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Signal environment mapping of the Automatic Identification System frequencies from space

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Abstract

This paper presents received signal strength data recorded by the NORAIS Receiver on the four VHF channels allocated to the use of the Automatic Identification System (AIS). The NORAIS Receiver operated on-board the Columbus module of the International Space Station from June 2010 to February 2015. The data shows that a space-based AIS receiver must handle transient strong signals from land-based interference and that the effectiveness of the two long range AIS channels recently allocated is severely reduced in select areas due to land based interference.

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Keywords: AIS; Vessel ID Sys; ISS; Columbus; Maritime VHF; NORAIS

1. Introduction

The Norwegian Defence Research Establishment (FFI) operated an Automatic Identification System (AIS) receiver, known as the NORAIS Receiver (Eriksen et al., 2010), on-board the Columbus module of the International Space Station (ISS) from June 2010 to February 2015. The official name for the operation of the AIS receiver on-board Columbus is Vessel ID Sys. In addition to receiving AIS messages and demonstrating space-based AIS as a security, safety and surveillance capability for European authorities, the NORAIS Receiver was designed to collect auxiliary data about the AIS signals and signal environment in space. The intention was to collect information that would contribute to the development of more advanced decoding algorithms, and investigate in-situ the challenges that space-based AIS receivers face. Among the auxiliary data is a received signal strength indicator (RSSI) value. The RSSI value is used in this paper to inform about the signal environment space-based AIS receiver systems will be subject to, both on the nominal AIS channels, 161.975 MHz and 162.025 MHz, and the channels intended for long range use, 156.775 MHz and 156.825 MHz. The long range frequencies were implemented, along with a long range AIS message, type 27, in the International Telecommunication Union recommendation ITU-R M.1371 (ITU, 2014). These long range frequencies are referred to as the space AIS frequencies in this paper.

This paper presents the signal levels experienced by the NORAIS Receiver on the standard AIS frequencies, the space AIS frequencies, and the temporal changes since the start of operations in June 2010 until June 2014. After a brief background in Sections 2 and 3 describes the methodology used collecting, processing and presenting the data and also discusses some important considerations for interpreting the results. Section 4 presents the results for the standard AIS frequencies while Section 5 presents the results for the space AIS frequencies. Section 6 presents

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a discussion of the results and their application. Finally, Section 7 concludes the results.

2. Background

For completeness, a high level introduction to the AIS system is appropriate: AIS is a ship-to-ship and ship-to-shore reporting system intended to increase the safety of life at sea and to improve control and monitoring of maritime traffic. AIS equipped ships broadcast their identity, position, speed, heading, cargo, destination, etc. to vessels and shore stations within range of the VHF transmission. The reporting interval depends on the message type and dynamic conditions of the vessel such as speed and rate of turn. The message types 1–3 with dynamic content such as position information are transmitted every 2–10 s depending on the dynamic conditions. If anchored or moored and moving slower than 3 knots the reporting interval is 3 min. The long range type 27 message reporting interval is every 3 min regardless of dynamic conditions. On ground level AIS stations on shore can typically receive AIS messages at distances about 40–50 nautical miles offshore. With a low noise, highly sensitive receiver capable of handling Doppler shifts up to ±4000 Hz (depending on altitude) an AIS receiver on a satellite can extend the range to global AIS message reception.

Simulations predicted, and in-orbit data verified, that in high density ship traffic areas, co-channel interference will degrade the performance of a space-based AIS system drastically (Eriksen et al., 2006; Helleren et al., 2008; Narheim et al., 2011). With an ever increasing AIS carrying fleet, a proposed solution for space-based AIS is the introduction of two channels dedicated to space-based AIS. Only the long range type 27 message shall be used on these new channels. The significantly longer transmission interval compared to the standard AIS reporting intervals and fewer bits in the message should increase the space-based AIS system capacity markedly because the co-channel interference is reduced (ITU, 2009).

2.1. The NORAIS Receiver

The NORAIS Receiver is installed in the Columbus module of the ISS connected to an external dipole antenna mounted on the forward facing side of the module. The NORAIS Receiver AIS payload was developed by Kongsberg Seatex AS and is a software defined radio that supports operation on any two channels within the maritime very high frequency (VHF) band from 156 MHz to 162.025 MHz. In addition to operating in the nominal mode decoding AIS messages, the payload also supports a sampling mode in which the raw signal, the in-phase and quadrature components, on a channel can be sampled for further processing on ground. The sampling frequency, number of bits and which bits to store is user configurable. The sampling frequency is however limited to integer fractions (0–9) of the 96 kHz internal intermediate frequency. The internal frequency itself is ten times the AIS message symbol frequency. The software defined radio also supports in-orbit upgrades, which have been performed several times during the 4.5 year operations period. The upgrades were developed based on data analysis of the collected AIS, auxiliary and sampling data.

The signal level measurements presented are calculated from a calibration curve measured at the antenna port input at the NORAIS Receiver, after any cable loss from the antenna mounted outside on the Columbus module. The signal level measurements presented herein may thus be considered to be on the lower end of what should be expected in orbit.

2.2. AISSat-1

The Norwegian AISSat-1 satellite is referenced later in the paper to demonstrate the effect different satellite orbit geometries have on the data analysis presented in this paper. AISSat-1 is a 6 kg nano-satellite built by the University of Toronto Space Flight Laboratory in Canada under contract from FFI (Helleren et al., 2012). The satellite was launched in July 2010 into a 635 km sun-synchronous orbit. AISSat-1 has a monopole antenna with full attitude control enabling the antenna to be pointed in any direction. The AIS payload is, for the purposes of this paper, identical to the NORAIS Receiver.

3. Methodology

Auxiliary measurement information such as time of reception, received signal strength and frequency shift relative to the receiver centre frequency is appended to every AIS message received. The received signal strength indicator (RSSI) value is calculated continuously by passing the amplitude of the signal samples (taken at a rate of 96 kHz) through an infinite impulse response (IIR) filter according to Eq. (1):

$$\mathrm{RSSI}(n) = \mathrm{RSSI}(n-1) + 0.1 \times (A(n) - \mathrm{RSSI}(n-1)) \tag{1}$$

where $A(n)$ is the signal amplitude of sample “n”. Conversion from the RSSI value to dBm is done via a calibration curve from pre-launch calibration of the RSSI values.

If the receiver is not able to find a training sequence, indicating the presence of an AIS message, within ~20 ms into a timeslot, the receiver creates an “empty” timeslot measurement with time of reception, received signal strength and receiver centre frequency information only. The receiver may not be able to find an AIS message training sequence for a number of reasons. One possibility is that there is no AIS message in the timeslot, another that there are several AIS messages received at the same time in the same timeslot corrupting the training sequence, or some other source of interference overlapping with the AIS message training sequence. Only such “empty” timeslot measurements are used to plot the signal levels in this paper, and may be considered the background noise level above which the signal level of an AIS message must be to have any reliable chance of being received. The background level comprises of all the components contributing to the energy in the signal, e.g. thermal noise of the antenna and receiver electronics and interference from ground and locally.

Note that it is not possible to rule out entirely that some of the background signal experienced originates locally from the ISS. With the large number of experiments and equipment on the ISS, there are many potential sources of interference. FFI, together with ESA and NASA, have for instance identified that the some part of the S-band equipment has spurious emissions in the NORAIS Receiver pass band. The interference mostly affects the 161.975 MHz channel, but is not constant in time. The datasets presented herein are from periods of little interference from the S-band equipment. However, it could be that there is other equipment on board contributing to the background signal experienced by the NORAIS Receiver. Sampling operations and background signal measurements from the Pacific Ocean, with little potential for land based interference, does not indicate any other local interference from the ISS. However, it could be that some equipment that FFI have not been able to identify is only active over the areas with high background signal level.

Two methods of presenting the data are discussed that are useful to interpret that data. Both methods couples the time of reception from the "empty" timeslot measurements with historic two line elements (TLE) orbit data for the ISS such that the signal level can be attributed to a geographic position. However, since the NORAIS Receiver antenna is near omnidirectional, a precise location of the transmitting source cannot be determined. One approach then is to assign the signal level to the sub satellite point, directly underneath the ISS. Another approach is to assign the signal level to the entire field of view. As time evolves, the sub-satellite approach will provide a better temporal view of the signal level variability compared with the field of view approach. Using the field of view approach however yields a better spatial understanding about geographically challenging areas.

3.1. Field of view approach to data presentation

The basis for the field of view approach to data presentation is the orbit and antenna configuration of the space AIS system. The result will be a map of the signal level as experienced by that particular space AIS system. The NORAIS Receiver for example will have the ISS and an omnidirectional antenna configuration. A different orbit or a directional antenna, for instance, would produce a slightly different map. The orbit effect on the field of view is illustrated by showing the typical ground coverage over a 24 h period from the NORAIS Receiver in the ISS ~350 km altitude, 51.6° inclination orbit in Fig. 1. compared to the plot for a 635 km altitude, 98.1° inclination orbit in Fig. 2. illustrated by AISSat-1 ground coverage. Both figures assume an omnidirectional antenna is used. While the ISS has a maximum number of views around 35° North and South, AISSat-1 has a maximum number of views around 70° and more North and South.

Typically 24 h have been used to present the background noise levels as well. For the field of view data presentation technique the NORAIS Receiver field of view is calculated every 10 s using an omnidirectional antenna and ISS two-line element data. For each 10 s time step all the received signal strength measurements are used to calculate the median or maximum signal received. The calculated median or maximum value is assigned to the entire field of view before advancing another 10 s, again assigning the calculated value from all the received signal strength measurements to the entire field of view. This 10 s advancement is repeated for the entire specified timeframe. At the end of the integration, the median or maximum value per grid cell is calculated from all the overlapping values. The best temporal resolution using this method is obviously 10 s. However, an AIS timeslot is only 26.7 ms, so even if the median or maximum signal measurement within 10 s seems high, it is still possible to find and decode AIS messages in the area. The probability of decoding any one particular message will, however, decrease with increasing background noise level.

The different fields of view, presented in Figs. 1 and 2, will mainly affect the extent and edges of the zones with different signal strength levels. A higher altitude and omnidirectional antenna would smear the high signal strength values received over a larger area since the field of view is larger. The effect is illustrated by comparing the difference between Figs. 3 and 4 showing the median signal level results for a synthetic noise source at 10°S, 130°W for the NORAIS Receiver and AISSat-1 respectively.

