 6.10 Ship detection probability curves for optimal combinations of ship reporting interval $\Delta T$ and observation time $T_{obs}$ when requiring a ship detection probability of better than 90%. Standard AIS messages are used.*

## 6.2 The LRAIS system that uses short LRAIS messages

We have calculated the ship detection probability for the LRAIS system that uses short LRAIS messages as a function of number of ships for up to 20 000 ships within the field of view. Observation times of $T_{obs} = 5$, 10, 15, 20, 30, 40, 50, and 60 min were used in the calculations. For each choice of observation time, the ship detection probability was calculated for five different ship reporting intervals $\Delta T_n = T_{obs} / n$, where $n = 1$, 2, 5, 10, and 20 is the number of reports transmitted by the ship during the observation period. Results from the calculations are presented in Figure 6.11-Figure 6.18 and Table 6.11-Table 6.18.

Based on the results, we have determined optimum ship reporting intervals with corresponding observation times for given numbers of ships within the field of view. Ship detection probabilities of better than 99% and 90% respectively were required.

Criteria when choosing the optimum ship reporting intervals were:

1) Keep the observation time as short as possible
2) If more than one ship reporting interval can be used (for a given number of ships, ship detection probability, and observation time), choose the ship reporting interval that gives the slowest decline in the ship detection probability curve.

Recommended ship reporting intervals with corresponding observation times are given in Table 6.19 and Table 6.20 for different number of ships within the field of view. The corresponding ship detection probability curves are shown in Figure 6.19 and Figure 6.20.

The calculations are valid for AIS sensor altitudes up to 1000 km and for all ship distributions.

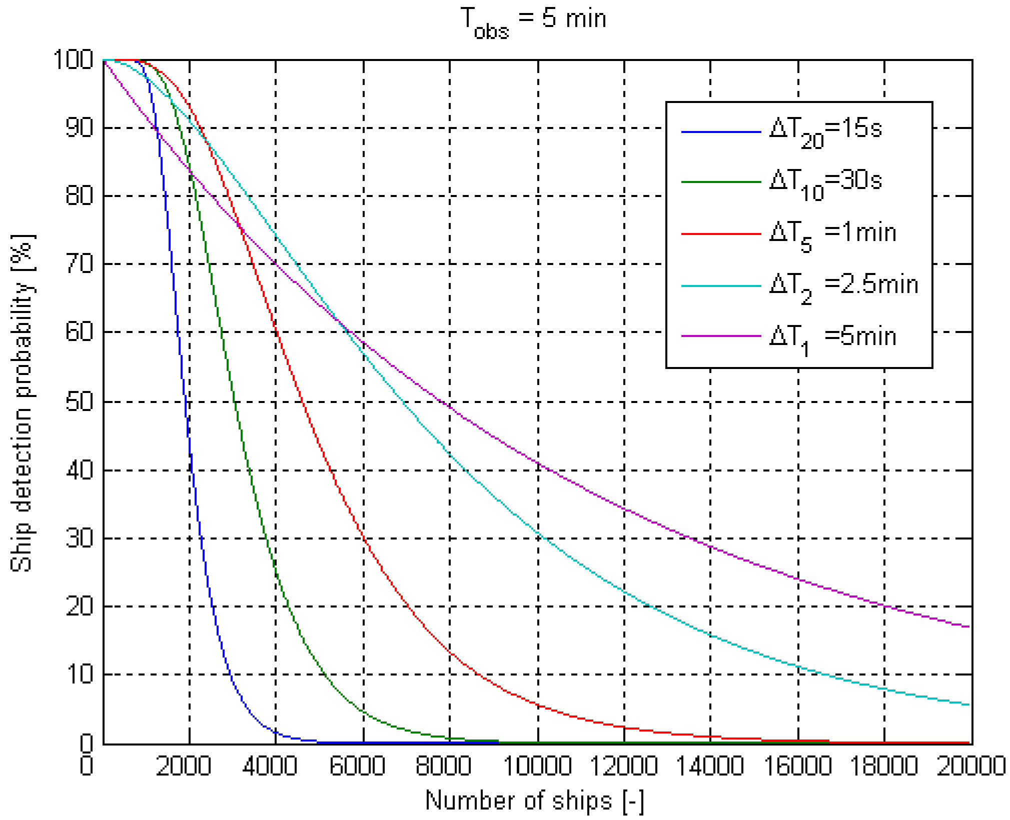


*Figure 6.11 Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =5 min. Short LRAIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=15s** | **$\Delta T_{10}$=30s** | **$\Delta T_5$=1min** | **$\Delta T_2$=2.5min** | **$\Delta T_1$=5min** |
| **1000** | 97.5 | 99.5 | 99.4 | 97.3 | 91.5 |
| 2000 | 43.9 | 84.3 | 92.9 | 91.1 | 83.7 |
| 3000 | 9.2 | 51.3 | 78.3 | 82.9 | 76.6 |
| 4000 | 1.6 | 25.1 | 60.4 | 74.1 | 70.1 |
| 5000 | 0.3 | 11.1 | 43.6 | 65.3 | 64.1 |
| 6000 | <0.1 | 4.7 | 30.2 | 57.0 | 58.7 |
| 7000 | <0.1 | 2.0 | 20.4 | 49.3 | 53.7 |
| 8000 | <0.1 | 0.8 | 13.5 | 42.4 | 49.1 |
| 9000 | <0.1 | 0.3 | 8.8 | 36.3 | 44.9 |
| 10 000 | <0.1 | 0.1 | 5.7 | 30.9 | 41.1 |
| 12 000 | <0.1 | <0.1 | 2.4 | 22.3 | 34.4 |
| 14 000 | <0.1 | <0.1 | 1.0 | 15.9 | 28.8 |
| 16 000 | <0.1 | <0.1 | 0.4 | 11.3 | 24.1 |
| 18 000 | <0.1 | <0.1 | 0.2 | 8.0 | 20.2 |
| 20 000 | <0.1 | <0.1 | 0.1 | 5.6 | 16.9 |

*Table 6.11 Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =5 min. Short LRAIS messages are used.*

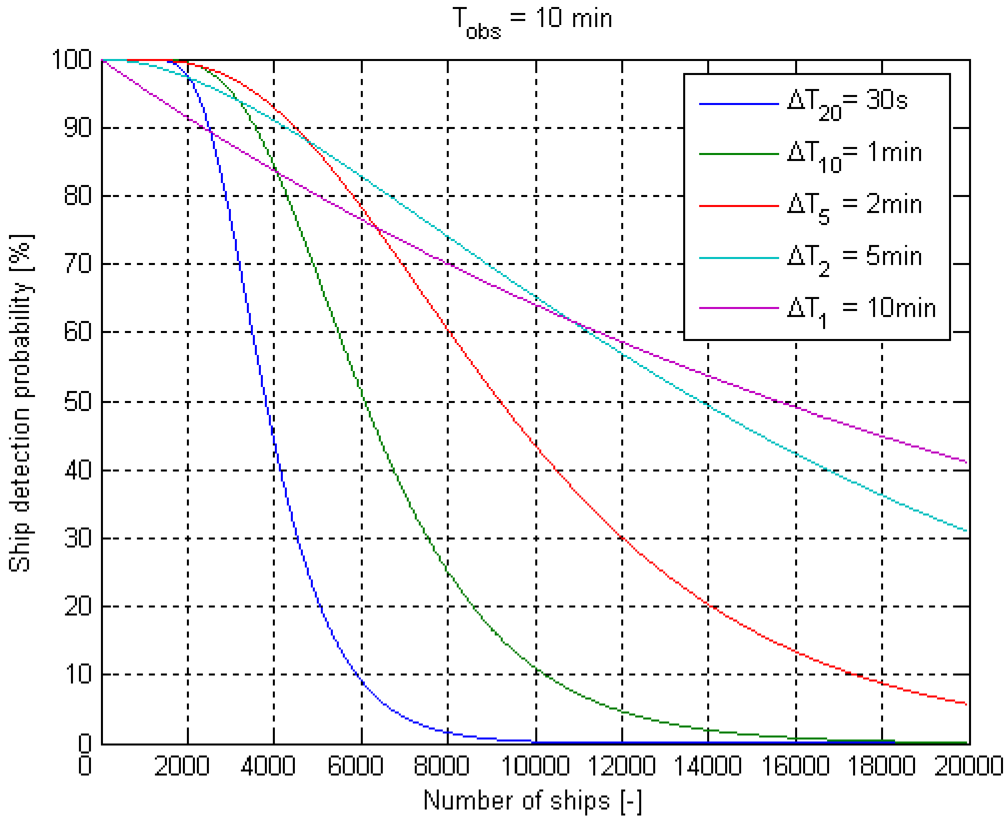


*Figure 6.12 Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =10 min. Short LRAIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=30s** | **$\Delta T_{10}$=1min** | **$\Delta T_5$=2min** | **$\Delta T_2$=5min** | **$\Delta T_1$=10min** |
| **1000** | >99.9 | >99.9 | >99.9 | 99.3 | 95.7 |
| **2000** | 97.5 | 99.5 | 99.4 | 97.3 | 91.5 |
| 3000 | 76.3 | 95.3 | 97.3 | 94.5 | 87.5 |
| 4000 | 44.0 | 84.3 | 92.9 | 91.1 | 83.7 |
| 5000 | 21.0 | 68.2 | 86.4 | 87.1 | 80.1 |
| 6000 | 9.2 | 51.3 | 78.3 | 82.9 | 76.6 |
| 7000 | 3.9 | 36.6 | 69.4 | 78.5 | 73.3 |
| 8000 | 1.6 | 25.2 | 60.4 | 74.1 | 70.1 |
| 9000 | 0.7 | 16.9 | 51.7 | 69.7 | 67.0 |
| 10 000 | 0.3 | 11.1 | 43.6 | 65.3 | 64.1 |
| 12 000 | <0.1 | 4.7 | 30.2 | 57.0 | 58.7 |
| 14 000 | <0.1 | 2.0 | 20.4 | 49.3 | 53.7 |
| 16 000 | <0.1 | 0.8 | 13.5 | 42.4 | 49.1 |
| 18 000 | <0.1 | 0.3 | 8.8 | 36.3 | 44.9 |
| 20 000 | <0.1 | 0.1 | 5.7 | 30.9 | 41.1 |

