FFI-rapport 2009/00315

ESA mulighetsstudie for et europeisk satellittbasert AIS system

Avsluttende rapport og abstrakt

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Forsvarets forskningsinstitutt (FFI)

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Satellitter

Satellittovervåking

Godkjent av

Richard Olsen	Prosjektleder
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Sammendrag

Denne rapporten gjengir rapportene ”Abstract” og ”Final Report” som FFI laget for den europeiske romorganisasjonen ESA under kontrakten: ”Contract No. 20492/06/NL/JA – Technology reference and proof of concept for a space based automated identification system for maritime security”. Studien ser på teknisk utvikling som kreves for å kunne tilby Europa en nyttig tjeneste for observasjon av skip via AIS signaler mottatt fra satellitter.

Rapportene som er gjengitt gir et sammendrag av resultatene fra studien. Kongsberg Seatex sammen med Norspace bidratt med studier av en AIS mottaker for rommet, mens Surrey Satellite Technology Limited har bidratt med studier av satellittplattform og konstellasjonsløsninger. FFI har stått for signalanalyse, analyse av brukerkrav, lover og regler et slikt system vil måtte forholde seg til samt utforming av overordnet konsept og forslag til en demonstrasjonsløsning.

Studien konkluderer med at ikke alle utfordringer rundt et globalt satellittsystem for mottak av AIS signal er løst og at det trengs mer kunnskap før man bør gjøre et endelig design av et operativt system. Første skritt på veien mot et operativt system bør være en demonstrasjonssatellitt med tre monopolantenner som kan både dekode AIS signaler ombord og lagre basebåndsignalet for prosessering på bakken.

ESA har tatt resultatene videre, både mot nye studier rundt mottakerutvikling og demonstrasjonssatellitt, og også med utvidede studier som ser på en endelig konstellasjon.

English summary

This report reproduces the reports ”Abstract” and ”Final Report”, that FFI produced for the European Space Agency under the contract: ”Contract No. 20492/06/NL/JA – Technology reference and proof of concept for a space based automated identification system for maritime security”. The purpose of the study was to evaluate the feasibility of a European operational system for monitoring ships by the reception of AIS signals from satellites.

The reports present the summary of the results found in the study. Kongsberg Seatex together with Norspace has contributed with studies of an AIS receiver for space, while Surrey Satellite Technology Limited contributed with studies of possible satellite platforms and possible constellations. As well as being prime, FFI has had the main activity in the areas of signal analysis, user requirements, data policy and regulations, as well as mission concept both for a full operational system and a demonstrator.

The study found that a global system for receiving AIS signals in space is achievable for most areas of the world, but that a few areas exist where challenges still remains. It strongly recommends building a demonstration satellite before concluding on the design of an operational system. The suggested demonstrator should be a satellite in low Earth orbit with three orthogonal monopole antennas, which can handle both signal processing on-board and on ground.

ESA has used the results of the study to continue the work on space based AIS, with new studies on both receiver development and a possible demonstration satellite, as well as further studies on an operational concept.

Innhold

1 Innledning

Denne rapporten inneholder et sammendrag av resultatene fra en konseptstudie på en konstellasjon av satellitter for mottak av navigasjonssignaler fra skip. Arbeidet som er gjengitt i denne rapporten representerer resultatet fra studien FFI gjorde for ESA[1] fra 2006-2008. Under arbeidspakken ”Recommendations and Conclusions” leverte FFI rapporten ”Abstract”, som er gjengitt i sin helhet i Appendix A og ”Final Report” , som er gjengitt i sin helhet i Appendix B. Denne rapporten sammen med den kortere oppsummeringsrapporten ”Executive Summary” er åpne rapporter som gjengir resultatene fra studien.

Det vil videre bli gitt en kort bakgrunn angående studien og en liste over leveransene før de originale rapporten som ble levert ESA kommer i Appendix A og Appendix B.

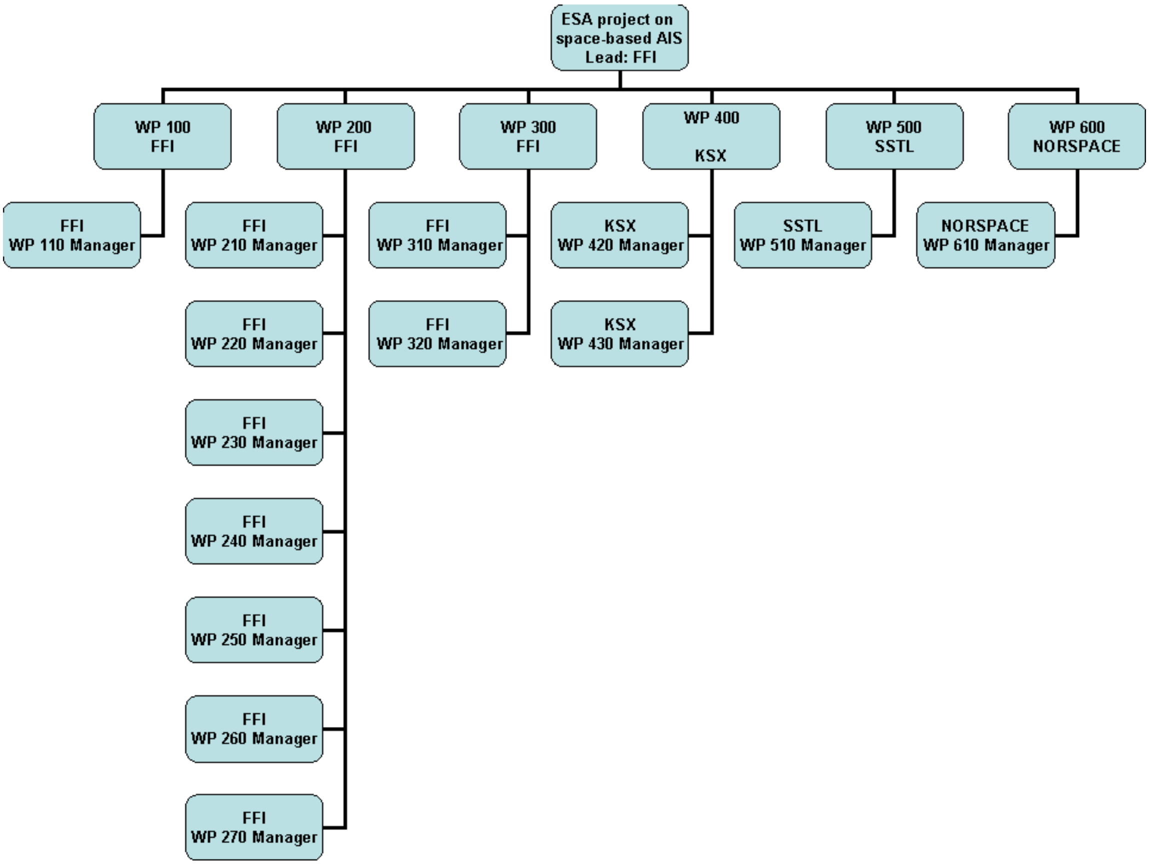
1.1 Bakgrunn

FFI fikk i desember 2006 en 12 måneders kontrakt med ESA for å se på en fase 0 studie av et europeisk satellittsystem for mottak av AIS meldinger. Studien varte noe lenger enn først planlagt og en såkalt ”Final Presentation” ble først avholdt ved ved ESTEC[2] sitt hovedkvarter i Nederland den 6. mai 2008. Etter dette fikk ESA muligheten til å komme med kommentarer på rapportene, før en endelig leveranse ble sendt høsten 2008. Den endelige leveransen markerte at kontrakten med ESA, ”Contract No. 20492/06/NL/JA – Technology reference and proof of concept for a space based automated identification system for maritime security” var avsluttet.

I studien hadde FFI med seg industripartnerne Kongsberg Seatex AS (KSX), Norspace AS og Surrey Satellite Technology Ltd (SSTL) som underleverandører. KSXs hovedoppgave var å designe en nyttelast som muliggjør mottak av AIS fra rommet, og Norspace var med for å dele sin erfaring med elektronikk i satellitter med KSX. SSTL er en britisk leverandør av satellittplattformer som bidro med sin kunnskap om valg av egnede satellitter og bakkestasjonskonsept. FFI hadde det overordnede ansvaret og hadde spesielt ansvar for analyser og kunnskap om mottak av AIS fra rommet. Figur 1.1 viser hvordan studien var organisert i arbeidspakker der ansvaret var fordelt mellom FFI og industripartnerne.

[1] European Space Agency

[2] Euroepean Space Research and Technology Centre



Figur 1.1 Organisasjonskart for studien, fordelt på arbeidspakker og partnere. Leveranser tilhørende de forskjellige arbeidspakkene kan finnes i Tabell 1.1.

Personell involvert i kontrakten hos FFI var Torkild Eriksen, Øystein Helleren, Richard Olsen, Øystein Olsen og Peter Selvik. Torkild Eriksen var prosjektleder for ESA kontrakten fram til 1.april 2007 da han gikk over i et oppdrag ved EU Satellite Center. Øystein Helleren overtok prosjektlederoppgaven. Prosjektet lå inn under 1002 INNOSAT[3] og 1104 INNOSAT-2 der Richard Olsen er prosjektleder. Størrelsen på hele kontrakten var på 500K Euro og første del av kontrakten var registrert som prosjekt 100209 hos FFI.

Første halvdelen av kontrakten så på brukerkrav, juridiske betenkninger og eventuelle konkurrerende system (LRIT[4]) for å gi en bakgrunn til å kunne komme opp med et konsept for et europeisk system for satellittbasert AIS. KSX kom fram til et konsept for en nyttelast (mottaker), og begynte på et detaljert design.

En stor utfordring for et system for mottak av AIS meldinger fra satellitt er at samtidig mottak av meldinger fra flere skip kan skje, og dette kan føre til tap av meldinger. FFI foretok derfor en rekke analyser og simulering for å finne fram til satellittbaner og antennesystemer som kan gi god dekning i alle europeiske farvann. Med denne bakgrunnen begynte FFI utarbeidelsen av en plan for hvordan et slikt satellittsystem kunne se ut. Dette ble gjort i samarbeid med SSTL som blant

[3] Innovativ bruk av satellittovervåking for det nye forsvaret
[4] Long Range Identification and Tracking

annet fokuserte på mulige satellittkonstellasjoner for å oppnå regelmessig og hyppig dekning av aller europeiske farvann.

Det viste seg at det var store utfordringer forbundet med fartøystettheten i europeiske farvann. Det ble derfor besluttet at andre halvdel av studien i større grad skulle fokusere på et forslag til et demonstrasjonskonsept som et første naturlig steg på vei mot en operativ tjeneste. Det ble allikevel gjort en del arbeid også på mulige operative konsepter. Den siste delen av studien inneholdt også et mer detaljert design av nyttelasten.

Studien konkluderte med at det i flere europeiske interesseområder ville være vanskelig å motta og dekode AIS meldinger fra alle skip på grunn av det store antallet AIS meldinger en satellitt vil motta samtidig. Det ble derfor sterkt anbefalt å satse på å først lage en demonstrasjonssatellitt før man gjorde endelige bestemmelser på et eventuelt operativt system. Det var trolig at det kunne gjøres en del forbedringer når det gjaldt dekodingsalgoritmer, og det ble anbefalt en satellitt med tre antenner og tre mottakere. En ”software defined radio” ble foreslått som nyttelastkonsept.

Dette demonstrasjonskonseptet ville muliggjøre både dekoding ombord i satellitten og lagring av data for testing av nye dekodingsalgoritmer på bakken. Nye algoritmer ville også kunne lastes opp og testes ombord i satellitten. Bruken av tre ortogonale monopoler ville også kunne gi et tredimensjonalt bilde av signalmiljøet i rommet, noe som igjen ville kunne brukes til å forbedre simulerings og modelleringsmodeller av systemet.

1.2 Leveranser i studien

Alle leveransene i studien er listet opp i Tabell 1.1. I parentes etter rapportnavnet er det markert (R) for rapport og (A) for animasjon. I tillegg er det markert hvilken bedrift som har vært ansvarlig for rapporten.

RES-210-10 User Needs and Requirements	(R) (FFI)
RES-220-20 Space-based AIS: Regulations and Data Policy	(R) (FFI)
RES-230-30 LRIT concept and impact on space based AIS	(R) (FFI)
RES-240-10 Space based AIS: Mission Concept	(R) (FFI)
RES-240-20 Preliminary Mission Requirements Document	(R) (FFI)
RES-240-30 Constellation Design and CONOPS	(R) (SSTL)
RES-250-10 Concept Definition of In-Orbit Demonstration	(R) (FFI)
RES-260-10 Development Plan and Cost Estimates	(R) (FFI)
RES-270-10 Final Report	(R) (FFI)
RES-270-20 Executive Summary Report	(R) (FFI)
RES-270-30 Abstract	(R) (FFI)
RES-310-10 Space-based AIS Signal Analysis	(R) (FFI)
RES-320-10 End-to-end Verification Simulator Model	(R) (FFI)
RES-320-20 Visualisation of System Performance Verification	(R) (FFI)
RES-320-20 Yagi simulation	(A) (FFI)
RES-320-20 Three monopoles simulation	(A) (FFI)
RES-420-10 Payload Analysis and Concepts of satellite receiving system	(R) (KSX)
RES-420-20 Preliminary Function and Performance Requirements Document	(R) (KSX)
RES-430-10 Payload System Requirements Document	(R) (KSX)
RES-430-20 Detailed Design for space-based satellite receiver system	(R) (KSX)
RES-430-30 Payload Interface Requirements Document	(R) (KSX)
RES-510-10 Platform Concepts and Definition	(R) (SSTL)
RES-610-10 Consolidation and evaluation of preliminary AIS receiver design	(R) (Norspace)

Tabell 1.1 Leveranser i ESA-studien: " Technology reference and proof of concept for a space based automated identification system for maritime security". R = rapport. A = animasjon.

2 Forkortelser

A	Animasjon
AIS	Automatic Identification System
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
FFI	Forsvarets forskningsinstitutt
KSX	Kongsberg Seatex
LRIT	Long-Range Identification and Tracking
R	Rapport
SSTL	Surrey Satellite Technology Ltd

Appendix A Abstract

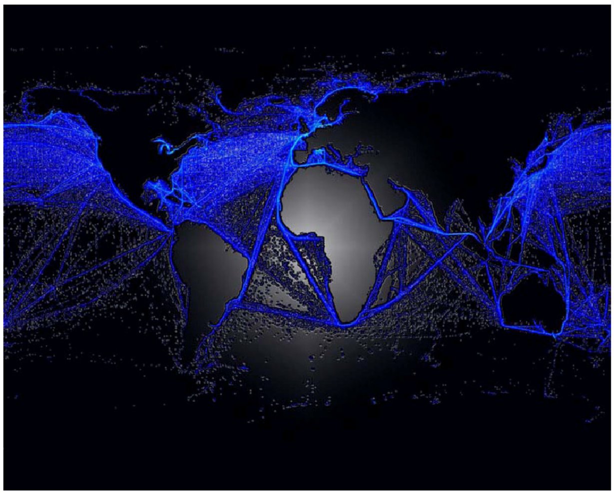
ESA ESTEC contract 20492/06/NL/JA

Technology Reference and Proof-of-Concept for a Space-Based Automatic Identification System for Maritime Security

RES-270-30

Abstract

Øystein Helleren



Forsvarets forskningsinstitutt/Norwegian Defence Research Establishment (FFI)

10.04.2008

Cover illustration: Global ship traffic routes.
Made with Adobe Photoshop as clean plastic wrap.
Artist: Øystein Olsen, FFI.

RES-270-30

ESA ESTEC contract 20492/06/NL/JA

Version 1.0

Keywords

Space based AIS

AIS payload

Software defined radio

AIS demonstration mission

AIS operational concept

Approved by

Richard Olsen	Company QA manager
Øystein Helleren	Project manager
Karsten Strauch	ESA manager

Change records

Issue	Date	Changes
1.0	10.04.2008	First draft of abstract

A.1 Abstract

WP 270 Recommendations and Conclusions
RES-270-30 Abstract v1.0
Date 10.04.2008

Abstract

There is a growing need to develop a global maritime surveillance capability to safeguard the security of people and infrastructure, the safety of life at sea, as well as the maritime environment. One candidate system to provide information to such services is the automatic identification system (AIS), a system transmitting information about vessel identity, position, heading, nature of cargo, destination etc. on dedicated frequencies in the maritime VHF band.

In addition to improving safety between vessels, many countries today use AIS extensively for maritime safety and security, monitoring and guiding traffic near the coast. As the AIS system transmits information on VHF, the coverage from the stations on land is limited to a few tens of nautical miles, depending on the height of the antenna. With security increasingly coming into focus in many areas of society today, there is a world wide interest in looking at receiving the AIS signals from space in order to also enable monitoring of activity further off the coasts.

From December 2006 to May 2008 the Norwegian Defence Research Establishment (FFI), together with Kongsberg Seatex AS, Norspace AS and Surrey Satellite Technology Ltd. worked on a study for the European Space Agency called "Technology Reference and Proof-of Concept for a Space-Based AIS System for Maritime Security". The study has focused on receiver technologies and antenna concepts, running advanced detection probability simulations to evaluate the best concepts and establish a technological reference for space-based AIS systems.

To better understand the user requirements for a space based AIS system, meetings were held with the Norwegian Coastal Administration, Coast Guard, the Norwegian Maritime Directorate and the British Defence Science and Technology Laboratory. In addition representative reports from European institutions were studied as well as some correspondence with the Directorate-General for Energy and Transportation, the Directorate-General for Fisheries and Maritime Affairs and the European Maritime Safety Agency.

While a more detailed user requirement study has started in April 2008, these first discussions were used to establish ten user requirements in the study. It was important for the users that such a system could cover areas far off the coast, and in general a global system to be able to track own ships. A clear understanding of the reliability must be given and it is important that the data is not too old. The need for update rates could vary, but in general at least once per hour, and the data should preferably not be older than 30 minutes. Of course, the cost is an important factor, especially considering that the coming Long Range Tracking and Identification System initiated from the International Maritime Organization, will provide more information on traffic on the high seas in 2009 than what is available in most countries today.

The system should seek to strike the best possible balance between an open safety-at-sea-focused system and a more closed security focused system, bearing in mind that open information can both be used in the fight against and be a tool for illegal activity. Thus the information in a space-

based AIS system should be encrypted and distributed on secure lines only to registered users. The distribution of data is suggested to be within three categories. The data should be available for governmental use for maritime security, for the respective owner of the vessels and possibly for use in some Value Added Products like oil spill monitoring combining radar imagery and AIS information.

Moving to the technical side of a space-based AIS system, the main challenge is the congestion of messages which will occur when a satellite pass over areas with high vessel density like the North Sea and the Mexican Gulf. The AIS system as such is though designed for ground based use. Originally designed as a collision avoidance system, each vessel transmits information every two to ten seconds. The system consists of a limited number of time slots where the messages can be transmitted. The system is designed to organize the vessels within contact of each other such that they do not use the same timeslots, and it also includes some randomization to ensure that if two vessels use the same timeslot once, they will use different timeslots for the next messages.

A satellite will observe many of these organized areas at the same time and thus, depending on the number of vessels observed, experience simultaneously received messages. When passing over the North Sea, almost every timeslot will be filled with 10-40 different AIS messages, and the satellite receiver system will have a difficult time decoding any of them.

One option for limiting the problem of AIS message congestion at the satellite is to introduce directive antennas in order to limit the field of view and achieve higher gain for some of the signals. FFI has developed an advanced program for analysing detection probabilities for a space-based AIS system. The program gives a global distribution of vessels transmitting AIS, based on ships reporting weather data, information on approximately how many vessels normally are found in certain areas, and information from aircraft trials with AIS in e.g. the North Sea. This program was used in the study to look at effects on detection probability per vessel of different antenna options and receiver characteristics.

While many different antenna configurations were simulated, only three are discussed here as they represent the main differences. The three are a Yagi array consisting of two Yagi antennas combined with a phase delay, a quadrifilar helical antenna, and three orthogonal monopole antennas.

Both gain and polarization affect the received signal level. When passing through the ionosphere, the phase of the AIS signals will be rotated due to an effect called Faraday rotation. This will result in that even a broadband antenna like the monopoles will lose some signal due to polarization mismatch. Using three monopoles with three receivers would mitigate this effect. Both the Yagi array and the monopoles are linear antennas, while the quadrifilar helical antenna is a circular polarized antenna. Because the AIS signals from the vessels are linearly polarized, the quadrifilar helical antenna will have a 3dB loss in polarization regardless of Faraday rotation from all directions.

Since there is a problem with signal congestion, circular polarized antennas show the worst detection probability, since the discrimination due to polarization match/mismatch is non existent. The Yagi array is the only solution which show a significant detection probability in difficult areas, while the three monopole solutions works best in areas with lower vessel density because it has a much larger field of view than the Yagi array. Figure 1 shows the accumulated vessel detection probability after 15 passes of a single satellite with a Yagi array.

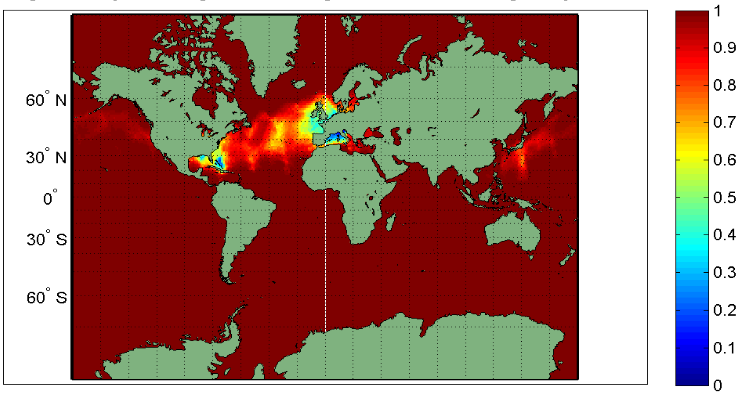


Figure 1 Detection probability after one day (15 orbits) using a single satellite with the asymmetric Yagi-array.