Furthermore, at the edge of the coverage area for an orbit or antenna configuration that does not provide truly global coverage may shift the origin of a noise source. The effect can also be seen comparing Figs. 3 and 4 for a synthetic noise source at 60°N, 0°E for the NORAIS Receiver and AISSat-1 respectively.

For the NORAIS Receiver, in the ISS orbit, the noise source origin appears to be closer to 70°N, 0°E because of the edge effect. This is because the few times the NORAIS Receiver sees 70°N, 0°E the noise source is also always within the field of view. For the AISSat-1 however, there are orbits where 70°N, 0°E is seen without the noise source in the field of view (e.g. coming from the north going south). Such orbits lowers the median signal level for 70° N, 0°E below that of the true noise source level.

3.2. Sub satellite approach to data presentation

The sub satellite approach also uses 10 s time steps from ISS TLE data. However, to emphasize the temporal variations in the signal level, the 10 s of data is simply plotted at

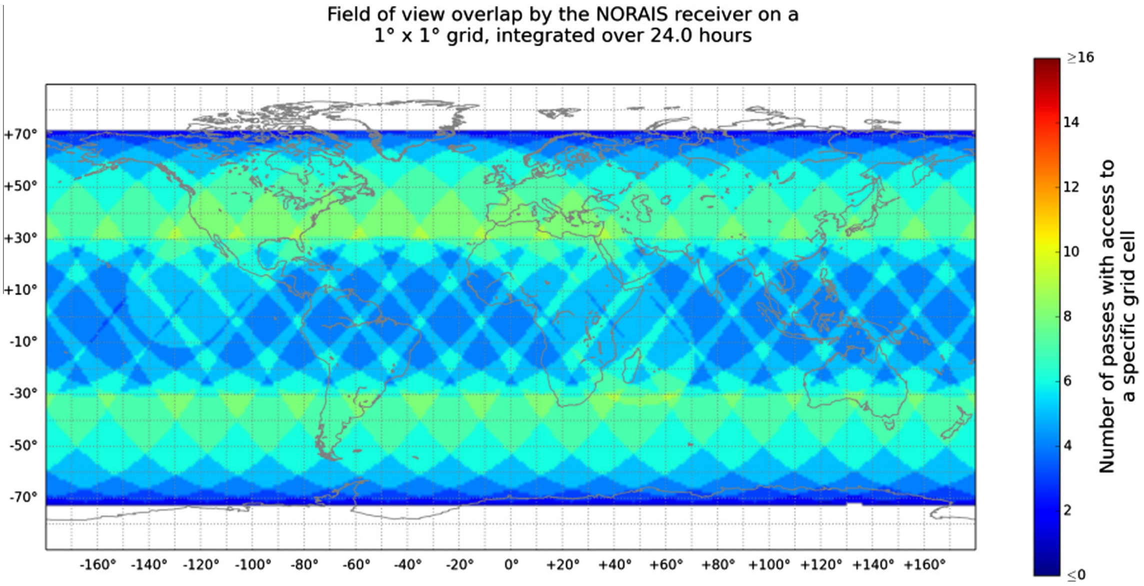

Figure 1. Typical ground coverage by the NORAIS Receiver, accumulated over a 24 h period.

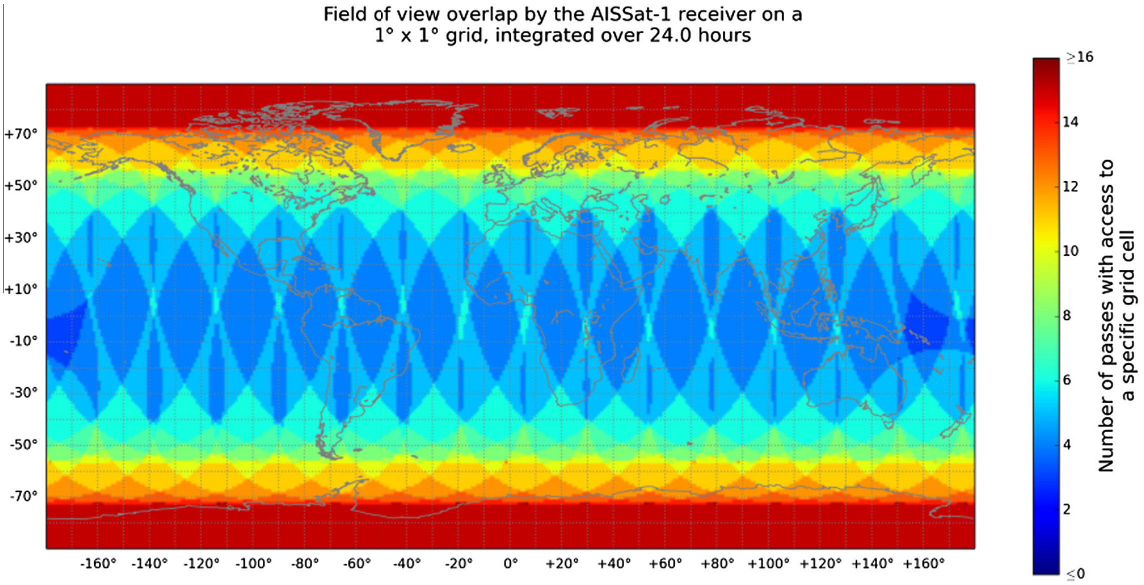

Figure 2. Typical ground coverage by the AISSat-1 Receiver, accumulated over a 24 h period.

the sub satellite point, not distributed over the field of view. While the information about the signal level in a geographical area is reduced, information about the time variability of the signal level at specific points in an orbit is examined. Even shorter timescales have also been investigated, in particular by raw sampling operations, but will not be addressed in this paper. Suffice to say, there is significant variation in the signal level down to sub-second timescales. If integrating over much longer timescales than 24 h, the sub-satellite presentation technique will approach the field of view presentation since the sub-satellite point will have covered more land area. The drawback is then that local interference from the ISS often varies and gaps in the data often occur. This makes comparison between different timeframes more difficult.

When examining the sub satellite approach plots the value lies in the change in signal level from point to point as this explains the time variability of the signal levels. If the signal level does not change, the colour on the plots will not change either. If the signal level changes systematically there will be a systematic change in the colour used as well. Likewise, if the signal level changes are more random, the colours will change randomly as well.

4. AIS1 and AIS2 measurements

The nominal AIS1 and AIS2 frequencies are 161.975 MHz and 162.025 MHz respectively. The NORAIS Receiver has been in operation for over 4 years, and the signal levels for only a limited selection of dates are

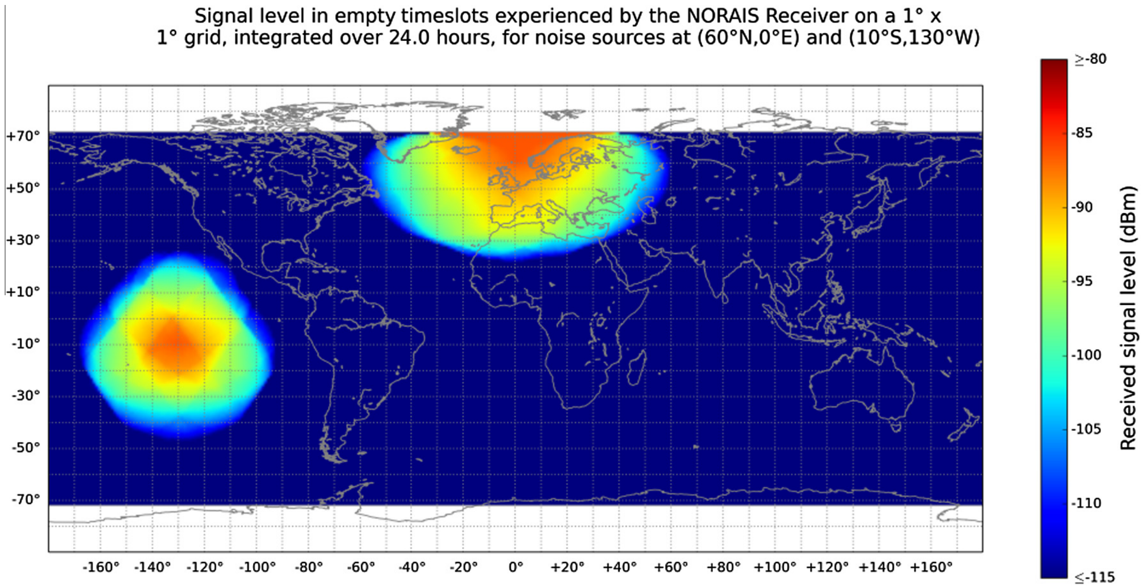

Figure 3. Plot illustrating how the NORAIS Receiver would experience a point source at 10°S, 130°W and 60°N, 0°E.