*Table 6.12 Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =10 min. Short LRAIS messages are used.*

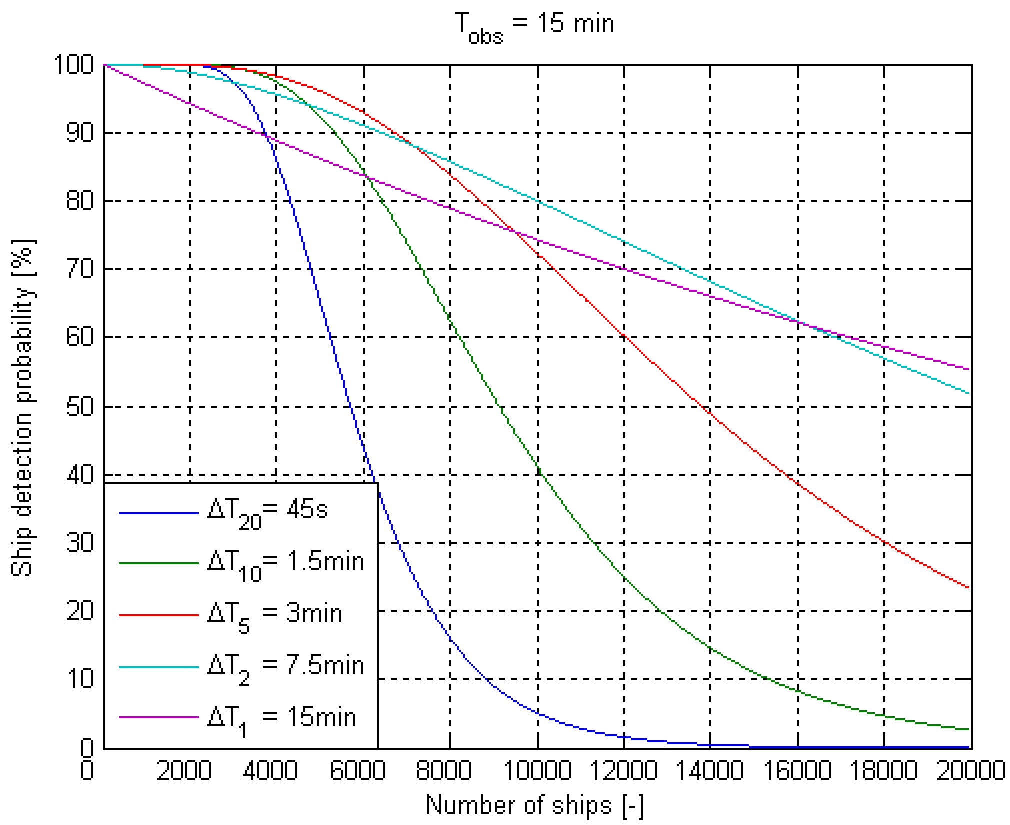


*Figure 6.13 Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =15 min. Short LRAIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=45s** | **$\Delta T_{10}$=1.5min** | **$\Delta T_5$=3min** | **$\Delta T_2$=7.5min** | **$\Delta T_1$=15min** |
| **1000** | >99.9 | >99.9 | >99.9 | 99.7 | 97.1 |
| **2000** | 99.9 | >99.9 | 99.9 | 98.8 | 94.2 |
| **3000** | 97.5 | 99.5 | 99.4 | 97.3 | 91.5 |
| 4000 | 85.9 | 97.4 | 98.2 | 95.5 | 88.8 |
| 5000 | 65.4 | 92.4 | 96.1 | 93.4 | 86.2 |
| 6000 | 44.0 | 84.3 | 92.9 | 91.0 | 83.7 |
| 7000 | 27.3 | 73.9 | 88.8 | 88.5 | 81.3 |
| 8000 | 16.1 | 62.5 | 83.9 | 85.7 | 78.9 |
| 9000 | 9.2 | 51.3 | 78.3 | 82.9 | 76.6 |
| 10 000 | 5.2 | 41.2 | 72.5 | 80.0 | 74.4 |
| 12 000 | 1.6 | 25.2 | 60.4 | 74.1 | 70.1 |
| 14 000 | 0.5 | 14.7 | 48.9 | 68.2 | 66.0 |
| 16 000 | 0.2 | 8.4 | 38.8 | 62.5 | 62.2 |
| 18 000 | <0.1 | 4.7 | 30.2 | 57.0 | 58.7 |
| 20 000 | <0.1 | 2.6 | 23.3 | 51.8 | 55.3 |

*Table 6.13 Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =15 min. Short LRAIS messages are used.*

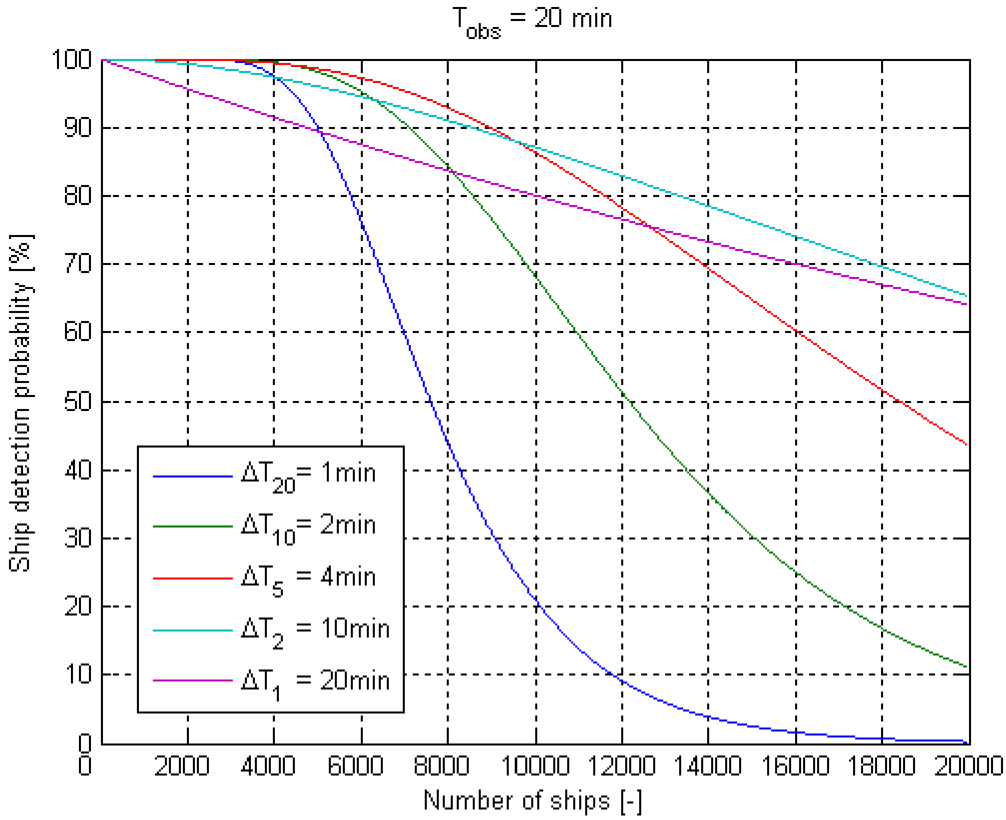


*Figure 6.14 Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =20 min. Short LRAIS messages are used.*

| Number of ships | Ship detection probability [%] | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=1min** | **$\Delta T_{10}$=2min** | **$\Delta T_5$=4min** | **$\Delta T_2$=10min** | **$\Delta T_1$=20min** |
| **1000** | >99.9 | >99.9 | >99.9 | 99.8 | 97.8 |
| **2000** | >99.9 | >99.9 | >99.9 | 99.3 | 95.7 |
| **3000** | 99.8 | 99.9 | 99.8 | 98.4 | 93.6 |
| **4000** | 97.5 | 99.5 | 99.4 | 97.3 | 91.5 |
| 5000 | 89.9 | 98.2 | 98.6 | 96.0 | 89.5 |
| 6000 | 76.3 | 95.3 | 97.3 | 94.5 | 87.5 |
| 7000 | 59.8 | 90.7 | 95.4 | 92.9 | 85.6 |
| 8000 | 44.0 | 84.3 | 92.9 | 91.0 | 83.7 |
| 9000 | 30.9 | 76.6 | 89.9 | 89.1 | 81.9 |
| 10 000 | 21.0 | 68.2 | 86.4 | 87.1 | 80.1 |
| 12 000 | 9.2 | 51.3 | 78.3 | 82.9 | 76.6 |
| 14 000 | 3.9 | 36.6 | 69.4 | 78.5 | 73.2 |
| 16 000 | 1.6 | 25.2 | 60.4 | 74.1 | 70.1 |
| 18 000 | 0.7 | 16.9 | 51.7 | 69.7 | 67.0 |
| 20 000 | 0.3 | 11.1 | 43.6 | 65.3 | 64.1 |