In addition to the antenna itself, there are different options for designing the radio that receives and decodes the AIS signals. In the study the receiver concepts; direct conversion, superheterodyne, double superheterodyne and software defined radio (SDR), were compared. The trade-off analysis showed that all technologies were capable of receiving AIS signals, but the choice ended on the SDR as the flexibility in the design was very attractive. The flexibility opens for different uses of the SDR, where one also can look at various modes used at certain times, e.g. one mode for areas with low vessel density and one for areas with high vessel density. The downside is increased power consumption and complexity.

A software defined radio consist of a front end with filtering and low noise amplifiers, a high speed analogue to digital converter and digital processing in a field programmable gate array. To support the system a power unit is needed converting the power from the satellite bus to the appropriate levels, a stable oscillator and a microcontroller unit to handle the communication to and from the gate array and the communication with the satellite on board computer and memory. The communication interface with the satellite could be through a RS-422 connection or via a controller area network protocol for low bit rates.

A set of objectives for a demonstration mission was identified in the study, and based on these, the payload concept of three orthogonal monopole antennas with three separate receiver cards a common power distribution unit and a common controller unit. Three operational modes were identified.

In the main mode the receivers decode the AIS messages and the payload operates with continuously with a duty cycle of 25 percent per orbit. This will show how AIS signals can be received from space.

The second mode is similar to the first, except that the payload operates continuously for 12 hours. This will enable a global mapping of AIS received from space, and this can be done on a regular basis in order to build up maps which show how traffic and detection probability vary with time.

In the final mode, the image in the gate array is changed so that instead of decoding the AIS messages, the three receivers only sample a down converted version of the original signal. This can then be processed on the ground, testing updated or new signal processing algorithms, which again can be uploaded to the payload if they are found to be better than the current one on the satellite. This will typically be tested in areas with high vessel density and only over 5-10 minutes, limited by the on-board memory capacity.

Looking at the satellite platform, the SSTL-100 has been selected as a heritage baseline following a trade-off in the study. Figure 2 shows the satellite designed in the stowed and operative configurations. The proposed solution is characterised by an extremely compact design which allows easy fairing accommodation for a piggy-back launch payload.

The second view presents the platform in the operative configuration with the appendages fully deployed and the high performance solar array in final position with a slant angle of -140°. The three antennas are placed on opposite corners to get the best antenna diagrams. The configuration has a total mass of ~60 kg including the AIS payload. No propulsion would be need and only ±10° 3D attitude control.

The operational orbit has been selected as Sun Synchronous with 15 ground tracks daily repetition. This leads to an operational altitude of 561 km with an inclination of 97.6° and an orbital period of 5752 sec (95.2 min).

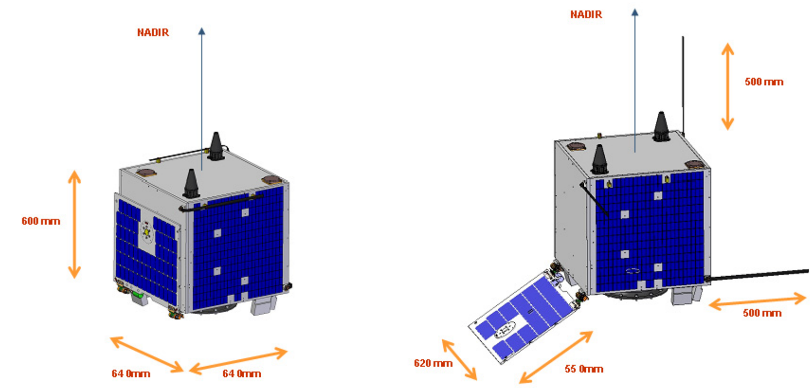


Figure 2 Platform Configuration: Stowed & Deployed (transparent deployed solar panel)

Looking at ground stations, the Svalbard and TrollSat stations in the Arctic and Antarctica are very attractive to use because both stations have access to the satellite in 10-15 orbits every day and thus there will be only a short delay from observation anywhere on Earth till downlink of data to ground. In addition, Guildford and Redu were identified as potential ground stations covering central Europe

Looking at a future operational concept for space based AIS, consisting of a constellation of satellites providing world wide updates every hour, several architectures were compared in the study. For an operational concept, only the Yagi array provides near acceptable detection probabilities in important areas like the North Atlantic. It is thus strongly recommended to go through a demonstration mission before planning a full operational system, unless someone in the meantime can prove that they have solved all problems with simultaneous arrival of AIS messages over busy European waters.

One possible solution for obtaining global coverage is to allocate a third AIS channel exclusively for space-based AIS. Used appropriately, this is sufficient to achieve almost global coverage every seventh orbit as seen in Figure 3.

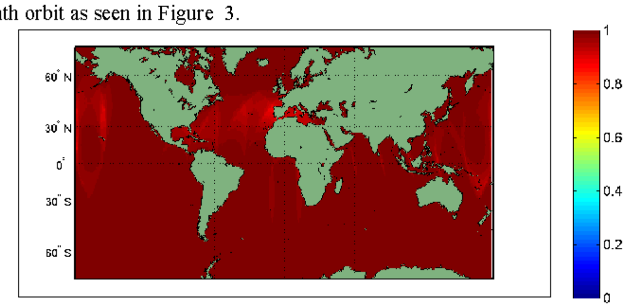


Figure 3 The cumulative detection probability after 7 orbits using a 3rd frequency.

The study shows that space-based AIS is feasible in many areas of the globe, but that challenges still remain in areas with high vessel density like the North Sea. As an operational system will depend on the willingness from stakeholder to commit to such a project, the first step should be to implement the demonstration mission proposed to test the concept and establish the best mitigation techniques for simultaneously received messages.

Appendix B Final Report

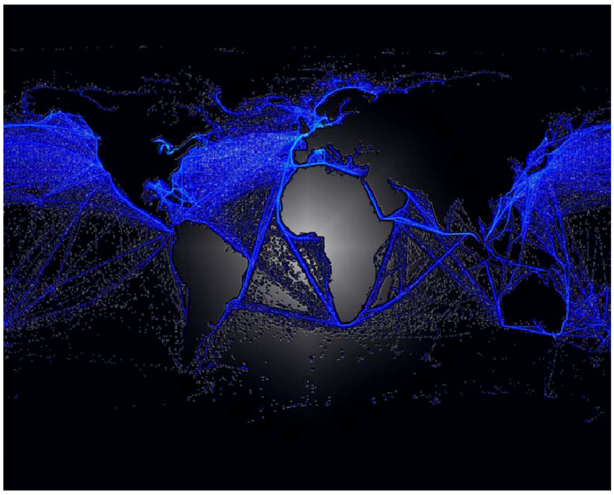
ESA ESTEC contract 20492/06/NL/JA

Technology Reference and Proof-of-Concept for a Space-Based Automatic Identification System for Maritime Security

RES-270-10

Final Report

Øystein Helleren



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10.04.2008

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Space based AIS

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Software defined radio

AIS demonstration mission

AIS operational concept

Approved by

Richard Olsen	Company QA manager
Øystein Helleren	Project manager
Karsten Strauch	ESA manager

Change records

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1.0	10.04.2008	First draft of final report

Executive summary

Executive summary is given as report RES-270-20, and an abstract is given in RES-270-30.

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Date 10.04.2008

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B.4 Preface

WP 270 Recommendations and Conclusions
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Preface

This report covers the work done under the ESTEC Technology Readiness Programme study: "Technology Reference and Proof-of-Concept for a Space-Based Automatic Identification System for Maritime Security", though some details may only be given in the technical notes delivered throughout the programme.

The work was possible thanks to the work from FFIs subcontractors, Kongsberg Seatex AS, Surrey Satellite Technology Ltd and Norspace AS. We would also like to thank the technical personnel at ESTEC; Karsten Strauch, Nader Alagha and Peter Rinous for guidance and support throughout the study.

Lastly a special thanks to all those who have been writing all the reports in the study:

- From Seatex
  - Mr. Per Christian Berntsen, Mr. Marius Røed Hanssen and Mr. Kristan Reiten
- From Norspace
  - Mr. Roger Spangelid, Mr. Håkon Indseth and Mr. Petter Hansen
- From Surrey
  - Mr. Maurizio Vanotti
- And from FFI
  - Dr. Torkild Erikssen, Dr. Øystein Olsen, Mr. Peter Selvik

B.5 Introduction

WP 270 Recommendations and Conclusions
RES-270-10 Final Report
Date 10.04.2008

1 Introduction

There is a growing need to develop a global maritime surveillance capability to safeguard the security of people and infrastructure, the safety of life at sea, as well as the maritime environment. One candidate system to provide information to such services is the Automatic Identification System (AIS), a system for transmitting information about vessel identity, position, heading, nature of cargo, destination etc. on dedicated frequencies in the maritime VHF band.

In addition to improving safety between vessels, many countries today use AIS extensively for maritime safety and security, monitoring and guiding traffic near the coast. As the AIS system transmits information on VHF, the coverage from land is limited to a few tens of nautical miles out to sea, and there is a high interest in looking at space based AIS receivers as a solution to also enable monitoring of activity in the high seas. This background chapter gives a short introduction to the AIS system as is, and introduces the user requirements and proposed architecture for a space based AIS system.

At the very end of 2006, the European Space Agency (ESA) negotiated with the Norwegian Defence Research Establishment (FFI) a contract on a study for European space based AIS: "Technology Reference and Proof-of-Concept for a Space-Based Automatic Identification System for Maritime Security". This report is the final report of this study.

From the statement of work one can find the description:
"This activity aims to investigate the possibility of extending the system to space for global maritime surveillance and give design, function and performance requirements for how the performance will be improved accordingly. To achieve this objective it is proposed to carry out a concept study for a space-based AIS comprising technology reference and proof-of concept action aimed at analysing the feasibility of a space based system to collect the signals and thereby monitor ship traffic.

The objectives of the study are as follows:

- *Study of technology and analysis of feasibility*
- *P/L Definition and Mission Requirements and Concepts*
- *Verification Concepts*
- *Programmatics, Recommendations and Conclusions*

The activity shall be performed in compliance with existing standards or regulations or compatibility with recommendations issued by international organizations within the maritime sector (such as IMO)."

The study has shown that challenges remain on how to make a space based system decode AIS messages in the highest trafficked areas of the world. Though some companies outside this work have lately claimed to have solved some of the difficulties, it remains to be seen if a system covering all European waters will be fully feasible the way the AIS system works today. An advance demonstration concept is proposed to give the understanding of the true signal environment in low Earth orbit. The proposed demonstration mission can receive AIS signals anywhere in orbit and has a design that also allows for comparisons of different signal processing techniques.

In other arenas, a dedicated frequency to be used for space-based AIS har been proposed. Simulations in the study show that this will enable global coverage with very simple spacecraft, antenna and receiver designs.

In this report a brief introduction will be given to the AIS system, and the coming Long-Range Identification and Tracking (LRIT) system. The user requirements for a space based AIS system will then be identified, followed by a discussion of applicable regulations and a preliminary data policy. The report will then focus on a discussion of payload options for an AIS receiver in space, followed by detection probability simulations for different mission architectures. The main results of the study are then summarized in the demonstration concept chapter. The report ends with a chapter looking ahead at possible operational architectures, and then summarizing conclusions and recommendations for the way ahead.

1.1 The AIS system

The AIS system utilizes VHF communication to transmit and receive AIS data, operating primarily on two dedicated VHF channels, AIS 1 – 161.975 MHz and AIS 2 – 162.025 MHz. Transmission alternates between the channels in order to balance the traffic between the available VHF channels. The frequencies AIS 1 and AIS 2 have been internationally coordinated and are used in most parts of the world. In order to make the system flexible it is also possible to use other sets of frequencies in the maritime VHF band. A base station may command the AIS transceivers to work on any pair of channels between 156 and 162, 025 MHz.

The system broadcasts the vessel's position, speed and course over ground as well as static and voyage related information. Short safety related text messages can be sent between vessels or broadcast from shore based AIS stations or Aids to Navigation like buoys and lighthouses. The on-board installed system is designed to operate automatically and as a stand-alone unit. In addition to transmission of AIS data, the system can continuously receive position information from other vessels or shore based stations.

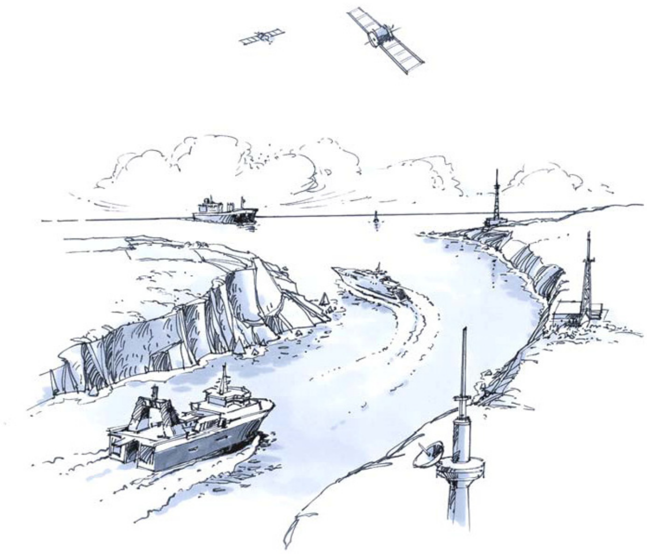


Figure 1.1 Overview of the AIS scenario. Ships use GPS satellites for positioning, and broadcast navigation information, which can be monitored by other ships and shore-based receiving stations.

1.1.1 Coverage

The radio coverage range is similar to other VHF applications and depends on the height of the antennas. The propagation differs from that of radar, due to the longer wavelength, so it is possible to "see" around bends and behind islands if the landmasses are not too elevated. A typical value to be expected between vessels is 20 - 30 nautical miles. From highly elevated base stations the coverage area may be up to 60-80 nautical miles.

1.1.2 AIS information content

AIS information is exchanged automatically between vessels, vessels and shore based stations and vessels and Aids to Navigation like buoys and lighthouses. The information transmitted by the AIS system is grouped into four categories:

1.1.2.1 Static data

- MMSI (Maritime Mobile Service Identity) number
- Call sign and name
- IMO number
- Length and beam

- Location of position fixing antennas on the ship

1.1.2.2 Voyage related data

- Ship's draught
- Hazardous cargo type
- Destination and ETA (at Master's discretion)
- Type of ship

1.1.2.3 Dynamic data

- Position with accuracy indication and integrity status
- Time in UTC
- COG (Course over ground)
- SOG (Speed over ground)
- Heading
- Navigational status
- Rate of turn

1.1.2.4 Safety-related messages

- Reading and writing short safety related messages.

The AIS terminal can include an MKD - Minim Keyboard and Display which can be used for transmitting and receiving text messages. Moreover, PC applications or electronic map systems (ECS, ECDIS) can be used as the user interface.

1.1.3 Data reporting and transmission rates

AIS data as stated above are autonomously sent at different update rates. The reporting rates are dependent on the ship's navigational mode. Dynamic information is dependent on speed and course alteration while static and voyage related data are transmitted every 6 minutes or on request. Thus fast ferries will report their navigational data at a higher update rate than ships at anchor.

Ship’s Manoeuvring Conditions	Nominal Reporting Interval
Ship at anchor	3 min.
Ship 0 to 14 knots	10 sec.
Ship 0 to 14 knots and changing course	3 1/3 sec.
Ship 14 to 23 knots	6 sec.
Ship 14 to 23 knots and changing course	2 sec.
Ship > 23 knots	2 sec.
Ship > 23 knots and changing course	2 sec.

Table 1.1 AIS reporting interval

1.1.4 AIS signal description

The AIS equipment is type approved according to the international recommendation IEC 61993-2. The communication parameters are given in the international recommendation ITU- 1371.

According to the standards, the AIS transmitter shall be able to work with both 25 kHz and 12.5 KHz channels in the entire maritime VHF band (156 - 162 , 025 MHz), at either 12.5 W or 2 W RF power.

According to the standards the required sensitivity for the AIS transceiver is -107 dBm @ 20 % PER (Packet Error Rate).

The AIS signal is GMSK modulated with a BT of 0.5. The data rate on the VDL (VHF Data Link) is 9600 bit / s. The VHF channels are divided into frames of one minute duration. Each frame is divided into 2250 slots, each slot being approximately 27 ms long. A position report will normally take one slot and a ship moving with a speed between 14 and 23 knots will transmit one position report, or use one slot every two seconds thereby occupying 30 out of the 4500 available slots every minute. If the speed increases, the report rate will increase accordingly.

The system may use up to 5 consecutive slots for longer messages if necessary. Each slot will typically carry 168 bits of data.

Transmitting of information is controlled by the SOTDMA protocol. (Self Organizing TDMA). In short, this protocol is designed to avoid that messages will collide on the air. When an AIS transceiver is turned on, it will listen for at last a minute without transmitting. During the start-up period the transceiver will listen for all other AIS vessels in the coverage area and build a slot allocation table showing which vessel uses which slot.

As all messages also includes information about which slot will be used in the next frame or minute, the AIS transceiver will know which slots have been allocated ahead in time and can therefore avoid transmitting at the same time as other transceivers. When the slot allocation table has been updated, the new transceiver selects a free slot, transmits the first position report and thereby allocates its next slots for future transmission.

This protocol works very well as long as all transceivers or vessels are within the same coverage area. For vessels outside the coverage area there is still a possibility for “colliding messages” on the air. As these ships are separated by a large amount, this is considered to be acceptable. Moreover, all vessels continuously transmit position reports, so if you loose a report due to collisions, there will soon be another report from the same vessel that can be received without problems. This works well as long as the number of vessels is not too large and there are free slots available. If the coverage area is too congested, however, message collisions will occur and the cells should be reduced in size by reducing transmitting power output. According to the AIS standards, the nominal transmitter power should be 12.5 W. If a coastal authority decides to reduce the coordinated cell size for a given geographic area, a local base station can be used to command AIS units in the area to transmit at a reduced level of 2 W.

The 12,5 kHz channel width option can similarly be used to increase the capacity of the system by doubling the number of RF channels available. So far this possibility has not been used by administrations.

In order to make the protocol work it is absolutely necessary that all transceivers have an accurate clock. The GPS PPS pulse is therefore used to synchronize the system. The internal GPS receiver is normally used only for providing PPS timing, the position is taken from the main GPS receiver on board. In cases of malfunction of the main GPS receiver, the internal receiver will be used as backup.

The modulated signal consists of a training sequence, start flag, data field including the slot reservation information, a CRC and a stop flag. The data signal is composed as shown in Figure 1.2, where the "comstate" parameter is used to reserve future slots: [1]

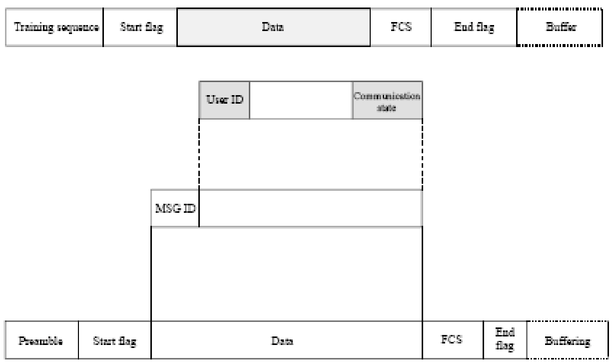


Figure 1.2 Timing details of the AIS signal[1]

Figure 1.3 shows the timing details of the AIS signal. In order to limit the emission band, the signal has a controlled envelope having fall and rise time in the order of 1 ms, [1].

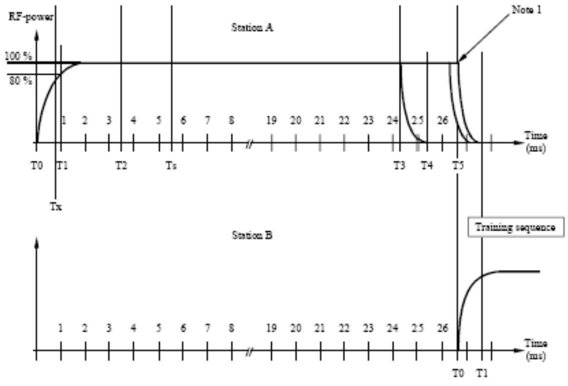


Figure 1.3 Transmission timing[1].

T(n)	Time (ms)	Description
T0	0.000	Slot start. RF power is applied (TX-ON)
Tx	0.832	Beginning of training sequence
T1	1.000	RF power and frequency stabilization time
T2	3.328	Start of transmission packet (start flag). This event can be used as a secondary synchronization source should the primary source (UTC) be lost
TS	4.160	Slot phase synchronization marker. End of start flag, beginning of data
T3	24.128	End of transmission, assuming zero bit stuffing. No modulation is applied during TX-OFF. In case of shorter data block, the transmission may end earlier.
T4	T3+1.000	The time when RF power should have reached zero
T5	26.670	End of slot. Beginning of next slot.

Table 1.2 Transmission timing as given in Figure 1.3[1].

Data	Bits	Comments
Ramp up	8 bits	
Timing sequence	24 bits	Necessary for synchronization
Start flag	8 bits	In accordance with HDLC ($7E_h$)
Data	168 bits	Default
CRC	16 bits	In accordance with HDLC
End flag	8 bits	In accordance with HDLC ($7E_h$)
Buffering	24 bits	Bit stuffing and distance delay
Total	256 bits	

Table 1.3 Transmission timing in number of bits[1].