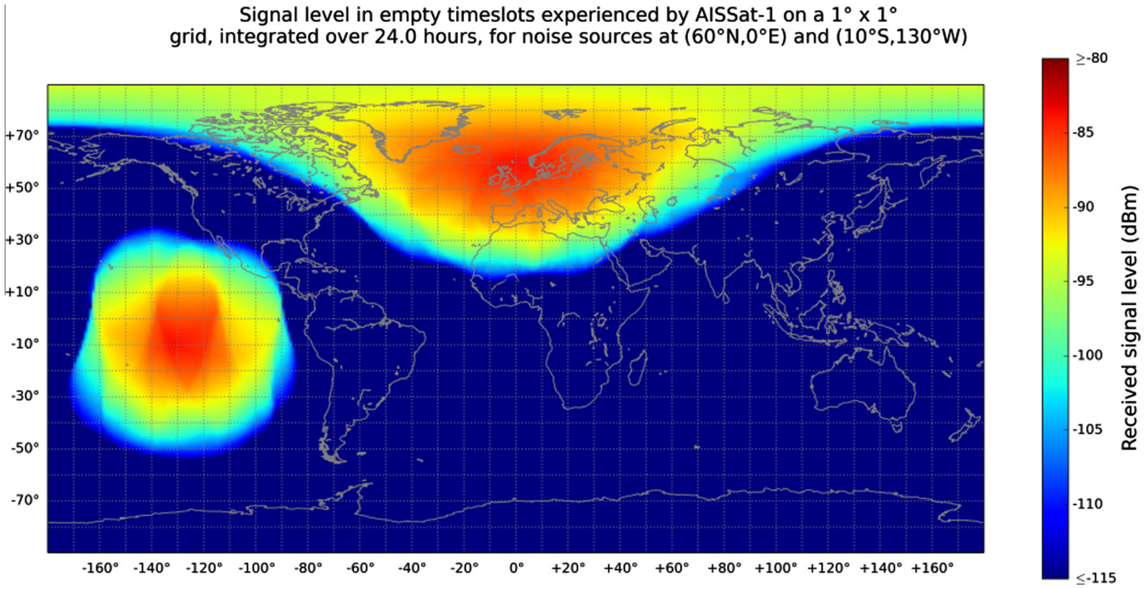

Figure 4. Plot showing how the AISSat-1 receiver would experience a point source at 10°S, 130°W and 60°N, 0°E.

presented in this paper. While the NORAIS Receiver records auxiliary signal environment data continuously in the nominal state, the experiment operations plan and local ISS interference renders large timeframes non-representative. For these reasons no data from 2010 or 2012 is presented. The first 6 months of operations were performed in 2010 and naturally included a lot of experimentation. During 2012 significant effort was put into developing algorithm upgrades. As a stepping stone to the final algorithm, one channel algorithms were used throughout 2012. Therefore no simultaneous recordings of two channels could be made.

4.1. Signal level measurements on AIS1

The median signal level in “empty” timeslots as experienced by the NORAIS Receiver on the AIS1 channel over 24 h is presented in Figs. 5, 6 and 7 for timeframes in January 2011, March 2011 and June 2014 respectively. The data is first presented using the field of view method previously discussed in Section 3.1.

At first glance it is apparent that there is an increase in background signal level over South America in 2014 compared with 2011. There also appears to be an increase over the southern half of Africa, north-eastern Australia and the

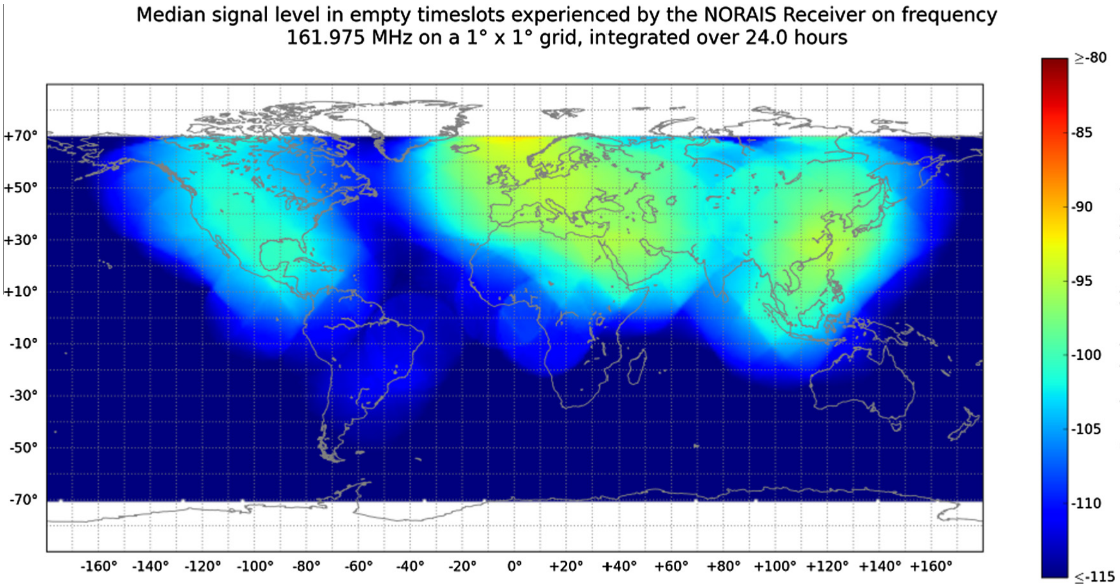

Figure 5. Median received signal strength in "empty" timeslots on frequency 161.975 MHz, the AIS1 channel, 10 January 2011.

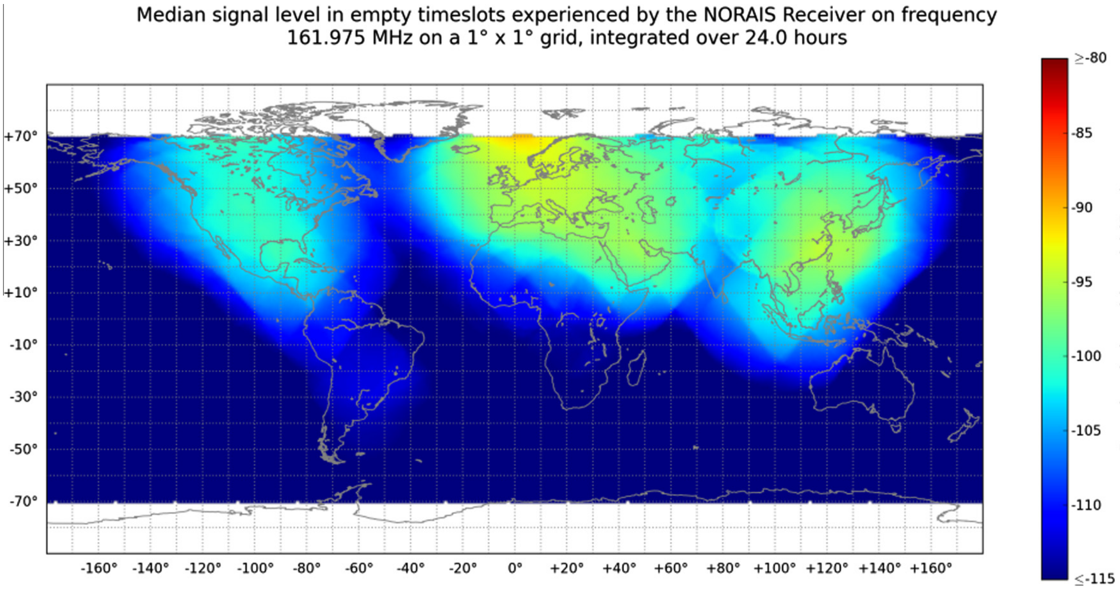

Figure 6. Median received signal strength in "empty" timeslots on frequency 161.975 MHz, the AIS1 channel, 24 March 2011.

mid-Atlantic Ocean in the same time-period. Furthermore there is a decrease seen over western Canada in 2014 compared with previous years.

In the south-western parts of the Pacific Ocean the vessel density is so low that the number of genuinely "empty" timeslot measurements overwhelms the few measurements that may be influenced by AIS messages from ships. As such, the background local noise level, derived from measurements in the most remote parts of the Pacific Ocean, is estimated to be −117 dBm in all the data presented. Over land and close to shore however, the background noise levels are significantly higher. On the one hand, this is expected as the vessel density increases closer to shore and particularly in the high traffic areas of the Gulf of Mexico, English Channel, North Sea, Mediterranean and East and South China Sea. The increased vessel density increases the number of AIS messages within the field of view of the space-based AIS receiver, increasing the probability of co-channel interference. When several messages arrive at the same time, the NORAIS Receiver is unable to decode the signal, and creates an "empty" timeslot measurement. However, the measurement is from a signal that contains AIS messages and this leads to increased signal measurements levels. The increased background signal level over land is not expected however since the frequencies are reserved for AIS messages only. Clearly there is land-based re-use of the frequencies. For the ground-based AIS system, the land-based re-use, as long as the

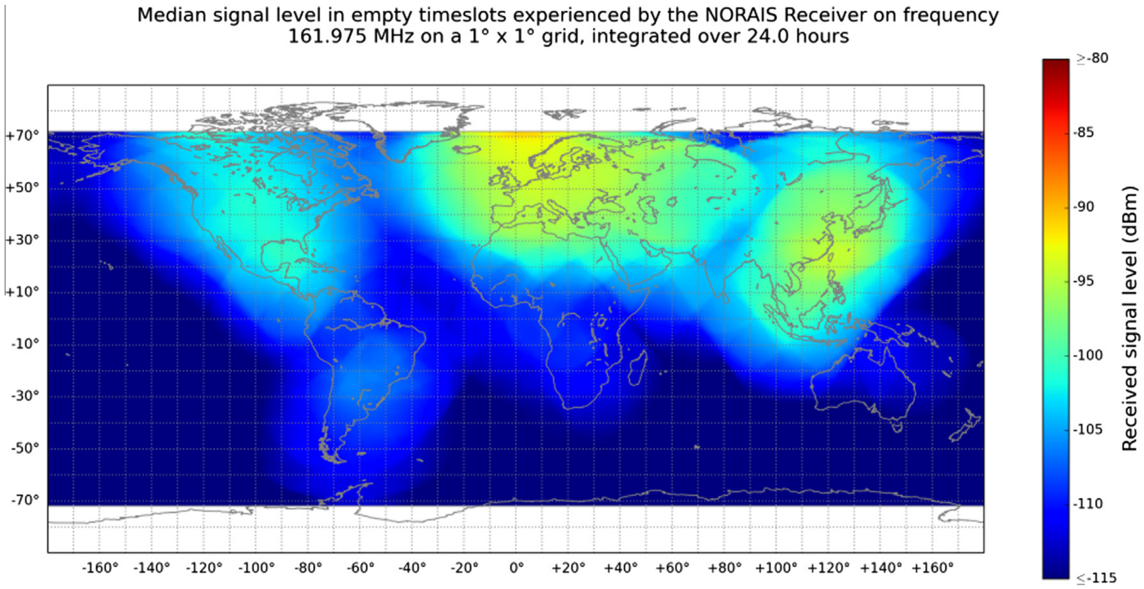

Figure 7. Median received signal strength in “empty” timeslots on frequency 161.975 MHz, the AIS1 channel, 13 June 2014.

re-use is more than 70 NM off the coast, is not problematic because of the range limitation due to the curvature of the earth. For a space-based system however, much greater land and coast areas are visible simultaneously, severely degrading the space-based AIS system.