*Table 6.14 Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =20 min. Short LRAIS messages are used.*

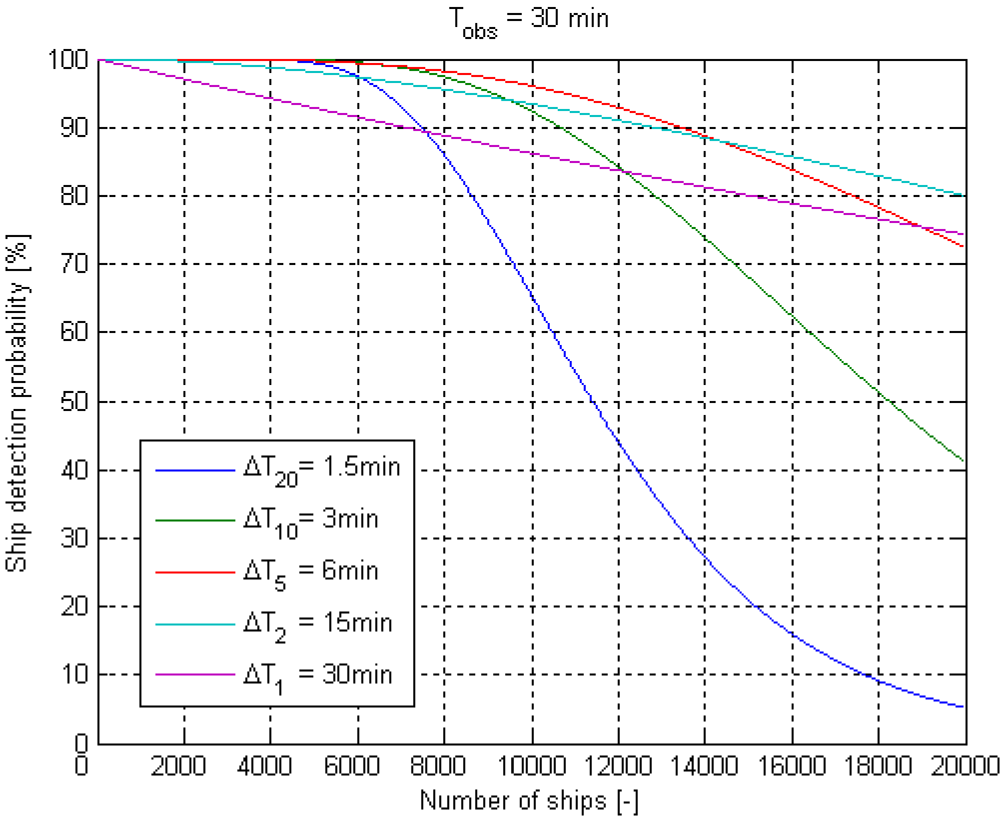


*Figure 6.15 Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =30 min. Short LRAIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=1.5min** | **$\Delta T_{10}$=3min** | **$\Delta T_{5}$=6min** | **$\Delta T_{2}$=15min** | **$\Delta T_{1}$=30min** |
| **1000** | >99.9 | >99.9 | >99.9 | 99.9 | 98.5 |
| **2000** | >99.9 | >99.9 | >99.9 | 99.7 | 97.1 |
| **3000** | >99.9 | >99.9 | >99.9 | 99.3 | 95.7 |
| **4000** | 99.9 | >99.9 | 99.9 | 98.8 | 94.2 |
| **5000** | 99.4 | 99.8 | 99.7 | 98.1 | 92.9 |
| **6000** | 97.5 | 99.5 | 99.4 | 97.3 | 91.5 |
| 7000 | 93.2 | 98.7 | 98.9 | 96.5 | 90.2 |
| 8000 | 85.9 | 97.4 | 98.2 | 95.5 | 88.8 |
| 9000 | 76.3 | 95.3 | 97.3 | 94.5 | 87.6 |
| 10 000 | 65.4 | 92.4 | 96.1 | 93.4 | 86.2 |
| 12 000 | 44.0 | 84.3 | 92.9 | 91.0 | 83.7 |
| 14 000 | 27.3 | 73.9 | 88.8 | 88.5 | 81.3 |
| 16 000 | 16.1 | 62.5 | 83.9 | 85.7 | 78.9 |
| 18 000 | 9.2 | 51.3 | 78.3 | 82.9 | 76.6 |
| 20 000 | 5.2 | 41.2 | 72.5 | 80.0 | 74.4 |

*Table 6.15 Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals $\Delta T$. The observation time is $T_{obs}$ =30 min. Short LRAIS messages are used.*

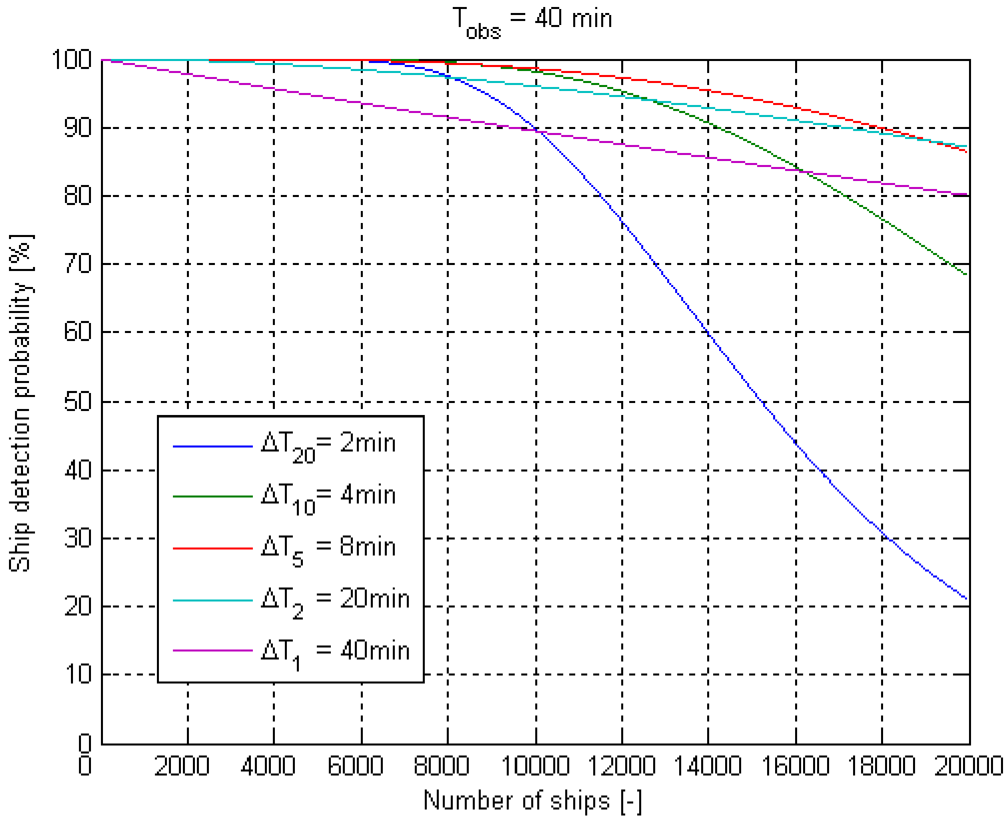


*Figure 6.16 Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals $\Delta T$ . The observation time is $T_{obs}$ =40 min. Short LRAIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=2min** | **$\Delta T_{10}$=4min** | **$\Delta T_5$=8min** | **$\Delta T_2$=20min** | **$\Delta T_1$=40min** |
| **1000** | >99.9 | >99.9 | >99.9 | >99.9 | 98.9 |
| **2000** | >99.9 | >99.9 | >99.9 | 99.8 | 97.8 |
| **3000** | >99.9 | >99.9 | >99.9 | 99.6 | 96.7 |
| **4000** | >99.9 | >99.9 | >99.9 | 99.3 | 95.7 |
| **5000** | >99.9 | >99.9 | 99.9 | 98.9 | 94.6 |
| **6000** | 99.8 | 99.9 | 99.8 | 98.4 | 93.6 |
| **7000** | 99.1 | 99.8 | 99.7 | 97.9 | 92.5 |
| **8000** | 97.5 | 99.5 | 99.4 | 97.3 | 91.5 |
| **9000** | 94.5 | 99.0 | 99.1 | 96.7 | 90.5 |
| 10 000 | 89.9 | 98.2 | 98.6 | 96.0 | 89.5 |
| 12 000 | 76.3 | 95.3 | 97.3 | 94.5 | 87.5 |
| 14 000 | 59.8 | 90.7 | 95.4 | 92.9 | 85.6 |
| 16 000 | 44.0 | 84.3 | 92.9 | 91.0 | 83.7 |
| 18 000 | 30.9 | 76.6 | 89.9 | 89.1 | 81.9 |
| 20 000 | 21.0 | 68.2 | 86.4 | 87.1 | 80.1 |