The AIS signal is very short (27 ms) and vulnerable to collisions on the air. Within a 50 nautical mile radius, the time delay between arriving messages transmitted simultaneously will be in the order of 0.3 ms and the signals will totally overlap each other. Depending on demodulator and decoder characteristics, it will be possible to decode a signal which is about 10 dB stronger than the other due to the capture effect.

For signals with similar amplitude it will not be possible to decode any of the signals with simple means.

1.1.5 AIS signal transmission

For transmission over sea the coverage area will be heavily dependent on the antenna height. For normal installations on board a vessel, antenna heights of about 15-20 meters above sea level will be quite normal, giving coverage areas in the order of 20-30 nautical miles. Antenna installation on board will be a vertical whip giving an omni directional coverage area. The vertical antenna will have a transmitting diagram like a doughnut, transmitting evenly in every horizontal direction, but with reduced power for inclinations. This antenna will have a zero point in the vertical direction, and no power is transmitted vertically. Figure 1.4 shows the antenna diagram for the vertical antenna :

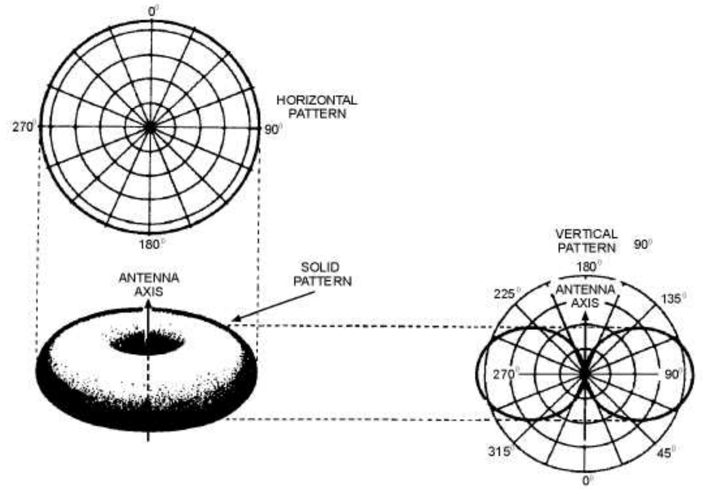


Figure 1.4 Vertical antenna diagram

1.2 AIS vs LRIT

The discussions on LRIT are based on the understanding of the system as of spring 2007. This is a system on its way to be implemented and for a full understanding of the system the reader is recommended to contact IMO for the most up to date specifications.

This summarizes the amendment made by the International Maritime Organisation (IMO) to the

Safety Of Life At Sea convention (SOLAS) on Long Range Identification and Tracking (LRIT). The performance standards and the functional requirements to the LRIT system are reviewed.

An important part of the work has also been to consider how LRIT and the space-based AIS concept developed in this ESA contract overlap or complement each other. The conclusion is that even though LRIT and space-based AIS are vessel tracking systems for the high seas, the LRIT system alone does not fulfil European ambitions for a data system that enhances the European SafeSeaNet.

The method has been to review documents on the adoption of the SOLAS amendments on LRIT made by IMO's Maritime Safety Committee in May 2006, as well as relevant documents on European maritime policies, ship reporting and tracking services. A brief survey has also been made among European data users and other stakeholders to collect user requirements and identify gaps to fill for future vessel tracking services.

IMO's Maritime Safety Committee (MSC) adopted the SOLAS amendments on LRIT on 19 May 2006 [2;3], with entry into force on 1 January 2008. This regulation shall apply to passenger ships, cargo ships of 300 gross tonnage and upwards, high-speed craft and the mobile offshore drilling units engaged on international voyages. Ships constructed on or after 31 December 2008 shall be fitted with LRIT from the start, ships constructed before this date not later than the first survey of the radio installation after 1 July 2009.

Ships shall automatically transmit the following information:

- the identity of the ship;
- the position of the ship (latitude and longitude); and
- the date and time of the position provided.

The LRIT equipment shall be capable of being switched off on board or be capable of ceasing the distribution of information:

- where international agreements, rules or standards provide for the protection of navigational information; or
- where the operation is considered by the master to compromise the safety or security of the ship.

Contracting Governments shall be able to receive LRIT information about ships as follows:

- the Administration shall be entitled to receive such information about ships entitled to fly its flag irrespective of where such ships may be located;
- a Contracting Government shall be entitled to receive such information about ships which have indicated their intention to enter a port facility, or a place under the jurisdiction of that Contracting Government, provided the ships are not located within the waters landward of the baselines of another Contracting Government; and
- a Contracting Government shall be entitled to receive such information about ships entitled to fly the flag of other Contracting Governments, not intending to enter a port facility or a

place under the jurisdiction of that Contracting Government, navigating within a distance not exceeding 1,000 nautical miles of its coast provided such ships are not located within the waters landward of the baselines of another Contracting Government; and

- a Contracting Government shall not be entitled to receive such information about a ship located within the territorial sea of the Contracting Government whose flag the ship is entitled to fly.

Contracting Governments shall bear all costs associated with any LRIT information they request and receive.

The Maritime Safety Committee shall determine the criteria, procedures and arrangements for the establishment, review and audit of the provision of LRIT information to Contracting Governments pursuant to the provisions of this regulation.

An *ad hoc* Working Group on Engineering Aspects of LRIT is established and shall report before MSC 82 in May 2007. The International LRIT Data Centre and the International LRIT Data Exchange should commence trials and testing of the LRIT system not later than 1 July 2008.

1.2.1 Overview

The LRIT system provides for the global identification and tracking of ships. The LRIT system consists of the shipborne LRIT information transmitting equipment, the Communication Service Provider(s), the Application Service Provider(s), the LRIT Data Centre(s), including any related Vessel Monitoring System(s), the LRIT Data Distribution Plan and the International LRIT Data Exchange. Certain aspects of the performance of the LRIT system are reviewed or audited by an LRIT Co-ordinator acting on behalf of all Contracting Governments. The system architecture is shown in Figure 1.5.

LRIT information is provided to Contracting Governments and Search and Rescue services entitled to receive the information, upon request, through a system of National, Regional, Co-operative and International LRIT Data Centres, using the LRIT International Data Exchange.

Each Administration (flag State) should provide to the LRIT Data Centre it has selected, a list of the ships entitled to fly its flag, which are required to transmit LRIT information, together with other salient details and should update such lists as and when changes occur. Ships should only transmit the LRIT information to the LRIT Data Centre selected by their Administration.

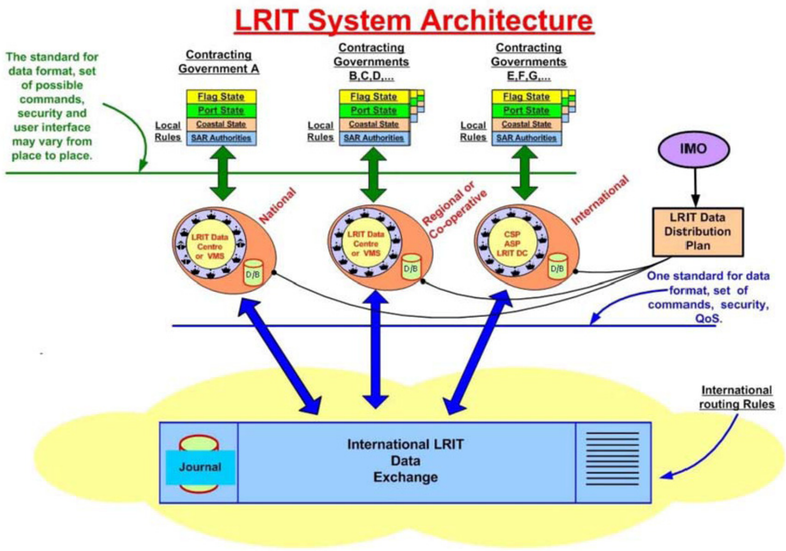


Figure 1.5 The LRIT system architecture.

The obligations of ships to transmit LRIT information and the rights and obligations of Contracting Governments and of Search and Rescue services to receive LRIT information are established in regulation V/19-1 of the 1974 SOLAS Convention.

1.2.2 Tracking vessels on the high seas

The LRIT system provides for global tracking of ships based on reports of the vessels' ID and position at a default interval of 6 hours.

Messages in the AIS system include the vessel ID and position as well as the heading, speed and the navigation status in the dynamic reports, and the cargo, route, destination and estimated time of arrival in the voyage reports. The AIS transmissions are continuous, and the update interval for a space-based tracking service is dependent on the satellite system.

Space based AIS could also be an important tool in identifying situations requiring search and rescue operations. Starting search and rescue operations after 12 hours (two missing reports anticipating LRIT's nominal reporting interval of 6 hours) may be too late.

The LRIT system is at present based on Inmarsat C and Inmarsat D+, that has poor or no coverage in Arctic and Antarctic waters. Space-based AIS will be planned with satellites in near polar orbit, and may serve as a source of LRIT information also in the High North and in the Southern Ocean.

For authorities responsible for vessel tracking, search and rescue, and fisheries monitoring, access to two different data systems gives a better ship tracking service, as well as knowledge of what ships are in an area in case of emergency, as well as a better chance of revealing anomalies.

1.2.3 Revealing and tracking IUU fishing

With respect to illegal, unreported and unregistered (IUU) fishing, European nations cooperate through the North East Atlantic Fisheries Commission and the Northwest Atlantic Fisheries Organization on denying black-listed vessels access to ports. Vessel tracking is crucial to determine which port IUU fishing vessels call at. Space-based AIS can contribute to such tracking, and enable authorities in Europe to act as the IUU vessels approach port.

AIS is at present mandatory on all fishing vessels above 300 tons or 45 meters on voyage within EU/EEA. A proposal for AIS on fishing vessels longer than 15 m was made by the European Commission [4]

> "Considering the large number of collisions involving fishing vessels that have clearly not been seen by merchant ships or which have not seen the merchant ships around them, extension of this measure to include fishing vessels with a length of more than 15 metres is very much to be desired" the Commission states in their proposal for establishing a Community vessel traffic monitoring and information system.

The European Parliament voted in April 2007 to set the requirement only for ships over 24 meters long [5]

Fisheries inspection is one of the main responsibilities of the Norwegian Coast Guard. The Coast Guard is planning to use LRIT in the waters surrounding Norway as well as in waters around Norwegian territory in Antarctica. As the cost for data access is not decided yet, the Coast Guard cannot say at what rate and for what ships they will ask for reports from.

Recognizing that the SOLAS amendment on LRIT does not include fishing vessels, international cooperation has been established to investigate ways of introducing LRIT to such vessels. For example, a requirement for LRIT reporting can be related to the license to fish. Until such regulations are in place, the only way to monitor fisheries and uncover IUU fishing by means of LRIT is to track transshipment vessels that will be subject to reporting.

1.2.4 Summary and conclusion

A comparison table of LRIT and space based AIS is set up in Table 1.4

According to IMO's implementation plan, ship reporting on LRIT will start in 2009. Responsible agencies have started planning towards this, but with the financial aspects as an unknown factor. These agencies are also aware of the space-based AIS initiative and other means of reporting that may be more comprehensive than LRIT.

	LRIT	Space-based AIS
Reporting Interval	6 hours (nominal) Down to every 15 minutes if requested	Dependent on constellation of satellite system. The user requirement is hourly updates.
Reporting Delay	Low	Up to 30+ minutes
Information Carrier	LRIT information is transmitted from the vessels through communication satellite networks to dedicated data centres which will redistribute to the end users which order the messages.	The AIS satellites receives the regular AIS messages the vessels report and downlink the information to a European mission control centre which will redistribute to registered users.
Cost	Not yet decided	Not yet decided
Message Information	Vessel ID Position Time	Vessel ID Position Time Course over ground Heading Speed over ground Navigational status Destination* Hull ID* Estimated time of arrival* Ship name*
Includes Fishing Vessels	Not today	Includes fishing vessels over 24 meters long**
Coverage Area	Out to 1000 nm out from the coast.. Globally for own vessels and vessels destined for the nations port	Globally***
Need for Extra Equipment onboard Vessels	Yes	No
Start of service	2009	The first demonstrational satellite in a European system could be operational from 2010

* included in voyage messages which are only transmitted every 6 minutes
** For fishing vessels operating in the EU/EEC area.
*** Dependent on satellite constellation the system may have reduced detection probability in some high density vessel areas.

Table 1.4 Comparison of LRIT and space-based AIS

A space-based AIS system will provide data to vessel tracking services and contribute to improved maritime situation awareness for European authorities'. The purpose of space-based AIS and LRIT are similar, whereas the systems are complementary: The data content of AIS and LRIT differ, the interval and time of the reporting differ, and the obligation to carry the system on fishing vessels differs. Therefore, efficient traffic monitoring on the high seas will benefit from use of both systems.

The plans to start using LRIT in tracking environment and security applications in national as well as European agencies from 2009 does not conflict with the development of a more comprehensive data acquisition system through space-based AIS data.

AIS and LRIT are complementary, and should be used together in future vessel tracking services. Actually, space-based AIS could serve as a source of LRIT data in Arctic and Antarctic waters where LRIT based on Inmarsat doesn't have coverage.

B.6 User Requirements and Regulations

2 User Requirements and Regulations

2.1 User Requirements

During the study, some selected stakeholders were contacted in order to get an understanding of the user requirements. With a focus on maritime security the main focus was on governmental institutions in Europe like coast guards, coastal administrations, and European institutions like DG FISH, DG TREN and EMSA. ESA has later requested a broader user requirements study, and this is started as a follow up to what was done in the original TRP study. In this report only results from the original TRP study are presented.

There will be many different users and stakeholders for a space-based AIS. FFI has gathered information from Norwegian users and stakeholders where contact was established prior to this contract. Information about the three entities, the Norwegian Coast Guard, the Norwegian Coastal Administration and the Norwegian Maritime Directorate, was gathered from meetings, e-mail correspondence, phone conversations and information available on the Internet web-pages of the different entities. Information from the Norwegian company Kongsberg Satellite Services AS has also been included to represent a possible private user of the information from the system.

SSTL supported FFI, by collecting user requirements from United Kingdom's Defence Science and Technology Laboratory (DSTL). In a system which clearly can be of use to both civilian and military authorities, DSTL presented the military requirements.

FFI also gathered input from pan European entities like the European Maritime Safety Agency (EMSA), the Directorate-General for Fisheries and Maritime Affairs and the Directorate-General for Energy and Transport. For these entities, FFI received information by e-mail correspondence and from available policy documentation. FFI also made use of a report regarding European Coastguards, produced in EU's 6th Framework Programme, Maritime Transport Coordination Platform.

As an example, some details from the report on " EU Coastguard Coordination: Feasibility Study on Long-Range Ship Monitoring & Data Transfer" [6], published in 2005 under the EU's sixth framework programme, Maritime Transport Coordination platform (MTCP) are given here. The document was prepared by Sequoyah International Restructuring and France Développement Conseil (FDC). The report, having the underlying premise that enhancement of the EU's SafeSeaNet system was desirable, concluded that:

- The amount of information transmitted by the vessel should be limited. Transfer of large datasets should be done via terrestrial networks.
- In order to enhance the usefulness of the SafeSeaNet system, more information concerning the vessel and its operations should be exchanged.

- A single window application within a port, region or country may serve as a primary capturing point for most of the required information.
- Access should be via a single data access layer at a European level, to safeguard the consistency of information provided to users.
- Given the importance Europe attaches to monitoring safety during the entirety of a vessel's voyage, the EC should define requirements for communication technologies and seek to harmonise these with other international bodies, including the IMO.
- In this regard it is noted that:
- Inmarsat C, currently in widespread use for GMDSS and general maritime communication purposes, can be adapted but only for IMO's LRIT functionality.
- In the future, the European Galileo-SMS system is a candidate for extended LRIT communications and its development should therefore be carefully specified.
- The Orbcomm system is being developed by the USCG for security rather than safety purposes, but complementary development by the EC could be beneficial.
- As currently conceived, only positioning is possible with Galileo. If Galileo is selected for European identification and tracking purposes, it would be necessary to extend its functionality to Galileo-SMS.
- IMO originally favoured LRIT information being limited primarily to issues of security. In ongoing IMO discussions, Member States therefore need to stress the importance of safe navigation in European waters.
- Proper measures should be taken in respect of information security, including data encryption and authentication of both supplier and user.

Following an e-mail request from FFI, FDC responded with some updated views regarding LRIT and AIS.

FDC believes information from an AIS system on the high seas will be more valuable, compared to LRIT, because the information is received much more frequently and as such will allow for backtracking to a specific point in time - circumstances / traffic situations leading up to an incident for example. Archived AIS information received every few seconds will provide much more useful information than LRIT, especially if LRIT information is received only once every six hours. However, if as voiced by the USCG, a new satellite AIS frequency is allocated, it is likely that Satellite AIS on this new frequency will broadcast far less frequently than surface AIS. FDC, however, still do not have any tangible information on how much garbling (data collision) will occur for Satellite AIS – with a swath diameter many times greater than surface AIS range and self organising time allocation.

As for timeliness, FDC would consider that once every six hours as prescribed within the LRIT regulations is sufficient until vessels are within say 100 nm of coast. From then on reports would be required more frequently, and for traffic convergence areas probably every 30 minutes until within AIS coverage. One should also consider that though Europe will have extremely good coastal AIS coverage, this is usually not the case outside Europe.

The information from the users and stakeholders identified was summarized into ten user requirements for use as a basis for the design of a European space-based Automatic Identification System for maritime security. A bias towards the requirements from the coast guard users is likely, as DSTL and the Norwegian Coast Guard, was better able to quantify their needs than other users. Also, the EMSA CleanSeaNet satellite service for marine oil spill detection and monitoring in European waters with its less than 30 minutes delivery requirement was used as an input regarding timeliness.

UR-#	Description	Requirement
UR-01	Geographic coverage	The system should allow for tracking of vessels carrying AIS in all European waters from the Barents Sea in the North to the Mediterranean in the South. It should also cover all other areas of the globe where European interests are at stake.
UR-02	Timeliness	The system should allow for hourly updates of the AIS information. The AIS messages should preferably be available on the ground in less than 30 minutes after they are received by a satellite.
UR-03	Accuracy	The system should allow for a positional accuracy of 500 meters and a timing accuracy of 1 minute.
UR-04	Capacity	The system should be able to handle several thousand ships at any one time with high detection probability.
UR-05	Validation	The system should seek to utilize any available information for validation of the positional information in the received AIS messages.
UR-06	Security	The system should seek to strike the best possible balance between an open safety-at-sea-focused system and a more closed security-focused system, bearing in mind that open information can both be used in the fight against and be a tool for illegal activity.
UR-07	Information	The system should allow for reception of both dynamic and static/voyage related information.
UR-08	Data Storage	The system should seek to store and retrieve historical data for several years, with the possibility to regain in correct timeframe, to be able to backtrack and understand historic activity.

UR-#	Description	Requirement
UR-09	Flexibility	The system should be able to accommodate future changes to the AIS system, e.g. changes in frequency and/or signal format.
UR-10	Cost	The system should seek the best possible solution at an acceptable cost.

Table 2.1 User Requirements

These are the requirements for an operational service. Some of the requirements may be conflicting. The combination of UR-02 and UR-01 may require a large satellite constellation which probably will come into conflict with UR-10.

2.2 Regulations

2.2.1 United Nations Treaties and Principles on Outer Space

The progressive development and codification of international law constitutes one of the principle responsibilities of the United Nations (UN) [7]. The main treaty concerning operations in outer space is the "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies". The treaty provides general regulations for operating vehicles in space. They would also apply to an AIS satellite mission, and cover such aspects as the basic premise that space be accessible for all signatory states, and that the organization responsible for launching a satellite, be it national or intergovernmental, is required to inform the UN about the satellite and orbit characteristics, as well as its function and the ownership.

Following the Outer Space Treaty the "Convention on International Liability for Damage Caused by Space Objects" covers the responsibilities and liability following damage caused by the use of outer space.

In 1986 the "Principles Relating to Remote Sensing of the Earth from Outer Space" were adopted by the UN. The term remote sensing used in these principles was defined in Principle I (a) [8]:

"The term "remote sensing" means the sensing of the Earth's surface from space by making use of the properties of electromagnetic waves emitted, reflected or diffracted by the sensed objects, for the purpose of improving natural resources management, land use and the protection of the environment;"

While a space-based AIS system will not directly sense the Earth's surface, but rather electromagnetic waves emitted from vessels on the surface, the information can still be used to improve resource management and protect the environment. The system should therefore seek to follow the intentions of the principles regarding sharing information on a non-discriminatory basis and on reasonable cost terms with States whose territorial waters are being monitored.

2.2.2 International Telecommunication Union

The space-based AIS system will need to have appropriate frequencies allocated for communication between the satellite(s) and ground stations in coordination with the International Telecommunication Union (ITU). Also, frequencies for inter-satellite communication must be filed for through the ITU, if future studies find such communication desirable. Tracking AIS messages from moving vessels using a satellite or a constellation of satellites would classify the system as a mobile satellite service. Fixed ground stations receiving data and telemetry from a satellite or constellation of satellites, should also open for use of frequencies allocated to fixed satellite services.

Frequency use must follow the ITU radio regulations and not interfere with other services on Earth or in outer space. An important paragraph in the radio regulations is article 22.1 about positive transmitter control: "Space stations shall be fitted with devices to ensure immediate cessation of their radio emissions by telecommand, whenever such cessation is required under the provisions of these Regulations." [9].

2.2.3 International Charter on "Space and Major Disasters"

The "Charter On Cooperation To Achieve The Coordinated Use Of Space Facilities In The Event Of Natural Or Technological Disasters" was established to utilize space systems for the use in disaster management [10].