The edge effect discussed in Section 3.1 is visible in the plots. Although there is no significant noise source in the Norwegian Sea between Norway and Iceland (70°N, 0° E), the NORAIS Receiver experiences a strong total signal when this area is within the field of view. Because of the orbit of the ISS, the high traffic areas of the North Sea, English Channel and the northern Mediterranean are always within the field of view at the same time as the affected area between Norway and Iceland.

In orbit experience has also shown that there are areas where the receiver experiences signals that are so strong that the ADC experiences overflow regularly. With nominal settings processing overflow occurs with signal levels in excess of -83 dBm. It is possible to reduce the receiver gain to postpone processing overflow until ADC saturation occurs when the signal level is in excess of -55 dBm. Experiments show that the affected areas are generally the same, but some variations can be seen, depending on the orbit at the time of signal reception. The strongest signals recorded by the NORAIS Receiver have been around -60 dBm.

Plots of the NORAIS Receiver field of view where the receiver experiences processing overflow are presented for the 24 h January 2011, March 2011 and June 2014 timeframes in Figs. 8, 9 and 10 respectively. Because of the overflow, it is impossible to say how strong the signals are, only that they are stronger than -83 dBm.

Comparing the median signal levels in Figs. 5–7 with the maximum signal levels in Figs. 8–10, it is clear that the maximum signal levels are not continuously experienced when the affected areas are within the field of view. It will be possible to detect AIS messages when these areas are within the field of view, but not during the short periods of time the space-based AIS receiver is experiencing the strong signals shown.

Using the sub satellite plotting method discussed in Section 3.2 for the 2014 dataset gives some insight into the time variability of the signal level. Figs. 11 and 12 show the median and maximum signal received per 10 s for a day in June 2014. In particular, there is further evidence that the very strong signals received are not constant in time. However, it is clear that a space-based AIS receiver front end must handle these strong signals levels on a daily basis. One particular example is the high signal level experienced for a short time (less than 10 s) just north of the Philippines in Fig. 12 that affects a large area in Fig. 10. The high signal level is transient, but any AIS message received from within the field of view at the same time would be lost.

It is clear that the signal level experienced when European waters are within the field of view is elevated. Other experiments have shown that the increase is not only from the great number of AIS signals received, but also from land based re-use. Another example of land-based re-use can be seen when the sub satellite point is over Kazakhstan and the signal level is elevated continuously for a long period. Interestingly, the orbits that are plotted above and below do not experience the same interference, nor do the crossing orbits. This means the interference, while constant when experienced, indicated by the strong presence in the median signal level plot of Fig. 11, is not always present.

Again it should be emphasized that it is possible to decode AIS messages even in the areas of high background signal level. An AIS message is very short in time (26.7 ms),

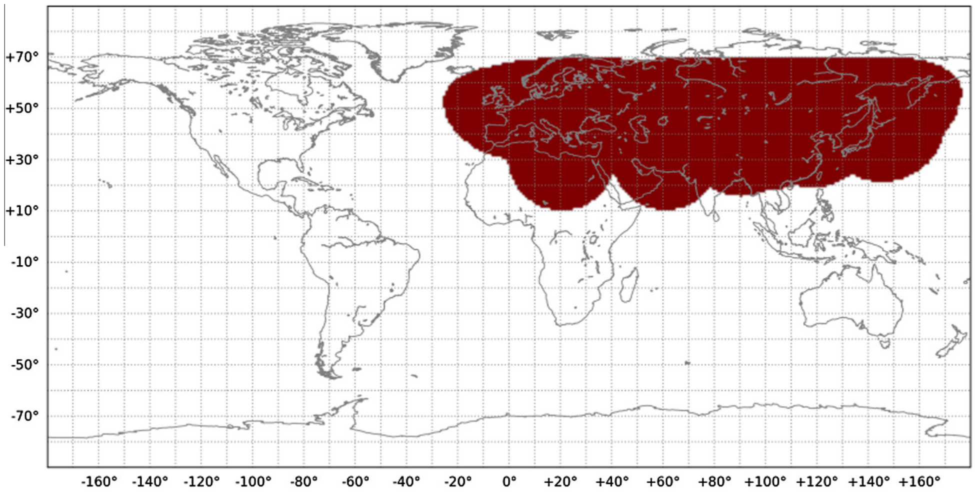

Figure 8. Plot showing NORAIS Receiver field of view when the received signal strength in “empty” timeslots exceeds −83 dBm on frequency 161.975 MHz, the AIS1 channel, 10 January 2011.

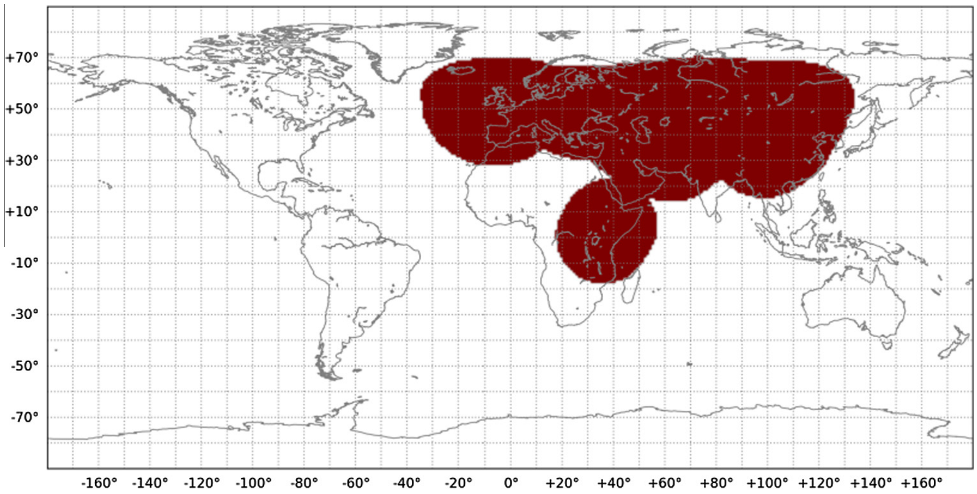

Figure 9. Plot showing NORAIS Receiver field of view when the received signal strength in “empty” timeslots exceeds −83 dBm on frequency 161.975 MHz, the AIS1 channel, 24 March 2011.

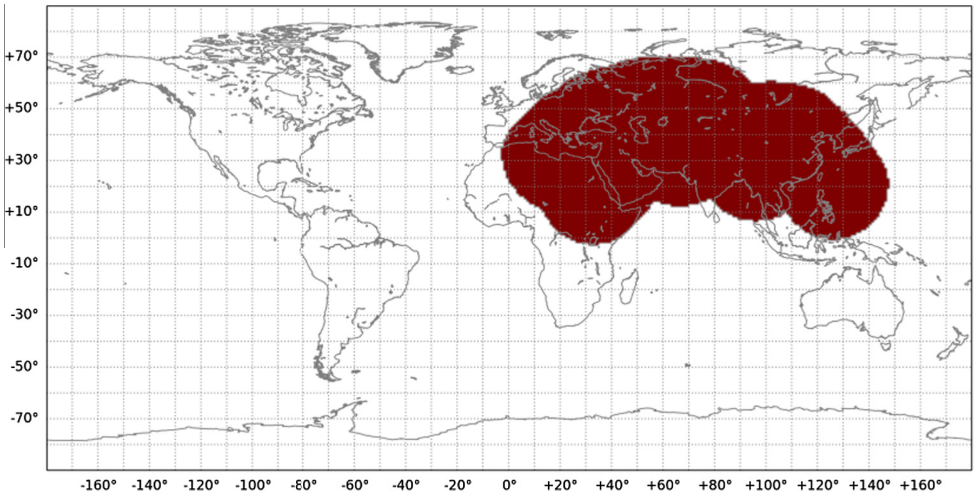

Figure 10. Plot showing NORAIS Receiver field of view when the received signal strength in “empty” timeslots exceeds −83 dBm on frequency 161.975 MHz, the AIS1 channel, 13 June 2014.

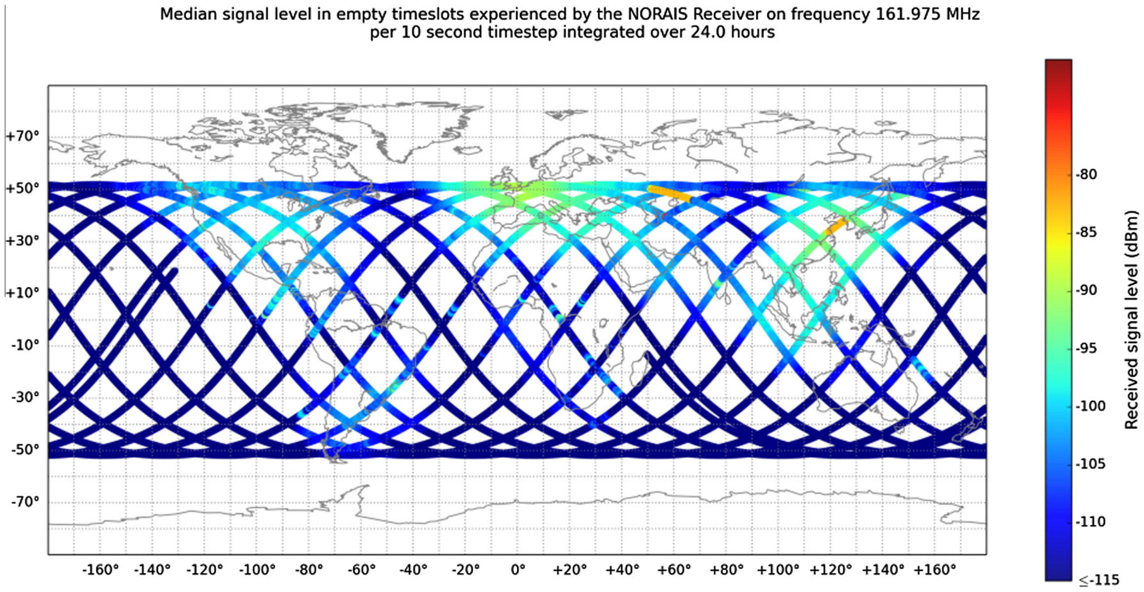

Figure 11. Median received signal strength in “empty” timeslots on frequency 161.975 MHz, the AIS1 channel, 13 June 2014.