*Table 6.16 Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals $\Delta T$ . The observation time is $T_{obs}$ =40 min. Short LRAIS messages are used.*

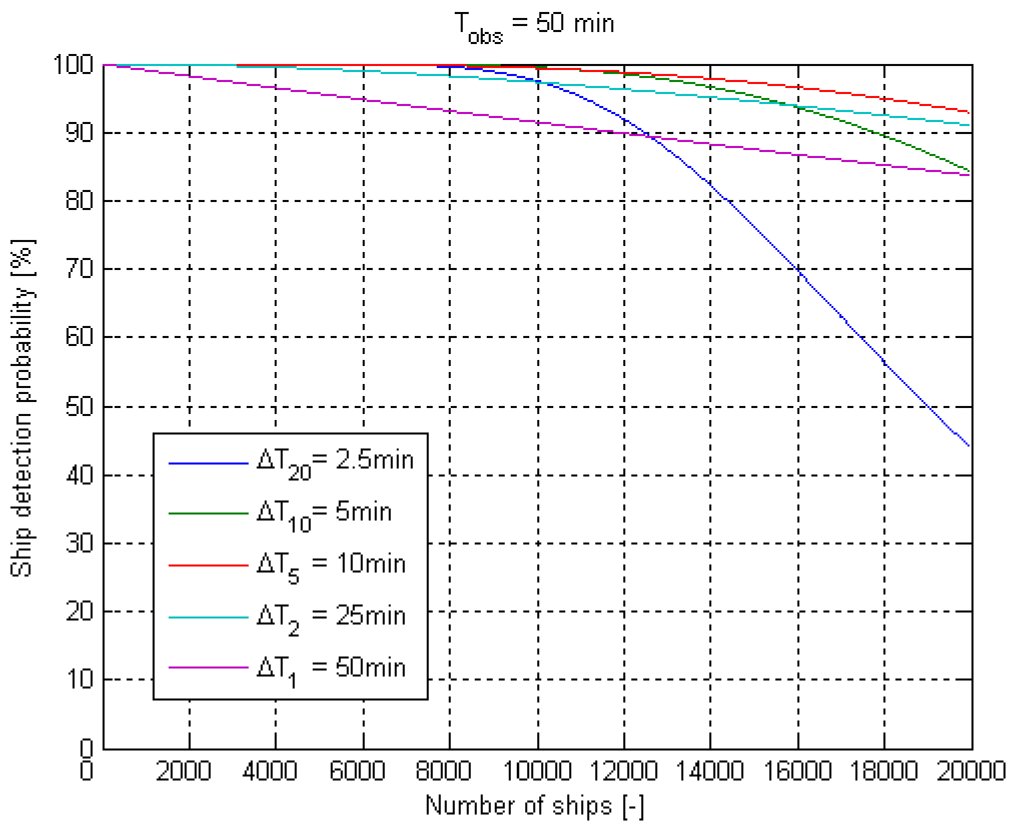


*Figure 6.17 Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals $\Delta T$ . The observation time is $T_{obs}$ =50 min. Short LRAIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=2.5min** | **$\Delta T_{10}$=5min** | **$\Delta T_{5}$=10min** | **$\Delta T_{2}$=25min** | **$\Delta T_{1}$=50min** |
| **1000** | >99.9 | >99.9 | >99.9 | >99.9 | 99.1 |
| **2000** | >99.9 | >99.9 | >99.9 | 99.9 | 98.2 |
| **3000** | >99.9 | >99.9 | >99.9 | 99.7 | 97.4 |
| **4000** | >99.9 | >99.9 | >99.9 | 99.5 | 96.5 |
| **5000** | >99.9 | >99.9 | >99.9 | 99.3 | 95.7 |
| **6000** | >99.9 | >99.9 | 99.9 | 99.0 | 94.8 |
| **7000** | 99.9 | >99.9 | 99.9 | 98.6 | 94.0 |
| **8000** | 99.6 | 99.9 | 99.8 | 98.2 | 93.1 |
| **9000** | 98.9 | 99.7 | 99.6 | 97.8 | 92.3 |
| **10 000** | 97.5 | 99.5 | 99.4 | 97.3 | 91.5 |
| 12 000 | 92.0 | 98.5 | 98.8 | 96.3 | 89.9 |
| 14 000 | 82.3 | 96.7 | 97.9 | 95.1 | 88.3 |
| 16 000 | 69.8 | 93.7 | 96.6 | 93.9 | 86.7 |
| 18 000 | 56.5 | 89.5 | 94.9 | 92.5 | 85.2 |
| 20 000 | 44.0 | 84.3 | 92.9 | 91.0 | 83.7 |

*Table 6.17 Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals $\Delta T$ . The observation time is $T_{obs}$ =50 min. Short LRAIS messages are used.*

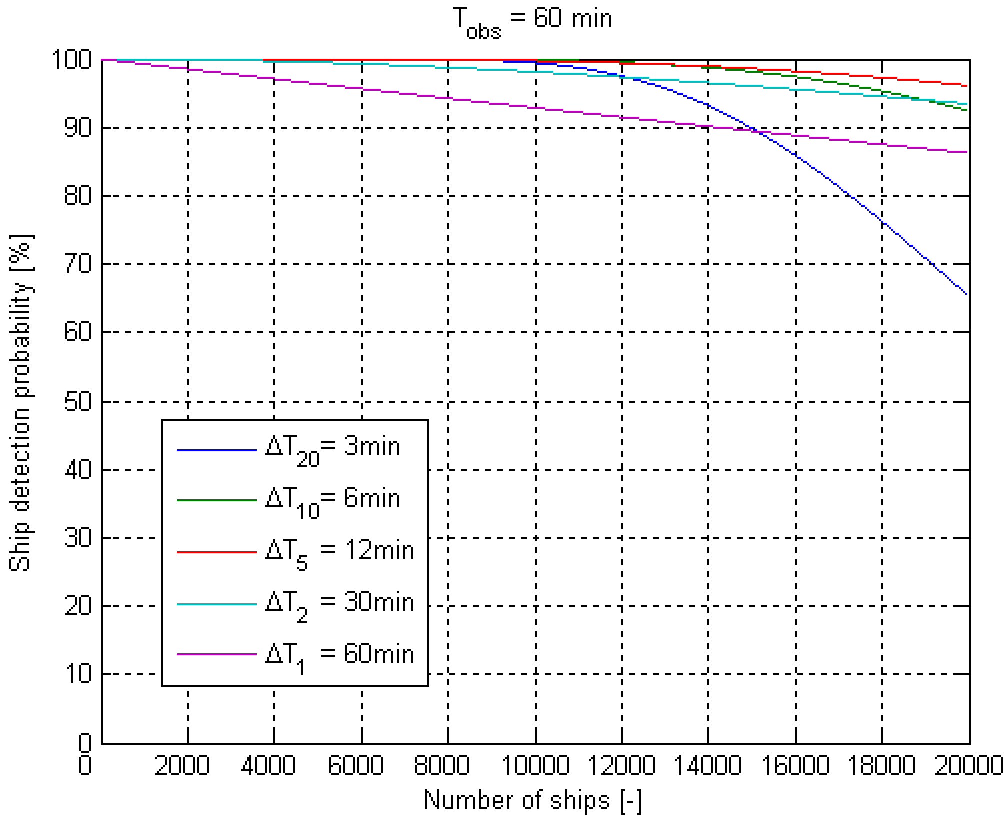


*Figure 6.18 Ship detection probability as a function of number of ships within the field of view for different ship reporting intervals $\Delta T$ . The observation time is $T_{obs}$ =60 min. Short LRAIS messages are used.*

| **Number of ships** | **Ship detection probability [%]** | | | | |
|---|---|---|---|---|---|
| | **$\Delta T_{20}$=3min** | **$\Delta T_{10}$=6min** | **$\Delta T_5$=12min** | **$\Delta T_2$=30min** | **$\Delta T_1$=60min** |
| **1000** | >99.9 | >99.9 | >99.9 | >99.9 | 99.2 |
| **2000** | >99.9 | >99.9 | >99.9 | 99.9 | 98.5 |
| **3000** | >99.9 | >99.9 | >99.9 | 99.8 | 97.8 |
| **4000** | >99.9 | >99.9 | >99.9 | 99.7 | 97.1 |
| **5000** | >99.9 | >99.9 | >99.9 | 99.3 | 96.4 |
| **6000** | >99.9 | >99.9 | >99.9 | 99.0 | 95.7 |
| **7000** | >99.9 | >99.9 | 99.9 | 98.8 | 94.9 |
| **8000** | 99.9 | >99.9 | 99.9 | 98.4 | 94.2 |
| **9000** | 99.8 | 99.9 | 99.8 | 98.1 | 93.6 |
| **10 000** | 99.4 | 99.8 | 99.7 | 97.3 | 92.9 |
| **12 000** | 97.5 | 99.5 | 99.4 | 96.5 | 91.5 |
| 14 000 | 93.2 | 98.7 | 98.9 | 95.5 | 90.1 |
| 16 000 | 85.9 | 97.4 | 98.2 | 94.5 | 88.8 |
| 18 000 | 76.3 | 95.3 | 97.3 | 94.5 | 87.5 |
| 20 000 | 65.4 | 92.4 | 96.1 | 93.4 | 86.2 |