The purpose of the charter is to:

- Supply during periods of crisis, to States or communities whose population, activities or property are exposed to an imminent risk, or are already victims, of natural or technological disasters, data providing a basis for critical information for the anticipation and management of potential crises;
- Participate, by means of this data and of the information and services resulting from the exploitation of space facilities, in the organisation of emergency assistance or reconstruction and subsequent operations.

Information from the space-based AIS system should be provided for use under the charter in the event that such information will contribute to new and valuable information on the situation.

2.3 Regulations concerning reception, distribution and use of AIS

2.3.1 Dissemination of data

IMO's intention for AIS has been the enhancement of safety at sea, the security of the maritime transport sector, as well as the security of coastal nations. AIS-based services on the world-wide web have emerged outside the regulations made by IMO. IMO has no means of regulating such services, except through regulations and policies in the member states, and has therefore made the following statement [11]:

> **Maritime security - AIS ship data**
> At its79th session in December 2004, the Maritime Safety Committee (MSC) agreed that, in relation to the issue of freely available automatic information system (AIS)-generated ship data on the world-wide web, the publication on the world-wide web or elsewhere of AIS data transmitted by ships could be detrimental to the safety and security of ships and port facilities and was undermining the efforts of the Organization and its Member States to enhance the safety of navigation and security in the international maritime transport sector.
>
> The Committee condemned the regrettable publication on the world-wide web, or elsewhere, of AIS data transmitted by ships and urged Member Governments, subject to the provisions of their national laws, to discourage those who make available AIS data to others for publication on the world-wide web, or elsewhere from doing so.
>
> In addition, the Committee condemned those who irresponsibly publish AIS data transmitted by ships on the world-wide web, or elsewhere, particularly if they offer services to the shipping and port industries.

This view may be supported by the governments of the member states. Depending on the state in question, however, it may not be possible to prohibit such activity based on current national laws.

With respect to a future European space-based AIS service, it is recommended that ESA and the stakeholders in European agencies and participating nations define a data policy that gives access in an open and non-discriminatory way as described under licensing, distribution and dissemination in section 3.1.5.

2.3.2 The SOTDMA patent

AIS uses the Self-Organizing Time Division Multiple Access (SOTDMA) communication protocol for access to the VHF data link (VDL). SOTDMA was developed by Håkan Lans and patented world wide by his company GP&C.

In a letter to IALA dated 10 October 1997, the patent holder waived his patent rights for SOLAS vessels: "For all AIS equipment installed in ships which fall within the IMO SOLAS convention, there will be no charge levied for said patent". This waiver has been the foundation for all further work within IALA involving the SOTDMA protocol.

However, the patent holder has tried to withdraw his waiver, followed by an extensive financial claim to all relevant manufacturers. This has led to a legal dispute between the patent holder, IALA and equipment manufacturers.

A space-based AIS sensor will only be a passive listener to the AIS transmissions from vessels, and will therefore not be an active user of the SOTDMA communication protocol.

The following legal questions relating to a space-based AIS sensor arise from the above situation:

1. Whether the SOTDMA patent prevents passive listening in space to AIS information from vessels that fall within the IMO SOLAS convention unless an agreement is established with the patent holder.
2. Whether AIS information obtained by a space-based AIS sensor can be freely distributed to the users of such AIS information.

These legal questions were forwarded to a patent lawyer at Oslo Patentkontor for evaluation. The short version of the response was the following:

> In order to infringe on the patent, an infringer must employ all elements in a claim. In this case there must be present a station reporting its own position, taken from a GPS reading and transmitted using the particular protocol in question. A receiver receiving the signals from this station is clearly not covered by the patent claims. Thus, there should be no restrictions concerning setting up a receiving station anywhere in space or on earth.

The conclusion of the evaluation is that space-based AIS will not conflict with the SOTDMA patent. The full version of the response from Oslo Patentkontor can be made available on request.

B.7 Data Policy and Data Handling

3 Data Policy and Data Handling

3.1 Data Policy

The space-based AIS data policy should take into account the policies and regulations of the afore-mentioned bodies: the UN, ITU and IMO. Ultimately, the policy will depend on the policies and regulations of the body or bodies owning and operating a space based AIS system. The following discussion assumes that the system is European, initially under the control of ESA during a development and pilot phase, subsequently transferred to an operational European entity responsible for surveillance and/or maritime security. We therefore anticipate that such a system be operated in two major phases: I.) Demonstration and Trials. II.) Full Operations.

This suggestion for a first iteration of a data policy for a space based Automatic Identification System for maritime security is based on consideration of data policy from "The initiative on Global Monitoring for Environment and Security (GMES)" [12;13] and existing European policies on Earth exploration from ESA [14-16] and on meteorological observations from EUMETSAT. [17-19].

3.1.1 Definitions

Name	Definition
Participating States:	States participating in the European Space Agency.
The System:	The AIS payload(s) on a satellite or on a constellation of satellites making up the space-based Automatic Identification System for maritime security.
Contributing States:	States contributing to the System.
Payload:	The AIS payload receiving AIS messages in space.
Operating Entity:	The entity in charge of receiving, archiving and distributing the AIS data from the satellite(s) in an operative system.
Satellite Operator:	The entity in charge of operating the satellite(s). (receiving housekeeping data, monitoring the orbit, transmitting commands to keep the system operational)
Users:	European or national governmental entities involved with Maritime Security. Owners of the vessels observed Private or public entities using the data in value added products

Table 3.1 Definition used in the data policy.

3.1.2 Ownership, privacy and confidentiality

For a demonstration phase, ESA, on behalf of the Participating States, should retain title to and ownership of all primary data originating from the AIS payload together with any derived products generated under ESA contract as well as other products to the extent that the contribution of the AIS payload is substantial and recognisable. ESA should protect these data through applicable legislation, including laws on databases, copyright and other appropriate forms of intellectual property rights.

In an operational phase, an Operating Entity other than ESA (e.g. European Maritime Safety Agency, EMSA) should be the owner of the data, similar to the practice in the organisation for meteorological satellite data, EUMETSAT. In the case where the satellite operator is a separate entity, the satellite operator should be the owner of the housekeeping data.

All data should be protected and accessible by appropriate electronic means. This could be achieved by encrypting the downlinked data and making it accessible through the Internet, or alternatively by making it available in a dedicated secure network. All access to the data should be limited to registered users. Access should be further restricted or denied if the majority of a board with members from all Contributing States finds that such access could endanger maritime security. All efforts should be undertaken to protect the data, products and services against unauthorised use.

3.1.3 Intellectual property rights and associated legal framework

The satellite(s) should be owned by ESA in the name of and on the behalf of the Participating States and should be registered by ESA pursuant to the United Nations Convention on Registration of Objects launched into Outer Space, entered into force on 15 September 1976. As a result, ESA would maintain jurisdiction and control over the satellite(s) and therefore would be entitled to stipulate the rules for utilisation of the data.

In the demonstration phase, ESA in the name of and on behalf of the Participating States should hold the full ownership and Intellectual Property Rights to the System's Data and Products. In the operational phase, the Operating Entity should hold the full ownership and Intellectual Property Rights to the Systems Data and Products.

The Intellectual Property Rights to data where the contribution from the System's Data is substantial and recognisable should be shared between the Operating Entity and the Service Provider generating the images.

The Intellectual Property Rights other than data based on the System's Data should be considered owned by the Service Provider generating the Value Added Service.

3.1.4 Standards and metadata

The Payload data format should follow the AIS standards in use, e.g. the base station standard

[20]. In addition to the AIS messages, extra information such as time of reception, Doppler shift, direction of incoming signal etc. should be stored using existing standards where available. For forwarding of AIS data from the System in near-real time, the AIS messages should follow standards allowing the messages to be integrated with systems using data from coastal networks of AIS base stations. If possible, one should seek to use a standard where time of reception can be included, as there will be some delay from when a satellite receives a message until it is available on the ground.

If possible, a tag of message quality should also be included. This could be added by the ground segment, based on position information received compared to origination of signal, duplicate IDs registered, black-listed vessels, registered unexpected breaks in AIS messages etc.

Metadata included in archived messages on the ground should include time of reception, ID of message received, ID of satellite (if constellation), position of satellite at the time of reception.

3.1.5 Licensing, distribution and dissemination

Distribution of the data should be consistent with United Nations Resolution 41/65 dated 3 December 1986 on Principles relating to Remote Sensing of the Earth from Space.

The data will be distributed to registered users according to three categories.

- Category 1 use: The Payload data should be available for Governmental use for Maritime Security. This includes both operational use and research use.
- Category 2 use: The Payload data should be available to the respective owner of the vessels.
- Category 3 use: The Payload data should be available for private and public entities for use in Value Added Products.

3.1.6 Pricing policy

Category 1 use: Contributing States should have the right to receive all Payload data in near-real time from the System at no cost except for the provision of decryption key units. Other States should have the right to receive all Payload data in near-real time from the System at/or near the cost of operating the distributing service in addition to the cost of decryption key units. For countries with a GNI per capita below or equal to USD 3,500 derived from World Bank statistics the cost should only include the cost of decryption key units.

Category 2 use: Vessel owners should have the right to receive all Payload data concerning their respective vessels in near-real time from the System at/or near the cost of operating the distributing service in addition to the cost of decryption key units.

Category 3 use: Category 3 users should have the right to receive Payload data in near-real time for use in Value Added Products at market cost. The cost should be comparable to the cost of Category 2 use.

3.1.7 Archiving policy

Both housekeeping and payload data should be stored for at least 10 years to allow for research and historical tracking of marine activity. An official archive should be kept by the Operating Entity.

3.1.8 Review

A board with members from all Participating States should review the System's Data Policy whenever it considers fit and normally every two years. A first official version of the System's Data Policy should be agreed upon before the launch of the first satellite.

3.2 Data Configuration and Handling

This chapter gives recommendations on the AIS data configuration and handling in the satellite based AIS system and what should be handled by the payload, the spacecraft and the ground segment.

3.2.1 Payload

Preferably the AIS data should be decoded to bit level on-board the payload. Then each AIS data package would contain 168 bits. In addition to the pure message data the time of reception is needed. The Doppler shift can be used for rough location of the origin of a signal. This would require information on the frequency offset of a received signal. Understanding the signal environment, and detecting interference would also require Received Signal Strength Indication (RSSI) information in each AIS time slot to be recorded.

In high density areas, the processing required for signal detection may need signal processing to be done on the ground. Thus the payload should be able to sample the base band signal for forwarding to ground. As the high density areas are close to populated areas, one could also consider a bent pipe solution where the base band signal is not sampled in the payload but directly mixed onto the downlink frequency and first sampled at the ground station.

The duty cycle of the payload should be close to 100 % (continuous operation) to achieve global coverage. In a trade-off situation, the duty cycle should at least be 20 % during orbits passing over or close by Europe, enabling continuous operation while observing these waters.

3.2.2 Spacecraft

The spacecraft should store all the payload data and prepare them for downlink. The spacecraft must also be able to handle real-time buffering of the data from the payload.

Before downlink the data should be encrypted and error correction coding should be added. For logging receive time of AIS messages, the spacecraft should keep an internal clock with accuracy within a few seconds. For mission control the requirement for orbit determination is not expected to be above what is given by the two-line elements, provided these will be available at least once per day. In addition status and health of the different subsystems on the spacecraft in use should also be downloaded.

The spacecraft should also receive commands from the ground station(s). The commands received should be validated as coming from a trusted source, error corrected and decoded. The spacecraft should then forward any commands going to the payload, and execute commands related to the other subsystems e.g. the attitude control system. The commands should be forwarded immediately or stored for forwarding until a certain position or time is reached as defined by the command.

3.2.3 Ground Segment

The ground segment should be responsible for establishing contact with a satellite as it passes over a ground station. When connection is confirmed, a request should be sent to the spacecraft to downlink the latest payload data, position data and housekeeping data. The data packages received should be error corrected and decoded.

Decoded AIS messages should be sorted by vessel ID and processed for any anomalies. Message positions should be compared with the rough location of the signals calculated from the frequency offset and satellite position. Together with a check for the last known time and position of the vessel ID, a quality tag should be added. The information should then be stored in a database.

The RSSI information should be used to create updated maps of the signal environment.

The decoded AIS messages, including time of reception, should be forwarded to registered users using standard AIS formats. The quality tag should also be considered to be included if it is possible within standard AIS formats. A list of vessels with non-"clean" quality tags could be forwarded on regular intervals.

In case the received signal is just the raw base band signal, the ground segment will first need to run the received base band signal through a signal decoding process to decode the AIS messages.

The ground segment should also include a track record on the latest satellite position data. Any anomalies registered from the payload and spacecraft housekeeping data should immediately result in an alarm at an operations centre.

The ground segment should be able to uplink commands to the S/C including updates and commands to the payload, request for detailed housekeeping data, S/C attitude and control commands.

B.8 AIS receiver concept

4 AIS receiver concept

This chapter covers the study on the AIS payload. The main part covers the work done by Kongsberg Seatex AS (KSX) on the receiver itself. Antennas are discussed at the end of the chapter. The work on antennas has involved all parties of the consortium, and antenna choices have been an important factor in the detection probability simulations performed throughout the study.

4.1 Receiver concept trade-off

Several architectures are possible for receiving AIS signals in the VHF band. The following illustrates different alternatives describing their advantages and possible weakness.

4.1.1 Standard superheterodyne receiver

This receiver is used in most communications systems and represents proven technology for space applications. Figure 4.1 shows the block diagram for a super heterodyne receiver with two intermediate frequencies.

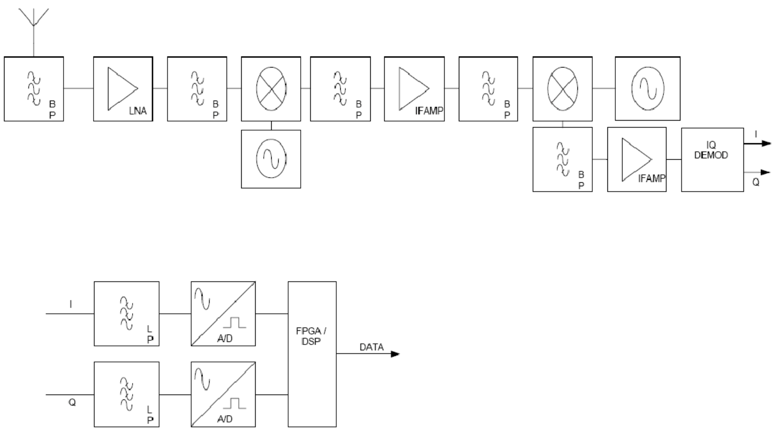


Figure 4.1 Double superheterodyne receiver

The signal is first filtered in a band pass filter passing the maritime band 156-162 MHz. If necessary, additional blocking filters may be used to suppress strong interfering frequencies like the Tracking, Telemetry and Command (TT&C) link.

The signal is amplified in a Low Noise Amplifier (LNA) and mixed down to an intermediate frequency (IF) where most of the signal amplification takes place. The receiver may have one or two IF stages depending on the level of amplification and the bandpass filtering needed. In order to suppress mirror images, a first IF with a high frequency is normally used. The main selectivity is then obtained at the second IF frequency.

Filtering can be performed with standard LC filters, X-tal filters, Ceramic filters or SAW -filters depending on bandwidth and bandpass requirements.

The amplified and filtered AIS signal is then demodulated in an IQ demodulator giving two orthogonal channels for further signal processing. The demodulation can be done by ordinary hardware demodulators or by digital means in an FPGA. Using digital techniques opens up a range of advanced methods for digital processing of the signal, thereby increasing filtering possibilities, demodulation accuracy and adaptive techniques for recovering signals in noise. Digital processing will, however, need more power than an ordinary hardware solution. The level of digital processing therefore is a tradeoff between demodulation efficiency and power consumption.

After demodulation the signal may be decoded by an FPGA or ordinary microprocessor before the final data message is sent to the onboard computer (OBC).

The superheterodyne receiver is considered state of the art technology and represents a well proven design. As this design has been used for space applications for decades it represents a low risk solution for an AIS receiver. An implementation with a hardware demodulator will not, however, be flexible enough for handling the adverse signal conditions in space regarding colliding messages and will have problems regarding large Doppler shifts.

4.1.2 Direct conversion receiver

This alternative is basically a superheterodyne receiver with zero IF frequency. The direct conversion receiver is shown in Figure 4.2.

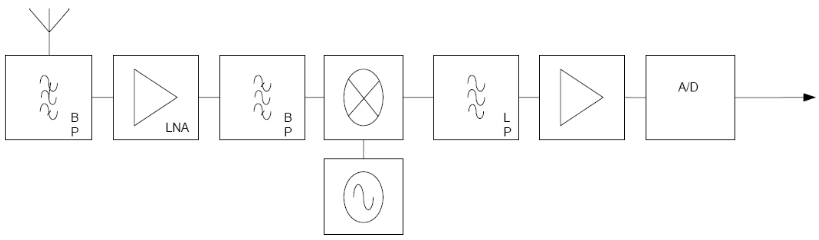


Figure 4.2 Direct conversion design

In this receiver, the signal is directly converted to baseband. This method has been popular with some GSM mobile phone manufacturers. The problem with this design is that all selectivity must be performed at the signal frequency which requires an X-tal filter or a SAW filter. It might be possible to use this design with an additional digital demodulator and signal processing unit and the design should be studied further.

4.1.3 SDR based design

Digital processing makes it possible to apply advanced algorithms for filtering and recovery of data content from the AIS messages. Having a digital design also makes it possible to upload new receiver implementations by changing firmware in the memory, thereby making the system very flexible. In space, it will be possible to upload new functionality by uploading new firmware to the AIS receiver. Moreover, a digital approach will give us some new tools to solve problems with colliding messages and Doppler shift.

It will be advantageous to make the digital transformation as early as possible in the receiver chain. One approach is to digitize directly at the carrier frequency. This is possible with fast A/D converters available today.

Figure 4.3 shows an SDR-based design:

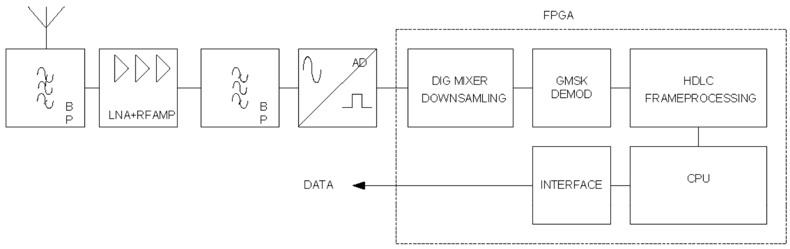


Figure 4.3 Software Defined Radio - SDR

In order to have a suitable signal for the A/D conversion, we need to bandlimit and amplify the AIS signal in an LNA. The level of amplification depends on the A/D requirements, but would typically be in the order of 60-80 dB taking the low signal level of - 115 dBm into account.

After bandpass filtering and A/D conversion, the signal is fed to an FPGA which performs the rest of the signal processing before delivering AIS data to the OBC.

Necessary functions in the FPGA will be digital filtering, mixing, downsampling, GMSK demodulation, HDLC frame processing, message decoding and a communication interface.

An oscillator for mixing and downsampling can be designed in the following way:

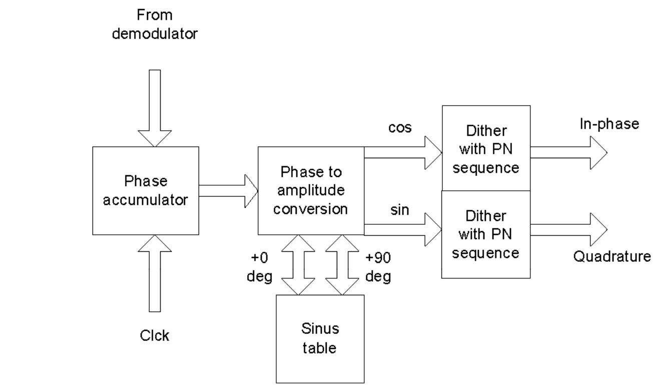


Figure 4.4 Direct digital synthesis

The GMSK demodulator can be implemented in the following way:

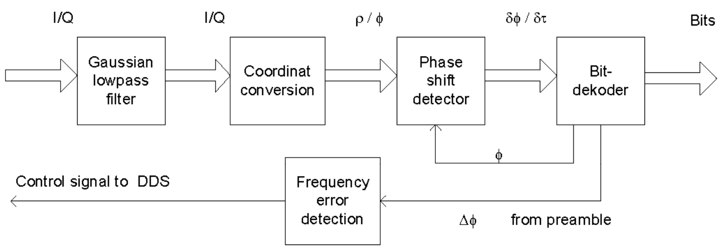


Figure 4.5 Digital GMSK demodulator

In order to achieve sufficient LNA amplification we need several stages of amplification and filtering. The following design will give the required gain and filtering performance:

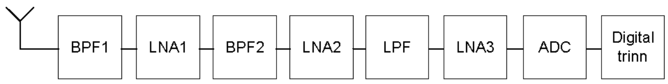


Figure 4.6 LNA with bandpass filters

An SDR receiver as described will have a very high degree of flexibility. Even if the structure seems complicated and there is a need to develop advanced processing firmware, this architecture is the best approach to solve the challenges in receiving AIS signals in space.

4.1.4 Bent pipe design

The bent pipe design for a receiver chain is also of interest, even if it is not a receiver by itself. The bent pipe principle relies on receiving the AIS signals in space, followed by amplification, filtering and frequency conversion to a suitable down link frequency. The bent pipe will, as the name indicates, receive the signals in space and send them unaltered, except for the frequency change, to the receiving station on Earth. The modulation of the AIS signals is not changed and the AIS signals, as received in space, can therefore be demodulated and decoded in the earth station. This concept has the great advantage that it will be possible to use more processing power on the gr ound than in the satellite. Figure 4.7 shows the principle idea for the bent pipe approach. The downlink may be S-band or any other downlink with sufficient capacity.