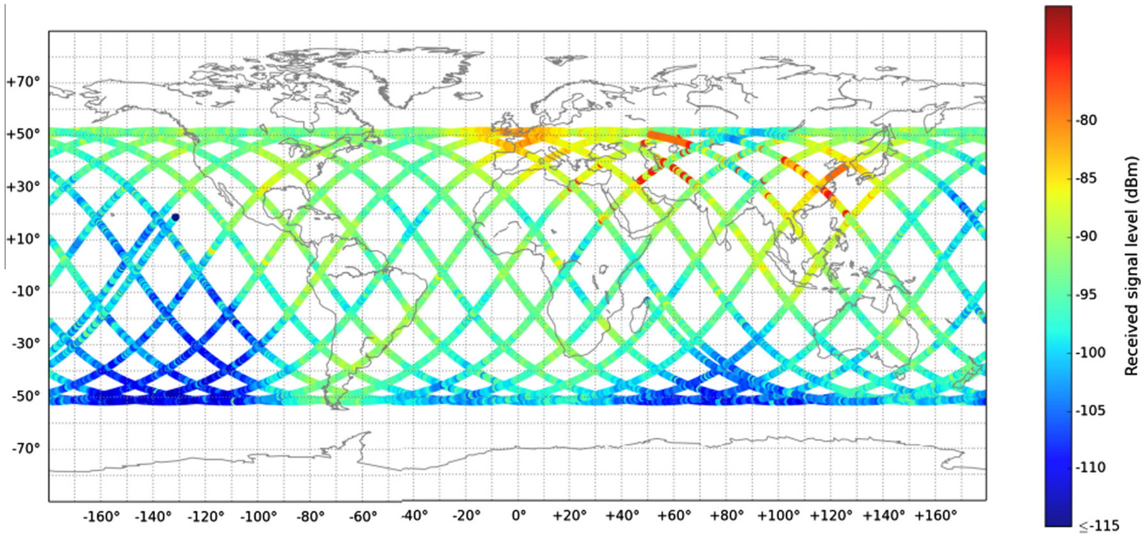

Figure 12. Maximum received signal strength in “empty” timeslots on frequency 161.975 MHz, the AIS1 channel, 13 June 2014.

and the elevated background signal is not constant in time, but most often varies from high down to the local background level many times during the 10 s time steps presented in this paper. Analysis of such short timescales is best done looking at sampling data, which is beyond the scope of this paper.

4.2. Signal level measurements on AIS2

The NORAIS Receiver continuously records, and FFI have continuously monitored, the background signal level measurements to look for seasonal or yearly changes, but without finding much difference year on year or between seasons. Therefore, not all plots shown for the AIS1 channel are presented again for the AIS2 channel, since as for the AIS1 channel there is not any practical difference between the data from 2011 to 2014.

The median signal level in “empty” timeslots as experienced by the NORAIS Receiver on the AIS2 channel over 24 h is presented in Figs. 13 and 14 for the timeframes in March 2011 and June 2014 respectively.

As for the AIS1 channel it is clear that there is an increased background signal level over South America. The increase over southern Africa is more pronounced on the AIS2 channel, and supports the indications seen in the AIS1 plots in the previous Section 4.1. Compared with the AIS1 channel once can also see that the AIS2 channel has a lower background signal level over the northern part of North America. This difference indicates land based interference that is mainly affecting the AIS1 channel.

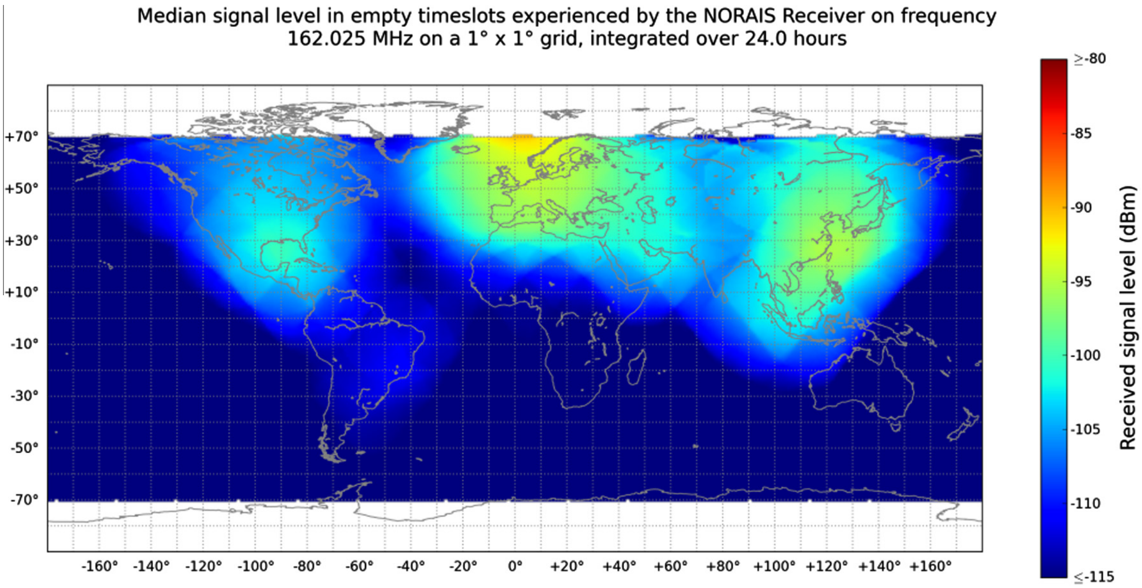

Figure 13. Median received signal strength in “empty” timeslots on frequency 162.025 MHz, the AIS2 channel, 24 March 2011.

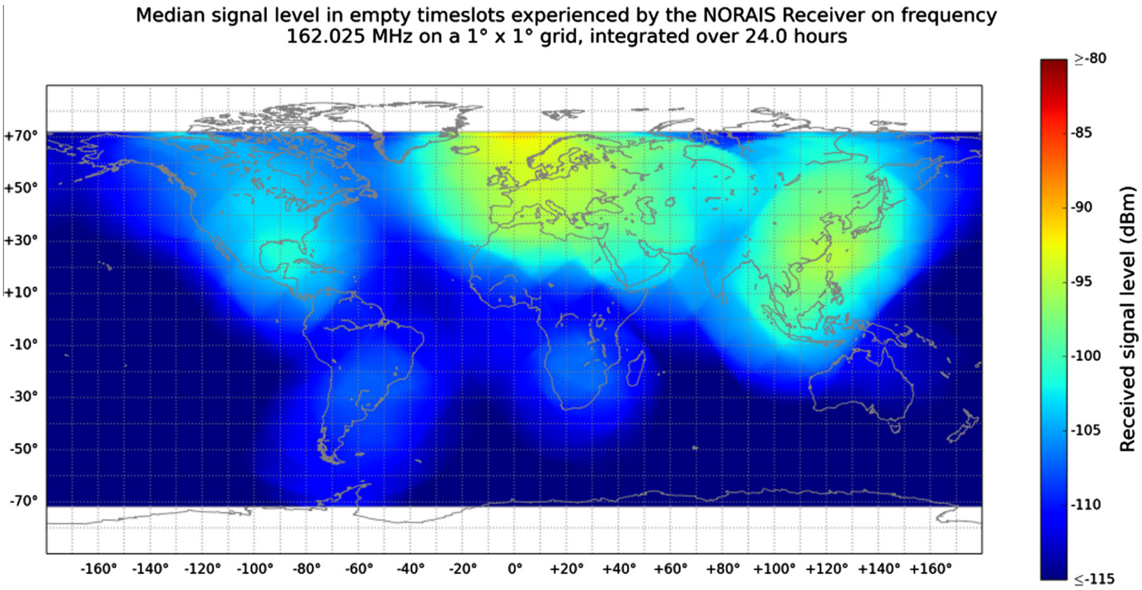

Figure 14. Median received signal strength in “empty” timeslots on frequency 162.025 MHz, the AIS2 channel, 13 June 2014.

The areas where the NORAIS Receiver experienced strong enough signals to cause processing overflow on the AIS 2 channel is shown in Figs. 15 and 16 for the 24 h March 2011 (field of view method) and June 2014 (sub satellite method) timeframes respectively.

Comparing the median and maximum signal level over eastern Africa from 2011 in Figs. 13 and 15 respectively again indicate that the strong signals are only briefly experienced. The median signal level is close to the local background level, while the receiver has experienced processing overflow in the same area.

5. AIS3 and AIS4 measurements

The AIS3 and AIS4 channels, on 156.775 MHz and 156.825 MHz, are allocated for transmission of message type 27, designed for long range reception, including space. The reporting interval of one message every 3 min for the type 27 messages increases the capacity of the transmission scheme used by the AIS system by reducing the likelihood of message collision at the space-based AIS receiver (ITU, 2009). However, with reduced reporting interval the space-based AIS receiver has fewer opportunities to receive the

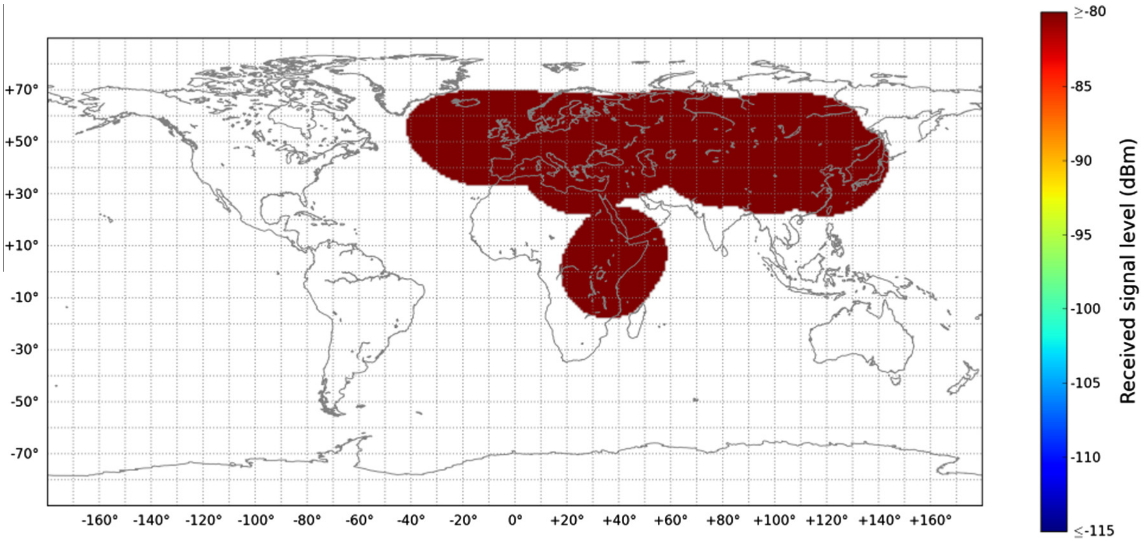

Figure 15. Plot showing NORAIS Receiver field of view when the received signal strength in "empty" timeslots exceeds −83 dBm on frequency 162.025 MHz, the AIS2 channel, 24 March 2011.