*Table 6.18 Ship detection probability for different numbers of ships within the field of view and different ship reporting intervals $\Delta T$ . The observation time is $T_{obs}$ =60 min. Short LRAIS messages are used.*

| Number of ships | Observation time, $T_{obs}$ | Reporting interval, ΔT | $n = T_{obs} /\Delta T$ |
|---|---|---|---|
| 1000 | 5 min | 1 min | 5 |
| 2000 | 10 min | 2 min | 5 |
| 3000 | 15 min | 3 min | 5 |
| 4000 | 20 min | 4 min | 5 |
| 5000 | 30 min | 6 min | 5 |
| 6000 | 30 min | 6 min | 5 |
| 7000 | 40 min | 8 min | 5 |
| 8000 | 40 min | 8 min | 5 |
| 9000 | 40 min | 8 min | 5 |
| 10 000 | 50 min | 10 min | 5 |
| 12 000 | 60 min | 12 min | 5 |

*Table 6.19 Best choice of observation time $T_{obs}$ and ship reporting interval $\Delta T$ for different numbers of ships within the field of view when requiring a ship detection probability of better than 99%. Short LRAIS messages are used.*

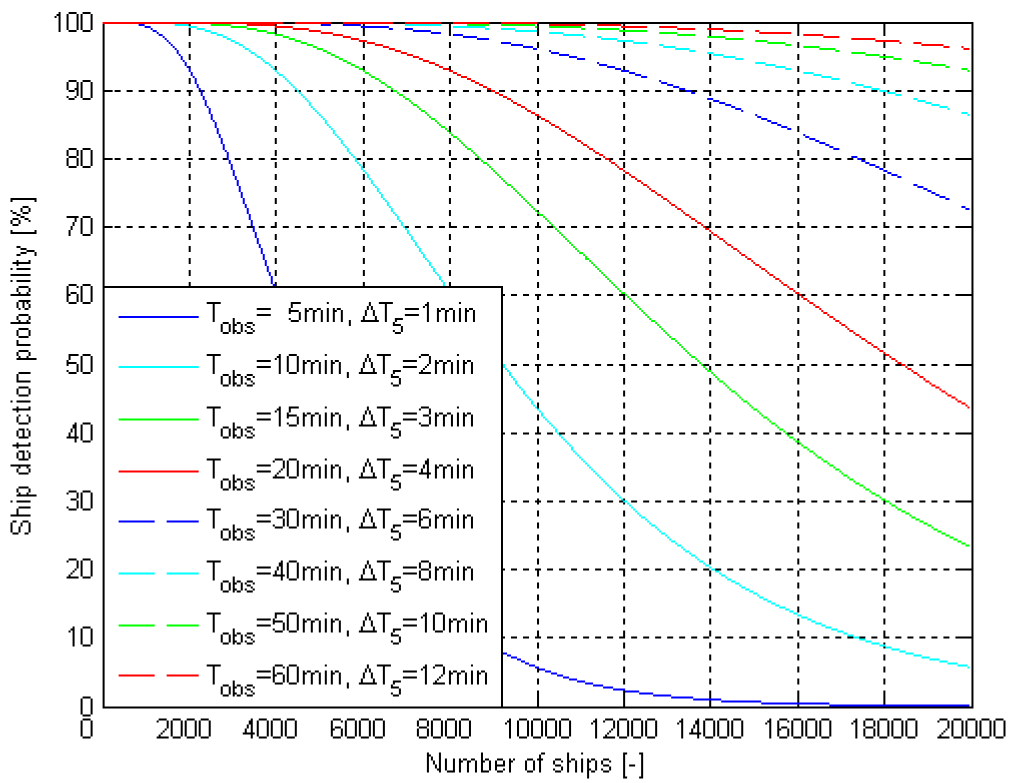


*Figure 6.19 Ship detection probability curves for optimal combinations of ship reporting interval $\Delta T$ and observation time $T_{obs}$ when requiring a ship detection probability of better than 99%. Short LRAIS messages are used.*

| Number of ships | Observation time, $T_{obs}$ | Reporting interval, ΔT | n = $T_{obs}$ /ΔT |
|---|---|---|---|
| 1000 | 5 min | 5 min | 1 |
| 2000 | 5 min | 2.5 min | 2 |
| 3000 | 10 min | 5 min | 2 |
| 4000 | 10 min | 5 min | 2 |
| 5000 | 15 min | 7.5 min | 2 |
| 6000 | 15 min | 7.5 min | 2 |
| 7000 | 20 min | 10 min | 2 |
| 8000 | 20 min | 10 min | 2 |
| 9000 | 30 min | 15 min | 2 |
| 10 000 | 30 min | 15 min | 2 |
| 12 000 | 30 min | 15 min | 2 |
| 14 000 | 40 min | 20 min | 2 |
| 16 000 | 40 min | 20 min | 2 |
| 18 000 | 50 min | 25 min | 2 |
| 20 000 | 50 min | 25 min | 2 |

*Table 6.20 Best choice of observation time $T_{obs}$ and ship reporting interval $\Delta T$ for different numbers of ships within the field of view when requiring a ship detection probability of better than 90%. Short LRAIS messages are used.*

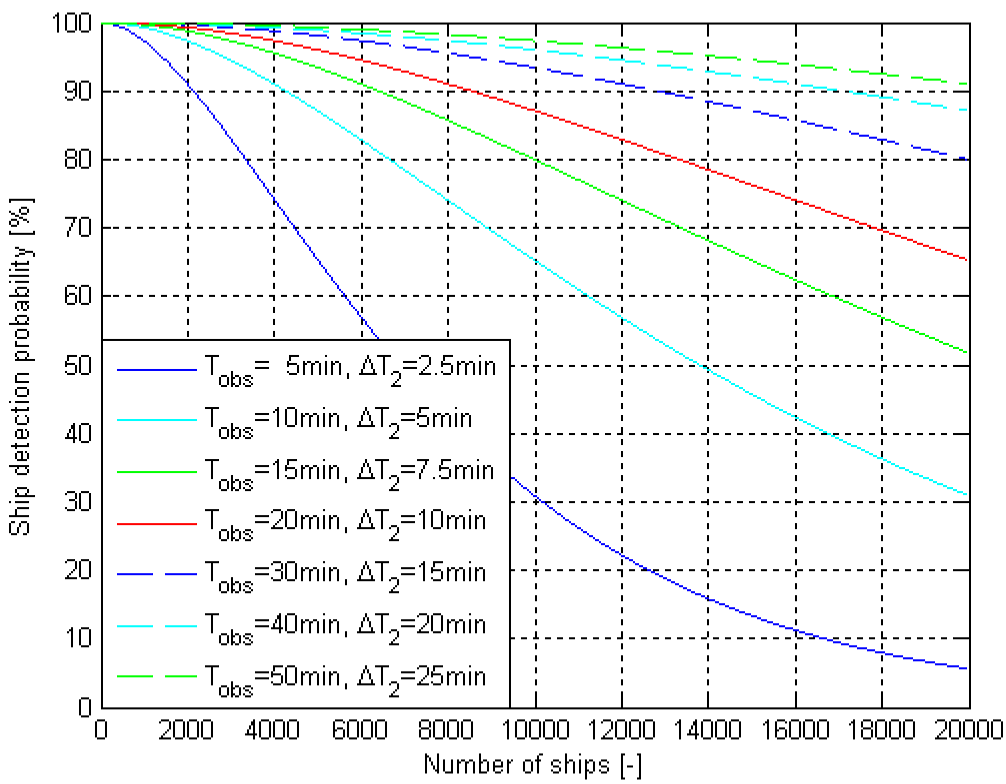


*Figure 6.20 Ship detection probability curves for optimal combinations of ship reporting interval $\Delta T$ and observation time $T_{obs}$ when requiring a ship detection probability of better than 90%. Short LRAIS messages are used.*

### 6.3 Comparison of the two LRAIS systems

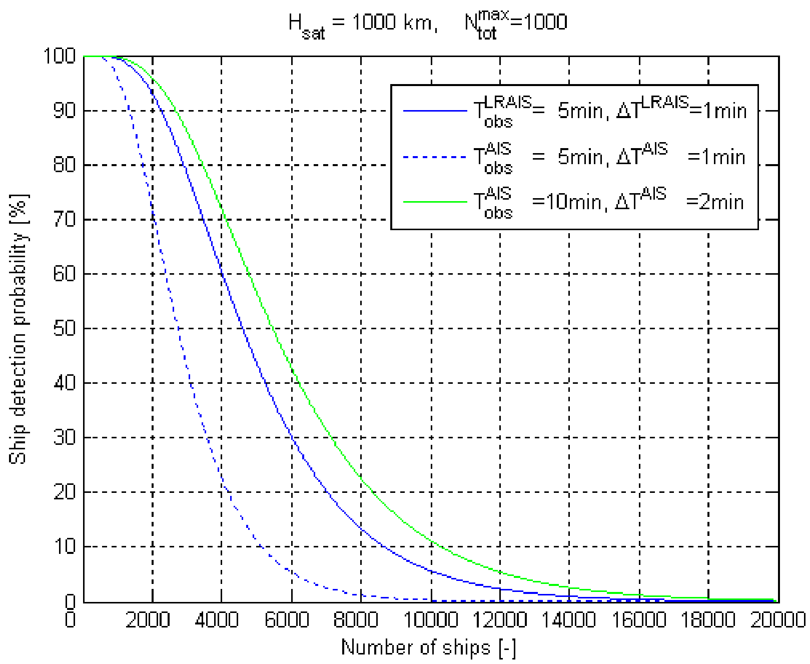


*Figure 6.21 Ship detection probability curves that are optimised for up to 1000 ships within the field of view and a ship detection probability of better than 99% . Green line shows results for standard AIS messages and blue line for short LRAIS messages. The blue dotted line shows results for standard AIS messages when using the same ship reporting interval and observation time as for short LRAIS messages.*