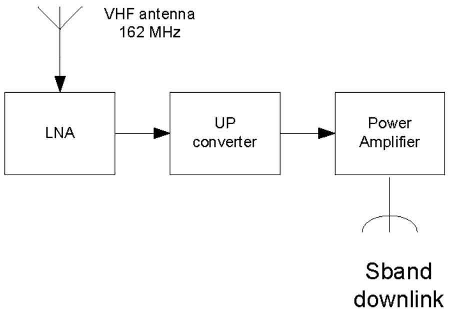


Figure 4.7 Bent pipe principle

In the bent-pipe scenario, the incoming RF signal is remodulated to a downlink frequency and sent back to the ground station in real time. No signal processing except for filtering, amplification and frequency translation is performed in the payload. As the signal is only frequency shifted to a new downlink frequency, the received signal on the ground will be an exact replica of the signal received in space. Except for the carrier frequency, the sidebands and modulation will be exactly the same. The major advantage of this scenario is that demodulation and decoding can now be done on the ground where we can apply more processing power than in space. This makes it possible to use more powerful computers and algorithms for demodulation and decoding of the AIS signals.

The basic requirement for this scenario to work, is that the space to ground link is active during data acquisition. This will only be the case as long as the base station can see the satellite. When the satellite is out of reach, no more signals will be received. A solution to this problem could be to digitize the signals without decoding them, store the digitized signals in memory, and transmit them when contact with the ground station is available. Demodulation and decoding could then be done on the ground.

The data rate needed in a digital bent pipe solution is the product of the sampling rate, number of AIS channels, number of receivers and the number of bits used per sample.

According to Nyquist's sampling theorem, with perfect filtering we will only need to sample with twice the bandwidth of the wanted signal. However, we should sample more often to compensate for imperfect filters.

The number of bits needed per sample depends on the dynamic range of the signal, the SNR margin and the SQNR margin. We want the quantization error to be low compared to the thermal noise floor, to avoid noise shaping by quantization. This means we need 15-20 dB for the signal dynamic range, 15 dB for the SNR margin and 20 dB for the noise floor-to-quantization noise margin. The accumulated dynamic range is 55 dB, or around 10 bits per sample since 1 bit ~ 6 dB dynamic range.

We should sample each of the quadrature channels twice per symbol, which means that the real frequency is oversampled by a factor of 4.

This leads to the following data rate requirement:

R = 10 bits/sample * 25 kHz * 4 samples/Hz * 2 AIS channels = 2 Mbit/s/receiver

Processing on board and downloading data for further on-ground processing is strictly speaking not a bent pipe approach. The bent pipe architecture is by definition retransmission of the received signal in its original form - without any processing - to the ground station.

The process described as partly processing on board and partly on ground is, however, an interesting approach which has the advantage that more of the processing can be done on the ground. It could also be an interesting approach to have a dual solution where decoding can be selected to be either in space on the ground.

4.1.5 Comparison of receiver architectures

	SDR	Analog bent-pipe	Digital bent-pipe	Superheterodyne
Stability	New design, unproven	Proven design in space	Proven design in space	Proven design in space
Flexibility	High, software upgradeable in field	High, data processing is done in ground station	High, most data processing is done in ground station	Static
Data storage	Store-and-forward of bytes	Requires ground station within sight	Store-and-forward of phase information, high complexity	Store-and-forward of bytes
Radiation susceptibility	High	Low	Medium	Low
Bug probability	High	Low	Low	Medium
Amount of components	Low	Medium	Low	High

	SDR	Analog bent-pipe	Digital bent-pipe	Superheterodyne
Cost	High due to development	Low – mature technology	Medium depending on level of processing	Low. Well proven technology

Table 4.1 Comparison of receiver architectures

Receiver Architecture	Advantages	Disadvantages
Direct Conversion	Simple and inexpensive hardware implementation. Minimum of components required. Local oscillator at same frequency as received signal gives simple oscillator design. Easy to realize required amplification at baseband frequency. Low power consumption.	All selectivity has to be provided at baseband frequency. May be difficult to achieve required adjacent channel suppression. Suppression of local oscillator signal at antenna terminals may be difficult.
Superheterodyne	Proven technology and used in most current applications. High oscillator frequency will give good mirror signal suppression. Intermediate Frequency amplifiers will give high gain and good selectivity.	Increased number of components. Need LC filtering for obtaining good selectivity. Depends on filter tuning (IF) for optimum results.
Double Superheterodyne	Use two or more IF's to obtain better gain and selectivity. State of the art solution for high grade receivers.	Increased number of components and higher cost.
Software Defined Radio – SDR	Flexible regarding change of receiver parameters. New software modules can be implemented on same hardware to obtain different receiver characteristics.	Complex implementation. Relies heavily on digital signal processing to obtain the same performance as superheterodynes. High power consumption due to signal processors and microprocessors needed.

Table 4.2 PROs and CONs of different receiver architectures

Demodulation and decoding may be done by hardware or software demodulators / decoders. The same advantages and disadvantages apply to the methods for demodulation and decoding. Hardware designs are easily implemented but have low flexibility. Software implementations are more complex but yield higher flexibility and consume more power.

The most important factors for selection of receiver architecture are:

1. Probability of success for reception of the wanted signals
2. Power consumption
3. Flexibility
4. Complexity

Receiver Architecture	Success factor	Power consumption	Flexibility	Complexity	Total
Direct Conversion	6	7	1	7	21
Superheterodyne	8	7	1	6	22
Double superheterodyne	9	6	1	5	21
SDR	9	4	8	3	24

Table 4.3 Rating of receiver architectures. Score : 1= bad 10= good.

Based on the simplified evaluation of performance and flexibility in Table 4.1, Table 4.2 and Table 4.3, the SDR solution is the best for a spaced based receiver. The differences are marginal, however, and all architectures are good candidates for a space based receiver. If major importance is placed on flexibility, the SDR solution is the best.

4.2 Interference issues

4.2.1 Internal interference

Reception of AIS signals in space may be influenced by internal and external interference. Internal interference may be generated from other S/C equipment such as switch mode power supplies and digital processing equipment. Switch mode supplies will typically generate a powerful carrier at the switching frequency which is typically in the range 10 – 100 kHz, and harmonic components which are a multiple of the switching frequency. The harmonics can be quite powerful. If within the AIS channels, they can degrade the signal to noise ratio substantially. Harmonics in the reception channels should therefore be avoided by all means. As the switch mode PSU normally has a low frequency stability, the harmonics may easily drift through the reception channel when temperature or load changes, thereby degrading the reception quality seriously. Care should therefore be taken in using switch mode supplies on board the S/C. It is recommended that all switch mode supplies have a frequency and a frequency stability that eliminates this problem.

The situation is similar regarding on board digital equipment. The clock generator may generate harmonics that fall in the pass band of the receiver. Moreover, the digital transitions themselves generate transients that may reduce the signal to noise ratio if radiated to the antenna system (White Noise). Great care should be taken in the development of the on board electronics in order to avoid radiated interference that may reach the receiver input. Filtering and shielding of the electronics is necessary to avoid radiation problems.

The third main interference source on the spacecraft is the TT&C downlink. The power amplifier may produce a considerable level of RF energy on the receiver input. Even if the downlink is at S-band or higher, care should be taken to reduce the power level impressed on the receiver input. Moreover, the receiver design has to take into account the power and frequency on the downlink, so efficient filters for this problem can be applied on the receiver side.

The TT&C transmitter should also be checked for spurious, out of band emissions and phase noise. Unwanted signals that fall within the AIS channels must be avoided.

2.4.2. External interference

The maritime VHF band is occupied with a multitude of transmitters. The band is congested with stations and heavily used in all kinds of marine operations. Transmitters are situated on board vessels and on shore. Moreover, the coastal marine service use base stations with directional antennas to cover the coastal areas and inland waterways. A satellite based receiver will see all of these transmitters simultaneously, and there is a considerable risk for interference with the AIS signals.

Fortunately the AIS channels have now been universally allocated and agreed upon. This will reduce the interference problem as we can narrow our working bandwidth to the two channels in question. (AIS ch A = 161,975 MHz, AIS ch B = 162,025 MHz). The receiver design will then concentrate on two 25 kHz channels with an intermediate channel of 25 kHz at 162,000 MHz.

The transmitting power in the maritime VHF band is normally restricted to 25 W. Due to symmetry considerations this is also the normal transmitting power for the base stations in this band. The AIS transmitting power is normally 12.5 W or 3 dB below what other transmitters in this band use. As the potentially interfering transmitters will be at least a channel away, a 3 dB interference ratio is not considered to be a problem. Co–channel interference requirements for the receiver should be at least 10 dBc, so other transmitters in the VHF maritime band should not represent a problem.

The most difficult frequency for the AIS receiver is probably the intermediate channel 162,000 MHz, as this frequency will be positioned between the two AIS channels and can not be suppressed by a first stage block filter. In Norway this frequency is allocated for testing and demonstration purposes and is therefore not used as much as the other channels in this band. It is, however, unclear if this is the case in other countries as well. Under any circumstances, this is still an adjacent channel to the AIS frequencies, and should not pose a problem as long as the transmitting power level is below 25 W.

Powerful VHF / FM transmitters in Band I, II and III (European FM and TV bands) could represent a problem if they produce spurious in the AIS channels. Their working frequency is, however, so far from the AIS channels that they will not represent a problem. So far we have not experienced any problems with spurious signals of this kind. Such spuriuos signals would also been detrimental to vessels and land based AIS receivers, so we do not believe that such transmitters constitute a problem for reception of AIS signals in space.

Another source of external interference could be the new AIS class B transponders. Class B transponders are designed for use on other vessels than SOLAS vessels, i.e. smaller vessels and leisure craft. The transmitting mode of Class B AIS will reduce the number of messages sent when they are in an area with Class A transponders. Moreover the power of Class B is 2 W, which is about 8 dB below the power of Class A. Class B transponders and Class A transponders in the same area should therefore not interfere with each other, and Class B transponders should not interfere with the reception of Class A transponders in the satellite.

The above considerations lead to the following design guidelines for the AIS receiver and the S/C electronics:

- The AIS receiver should be designed for narrow band reception (25 kHz) of two AIS channels only. (SAW or XTAL filters may be used).
- The receiver should have an input block filter reducing the bandwidth to about 100 kHz before amplification. (Good engineering practice).
- The receiver design should include band stop filters for the downlink frequency.
- The receiver should have band stop filter for any image frequency.
- The on board electronics should not produce white noise or spourius in the AIS channels.

It should be noted that a strategy with two narrow channel filters and a narrow input block filter could make reception on a third dedicated AIS LRIT frequency more complicated. There is an initiative to allocate a third VHF frequency in the maritime VHF band for Long Range Identification and Tracking of AIS transponders. If a new frequency for this dedicated use is implemented, it could be chosen outside the input block filter bandwidth. The final design of the receiver should therefore take into account the possible need for reception of a third AIS frequency anywhere in band 156 – 162 MHz.

Questions have been raised regarding the need for an automatic level control in the receiver. This issue has been discussed with the following result:

AIS uses GMSK modulation. All information is contained in the phase of the signal and there is no need to consider the amplitude of the signal.

- Assuming signal levels of below – 100 dBm even 1000 simultaneous carriers will give a combined power level of less than – 70 dBm. This is well inside the linear part of the LNA. From a power level point of view, no Automatic Gain Control (AGC) is necessary.
- AIS signals will be in the range of –115 to –100 dBm. This is a small dynamic range and should not indicate a need for an AGC function.
- If many AIS signals are present at the same time (co-channel interference) the signals will be so garbled that successful demodulation is less likely. An AGC function will not be able to rectify this.
- An AGC function requires an electronically controlled attenuator in the signal path. This

Norspace has the following comments to the AGC question:

- As long as the combined peak value of the signals are lower than the threshold for distortion there is less need for adjustment the dynamic range.
- For FM reception the strongest signal will dominate. The strongest (wanted) signal will be demodulated and amplitude noise in the received channel will be suppressed.
- Using 100 kHz filtering will probably reduce the need for gain adjustment.
- If several signals are present and the sum of the unwanted signals is stronger than the wanted signal, a linear RF amplifier should be used. Due to possible intermodulation from the first stage it may be necessary to adjust the gain before the last stage and use a channel filter after the last amplifier stage.

Summing up, Seatex concludes with the following remarks:

- The current laboratory model has been tested with signals at – 115dBm and –110 dBm with excellent results.
- Even with an in band (156-162 MHz) blocking frequency at – 50 dBm and a signal level of –115 dBm we have less than 3 % Packet Error Rate (PER) . This shows that the receiver LNA has excellent linearity and intermodulation characteristics and that an AGC is not required since an accumulated in band interfering signal of – 50 dBm will never be experienced in practice.
- Regarding the use of 100 kHz filter we think that this is a good solution if we are only to receive the two AIS channels and possibly 162.000 MHz at the same time. If we want to be able to receive a third frequency anywhere in the maritime band, a 100 kHz filter is not suitable.
- The basic design used in this study assumes a broad band LNA (6 MHz) to prepare for a third frequency anywhere in the maritime VHF band.

4.3 Digital Signal Processing in SDR architecture

The DSP firmware architecture is shown in Figure 4.8. As we can see, several channels are implemented in the FPGA, and they are all connected to the same ADC and data buses. In order to decode a GMSK modulated AIS signal correctly, we need a quadrature mixer which outputs the I and Q components of the signal, which is done by multiplying with sine and cosine signals at the carrier frequency. The sine/cosine signals are generated in a Direct Digital Synthesizer (DDS). The two resulting signals must be filtered and decimated in a filtering chain, before converting from Cartesian to polar coordinates. The GMSK demodulator decodes the phase of the signal into a bit stream, which is transformed into bytes in the data frame recovery module. The firmware also corrects frequency errors and finds the best sampling time based on a correlator bank.

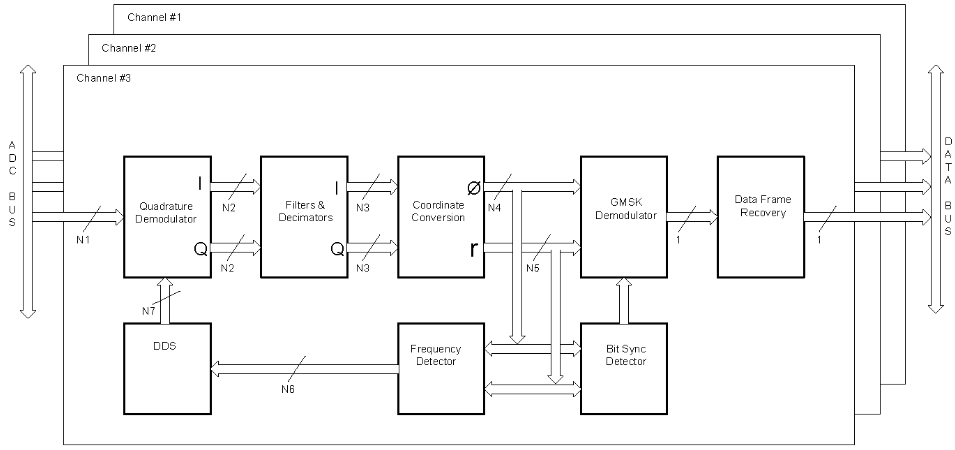


Figure 4.8 Block diagram of the DSP firmware

4.3.1 Sampling rate

Before the signal can enter the digital front end, it must be converted to digital samples. The sampling frequency must be at least twice as high as the highest frequency component of the input signal, which means at least 12 MHz. The direct down-conversion SDR architecture uses band pass sampling [Vaughan91], which means sampling below the Nyquist requirements for the carrier frequency while oversampling the modulation bandwidth with regards to the highest baseband frequency component.

This approach actually uses the ADC as a downconverter, and it is important that all frequencies outside the wanted band are sufficiently filtered, otherwise they can be aliased into the bands of interest after down-conversion.

For VHF frequencies, it is possible to sample directly on the RF signal. The information is in the slowly varying phase of the carrier, and by under-sampling the carrier we can save power by using a lower sampling rate, fs. The centre of the band of interest is at 159 MHz, and we want this frequency to be placed at fs/4 to avoid the image frequencies wrapping into the down-converted band. This means that the sampling rate can be found by solving for x in

$$159 = (N + ¼)\, x$$

where N is the under-sampling factor. To reduce power usage due to high sampling rates we want N as high as possible, but on the other hand, a high under-sampling ratio will cause low signal levels, as we sample the Nth harmonic component of the signal. We select this factor to be 3, so our optimal sampling rate is 49 MHz.

4.3.2 Digital tuning

Tuning is the first part of the digital part of the receiver. The sampling process gives us the full bandwidth of interest, and the tuner shall be able to select one channel, convert it down to baseband, filter away the unwanted information and change the sample rate to a practical value.

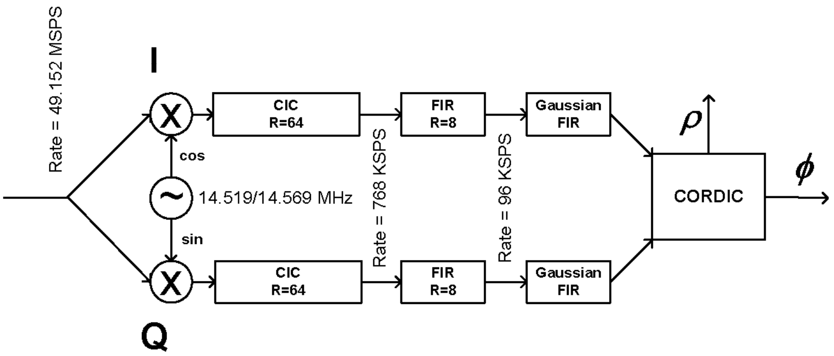


Figure 4.9 Tuner block schematic

4.3.3 Frequency and bit timing correction

The phase signal is passed from the coordinate conversion block to the frequency and bit sync detectors. These blocks need 8 bits of the preamble to correct frequency errors and bit timing errors, which is done simultaneously with an averaging filter and a matched filter for the training sequence.

A preamble consisting of alternating 1's and 0's will cause the phase signal to form a sine wave around a straight line, if the frequency error is constant. If there is no frequency difference between the numerical local oscillator and the received signal, the phase signal will oscillate around a horizontal line. Else, the line will have a non-zero slope.

The frequency correction is done by finding the average slope of the phase signal, multiplying with a correction factor and passing the result to the numerical oscillator. The slope is computed with an averaging filter, which uses 2 periods of the preamble, i.e. 8 bits.

At the same time, the phase signal is passed through a matched filter. This filter has an impulse response consisting of square pulses, where the zero-crossings equal those of a perfectly received preamble. Such a filter operation is similar to using a correlator bank, but is easier to implement and needs only a simple peak detector to find the optimal decision sample. The phase signal has a sample rate of 10 samples per output bit, which means we should pick one of 10 for making bit decisions for each burst. The frequency and timing error through the burst are assumed to be constant.

4.3.4 Robustness against co-channel interference

The system shown in Figure 4.8 has no protection against time slot collisions. However, as seen from Figure 4.10, it will be robust against time slot collisions as long as the signal to interference ratio is 8 dB or better. The algorithm also needs at least 8 bits of "clean" preamble for frequency and timing correction. Figure 4.10 shows a scenario of two colliding AIS messages with different signal-to-interference ratios, where the X axis denotes the bit number in the message and the Y axis shows accumulated number of bit errors at the corresponding bit. The total number of bit errors for an S/I margin is shown at the end of the message, i.e. at bit number 204, and for a margin down to 8 dB there are no bit errors. For 7 dB we get a bit error around bit number 60 of the message, and when the difference in signal power between the messages is as little as 5 dB, we get 8 bit errors in total, the first occurring at bit number 10.

Based on the assumption that all signals are equally influenced by the ionosphere, the entire difference in signal amplitude must come from a difference in path loss. A path loss difference of 8 dB equals a path difference of 900 km and a difference in arrival time of 3 ms. This means that signals which collide in a time slot will be decodable if one of them arrives 3 ms or more later than the other, since this also ensures that the signal power margin is higher than 8 dB.

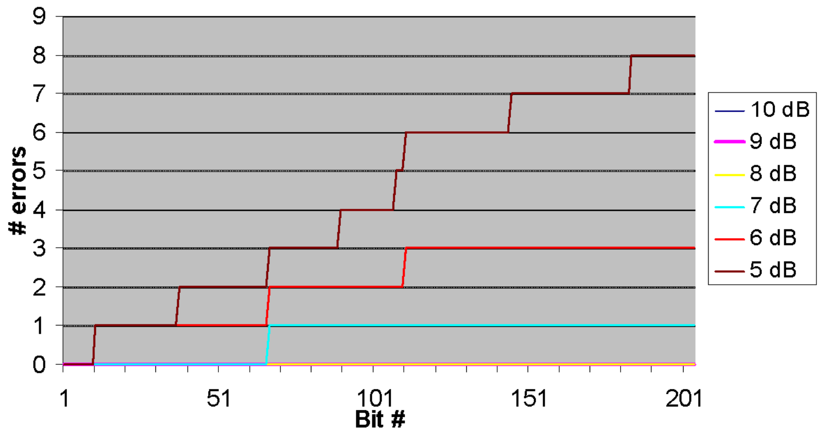


Figure 4.10 Accumulated bit errors from simulations.

There is no gain control in the SDR receiver. The GMSK signal is essentially an FM/PM signal and no information is coded in the amplitude. Gain control is not considered necessary for this receiver as the information is only coded in the phase changes of the carrier. An RSSI function will, however, be implemented for information about the carrier level. If a need for gain control for any reason is deemed necessary, this can be implemented by using the RSSI signal.

4.3.5 Receiver characteristics

Some of the receiver characteristics are summarized in Table 4.4.