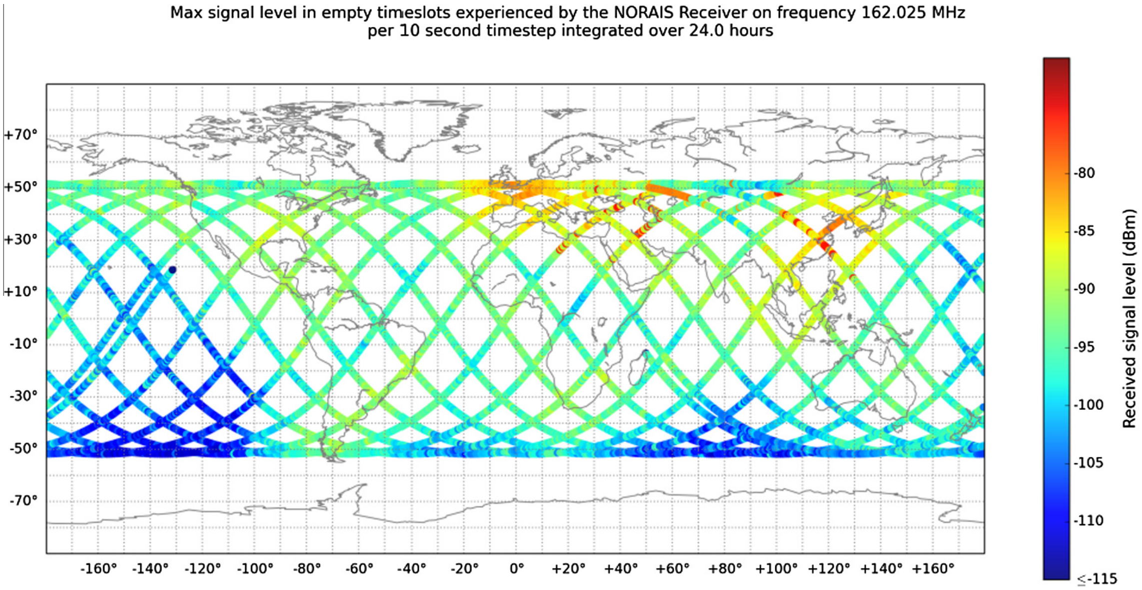

Figure 16. Maximum received signal strength in "empty" timeslots on frequency 162.025 MHz, the AIS2 channel, 13 June 2014.

AIS message, and a good signal to noise ratio is critical for reliable reception. The two NORAIS Receiver channels are nominally set to the AIS1 and AIS2 channels, but measurements on the AIS3 and AIS4 channel was performed in 2010 and 2014 as part of the experimentation plan. In this chapter measurements from 2010 to 2014 are compared.

5.1. Signal level measurements on AIS3

The median signal level in "empty" timeslots as experienced by the NORAIS Receiver on the AIS3 channel over 24 h is presented in Figs. 17 and 18 for timeframes in September 2010 and April 2014 respectively.

Comparing the 2014 data with the 2010 data it appears to be reduction in the background noise level in the western parts of Southern Europe and an increase in the western parts of South America and India.

The maximum background signal strength seen in the 2014 data is presented in Fig. 19 using the sub satellite plotting method to show the time variability of the data. The variation in colour implies that the high signal levels are not constant in time and is sometimes only present in one 10 s step, before disappearing for several 10 s steps. No systematic repetition has been found.

Comparing the maximum received signal level results from 2014 on the AIS3 channels with that of the AIS1 and AIS2 channels, there does not appear to be much

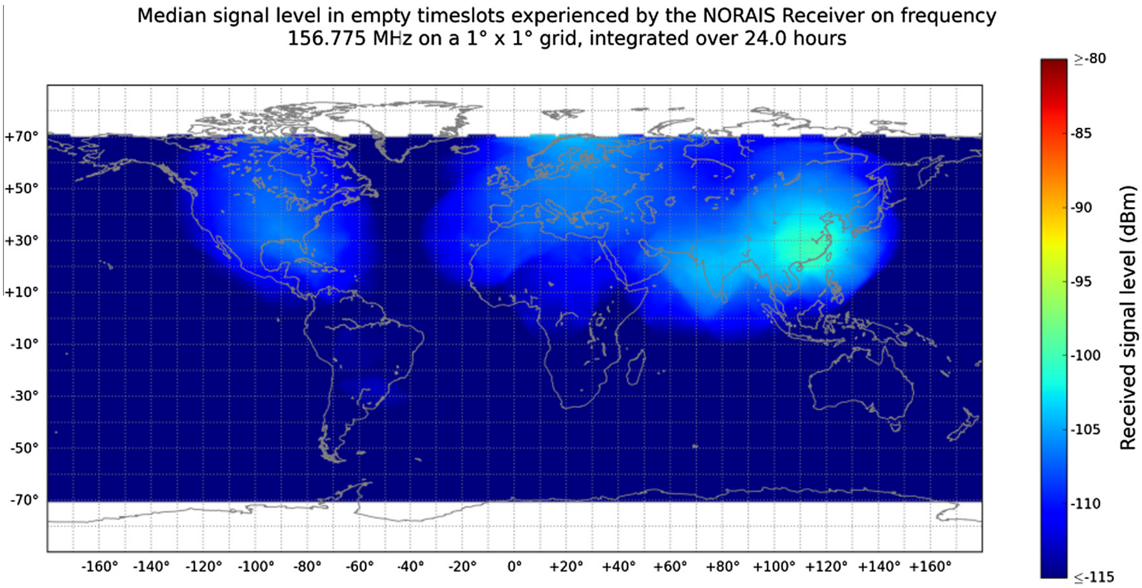

Figure 17. Median received signal strength in “empty” timeslots on frequency 156.775 MHz, the AIS3 channel, 20–21 September 2010.

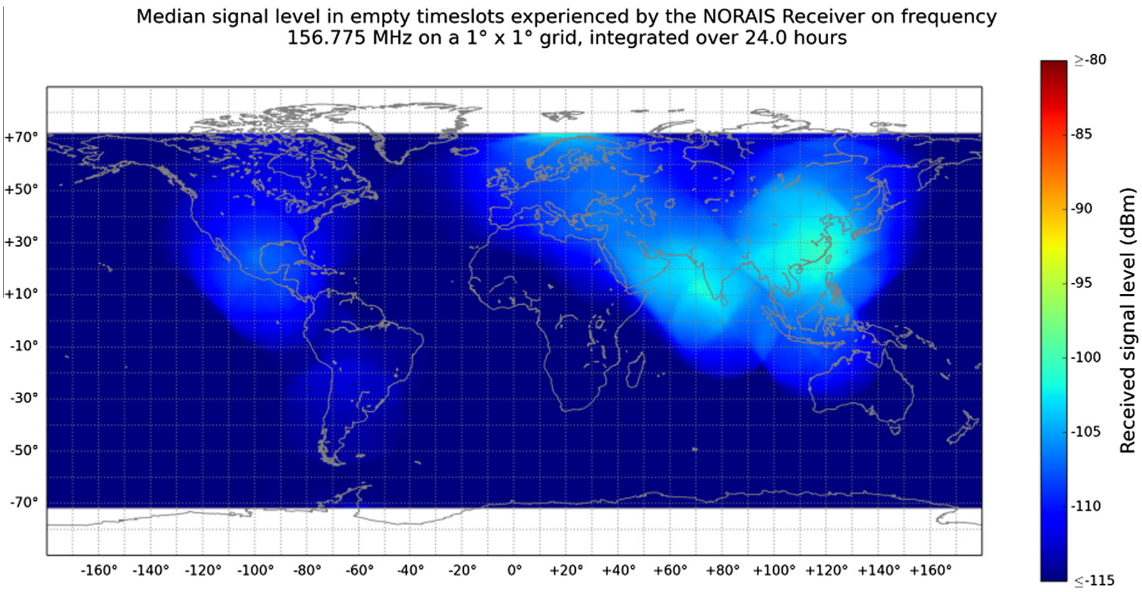

Figure 18. Median received signal strength in “empty” timeslots on frequency 156.775 MHz, the AIS3 channel, 1 April 2014.

difference in the locations of increased background signal level experienced by the NORAIS Receiver. The origin of the high signal level area over Europe is further east on the AIS3 channel however. It is clear that even though the median level is generally much lower compared with the AIS1 and AIS2 channels, the NORAIS Receiver still experiences processing overflow in the same areas when operating on the AIS3 channel.

5.2. Signal level measurements on AIS 4

The median signal level in “empty” timeslots as experienced by the NORAIS Receiver on the AIS4 channel over 24 h is presented in Figs. 20 and 21 for timeframes in September 2010 and April 2014 respectively.

Comparing the 2014 data with the 2010 data it appears to be a reduction in the background noise level in the Baltic, North Sea and over Indonesia, and an increase from the western part of South America.