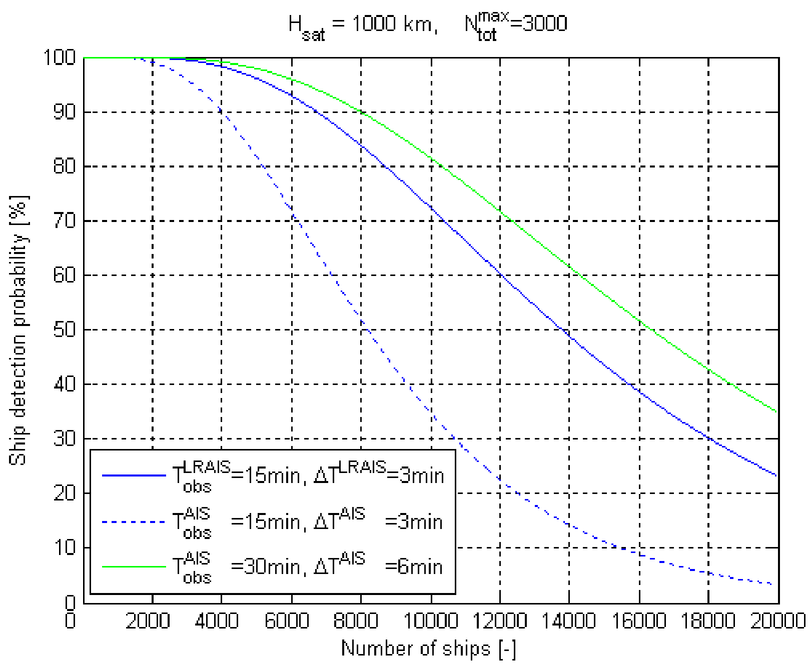


*Figure 6.22 Ship detection probability curves optimised for up to 3000 ships within the field of view with a ship detection probability of better than 99% . Green line shows results for standard AIS messages and blue line for short LRAIS messages. The blue dotted line shows results for standard AIS messages when using the same ship reporting interval and observation time as for short LRAIS messages.*

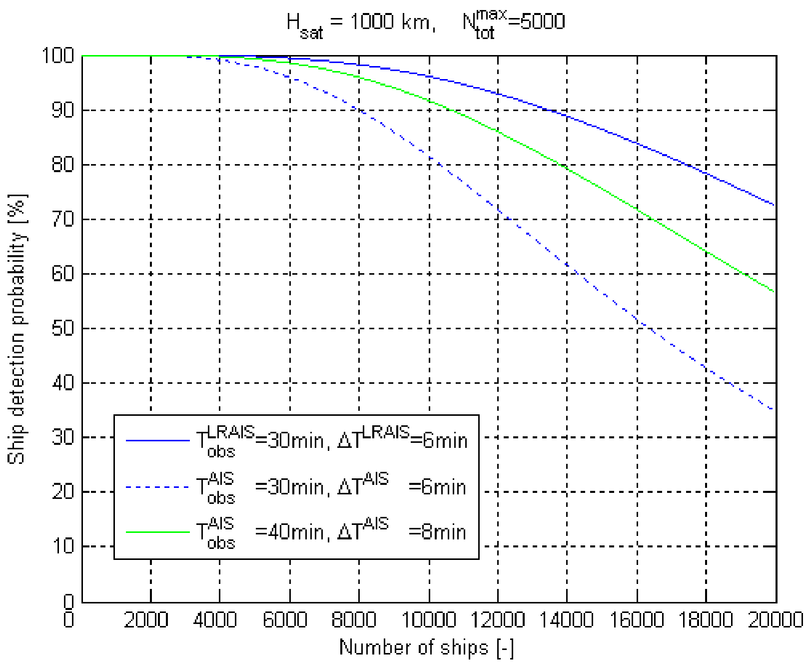


*Figure 6.23 Ship detection probability curves optimised for up to 5000 ships within the field of view with a ship detection probability of better than 99% . Green line shows results for standard AIS messages and blue line for short LRAIS messages. The blue dotted line shows results for standard AIS messages when using the same ship reporting interval and observation time as for short LRAIS messages.*

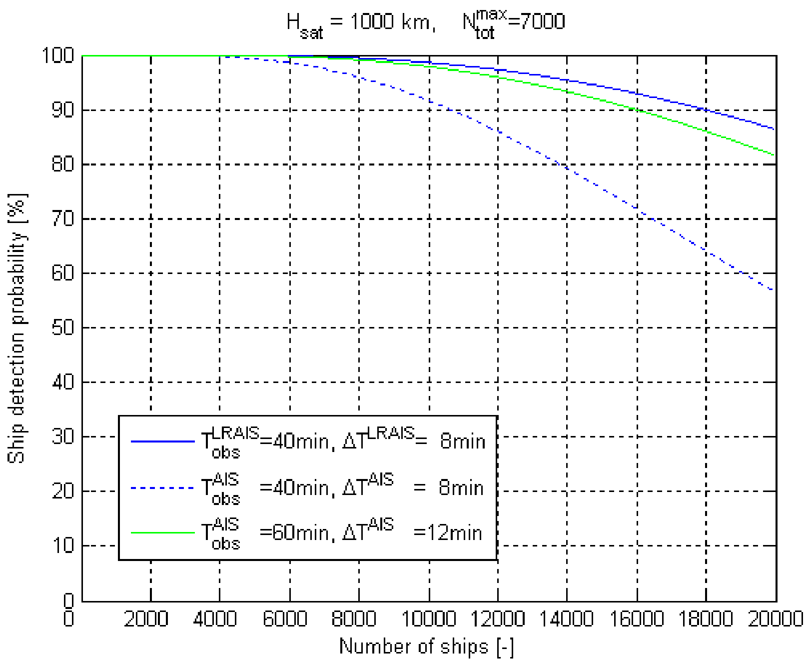


*Figure 6.24 Ship detection probability curves optimised for up to 7000 ships within the field of view with a ship detection probability of better than 99% . Green line shows results for standard AIS messages and blue line for short LRAIS messages. The blue dotted line shows results for standard AIS messages when using the same ship reporting interval and observation time as for short LRAIS messages.*

# 7 DISCUSSION

We have performed analyses to optimise the existing AIS system for LRAIS. We have studied both an LRAIS system that uses short LRAIS messages and an LRAIS system that uses standard AIS messages. Figure 6.1-Figure 6.8 and Table 6.1-Table 6.8 present the results for the LRAIS system that uses standard AIS messages. Figure 6.11-Figure 6.18 and Table 6.11-Table 6.18 present the results for the LRAIS system that uses short LRAIS messages.

We will first discuss some general properties of the system in Sections 7.1-7.3. These properties are the same for both LRAIS systems. We will then proceed to discuss the specific results for each of the two LRAIS systems in Sections 7.5-7.6. Finally, we give a short summary in Section 7.7.

## 7.1 Ship detection probability, observation time, and number of ships

From Figure 6.1-Figure 6.8 and Figure 6.11-Figure 6.18 we see that *increasing* the number of ships *decreases* the ship detection probability for given observation time and ship reporting interval. This result can also be found directly from Equation (5.1).

We further see that *increasing* the observation time *increases* the ship detection probability for given number of ships and ship reporting interval. Figure 6.1, Figure 6.2, and Figure 6.7 show the ship detection probability curves for observation times of 5, 10, and 50 min respectively. For 4000 ships within the field of view and a ship reporting interval of 5 min the corresponding ship detection probabilities are 55%, 93%, and 100%. This result can also be found directly from Equation (5.1).

Finally, we notice that *increasing* the observation time *increases* the number of ships that the system can handle with a given ship detection probability. Figure 6.1, Figure 6.2, and Figure 6.7 show the ship detection probability curves for observation times of 5, 10, and 50 min respectively. For a ship detection probability of 90% and a ship reporting interval of 5 min the corresponding numbers of ships that the system can handle are 700, 2500, and 10 500.

## 7.2 Number of reports

Figure 6.1-Figure 6.8 and Figure 6.11-Figure 6.18 illustrate the behaviour of the ship detection probability curves with respect to the number of reports transmitted from a ship during the observation period. Each figure shows the ship detection probability curves for several different numbers of reports.

We first notice that *low* numbers of reports give a *slower* decline in the ship detection probability curve than high numbers of reports. Further, we see that *low* numbers of reports give a *higher* ship detection probability when there are *many* ships within the field of view, while *high* numbers of reports give a *higher* ship detection probability when there are *few* ships within the field of view.