Parameter	Requirements	Remarks
Carrier Frequency Offset (Including Doppler)	Maximum values normalized to the symbol rate	Carrier frequency may be offset ±1 kHz due to oscillator drift and ±4 kHz due to Doppler shift.
Receiver Linear Distortion: Gain Slope	Maximum in dB/Hz or dB/Rs	Mainly due to Rx front end filter. For end-to-end analysis it should include the impact of Tx filters. As this is an analogue broadband design, the gain slope should be better than ±1 dB within the frequency band 156 to 162 MHz.
Receiver Linear Distortion: Gain Ripple	Peak-Peak value in dB	Better than ±0.5 dB
Receiver Linear Distortion: Group Delay Slope	Maximum value in µsec per Hz (or per Rs)	Due to broad band analogue design this should be negligible.
Receiver Linear Distortion: Group Delay Ripple	µsec P-P over transmitted bandwidth	Due to broad band analogue design this should be negligible.
I/Q Gain and Phase Imbalance caused by receiver	Could be expressed in terms of sideband suppression	As the I/Q demodulator is implemented digitally there should be no gain or phase imbalance in the receiver chain.
Linear Distortion: Group Delay Ripple	µsec P-P over transmitted bandwidth	Due to broad band analogue design this should be negligible.
Burst-to-Burst Power Variation seen at the Receiver	Maximum variations to be reported in dB	Maximum input signal = - 100 dBm Minimum input siganl = - 115 dBm Input signal dynamic range = 15 dB
Quantization Error due to ADC	For example, can be reported in terms of SINAD or ENOB	Due to over-sampling, the impact is expected to be negligible. Also, the dynamic range is quite small making the quantization error small.
Aliasing Noise due to imperfect anti-aliasing filter	Signal fold-over characteristics	Mirror frequencies to be attenuated at least 40 dB
Third-Order Inter-modulation Distortion	Reported in dBc	Design requirement 40 dBc

Table 4.4 Receiver characteristics

A lab prototype showed the following power consumption (only one receiver):

Component	Voltage [V]	Current [mA]	Power [mW]
TCXO	3,3	15	49,5
LNA	3	120	360
ADC	3	50	150
FPGA I/O voltage	3,3	10	33
FPGA core voltage	2,5	60	150
FPGA core voltage	1,2	250	300
Microcontroller	3,3	7	23,1
Flash memory	3,3	5	16,5
Total			1082,1

Table 4.5 Receiver prototype power consumption breakdown

4.4 Architecture for demonstration concept

During discussion in the second half of the study, a common understanding of the desired design for a demonstration payload was established, with a sketch of the payload electronic box as given in Figure 4.11 and payload characteristics as given in Table 4.6.

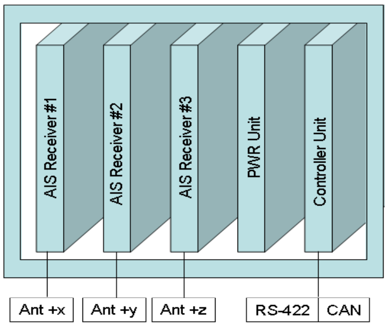


Figure 4.11 Sketch of demonstration mission payload receiver box for three orthogonal monopoles.

ID	AIS demonstration payload characteristics	
1.	Dimension (W×L×H)	150x250x150 mm (3 receivers) 150x250x75 mm (1 receiver)
2.	Power	28VDC unregulated power
3.	Payload total power consumption	15 W (3 receivers) 5 W (1 receiver)
4.	Pointing requirements	± 10 degrees
5.	Antenna requirements	Length ~0.50 m MAX (1 monopole) Weight ~ 1 kg MAX (1 monopole)

ID	AIS demonstration payload characteristics	
6.	Harness	0.150 kg (1 monopole)
7.	1 receiver	0.7 kg – electronics 0.5 kg – aluminium housing
8.	3 receivers	1.5 kg – electronics 1.2 kg – aluminium housing
9.	Temperature	-20°C to + 50°C

Table 4.6 Payload Design Characteristics.

4.5 Identified requirements for AIS Receiver

In this section some of the identified payload requirements are listed.

4.5.1 Functional and Performance Requirements.

The AIS receiver shall have the following functional and performance requirements:

REC-#	Requirement	Comment
REC-01	Receiver Frequencies	Simultaneous reception of AIS frequencies 161,975 MHz and 162,025 MHz
REC-02	Channel bandwidth and spacing	25 kHz
REC-03	Modulation Scheme	GMSK (2 channels TDMA, 9.6kbps)
REC-04	Modulation Index	0.5
REC-05	Bandwidth-Time (BT)	Max 0.5
REC-06	Frequency Error	+/-3 kHz (Doppler) in addition to +/-1 kHz (TDMA).
REC-07	Time tolerance	8 ms difference in arrival-time due to different propagation distance
REC-08	Sensitivity	-115 dBm for 20% PER
REC-09	Maximum signal level	-100 dBm for 20 % PER
REC-10	Co-channel rejection	-10 dBc, 20%PER AIS receiver signal -115 dBm
REC-11	Adjacent channel selectivity	+10 dBc, 20% PER AIS receiver signal -115 dBm
REC-12	Spurious response rejection	+30 dBc, AIS receiver signal -115 dBm
REC-13	Intermodulation response	2 signals at -105 dBm so that IMD3 is at AIS receiver frequency., 20 % PER
REC-14	Blocking	1 signal at -85 dBm in-band, (not same freq as AIS receiver signal). AIS receiver signal at -115 dBm 20% PER
REC-15	Temperature	-25 to +55 °C.

REC-16	Power and voltage	Max. 4 W, shall include power down feature Feed voltage from S/C power bus is 28 V DC
REC-17	Radiation tolerance	If possible, RadHard/RadTol-components should be used.
REC-18	PCB Area	Max 90*90*40 mm
REC-19	Data interface, normal operation	115,2 kbit/s CAN bus
REC-20	Data interface, digital bent-pipe	10 Mbit/s RS-422
REC-21	Monitor /Debug interface	RS 232
REC-22	Message capacity	2250 msg /Channel /minute
REC-23	Reconfiguration from uplink	By upload from ground station via OBC
REC-24	EMC	Levels to be tested : Radiated emission, Immunity and conducted on power line
REC-25	Dimensions	For a payload with 3 receivers: Power drain < 15 W PCB area 300x100x40 mm^3 Mass <1,5 kg electronics and 1,2 kg aluminum housing
REC-26	Tests	Temperature Shock Vibration Sensivity BER @ - 115 dBm
REC-27	RSSI	The receiver shall provide RSSI measurements

Table 4.7 Receiver functional and performance requirements

Doppler shift:
The receiver should be able to resolve frequency errors due to Doppler shift of ±4 kHz without degradation.

Co-channel interference:
The receiver should be able to resolve co-channel interference at interference levels of – 10 dBc without degradation. According to Figure 4.12, an optimal coherent receiver (OCR) can operate on a SNR of 7-8 dB and still maintain a bit error rate of 10^{-3} and packet error rate at 20%, while the differential receivers (CMFNR, DDNR) need at least 12 dB of SNR.

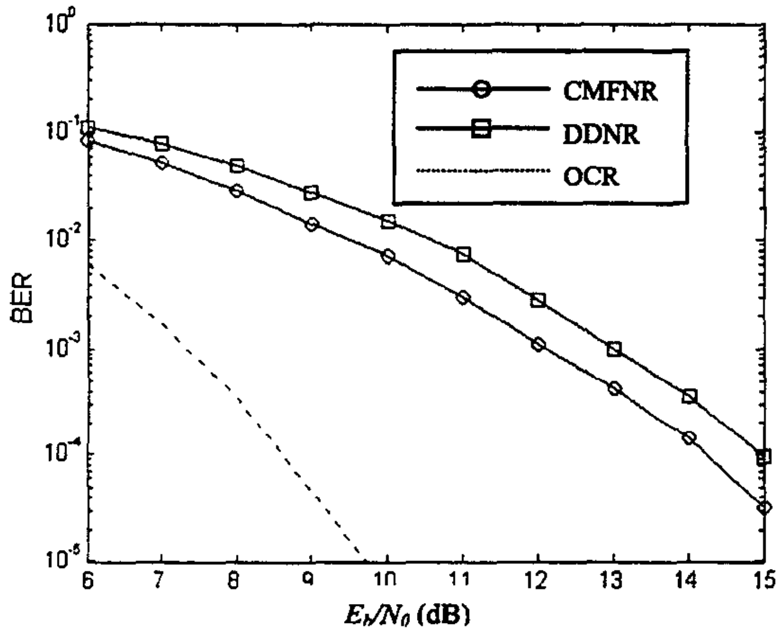


Figure 4.12 BER vs Eb/N0 for GMSK receivers [21]

4.5.2 Operational Requirements

The operational requirements relate to how the receiver is used by the spacecraft OBC and the ground stations. The following operational requirements apply:

REC-#	Requirement	Comment
REC-28	Power on / off	The receiver can be switched on / off by a telecommand from the OBC. The telecommand is generated by the OBC and transmitted to the receiver processor which executes the command.
REC-29	Firmware upload	New firmware can be uploaded from ground station. Receiver processor must handle upload functionality and version switching.
REC-30	Power on GPS	If GPS is used for internal timing the OBC processor must handle on/off functionality for the GPS receiver.
REC-31	Status : Off	In the off status the receiver will consume no power except for idle power for current switching which should be very low

REC-#	Requirement	Comment
REC-32	Status : Standby	In the standby situation the receiver should be switched on an ready to receive control commands, ie the processor part should be on, but the receiver part should be switched off to save power.
REC-33	Status : Operational	In the operational situation the receiver should be turned fully on and be ready to receive signals on the AIS frequencies

Table 4.8 Receiver operational requirements

4.5.3 Environmental Requirements

Shock and vibration requirements

The minimum of shock and vibration requirements for the EUT is given by the Auxiliary Satellite User's Manual for the specific launch vehicle. In the following, the shock and vibration requirements for the Ariane 5 launch vehicle are used as a reference, obtained from the auxiliary satellite user manual.

REC-#	Requirement	Comment		
REC-34	Shock level	Longitudinal Static + Dynamic	Lateral Static + Dynamic	
		-7.5 g / + 5.5 g	±6 g	
REC-35	Vibration level	Sinusoidal vibrations:		
		Longitudinal:	4-6 Hz	25 mm
			6-100 Hz	3.75 g
		Lateral:	2-6 Hz	20 mm
			6-100 Hz	2.5 g
		Random spectrum:	20-1000 Hz	0.0727 g^2/Hz
REC-36	Fundamental frequencies	To avoid interactions with the launch vehicle fundamental frequencies, the EUT must satisfy the following requirements:		
		Longitudinal	> 90Hz	
		Lateral	> 45 Hz	

Table 4.9 Receiver shock and vibration requirements

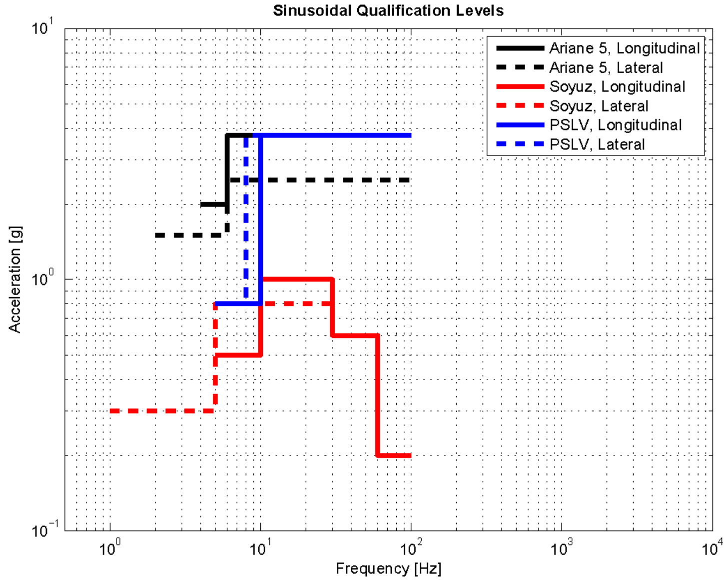


Figure 4.13 Sinusoidal qualification levels for the Ariane 5, PSLV and Soyuz launch vehicles.

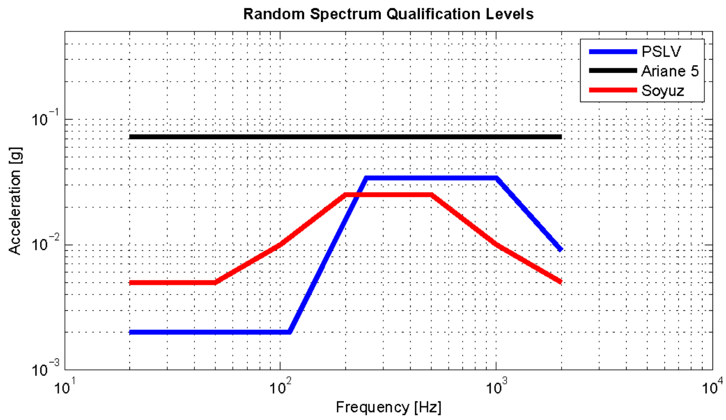


Figure 4.14 Random spectrum qualification levels for the Ariane 5, PSLV and Soyuz launch vehicles.

Thermal requirements

The temperature limit for both operational and storage are typical values for space applications.

REC-#	Requirement	Comment
REC-37	Active/Operational temperature limits	-25˚C to +55˚C (the EUT should be able to cold start at -40˚C)

REC-#	Requirement	Comment
REC-38	Inactive/Storage temperature limits	-40˚C to +85˚C
REC-39	Temperature test window	-50˚C to +95˚C

Table 4.10 Receiver thermal requirements

EMC requirements

REC-#	Requirement	Comment
REC-40	Noise level at power bus	< 1 mV @ 150-170 MHz
REC-41	Spurious from on board external electronics	< - 130 dBm @ 150 - 170 MHz
REC-42	Blocking signal from downlink at receiver input	Depends on downlink frequency and input filter characteristics. Filter should attenuate downlink frequency at least 60 dB
REC-43	Compliance of SDR receiver to IEC 60945	Relevant parts regarding : Radiated emission Conducted emission Radiated susceptibility Susceptibility to conducted noise Susceptibility to static discharges
REC-44	Compliance of other onboard electronics to IEC 60945	Other relevant standards for S/C electronics may apply.

Table 4.11 Receiver EMC requirements

Total ionizing dose (TID)

REC-#	Requirement	Comment
REC-45	TID for a two year life expectancy	5 Krad (including 66.7% safety margin) (based on SSTL's simulations)

Table 4.12 Receiver total ionizing dose requirement

4.5.4 Interface Requirements

REC-#	Requirement	Comment
REC-46	Power connector	Standard power connector , space qualified
REC-47	Antenna connector	SMA, space qualified
REC-48	Serial data connector	RS422, space qualified
REC-49	Communication protocol	Communication protocol between OBC and payload will be on serial line. CAN protocol to be implemented if necessary for communication with other onboard systems. In bent pipe operation RS422 must be used due to data speed requirements.

Table 4.13 Receiver interface requirements

4.5.5 Redundancy Requirements

REC-#	Requirement	Comment
REC-50	Redundancy	One SDR receiver for each polarization with capability of implementing software with an effective Single Event Upset (SEU) mitigation strategy. Additional redundancy should be considered. In case of one receiver payload, an additional backup receiver may be used. The backup receiver can be an equivalent SDR receiver or a conventional superheterodyne receiver. In case of three-receiver payload, the three receivers can be backup for each other. Other redundancy strategies like 2+1 or 3+1 may also be considered.
REC-51	Software	Triple Modular Redundancy (TMR) and cyclic restart TMR: All signal processing are performed in parallel to each other to prevent SEU to alter the process. A voting process decides which process is corrupted and further disregarded. Cyclic restart: The system shuts down and new firmware is uploaded form an EPROM in a pre-scheduled order every 60 seconds. The system then reboots and is online within one AIS time slot (27 ms).

Note: Some components might have an embedded redundancy system, but in the case of TMR in FPGAs, it must be implemented in the program code. Xilinx provides a tool for TMR implementation in their FPGAs.

Table 4.14 Receiver redundancy requirements

4.5.6 Verification and Test Requirements

The receiver and satellite assembly must be tested during production, assembly and final production. The applicable standards are the ECSS-E-10-03A hardware standard combined with the ECSS-E-10-02 standard, which concerns test tailoring. Further, for software testing the ECSS-E-40 standard applies. A good test plan is essential to secure that all parts of receiver chain perform flawlessly. Special consideration should be given to integration test and final operational tests. The design of receiver and OBC / Downlink must take into consideration how the units will be tested before and after integration. A test plan should be developed as early as possible in the project and maintained and updated throughout the project.

REC-#	Requirement	Comment
REC-52	AIS receiver testing	Compliance with basic receiver requirements as listed in the chapter on functional and performance requirements. (Sensitivity, Packet Error Rate, intermodulation, temperature etc)
REC-53	EMC testing of AIS receiver	EMC tests (Noise, Immunity, Radiation, Conducted)
REC-54	EMC testing of satellite with AIS receiver	EMC tests (Noise, Immunity, Radiation, Conducted and compatibility of payload and satellite electronics)
REC-55	Final operational test	Prior to launch
REC-56	Antenna test	Verification of antenna parameters and antenna diagram
REC-57	Overall test plan	Test document describing test hierarchy, test setup, test requirements, test results and test documentation.
REC-58	Test functionality	The payload and software must be designed for efficient testing of functionality.
REC-59	Test environment	Adequate test facilities including test instruments, test jigs and test software must be developed as a part of the payload development.
REC-60	Test prototypes	A number of test prototypes should be manufactured in order to test efficiently and to evaluate production spread of parameters.
REC-61	Data interface tests	Testing of telecommand functionality.
REC-62	Data command tests	Testing of command functionality (on, off, mode setting, upload functionality etc)
REC-63	Shock and vibration tests	The payload must exposed to the required levels of shock and vibrations stated in the auxiliary satellite vehicle manual for the given launch vehicle, and tested according to the applicable standards.
REC-64	Thermal cycle tests	The payload must be tested within the temperature window of Tmin=-50˚C to Tmax=+90˚C according to the applicable standards.1

Table 4.15 Receiver verification and test requirements

4.6 Antenna options

The choice of antenna is important, influencing both the S/C complexity and the achievable detection probability. In this section the three main antenna concepts are discussed, the double Yagi, the quadrifilar helix and the three orthogonal monopoles. Other concepts where also simulated during the study, but these represent the main principles to be considered in a trade-off analysis.

4.6.1 Double Yagi antenna

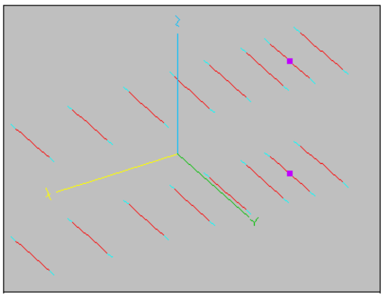


Figure 4.15 Antenna array of a large double Yagi antenna.

The large double Yagi array uses two eight-element Yagi antennas spaced 1.2 metres apart with a boom length of 2.4 metres and with element widths of .902 meters. This is the most promising antenna configuration when looking at detection probability all around the globe. It will efficiently reduce the field of view (FOV) and thus limit the problem of AIS messages arriving in the same time slot. This antenna is linearly polarized and may thus also passively make use of the Faraday rotation to discriminate between AIS messages arriving at the same time. By combining the signals from the two arrays with a phase delay, one can also reduce the effect of secondary lobes, by pointing these lobes out into space.

The narrower FOV would result in a higher number of S/C needed to satisfy the hourly update in the user requirements. The main challenge with the use of a double Yagi array is that it would add considerable complexity to the S/C because of the two deployable structures needed. This would add challenges to the thermal design and introduce extra possibilities for failure. A narrow FOV would also require more from the attitude control system of the S/C, adding to the complexity.

4.6.2 Quadrifilar helix antenna

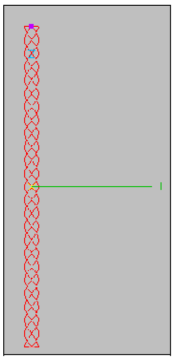


Figure 4.16 A 5-turn quadrifilar helix antenna.

The main quadrifilar helix antenna considered is a 5 turn with a diameter of 0.182 meters and length of 3.885 meters. This solution offers a slightly reduced FOV with a simpler design then the double Yagi. A single quadrifilar helix antenna will be easier to deploy as it can come out from the main body of the S/C and can be packed very compact before launch. Deploying the quadrifilar helix antenna will also involve only one operation. The use of a quadrifilar helix will probably require some simple attitude control (~ ±10°).

The FOV achieved by the quad antenna will not be as narrow as the one from the double Yagi. The antenna will also have side lobes that will receive AIS messages. In addition, the circular polarization will remove the effect of the Faraday rotation, which will increase the number of messages received. This will lower the detection probability due to increased occurrences of simultaneous arrivals of AIS messages.

4.6.3 Three orthogonal monopole antennas

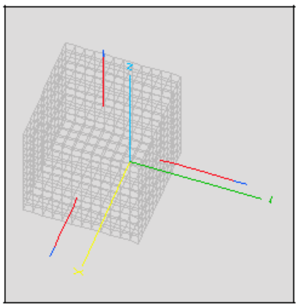


Figure 4.17 Three orthogonal monopole antennas.

Three orthogonal monopole antennas represent the simplest solution considered. Each antenna would have a length of ~ 0.5 metres. This concept would give a FOV to the horizon, representing the largest FOV of the three antenna solutions. The use of three orthogonal antennas with three independent receivers would ensure independence from polarization effects like Faraday rotation, while still making use of this effect on the single antennas. This solution will also be the least complex for the S/C as it will have very low demands on the attitude control system.