Plots of the NORAIS Receiver field of view where the receiver experiences processing overflow on the AIS4 channel are presented for the 24 h timeframe of 2010 and 2014 in Figs. 22 and 23 respectively. Again, many of the same areas as for AIS1, AIS2 and AIS3 stand out. When the space-based AIS receiver has these areas within its field of view, the receiver performance will decrease. Since the median values are so much lower, these maximum signal

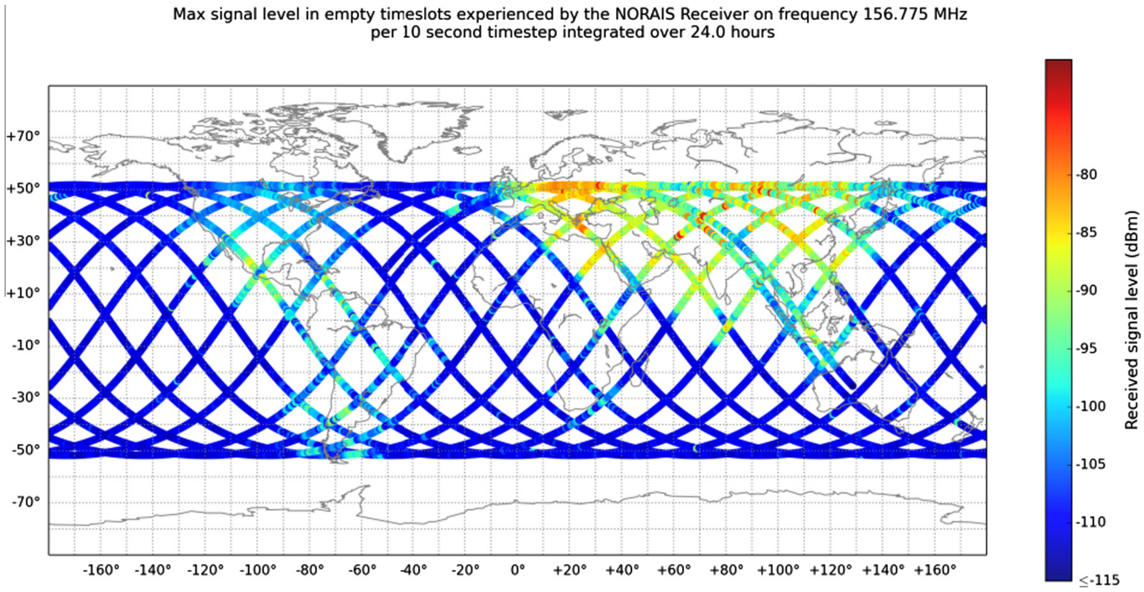

Figure 19. Maximum received signal strength in “empty” timeslots on frequency 156.775 MHz, the AIS3 channel, 1 April 2014.

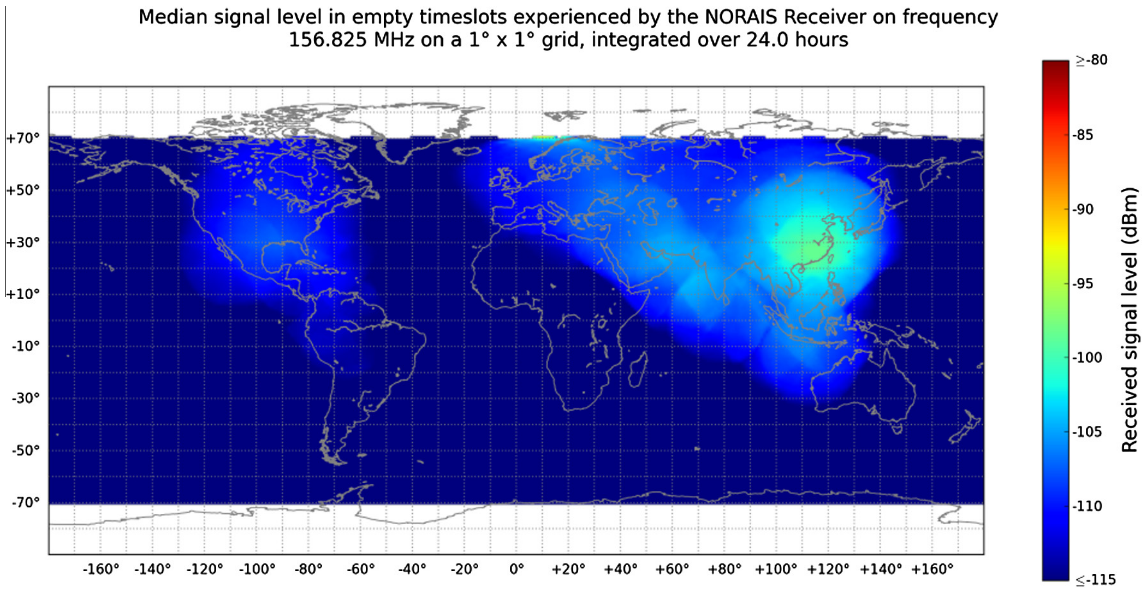

Figure 20. Median received signal strength in “empty” timeslots on frequency 156.825 MHz, the AIS4 channel, 20–21 September 2010.

levels are only experienced briefly. It will still be possible to detect AIS messages, but a part of the integration time is rendered useless.

Interestingly, even though the median signal level appears reduced in the Baltic and North Sea areas in the 2014 data, the receiver did not experience processing overflow in those areas in 2010, but did in 2014.

6. Discussion

While it is expected that the background signal level will be high in the high density traffic zones due to AIS message collision from many ships within the field of view, there is evidence of additional sources of increased background signal level. Measurements on all four AIS channels show that the NORAIS Receiver experiences processing overflows every day in the same areas, albeit only for brief periods at a time. This additional interference reduces the performance of space-based AIS receivers.

The high density traffic zones of the Gulf of Mexico and East and South China Sea stand out as areas of increased background signal level for the AIS3 and AIS4 channels as they do for the AIS1 and AIS2 channels. However, since there are so few vessels using AIS3 and AIS4, the elevated background signal must originate from land-based re-use of the channels that will significantly reduce the effectiveness of the space AIS frequencies. For example, in the 2010 dataset, the NORAIS Receiver did not detect any

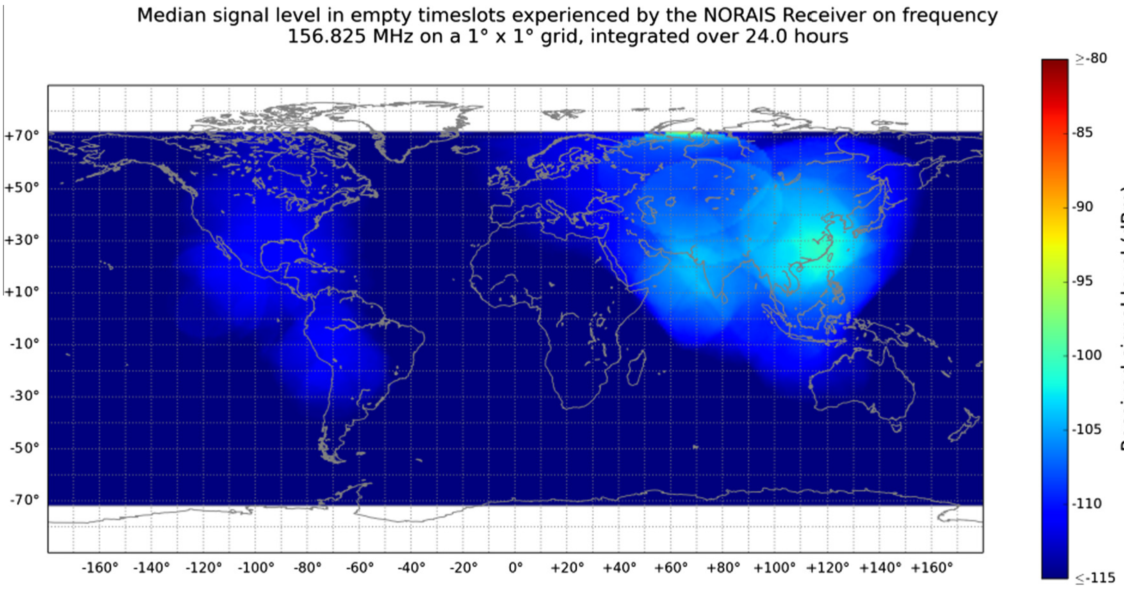

Figure 21. Median received signal strength in “empty” timeslots on frequency 156.825 MHz, the AIS4 channel, 1 April 2014.

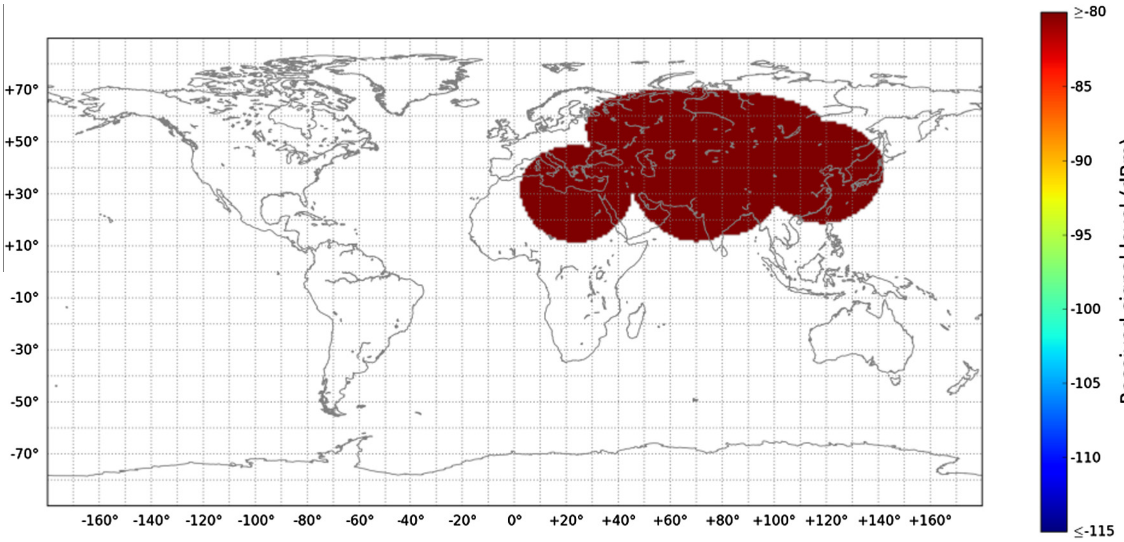

Figure 22. Plot showing NORAIS Receiver field of view when the received signal strength in “empty” timeslots exceeds −83 dBm on frequency 156.825 MHz, the AIS4 channel, 20–21 September 2010.

AIS signals on the AIS3 and AIS4 channels. In the 2014 dataset, a total of 2267 unique MMSI were detected for the entire month of operations on AIS3 and AIS4. However, the areas of increased background signal level are the same in both the 2010 and 2014 data, indicating that the interference is land-based and not due to co-channel interference from AIS message collision.