The number of reports $n$ turns out to be a crucial parameter for the overall system performance and must be fine tuned in order to achieve optimum system performance. It relates directly to the ship reporting interval $\Delta T$ and the observation time $T_{obs}$ through the formula

$$n = \frac{T_{obs}}{\Delta T} \tag{7.1}$$

If the number of reports is *too high*, the system will receive very many reports from each ship during the observation time. The system will then become saturated, and this results in a *decrease* in the ship detection probability. On the other hand, if the number of reports is *too low*, the system will receive so few reports from each ship that it may easily fail to detect the ship at all, and the ship detection probability again *decreases*.

Careful analyses were performed to determine the optimum choice of number of reports for the system. Table 6.9-Table 6.10 present the results for the LRAIS system that uses standard AIS messages. The results are based on analyses of Figure 6.1-Figure 6.8 and Table 6.1-Table 6.8. Table 6.19-Table 6.20 present the results for the LRAIS system that uses short LRAIS messages. The results are based on analyses of Figure 6.11-Figure 6.18 and Table 6.11-Table 6.18.

Table 6.9 (standard AIS messages) and Table 6.19 (short LRAIS messages) show that when requiring a ship detection probability of 99%, the optimum number of reports is $n_0$ =5. This is the same both for the LRAIS system that uses standard AIS messages and the LRAIS system that uses short LRAIS messages. On the other hand, when requiring a ship detection probability of only 90%, the optimum number of reports decreases to $n_0$ =2 (see. Table 6.10 and Table 6.20).

The optimum number of reports is dependent on the requirement to the ship detection probability and seems to decrease when the requirement decreases. Analyses have further shown that the optimum choice of number of reports for the system is independent of the observation time, see also Figure 6.1-Figure 6.8, Figure 6.11-Figure 6.18, Table 6.1-Table 6.8, and Table 6.11-Table 6.18.

## 7.3 The intersection point for the ship detection probability curves

The analyses have revealed some interesting characteristics of the intersection points for the ship detection probability curves.

From Figure 6.1-Figure 6.8 (standard AIS messages) we notice that the ship detection probability curves for *two different ship reporting intervals* seem to always intersect for the same *number of ships* independently of how long the observation time is. Figure 6.11-Figure 6.18 (short LRAIS messages) show similar behaviour. Information about the intersection points for the ship detection probability curves for different pairs of ship reporting intervals $\Delta T_a$ and $\Delta T_b$ is summarized in Table 7.1. The table confirms the above observation, and also shows that the ship detection probability at the intersection point increases with increasing observation time. It can be shown analytically that the system will have this behaviour (4), but the analytical proof has not been included in this report.

| | $\Delta T_a$=1min, $\Delta T_b$=5min | | | | $\Delta T_a$=6min, $\Delta T_b$=30min | | | |
|---|---|---|---|---|---|---|---|---|
| | $T_{obs}$ | $N_{tot}$ | P | Reference | $T_{obs}$ | $N_{tot}$ | P | Reference |
| **AIS** | 5 min | 1 900 | 75% | Figure 6.1 | 30 min | 11 200 | 76% | Figure 6.5 |
| | 10 min | 1 900 | 94% | Figure 6.2 | 60 min | 11 200 | 94% | Figure 6.8 |
| **LRAIS** | 5 min | 3 200 | 76% | Figure 6.1 | 30 min | 19 000 | 77% | Figure 6.5 |
| | 10 min | 3 200 | 94% | Figure 6.2 | 60 min | 19 000 | 94% | Figure 6.8 |

*Table 7.1 Characteristics of the intersection point for the ship detection probability curves for different pairs of ship reporting interval* $\Delta T_a$ *and* $\Delta T_b$. $T_{obs}$ *is the observation time,* $N_{tot}$ *is the number of ships within the field of view, and* $P$ *is the ship detection probability. Results are shown for both the LRAIS system that uses standard AIS messages and the LRAIS system that uses short LRAIS messages.*

| | $n_a$=2, $n_b$=5 | | | | $n_a$=1, $n_b$=10 | | | |
|---|---|---|---|---|---|---|---|---|
| | $T_{obs}$ | $N_{tot}$ | P | Reference | $T_{obs}$ | $N_{tot}$ | P | Reference |
| **AIS** | 5 min | 1 300 | 88% | Figure 6.1 | 5 min | 1 200 | 84% | Figure 6.1 |
| | 10 min | 2 800 | 88% | Figure 6.2 | 10 min | 2 400 | 84% | Figure 6.2 |
| | 15 min | 4 200 | 88% | Figure 6.3 | 15 min | 3 700 | 84% | Figure 6.3 |
| | 20 min | 5 700 | 88% | Figure 6.4 | 20 min | 4 800 | 84% | Figure 6.4 |
| | 30 min | 8 400 | 88% | Figure 6.5 | 30 min | 7 200 | 84% | Figure 6.5 |
| | 40 min | 11 400 | 88% | Figure 6.6 | 40 min | 9 600 | 84% | Figure 6.6 |
| **LRAIS** | 5 min | 2 400 | 88% | Figure 6.1 | 5 min | 2 000 | 84% | Figure 6.1 |
| | 10 min | 4 800 | 88% | Figure 6.2 | 10 min | 4 100 | 84% | Figure 6.2 |
| | 15 min | 7 100 | 88% | Figure 6.3 | 15 min | 6 100 | 84% | Figure 6.3 |
| | 20 min | 9 600 | 88% | Figure 6.4 | 20 min | 8 100 | 84% | Figure 6.4 |
| | 30 min | 14 300 | 88% | Figure 6.5 | 30 min | 12 100 | 84% | Figure 6.5 |
| | 40 min | 19 000 | 88% | Figure 6.6 | 40 min | 16 100 | 84% | Figure 6.6 |

*Table 7.2 Characteristics of the intersection point for the ship detection probability curves for different pairs of numbers of reports* $n_a$ *and* $n_b$. $T_{obs}$ *is the observation time,* $N_{tot}$ *is the number of ships within the field of view, and* $P$ *is the ship detection probability. Results are shown for both the LRAIS system that uses standard AIS messages and the LRAIS system that uses short LRAIS messages.*

From Figure 6.1-Figure 6.8 (standard AIS messages) we further notice that the ship detection probability curves for *two different numbers of reports* seem to always intersect for the same *ship detection probability* independently of how long the observation time is. Figure 6.11-Figure 6.18 (short LRAIS messages) show similar behaviour. Information about the intersection points for the ship detection probability curves for different pairs of numbers of reports $n_a$ and $n_b$ is summarized in Table 7.2. The table confirms the above observation, and also shows that the number of ships at the intersection point increases with increasing observation time. It can be shown analytically that the system will have this behaviour (4), but the analytical proof has not been included in this report.

## 7.4 The LRAIS system that uses standard AIS messages

We will now discuss the specific results for the LRAIS system that uses standard AIS messages.

Table 6.9 shows the optimum choice of observation time and ship reporting interval in order to handle a certain number of ships within the field of view when requiring a ship detection probability of **99%** or better. The results are based on analyses of Figure 6.1-Figure 6.8 and Table 6.1-Table 6.8. The optimum choice of number of reports was found to be $n_0 = 5$ for this case. The results show that with an observation time of 15 min the system can handle about 2000 ships within the field of view. This increases to 8000 ships if the observation time is 60 min. Figure 6.9 shows the corresponding optimised ship detection probability curves.

Table 6.10 shows the optimum choice of observation time and ship reporting interval in order to handle a certain number of ships within the field of view when requiring a ship detection probability of **90%** or better. The results are based on analyses of Figure 6.1-Figure 6.8 and Table 6.1-Table 6.8. The optimum choice of number of reports was found to be $n_0 = 2$ for this case. The results show that with an observation time of 15 min the system can handle about 3000 ships within the field of view. This increases to 14 000 ships if the observation time is 60 min. Figure 6.10 shows the corresponding optimised ship detection probability curves.

Table 7.3 summarizes some of the results for ship detection probability requirements of 99% and 90% respectively based on Table 6.9-Table 6.10. The table shows that accepting a lower ship detection probability for the system increases the number of ships that the system can handle.

| **$T_{obs}$** | **$N_{tot}$** | |
|---|---|---|
| | **P=99%** | **P=90%** |
| 15 min | 2000 | 3000 |
| 30 min | 4000 | 7000 |
| 60 min | 8000 | 14 000 |

*Table 7.3 Number of ships $N_{tot}$ that can be handled by an LRAIS system that uses standard AIS messages as a function of different observation times $T_{obs}$. Results are shown for ship detection probability requirements of 99% and 90%.*

## 7.5 The LRAIS system that uses short LRAIS messages

We will now discuss the specific results for the LRAIS system that uses short LRAIS messages.

Table 6.19 shows the optimum choice of observation time and ship reporting interval in order to handle a certain number of ships within the field of view when requiring a ship detection probability of **99%** or better. The results are based on analyses of Figure 6.11-Figure 6.18 and Table 6.11-Table 6.18. The optimum choice of number of reports was found to be $n_0 = 5$, which is the same as for the case with standard AIS messages. The results show that with an observation time of 15 min the system can handle about 3000 ships within the field of view.

This increases to 12 000 ships if the observation time is 60 min. Figure 6.19 shows the corresponding optimised ship detection probability curves.