The three antenna solution will cover the largest area and thus the main challenge with this solution is simultaneous arrival of AIS messages. This solution is still competitive compared to the quadrifilar helix because of the Faraday rotation signal discrimination, and it allows for advanced signal processing on the ground by using a sample and forward solution on each of the receiving chains. Combining the signal from the three antennas with respect to gain and phase could steer a low gain area to block out interfering signals. This would increase the number of messages received in areas with high detection probability, but it is not sufficient to achieve any significant increase in the detection probability in high vessel density areas. To understand better what can be achieved by advanced signal processing, this is the most attractive solution for a technology demonstration mission.

B.9 Detection probability simulations

WP 270 Recommendations and Conclusions
RES-270-10 Final Report
Date 10.04.2008

5 Detection probability simulations

This chapter covers the simulations done in this study by FFI on our AIS simulations software.

5.1 AIS Link budget

A first step in evaluating the prospects for space-based AIS is a careful AIS signal wave propagation analysis. Both FFI and the Joint Spectrum Center (JSC) in the US have made such analyses. Several factors such as output power, antenna configuration and gain, propagation distance, atmospheric and ionospheric conditions, free space loss, fading, etc. affect the received signal strength.

5.1.1 Minimum detectable signal

Receiver noise originates mainly from transmission lines/filters and the Low Noise Amplifier (LNA). Additional contributions do exist, but they are divided by the LNA gain and hence negligible [22]. Therefore, the system noise temperature is simply

$$T_r = T_{ant} + \frac{T_0(1-L_r)}{L_r} + \frac{T_0(F-1)}{L_r}, \qquad (5.1)$$

where T_{ant} is the antenna noise temperature, T_0 is a reference temperature of 290K, L_r is line loss between antenna and LNA and F is the noise figure of the LNA. Assuming a line loss of -2.5dB and a noise figure of 3dB, then L_r and F are respectively 0.56 and 1.99. This gives a system noise temperature of approximately 1000K if the antenna noise temperature is 300K. The noise level of the system is

$$NL = 30 + 10\mathrm{Log}(kT_r) + 10\mathrm{Log}(B) = -124.6\mathrm{dBm}, \qquad (5.2)$$

given the bandwidth B (25000Hz) and Boltzmann's constant k. Simulations done for the ZA-002 satellite software radio [23] lead to a 20% packet error rate at -117dBm given equation (5.2). This report defines -117dBm as the minimum detectable signal.

5.1.2 Signal strength at Low Earth Orbit

Table 5.1 shows the link budget at the horizon for a satellite in LEO. The polarization mismatch loss varies with antenna design, antenna orientation, the total electron content in the ionosphere and position of satellite relative to Earth's magnetic field. It is set at -3dB, which is the polarization mismatch loss when transmitting from a linear to a circular polarized antenna.

PARAMETERS	VALUES
GEOMETRY	
Satellite altitude (km)	600

ESA ESTEC contract 20492/06/NL/JA 68 Technology Reference and Proof-of-Concept for a Space-Based AIS System for Maritime Security

PARAMETERS	VALUES
Minimum transmit elevation angle (deg)	0
Satellite antenna off-axis angle (deg)	66.1
Maximum slant range (km)	2831
Maximum surface range (km)	2664
POWER	
Transmit power (dBm)	41.0
Transmit gain (dBi)	2.0
Transmit cable & miscellaneous losses (dB)	-3.0
Free space propagation loss at maximum range (dB)	-145.6
Polarization mismatch loss (dB)	-3.0
Satellite antenna gain at the horizon (dBi)	1.4
Satellite RF line/filter losses (dB)	-2.5
Other losses (dB)	-1.0
Received power at satellite (dBm)	-110.7
Satellite sensitivity (dBm) for 20% packet error rate	-117.0
Net Margin (dB)	6.3

Table 5.1 Ship to satellite link budget at the given slant range assuming a vertical dipole antenna, which has a constant gain at the horizon. The polarization mismatch loss depends on the local geomagnetic field and the electron content along the line sight since this antenna is linear polarized. The loss is set to -3dB as a typical value, although the polarization mismatch loss does vary a lot due to Faraday rotation.

ITU[24] specifies the required receiver characteristics for Class A shipborne mobile equipment and requires a receiver sensitivity of at least -107dBm for 20% packet error rate. Section 5.1.1 shows that a space based receiver can theoretically achieve a sensitivity that is 10dB better than the ITU specifications. Mathabo & Rooyen [23] provide a bit error probability curve for GMSK. The packet error rate at a satellite sensitivity of -120dBm is 90%, using the same assumptions as in Table 5.1 .

Figure 5.1 displays the received power (dBm) at a satellite with a horizontal dipole antenna and an altitude of 600km. The axes show the positions of transmitters relative to the sub-satellite point located at 75°N, 20°E. The link budget uses the same assumptions as those made in Table 5.1. The Faraday rotation was estimated from the International Geomagnetic Reference Field[1] and a high electron content global ionosphere map produced by CODE[2]. The polarization mismatch loss is found from

$$f = (\vec{u}_E \cdot \vec{u}_A)^2 \qquad (5.3)$$

for a linear polarized antenna. $\vec{u}_E$ is the unit vector along the direction of the oscillating electric

[1] http://swdcdb.kugi.kyoto-u.sc.jp/igrf/
[2] http://www.cx.unibe.ch/aiub/ionosphere.html

field of the received signal while $\vec{u}_A$ is the corresponding direction for a signal transmitted from the satellite to the ship. Figure 5.1 shows polarization mismatch loss as the blue lines crossing the link budget map. This pattern varies as the conditions of ionosphere and the satellite position change.

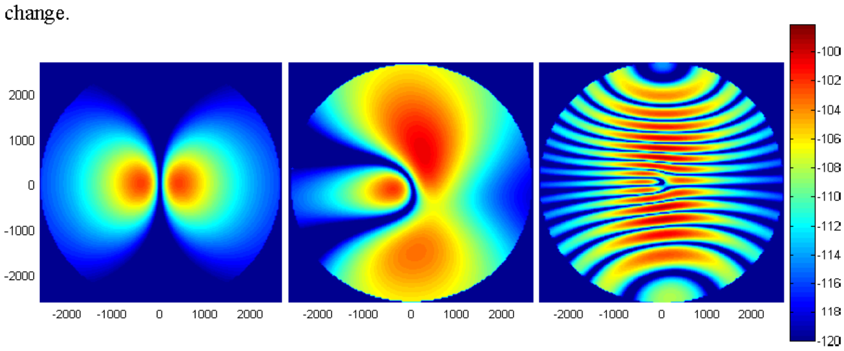


Figure 5.1 Received power (dBm) at a satellite with a horizontal dipole antenna and an altitude of 600km. The axes show the position in km of a transmitter relative to the sub-satellite point located at 75°N, 20°E. The y-axis is along the 20°E-longitude line. All figures include polarization mismatch loss, but only the two rightmost figures include Faraday rotation. They show Faraday rotation from low and high (right figure) electron density ionospheres.

A base estimate of the global vessel distribution was derived from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS[3]). It contains basic weather data reports from ships, buoys etc. Ship positions were extracted from six years of data to estimate a global vessel distribution. The number of ships reporting weather data is quite low and these ships are mostly large cargo transporters. Therefore, it is necessary to rescale and update the global map with measured vessel distributions. The vessel distribution was first normalized to 50,000 vessels, which gave vessel numbers consistent to within 10% on the American Atlantic and Pacific seaboards and along the Nordic and Baltic coasts. Analysis of this data does not show any significant trends in the number of vessels, but this might be a reflection of the number of vessels reporting weather data and not of the total number of vessels at sea.

[3] http://icoads.noaa.gov

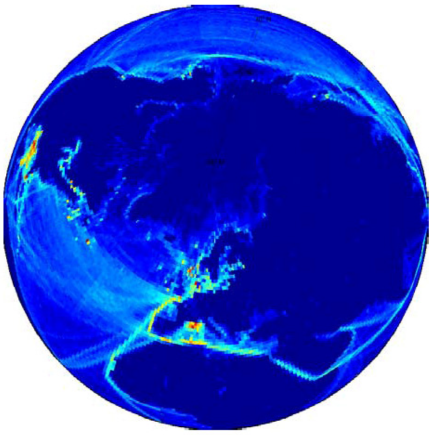


Figure 5.2 A global vessel density map derived from the International Comprehensive Ocean-Atmosphere Data Set and from measured vessel distributions in Northern Europe, Greenland, Newfoundland, US Pacific Seaboard, US Atlantic Seaboard, the Great Lakes and the Gulf of Mexico.

The number of Class A vessels increases slowly in European waters. Simple counting of the number of vessels entering and leaving European waters indicates an increase of at most a few percent per year. The increase in ship traffic appears to be closely tied to economic conditions with most of the increase happening in developing economies.

5.2 Class B shipborne mobile equipment

Class B transponders will be carried by yachts, leisure boats and small vessels and will increase the number of vessels transmitting on the two maritime channels 87B and 88B allocated for AIS. The transponders will transmit at 1-2 watts. This is only 8dB less than Class A transponders and thus there is a possibility for some interference caused by Class B traffic. Marketing of Class B equipment only became common in 2006. It is difficult to estimate how common such equipment will become. Fortunately, Class B transponders will have longer reporting intervals than Class A transponders [1]. This implies that there is room for a large number of vessels with Class B equipment without significantly decreasing the detection probability of Class A transponders from space.

Messages from Class B transponders will be difficult to detect, especially if the vessel is close to the horizon as seen from the spacecraft. The link budget in Table 5.1 shows that the received signal strength will then be below the limit given by the 20% packet error rate. Even though Class B transponders are designed to avoid local message collisions, collisions between messages from Class A and Class B transponders cannot be avoided when observing from space. Vessels carrying Class B transponders in areas such as the North Sea or the Mediterranean Sea will therefore not be detected from space due to the relative low signal strength.

Flight experiments performed for FFI in late May 2007 showed 59 Class B equipped vessels during a 4-day flight campaign covering Great Britain, Northern Germany and Southern Norway. Simulations show that the detection probabilities for Class A equipped vessels are not significantly decreased even if 40,000 Class B transponders are added to the vessel density map. The Class B equipped vessels were all placed within 50nm of the closest coastlines, with approximately 8,000 vessels in European waters.

5.3 Co-channel interference

Figure 5.3 shows the required observation time to achieve 95% detection probability as a function of the number of vessels seen by the satellite. This simulation used a horizontal across-track dipole antenna, a D/U of 10dB and a sun-synchronous orbit with an altitude of 600km. It shows that an AIS-satellite can detect approximately 1200 vessels within a satellite's field of view.

Message collisions are a significant problem whenever waters with large vessel densities are within the spacecraft field of view. Figure 5.4 shows the number of slots as a function of the number of colliding messages in a 10-second interval. The spacecraft altitude is 600km and the field of view is to the horizon. There are no slots with less than 4 message collisions and there are more than 45 slots were 10 messages collide. The received signal strengths of the messages have a range of about 30dBm depending on the antenna type. This implies that we cannot expect to decode the strongest message if there are more than 3 or 4 message collisions in a given slot.

The results shown in Figure 5.4 are from an area with approximately 5,000 vessels. It does not take into account double message collisions due to differences in light travel times. The average number of messages received within any given slot is above 20 if the North Sea and the Baltic Sea are within the field of view. Figure 5.5 shows the typical signal strengths when 12 messages arrive at the same time. It is calculated by taking every 100th slot with 12 messages, sorting the messages by signal strength within each slot and then averaging each position over all the slots. The strongest signal is typically 2dB stronger then next strongest signal, and with a ratio of 4dB in 5% of the slots. The combined signal strength of the 11 weakest messages in Figure 5.5 is -98dBm. In other words, to decode the strongest message, it would be necessary to decode a message 5dB below the effective noise floor.

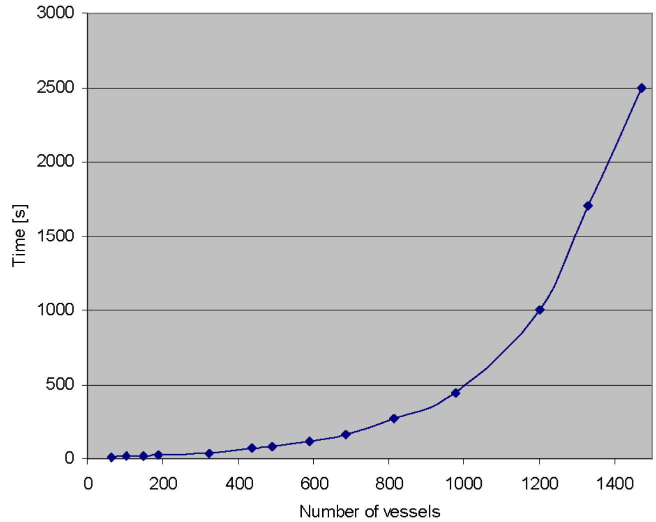


Figure 5.3 The required observation time for 95% detection probability given the number of vessels within the satellite field of view.

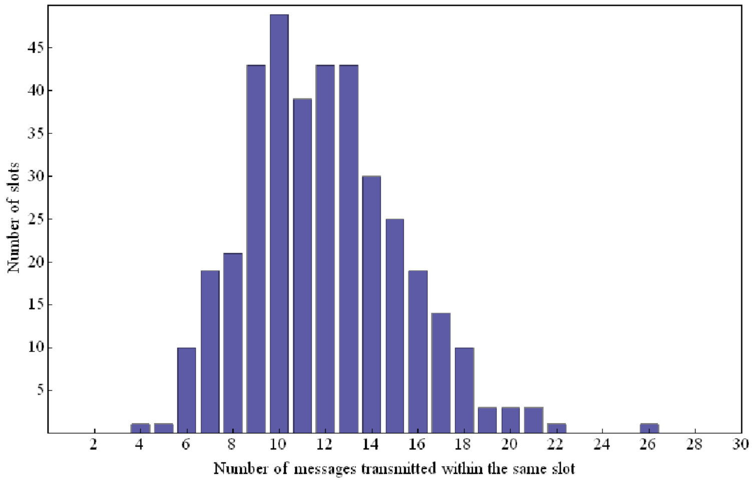


Figure 5.4 This figure shows the number of slots as a function of the number of colliding messages.

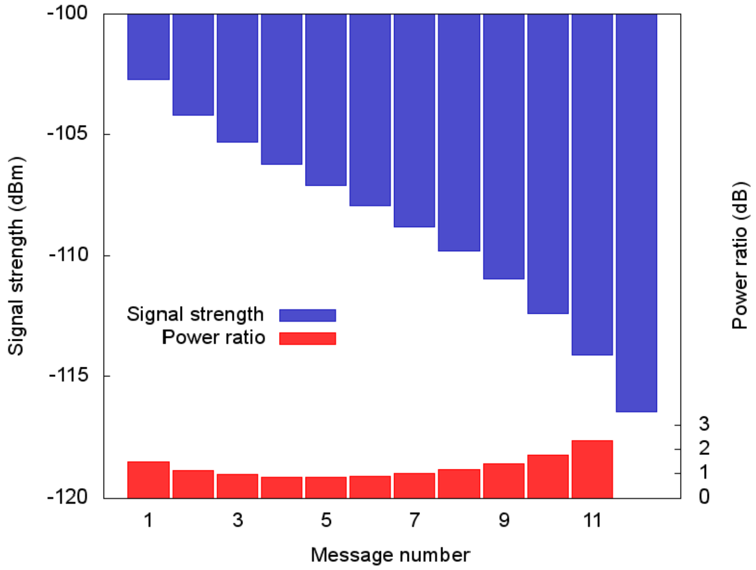


Figure 5.5 Typical received signal strengths (blue) with 12 colliding messages. The red bars show the power ratio between message n and n+1.

Unless otherwise specified, the minimum detectable signal was set to -115dBm with a fixed D/U ratio of 8dB. These numbers are based on link calculations by KSX and on the theoretical performance of differential receivers and a bandwidth of 25 kHz.

5.4 Summary of simulations performed in the study

The study on global vessel detection probabilities covered:

- A realistic vessel density distribution in European waters with perhaps an exception in the western parts of the Mediterranean Sea.
- Detailed AIS signal wave propagation analyses to confirm the possibility of receiving AIS messages in space
- A software model developed at FFI to simulate reception of AIS messages in Earth orbit
- The detection probability maps' sensitivity to the antenna configuration
- Sensitivity analyses with respect to the co-channel interference
- Sensitivity analyses with respect to Doppler shift of the received signal
- Detection probability anticipating of a third AIS channel exclusively for space-based AIS

Table 5.2 provides a summary of the simulations performed as a part of the study.

Orbit	TA	Antenna	FOV	Result
600km[4]		1/2λ dipole	Horizon	Class B vessel do not interfere with reception in space of Class A vessels
600km[5]		1/2λ dipole	Horizon	No detection in Northern Atlantic and Pacific Ocean and the North Sea
400 - 600km[5]		Equation	≤1000km	Determined requirements on antenna pattern and field of view
400 - 600km[5]		Helical	Horizon	Applicable for orbits below 400km
600km[5]		Yagi array	1200km	Non-zero detection probability in areas with high vessel densities
600km[5]		Yagi array	1200km	Detection probability after 15 passes is comparable to 8 passes with a 2dB improvement in D/U ratio
600km[5]		1/2λ dipole	Horizon	A 3rd frequency can achieve global coverage in every pass
15° inclination[6]	MS	2.1λ quad helix	4500km	60% detection
15° inclination[6]	MS	1/2λ dipole	Horizon	60% detection probability with 3 different antennas orientations and 3 receivers
17.5° inclination[6]	MS	2.1λ quad helix	4500km	70% detection probability
17.5° inclination[6]	MS	1/2λ dipole	Horizon	75% detection probability with 3 antennas and 3 receivers
20.0° inclination[6]	MS	2.1λ quad helix	4500km	60% detection probability
20.0° inclination[6]	MS	1/2λ dipole	Horizon	75% detection with 3 antennas and 3 receivers
600km[5]	MS	2.1λ quad helix	4500km	Performs worse than single dipoles
600km[5]	MS	1/2λ dipole	Horizon	70% detection probability with 3 antennas and 3 receivers
600km[5]	AO	Yagi array	1200km	50% detection probability
600km[5]	AO	2.1λ quad helix	4500km	Comparable to a single dipole
400 - 600km[5]	NS	Yagi array	≤1200km	Non-zero detection probability
340 & 425km[7]	MS	2.1λ quad helix	1800km – 2400km	50 – 70% detection probability
340 & 425km[7]	AO	2.1λ quad helix	1800km – 2400km	35 – 50% detection probability
340 & 425km[7]	MS	1/2λ dipole	Horizon	55 – 65% detection probability
340 & 425km[7]	AO	1/2λ dipole	Horizon	18 – 27% detection probability
400 - 600km[5]		SSTL 100	Horizon	No significant difference between ideal half-wave dipole and monopoles on a satellite
400 - 600km[5]		SSTL 100	Horizon	Significant gain in detection probability when lowering orbit from 600 to 500km
600km[5]	NO	SSTL 100	Horizon	3 antennas achieve passes with more 90% detection probability
600km[5]		1/2λ dipole	Horizon	No significant difference between earlier simulations and current receiver parameters

[4] Sun synchronous
[5] Sun synchronous
[6] 600km altitude
[7] International Space Station

Orbit	TA	Antenna	FOV	Result
600km[5]		Small Yagi array	1500km	Electron content in the ionosphere does not significantly change the detection probabilities
750km[8]	AM	2.1λ quad helix	4500km	Orbcomm constellation not useful in European waters of interest
600km[5]		Corner reflectors		Corner reflector of sizes up 1.6λ do not provide significant detection probability in areas with high vessel densities
400 - 900km		Helix/Single Yagi		Provide no more 30% detection probability in the North Sea at 400km
600km[5]		Yagi array, 1 – 10dB D/U	1200km	40% detection probability in areas with high vessel densities at 6dB D/U.
600km[5]		2.1λ quad helix, 1 – 10dB D/U	4500km	Zero detection probability in areas with high vessel densities at any D/U.
600km[9]		Yagi array, 1 – 10dB D/U	1200km	A Walker constellation with 48 satellites can be replaced with constellation of 8 satellites in sun-synchronous and equatorial orbits

Table 5.2 Summary of the simulation performed as a part of this study. The TA column denotes target area. These can be the Mediterranean Sea (MS), northern Atlantic Ocean (AO), the North Sea (NS) and a combination of all three (AM) and global result if blank.

5.5 Considerations for the demonstration concept

The following simulations were used in the choice of orbit and antenna architecture for the demonstration concept, which is discussed in chapter 6.

5.5.1 Detection probabilities as a function of altitude

The detection probability changes as a function of the satellite's altitude. Any changes in the altitude changes both the field of view and the available observation time. The ideal selection of parameters will have a reasonably small field of view to avoid message collisions and the longest possible observation time. These design goals contradict each other, but since the field of view dominates the detection probability, a LEO should be selected. These simulations use a full wire grid model of the SSTL 100 microsatellite with monopoles. There are no significant differences between the full wire grid model and the ideal dipole model, and lowering the orbit does increase the detection probabilities.