The type 27 message transmitted on AIS3 and AIS4 is particularly vulnerable since it is only transmitted every 3 min. For a satellite in 600 km altitude orbit, the best case scenario is about 12 min view time of one particular ship, which equals maximum four emitted type 27 messages per ship. With the various attenuating effects occurring between the ship and satellite some messages will be lost. With additional interference that may overlap with the remaining messages, the probability of receiving the type 27 messages is severely reduced.

Analysis of in-orbit data from FFI’s space-based AIS assets has enabled the calculation of the power distribution of transmitted signal strengths by the ships shown in Fig. 24 (Olsen, 2012). From Olsen’s results, the distribution of the received signal strengths at any satellite, with any antenna configuration may be estimated. The resulting received signal strength distribution for the NORAIS Receiver is shown in Fig. 25. The results take into account the dipole antenna gain and any polarization mismatch incurred during propagation in addition to evenly distributing ships within the field of view. While both the

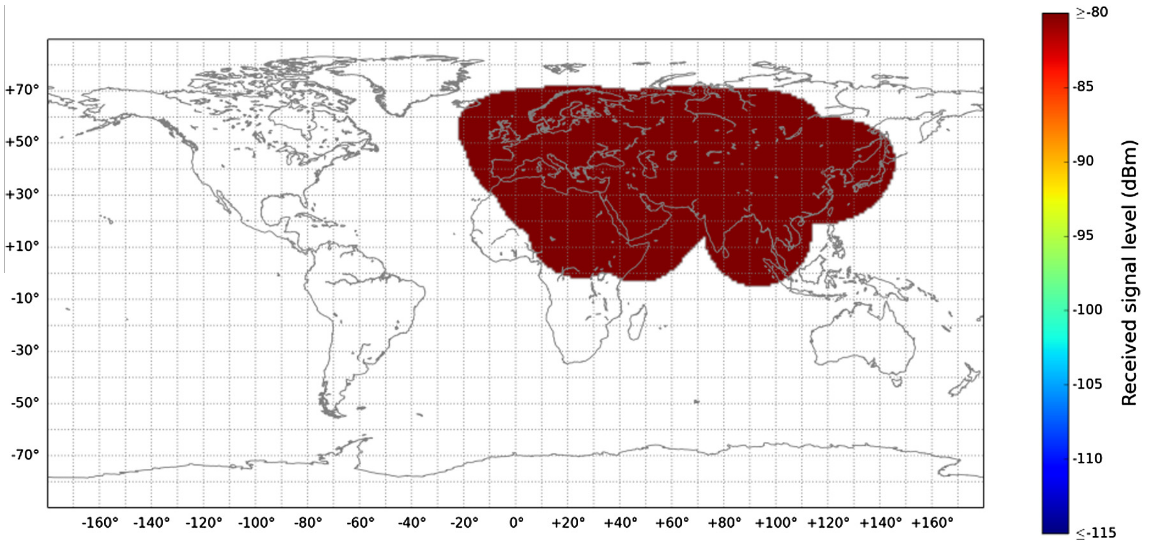

Figure 23. Plot showing NORAIS Receiver field of view when the received signal strength in "empty" timeslots exceeds −83 dBm on frequency 156.825 MHz, the AIS4 channel, 1 April 2014.

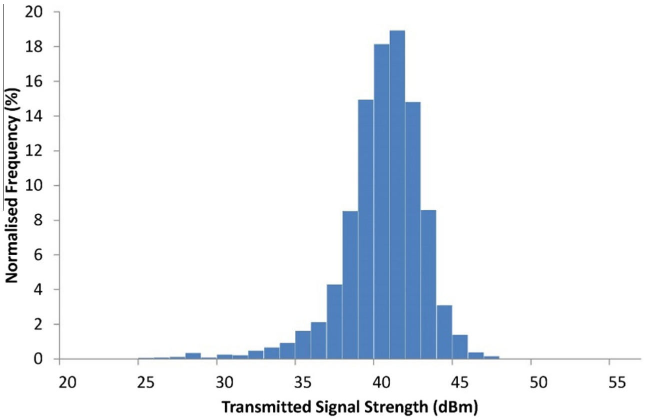

Figure 24. Histogram of transmitted signal strengths (dBm) calculated from space-based AIS data.

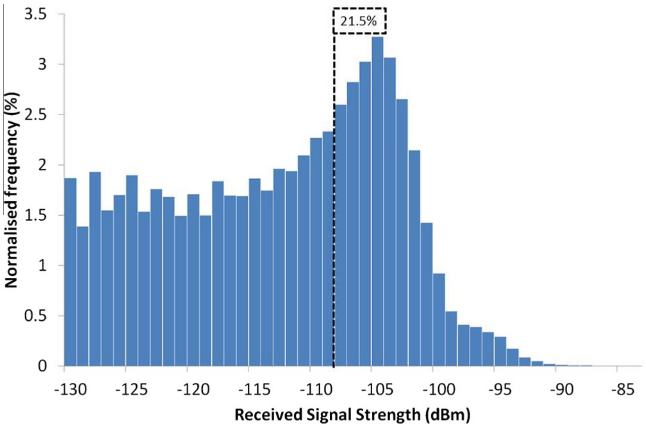

Figure 25. Histogram of the 63% received signal strengths (dBm) at the NORAIS Receiver that are stronger than −131 dBm.

AIS ship antennas and the NORAIS Receiver antenna are linearly polarised, the propagation through the ionosphere can rotate the plane of polarization. For full details of assumptions behind the calculation of the results the reader is referred to Olsen's report (Olsen, 2012).

The signal-to-noise ratio required for reliable detection increases with increasing number of bits in the message. Reliable detection is here defined as less than 20% packet error rate (PER), in line with the AIS standard. The standard AIS position report, type 1–3, transmitted on AIS1 and AIS2 is 168 bit long, while the type 27 message transmitted on AIS3 and AIS4 is only 96 bit long. For the NORAIS Receiver ground testing shows that 9.5 dB signal to noise ratio is required for reliable detection of 168 bit messages (without co-channel interference). While not specifically tested, it is estimated that reliable detection of 96 bit messages can be done with 9 dB signal to noise ratio. Remembering that the background noise level on-board the ISS is −117 dBm, the required signal to noise ratio for reliable detection indicate minimum signal strength levels about −108 dBm.

Fig. 25 shows that 21.5% of AIS signals have signal strengths greater than −108 dBm for the ISS altitude. If the background noise level is increased to −103 dBm as the worst case median values seen on the AIS3 and AIS4 channels, less than 0.33% of AIS messages have the required signal strength greater than −94 dBm. Note that for the AIS1 and AIS2 channels, a major part of the challenge is co-channel interference that can further significantly reduce the number of AIS messages one can reasonably expect to decode.

Still, it is important to realise that detection is still possible for signal strengths below these limits, but the probability decreases. On a similar note, while the median background signal levels are very high over Europe on AIS1 and AIS2 for instance, the NORAIS Receiver still detects messages from the area. As discussed, even though the median value is high, the background noise level is not constant and there will be timeslots where the background noise enables detection, however unreliably. The space-based AIS system tracking capability, i.e. the ability to repeatedly re-detect ships as they move around the globe, will be lowered in the areas of elevated background levels.

Keep also in mind that the results discussed in this section is only directly applicable to the NORAIS Receiver. Generally, a lower background noise level from the satellite platform will reduce the minimum signal level required for reliable detection. Likewise, an improvement in the receiver performance will reduce the signal to noise ratio required. Several strategies to improve the performance of the satellite AIS receiver have been presented since the launch of the NORAIS Receiver in 2009, including higher performance algorithms (Burzigotti et al., 2012; Colavolpe et al., 2014; Hassani et al., 2015), multiple receivers and antennas (Zhou et al., 2012), digital beamforming of the antenna patterns (Maggio et al., 2014) or a combination of all concepts (Picard et al., 2012) to name a few initiatives. Using the new strategies, the required signal to noise ratio has been lowered, and the robustness with respect to interference has been increased. For example, in February 2015 the NORAIS Receiver was replaced by the next generation NORAIS-2 Receiver. As for the NORAIS Receiver, the AIS payload was developed by Kongsberg Seatex AS with FFI as the project managers and later the experiment principal investigators. The NORAIS-2 Receiver implemented higher performance algorithms compared with the NORAIS Receiver, and achieved 20% PER for 168 bit messages at ca. 8 dB signal to noise ratio during ground testing. Kongsberg Seatex AS has continued to develop their satellite AIS receiver products and the latest development, the Novel SAT-AIS Receiver (NAIS), supported by the European Space Agency in the ARTES 21 SAT-AIS programme (ESA, 2015), should achieve 20% PER for a 168 bit message at 6 dB signal to noise ratio. The latest performance improvement is made through ever more advanced algorithms and the use of multiple antennas.

7. Summary

From the results presented in this paper it is apparent that the median background signal level, estimated from the NORAIS Receiver RSSI measurements, is lower on the AIS3 and AIS4 channels compared with AIS1 and AIS2 in areas that are problematic for space-based AIS, such as the Gulf of Mexico, East and South China Sea, Mediterranean, Baltic and North Sea. However, based on the estimated required signal to noise ratio for reliable detection, even on the AIS3 and AIS4 channels the median signal levels in several of these areas are higher than the level considered tolerable.

For the AIS1 and AIS2 channels, the signal level increases in the high traffic density areas as a result of co-channel interference. From the plots showing the areas where processing overflow occurs, it is also evident that there is land-based interference compounding the challenges in the high traffic density areas.

Further it was showed that the strong signal levels experienced are not constant in time, and will not prevent detection of AIS messages altogether, but reduce the reliability of detection.

Perhaps troublesome is the increase in signal level measurements seen in the latest measurements from previously low level areas such as southern South-America and central Africa. The increase is seen across all four AIS channels.

Overall, the NORAIS Receiver has proven to be an excellent instrument to monitor and map the signal level on the AIS1, AIS2, AIS3 and AIS4 channels experienced in space. With the flexibility of selecting any channel within the maritime VHF band from 156 MHz to 163 MHz, the NORAIS Receiver could also map other channels in search for additional suitable frequencies for space AIS.

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