Table 6.20 shows the optimum choice of observation time and ship reporting interval in order to handle a certain number of ships within the field of view when requiring a ship detection probability of **90%** or better. The results are based on analyses of Figure 6.11-Figure 6.18 and Table 6.11-Table 6.18. The optimum choice of number of reports was found to be $n_0 = 2$, which is the same as for the case with standard AIS messages. The results show that with an observation time of 15 min the system can handle about 6000 ships within the field of view. This increases to more than 20 000 ships if the observation time is 60 min. Figure 6.20 shows the corresponding optimised ship detection probability curves.

Table 7.4 summarizes some of the results for ship detection probability requirements of 99% and 90% respectively based on Table 6.19-Table 6.20. The table shows that accepting a lower ship detection probability for the system increases the number of ships that the system can handle.

| $T_{obs}$ | $N_{tot}$ | |
|---|---|---|
| | **P=99%** | **P=90%** |
| 15 min | 3000 | 6000 |
| 30 min | 6000 | 12 000 |
| 60 min | 12 000 | >20 000 |

*Table 7.4 Number of ships $N_{tot}$ that can be handled by an LRAIS system that uses short LRAIS messages as a function of different observation times $T_{obs}$. Results are shown for ship detection probability requirements of 99% and 90%.*

## 7.6 Comparison of the two LRAIS systems

From Table 6.9-Table 6.10 and Table 6.19-Table 6.20 we see that the LRAIS system that uses standard AIS messages requires longer observation time than the system that uses short LRAIS messages in order to handle the same number of ships. From Equation (5.1) it can be shown that the relation between the required observation times $T_{obs}^{AIS}$ and $T_{obs}^{LRIT}$ for the two systems is[1]

$$T_{obs}^{AIS} = (1+s) \cdot T_{obs}^{LRIT} = 1.7 \cdot T_{obs}^{LRIT} \tag{7.2}$$

i.e., the LRAIS system that uses standard AIS messages requires 1.7 times longer observation time than the LRAIS system that uses short LRAIS messages in order to handle the same number of ships.

Figure 6.21-Figure 6.24 compare the ship detection probability curves for the two LRAIS systems. We notice that for the same observation time and ship reporting interval the LRAIS system that uses short LRAIS messages can handle a larger number of ships than the LRAIS system that uses standard AIS messages. From Equation (5.1) it can be shown that the relation between the number of ships $N_{tot}^{AIS}$ and $N_{tot}^{LRIT}$ that can be handled by the two systems is

$$N_{tot}^{LRIT} = (1+s) \cdot N_{tot}^{AIS} = 1.7 \cdot N_{tot}^{AIS} \tag{7.3}$$

[1] By substituting $\Delta T = T_{obs}/n$ into Equation (5.1) and solving for $T_{obs}$.

i.e., the LRAIS system that uses short LRAIS messages can handle 1.7 times more ships than the LRAIS system that uses standard AIS messages.

Table 7.5 shows corresponding values of $N_{tot}^{AIS}$ and $N_{tot}^{LRIT}$ for different ship detection probabilities based on Figure 6.22. The table confirms the above result.

| **P** | $\mathbf{N_{tot}^{AIS}}$ | $\mathbf{N_{tot}^{LRAIS}}$ | $\mathbf{N_{tot}^{LRAIS} / N_{tot}^{AIS}}$ |
|---|---|---|---|
| 30% | 4000 | 6700 | 1.7 |
| 60% | 7000 | 12 000 | 1.7 |
| 90% | 10 800 | 18 000 | 1.7 |

*Table 7.5 Corresponding values of $N_{tot}^{AIS}$ and $N_{tot}^{LRIT}$ for different ship detection probabilities. The numbers are based on Figure 6.22.*

Finally, we notice that the optimum choice of number of reports $n_0$ for given ship detection probability requirement $P$ is the same for both LRAIS systems, see Table 6.9-Table 6.10 and Table 6.19-Table 6.20.

## 7.7 Summary

The following general properties of the system were found:

1) *Increasing* the number of ships *decreases* the ship detection probability.
2) *Increasing* the observation time *increases* the ship detection probability.
3) *Increasing* the observation time *increases* the number of ships that the system can handle.
4) The ship detection probability curves *for two different ship reporting intervals* always intersect for the same *number of ships*. The ship detection probability at the intersection point increases with increasing observation time.
5) The ship detection probability curves for *two different numbers of reports* always intersect for the same *ship detection probability*. The number of ships at the intersection point increases with increasing observation time.

There exists an optimum value $n_0$ for the number of reports. This value is $n_0 = 5$ when the ship detection probability requirement is 99% and $n_0 = 2$ when the ship detection probability requirement is 90%.

The LRAIS system that uses short LRAIS messages can handle 1.7 times *more ships* than the LRAIS system that uses standard AIS messages when all other parameters in the system are the same.

The LRAIS system that uses standard AIS messages needs 1.7 times *longer observation time* than the LRAIS system that uses short LRAIS messages to obtain the same system performance.

The analyses have shown that the LRAIS system that uses short LRAIS messages can handle up to 3000 ship with a ship detection probability of 99% when the observation time is 15 min and the ship reporting interval is 3 min, and up to 12 000 ships when the observation time is 60 min and the ship reporting interval is 12 min. Corresponding numbers for the LRAIS system that uses standard AIS messages are 2000 ships and 8000 ships respectively.

## 8 SUMMARY

The recently introduced Universal Shipborne Automatic Identification System (AIS) is a ship-to-ship and ship-to-shore reporting system using the maritime VHF band to broadcast messages that contain detailed information about vessel identity, position, nature of cargo, etc. Previous studies have shown that the AIS messages could be received from space, and that a space-based AIS system could handle up to 900 ships within the field of view with a ship detection probability of better than 99%.

There is an increasing requirement for global tracking of sea-going vessels. This report has investigated the possibility of optimising the existing AIS system for LRAIS, and suggests to do so by implementing the following:

1) Separate VHF channel for LRAIS
2) Short LRAIS messages
3) Longer ship reporting interval

This will increase the ship detection probability and the number of ships that can be handled by the system.

The analyses have shown that the suggested LRAIS system could handle up to 3000 ships with a ship detection probability of 99% or better when the observation time is 15 min and the ship reporting interval is 3 min. Increasing the observation time to 60 min, and the ship reporting interval to 12 min, increases the number of ships that the system could handle to more than 10 000. In principle, the system could be optimised to handle any number of ships by choosing a sufficiently long observation time.

# APPENDIX

## A SHORT LRAIS MESSAGES

The AIS reporting system is based on the broadcasting of digital messages that are entered into a 1 minute long message frame of 2250 message slots. Each message is limited to 256 bits and occupies a timeslot with length 26.67 ms. A distance delay buffer is used to prevent overlap between adjacent AIS messages for differences in the signal path length of up to about 200 nm (6). For larger differences in the signal path length overlap may occur. This would reduce the ship detection probability for a space-based AIS system.

The idea behind introducing a short LRAIS message is to increase the distance delay buffer so that larger differences in the signal path length can be tolerated without causing overlap between adjacent messages. This is suggested done by reducing the content of the data field in the message since an LRAIS system does not need as detailed information about the ships as the AIS system is currently providing.

The short LRAIS message should contain the following information:

1) Identity
2) Position ( $\pm 185$ m )

and possibly also course over ground and speed over ground (7), see Table A.1.

Table A.2 shows the total content of the short LRAIS message (7). The message is 256 bits long, and the data field uses 88 bits while 92 bits are reserved for the distance delay buffer (compared to 12 bits in standard AIS messages). With a distance delay buffer of 92 bits, differences in the signal path length of up to 1550 nm can be tolerated. AIS sensor altitudes up to 1000 km are therefore acceptable for an LRAIS system that is based on the use of short LRAIS messages[1].

| Parameter | Number of bits | Description |
|---|---|---|
| User ID | 30 | MMSI number |
| Position Accuracy | 1 | Position accuracy flag: 1=high; 0=low |
| Longitude | 18 | Longitude in 1/10 min<br>( $\pm 180°$ , East = positive, West = negative) |
| Latitude | 17 | Latitude in 1/10 min<br>( $\pm 90°$ , North = positive, South = negative) |
| COG | 9 | Course over ground in whole degrees |
| SOG | 7 | Speed over ground in whole knots |
| Time Stamp | 6 | |
| **Total number of bits** | **88** | |

*Table A.1 The content of the data field in the short LRAIS message. This table corresponds to Table 15a in (6).*

| Parameter | Number of bits | Description |
|---|---|---|
| Ramp up | 8 | |
| Training sequence | 24 | |
| Start flag | 8 | In accordance with HDLC ($7E_h$) |
| **Data** | **88** | **LRAIS data** |
| CRC | 16 | In accordance with HDLC |
| End flag | 8 | In accordance with HDLC ($7E_h$) |
| Buffer 1 | 12 | Bit stuffing, repeater delay, and jitter |
| Buffer 2 | 92 | Distance delay bits |
| **Total number of bits** | **256** | |

*Table A.2 The content of the short LRAIS message. This table corresponds to Table 5 in (6).*

[1]For AIS sensor altitudes up to about 1000 km the signal path difference between a message received from the area right under the AIS sensor (nadir) and a message received from close to the horizon is less than 1550 nm.

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