[8] Orbcomm constellation
[9] Walker constellation (65° inclination)

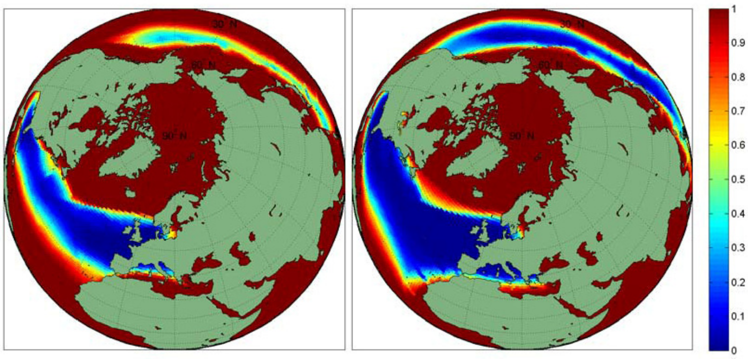


Figure 5.6 24 hours detection probability from 400km (left) and 600km (right)

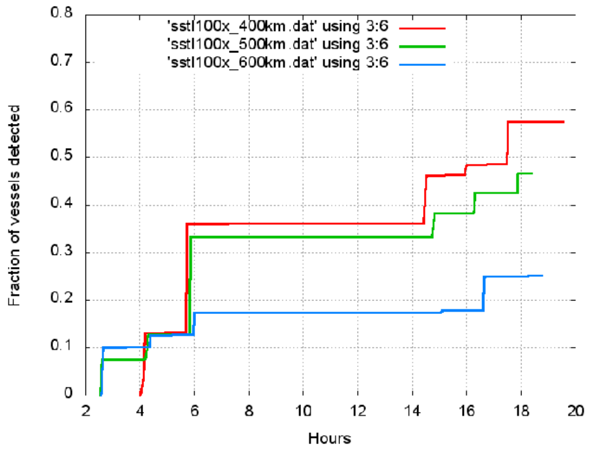


Figure 5.7 Detection probabilities from altitudes of 400km (red), 500km (green) and 600km (blue) in the Mediterranean Sea. These simulations used a single receiver and a sun-synchronous orbit.

5.5.2 Number of monopoles

These simulations compare the performance for one, two and three monopoles with independent receivers placed on the SSTL 100 microsatellite in a 600km sun-synchronous orbit. Figure 5.8 and Figure 5.9 cover Norwegian waters and the Mediterranean Sea. The combination of three antennas has two passes with more than 90% detection probability and eight passes with more than 85% detection probability in Norwegian Waters. Any combination of two antennas achieves two passes with more than 85% detection probability. A single antenna does not achieve 75% detection probability in any pass.

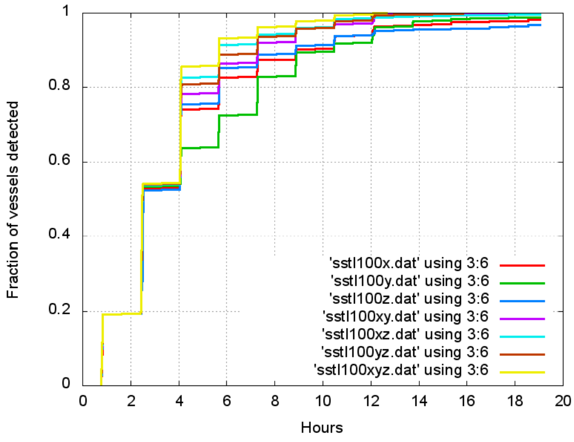


Figure 5.8 The results from simulations with monopoles along the x, y and z-axis of the spacecraft and combinations of these antenna with independent receivers. These results cover Norwegian waters north of 62° latitude.

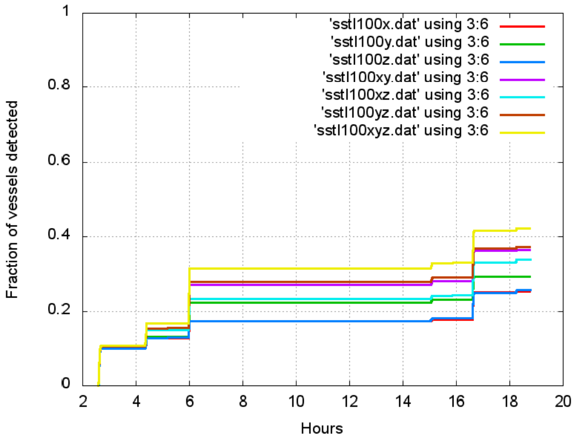


Figure 5.9 Results corresponding to Figure 5.8 in the Mediterranean Sea

The antennas were oriented such that the x-antenna was along the instantaneous vertical axis, y-antenna pointed along track and z-axis pointed across track. The detection probability changes with the orientation of the antenna, the target area and the orbit with respect to the target area. No single antenna performs best or worst in all cases, but the vertical antenna is never the best antenna. If it is desirable to fly with two antennas and two receivers, then they should both be parallel to Earth's surface.

5.6 Considerations for an operational constellation

The operational constellation discussed in chapter 7 has a baseline architecture utilizing a double Yagi antenna configuration. This was because this was the only solution to show relatively high detection probability in areas of high vessel density.

Any single Yagi antenna that is capable of detection of vessels in European waters will be impossibly large, i.e. at least 10 meters long. The main problem is the strength of the secondary lobes. One possibility is to combine two smaller antennas and then introduce a constant phase shift between the antennas. The purpose of the phase shift is to introduce asymmetrical secondary lobes. The antenna can then be oriented such that most of the secondary lobes point away from the Earth. Figure 5.10 shows an example of such an antenna diagram. Each antenna consists of 8 elements including one reflector and one center-fed dipole. The lengths of the antennas are 2.4 meters and they are separated with 0.65λ (1.2m). The phase shift between the antennas is 30°. This antenna has best performance if the main lobe is oriented 40° from the vertical. Furthermore, an across-track orientation is slightly better than an along-track orientation. Figure 5.11 and Figure 5.12 show the link budgets for a satellite with an altitude of 600km. Finally, Figure 5.13 depicts the global detection probability after 15 passes using the expected receiver sensitivity and performance from a 600km sun-synchronous orbit.

A single Yagi antenna with a performance comparable to the 6-turn helix must be approximately four meters long. The conclusion is that a combination of two smaller directive antennas can be oriented to achieve the performance of a much larger antenna.

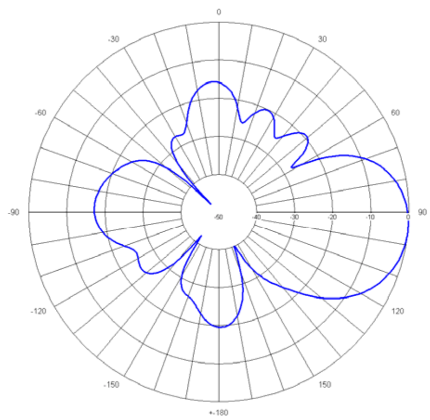


Figure 5.10 Antenna diagram for a Yagi array consisting two antennas. Each antenna consists of 8 elements including one reflector and one center fed dipole. The lengths of the antennas are 2.4 meters and they are separated with 0.65λ (1.2m). The phase shift between the antennas is 30°.

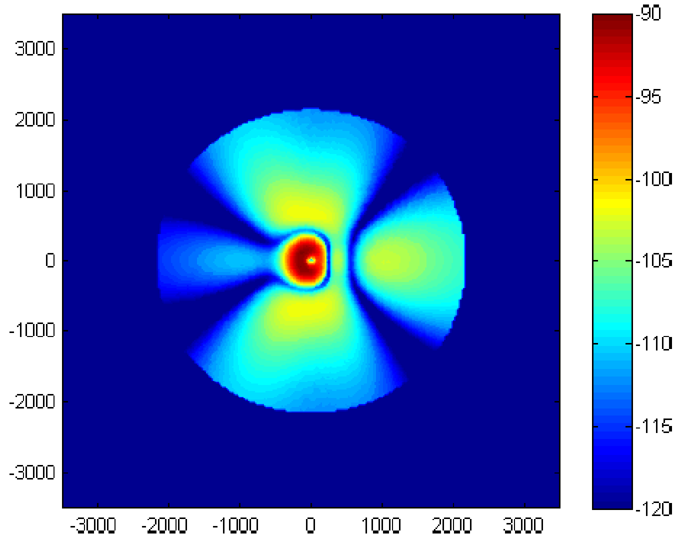


Figure 5.11 The received power in dBm relative to the sub satellite point using the Yagi array at an altitude of 600km. The main lobe is oriented 0° to the vertical. Polarization mismatch loss has not been included in this figure. Its purpose is to demonstrate the projection of the antenna pattern onto the surface of the Earth.

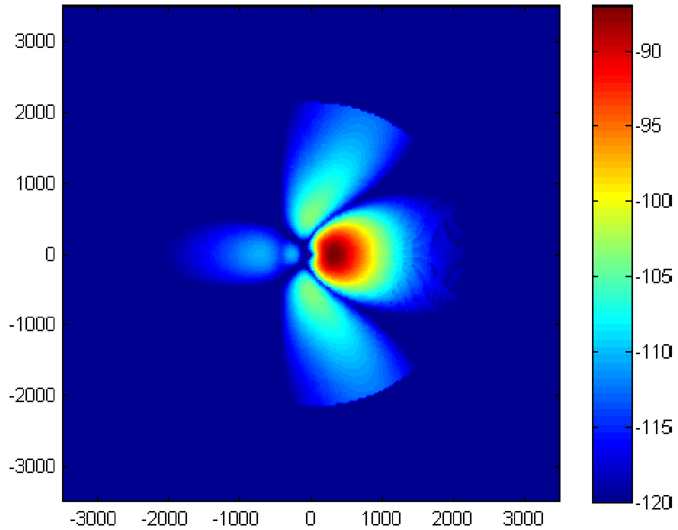


Figure 5.12 The results corresponding to Figure 5.11 using a Yagi array with the main lobe is oriented 40° to the vertical.

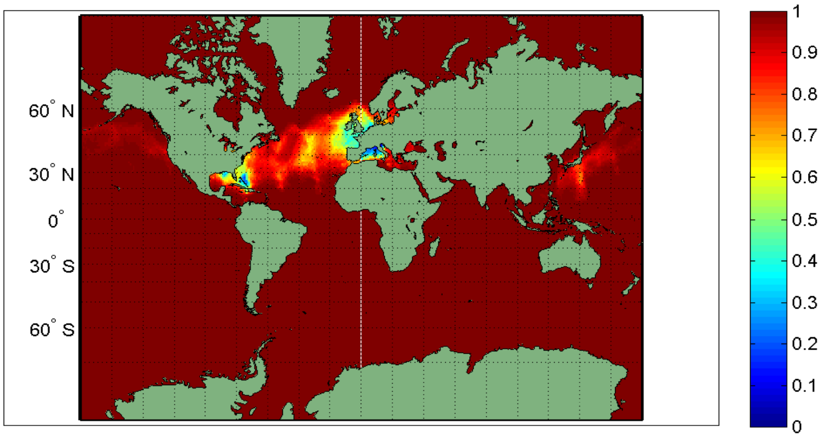


Figure 5.13 Detection probability after one day (15 orbits) using a single satellite with the asymmetric Yagi-array. This simulation used a 600km sun-synchronous orbit with the receiver sensitivity set to -115dBm with a D/U of 8dB. The asymmetry in the Atlantic corridor is caused by the vessel distribution, which contains too many vessels near Europe. The original vessel distribution spread the number of vessels uniformly in the Northern Atlantic Ocean. The distribution was later updated with data from flight experiments near the Bay Biscay. This increased the number of vessels in the shipping lane towards the Strait of Gibraltar, but did not remove vessels further out in the Atlantic Ocean.

B.10 Demonstration Concept

6 Demonstration Concept

6.1 Demonstration Concept - Mission objectives

The main objective of a demonstration mission should be to demonstrate the concept of a European system for receiving AIS information from space, to test the technology developed for this application, to establish knowledge about the signal environment, and to identify any new development needed for a future operational system.

After discussions during the PM3 meeting and later work, a list of demonstration requirements has been established. The list is given in the next pages, where Table 6.1 describes the mission requirements and what information they are based on. They are based on user requirements, simulations, payload concept and the mission purpose as defined above.

Table 6.2 is a matrix of the demonstration requirements and some selected choices for antenna and receiver technology.

DR-#	What to demonstrate	Based on	How
DR-01	Detect AIS class A vessel traffic data outside the AIS coastal base station range	User requirements	AIS receiver in space to validate the signal environment of message collisions etc.
DR-02	Detect > 90 % of the AIS Class A vessels during one pass along the Norwegian coast north of 62 degrees North.	Simulations	Compare AIS information received in space with information from AIS base stations.
DR-03	Demonstrate utilizing of the Faraday rotation for optimal vessel detection	Simulations	Simultaneously reception from antennas with two different polarizations. Showing the difference in AIS messages received.
DR-04	Identify detection probability in high vessel density areas	Simulations	Do measurements campaigns in the North Sea and the Mediterranean, where results are compared with AIS data from coastal networks and e.g. airborne AIS receivers.
DR-05	Validation in an area with expected detection probability >90% and with accessibility to SAR data.	User requirements	Do a measurement campaign e.g. in the Barents Sea, combining SAR, satellite-based AIS and maybe aircraft observations.
DR-06	Demonstrate the separation of signals utilizing the Doppler effect.	Payload concept	On-ground processing where a digital channel filter is tuned to exclude signals from a specific frequency band. Compare detection probability with and without this filter
DR-07	Demonstrate the possibility of tracking vessels in open ocean areas	User requirements	Demonstrate tracking of vessel in the Pacific Ocean, South Atlantic and Barents Sea.
DR-08	Demonstrate monitoring of a selected region of interest.	User requirements	Have monitoring campaigns focusing on AIS reception in: The Barents Sea, the Mediterranean, the North Atlantic
DR-09	Demonstrate <1 hour from vessel detection to data available for potential users.	User requirements	For a demonstration campaign, use downlink facilities both in Arctic and Antarctic to demonstrate downlink capabilities of less than one hour, including data processing on ground and distribution to a potential user.
DR-10	Demonstrate use of firmware uploading.	Payload concept	Successfully upload new firmware in the SDR and verify operation of the payload with new firmware.
DR-11	Validate AIS signal link budget.	Payload concept	Measure the received signal strength in each AIS message and estimate the signal to noise ratio.
DR-12	Validate new development of receiver in space environment.	Payload concept	Successfully operate an SDR payload for space based AIS reception

DR-#	What to demonstrate	Based on	How
DR-13	Demonstrate combination of different antennas raw base band signals on ground.	Payload concept	Demonstrate reception of different AIS vessels by combining the raw base band signal from two or three orthogonal antennas with different phase delays.
DR-14	Demonstrate further development of signal separation algorithms on ground.	Payload concept	Develop new decoding algorithms based on an oversampled version of the base band signal from both the AIS channels
DR-15	Demonstrate different on-board decoding algorithms.	Payload concept	Upload firmware images with new algorithms developed on ground.
DR-16	Demonstrate the possibility of using maritime VHF channel 28, 162.000 MHz as a possible third AIS channel for space based reception	Payload concept	Do a campaign of global mapping of interference on 162.000 MHz and demonstrate switching one of the AIS receive channels from 162.025 MHz or 161.975 MHz to 162.000 MHz
DR-17	Demonstrate correlation of real detection probabilities and the simulations	Simulations	Compare detected AIS information in coastal areas with information from AIS base stations. Compare the resulting detection probabilities with the probabilities given in the simulations. Update the simulations.
DR-18	Demonstrate global mapping of the signal strength and interference at the AIS frequencies	Simulations	Measure signal (interference) level in all timeslots for both AIS channels for as long as is needed to give a reasonable global mapping. (12 consecutive hours should be enough for a dipole solution). Such a demonstration campaign should be repeated on a regular basis (monthly/weekly) to build statistical confidence to the global maps produced.
DR-19	Identify precursor need in terms of specifying definitions for a full operational system	Mission purpose	Be a step towards an operational system, giving answers to limitations and possibilities for an operational system.
DR-20	Demonstrate evolution of global received AIS traffic density over the mission lifetime	Simulations	Have monthly campaigns where AIS messages are received from all parts of the globe within 48 hours.
DR-21	Validate co-channel interference mitigation techniques	Payload concept	

Table 6.1 Description of demonstration requirements

DR-#	Double Yagi	Helix	Single Dipole	Two Dipoles	Three dipoles	Corner reflector	SDR	BP	DBP
DR-01	X	x	x	x	x	x	x	x	x
DR-02	0	0	0	0	x	0	x	x	x
DR-03	0	0	0	x	x	0	x	x	x
DR-04	X	x	x	x	x	x	x	x	x
DR-05	X	x	x	x	x	x	x	x	x
DR-06	n/a	n/a	n/a	n/a	n/a	n/a	x	x	x
DR-07	X	x	x	x	x	x	x	0	x
DR-08	X						x	0	x
DR-09	n/a	n/a	n/a	n/a	n/a	n/a	x	0	x
DR-10	n/a	n/a	n/a	n/a	n/a	n/a	x	0	0
DR-11	X	x	x	x	x	x	x	x	x
DR-12	n/a	n/a	n/a	n/a	n/a	n/a	x	0	0
DR-13	0	0	0	x	x	0	0	x	x
DR-14	n/a	n/a	n/a	n/a	n/a	n/a	0	x	x
DR-15	n/a	n/a	n/a	n/a	n/a	n/a	x	0	0
DR-16	X	x	x	x	x	x	x	0	x
DR-17	n/a	n/a	n/a	n/a	n/a	n/a	x	x	x
DR-18	n/a	n/a	n/a	n/a	n/a	n/a	x	0	0
DR-19	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
DR-20	X	x	x	x	x	x	x	0	0
DR-21	n/a	n/a	n/a	n/a	n/a	n/a	x	x	x

x	Requirement can be fulfilled
n/a	Not applicable
0	Requirement cannot be fulfilled
	Requirement can be partly fulfilled (e.g. in some selected area etc.)

Table 6.2 Demonstration requirement matrix for different antenna and receiver options.

6.2 Payload

The internal payload architecture consists of three independent AIS transponders, each one connected to a dedicated monopole antenna.

The AIS receiver filters, amplifies, demodulates and decodes the AIS signals. The output from the decoder will be standard AIS messages. Depending on the wanted interface protocol, the AIS data can be coded for further transmission via the on board computer and the downlink to ground.

The communication between the payload and the OBC is based on a serial communication link transmitting AIS data from the payload to the OBC. Control messages are used for transmitting command and control messages between the payload and the OBC.

The AIS receiver is powered from the on-board power bus. A dedicated internal power interface board is in charge of managing the On/Off switch for the payload.

The transponders and the power I/F are then connected to the payload controller, responsible for the data management and payload operations. The controller is connected with the platform via a CAN node.

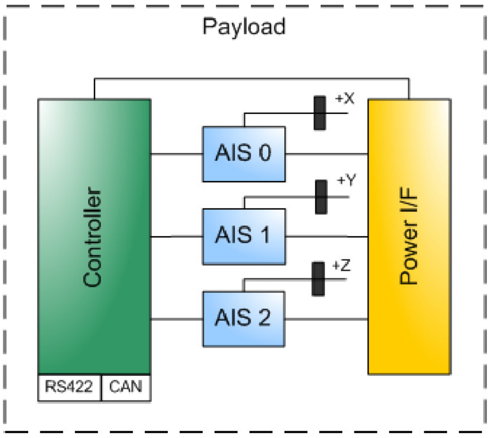


Figure 6.1 Include PL block diagram

The payload operates in two modes:

- Mode 1: Software Defined Radio (SDR)
- Mode 2: Digital Bent Pipe (DBP)

6.2.1 Software Defined Radio

In the SDR-based receiver, conversion to digital format is done directly at the signal frequency. This approach gives a very flexible design as filtering and processing are now done in software and changes to parameters can easily be introduced. By changing the processing software a range of receivers with different functionality can be implemented using the same hardware. Moreover, new software can be uploaded to the receiver for maintenance or change of functionality.

In Mode-1 the satellite should be able to provide a duty cycle of 25% per orbit. In the perspective of a full operational service, the possibility of global coverage needs to be considered.
The data rate for Mode-1 (Software Defined Radio) is:

256 bit x 4500 msg/min = **19.2 kbps**

6.2.2 Digital Bent Pipe

In the "Bent Pipe" design, the AIS signal is received at the AIS antenna, filtered, amplified, frequency translated to a downlink frequency, amplified and transmitted to the ground station.

Basically no signal processing is performed, only filtering, amplification and frequency translation of the AIS signal.

The main advantage of this approach is that the receiving process is moved to the ground where more complex receivers and more signal processing resources are available. The complexity of the payload is thereby reduced, giving higher safety for correct operation.

Mode 2 has been selected as experimental in order to analyse the potential of introducing a Digital Bent Pipe solution. The satellite should provide a duty cycle of 7% during one single orbit:

10 bits/sample x 25 kHz x 4 samples/Hz x 2 ch = **2 Mbps**

The Digital Bent Pipe solution requires an RS422 interface in order to transmit data to the Solid State Data Recorder.

6.3 Operational approach

The demonstration mission should aim at 2 years of operational time. The mission will gather AIS data to answer the mission objectives given in table 2.1. Looking at these demonstration requirements, one can find the duty cycle needed in the different modes of operation.

An expected minimum duty cycle for a nominal operation in the SDR modus can be found looking at DR-07 and DR-08. For tracking and monitoring of vessels in the Barents Sea, every orbit covers part of the area of interest and the payload should therefore be able to operate on every orbit. The duty cycle per orbit can be found from the goal of monitoring the North Atlantic. Assuming this will be limited between 20 degrees north and 60 degrees north, covering this area will require a duty cycle per orbit of ~25%.

DR-18 and DR-20 requires a more dedicated operational mode for global monitoring. To fulfil

DR-18 the payload should be operated continuously for minimum 12 consecutive hours. This should also be repeated at least once per month, and the satellite provider should specify how often such campaigns can be operated. As it is a demonstration mission, there is no requirement to go directly back to nominal mode. However, this should be done within 24 hours after the end of the global monitoring mode.

DR-13 and DR-14 requires an operational mode utilizing the digital bent pipe mode. Operating over 6 minutes will give information from 6 x 4 500 = 27 000 AIS timeslots (assuming the use of both AIS channels), and it will ensure that all vessels within the field of view during the observation time should have transmitted static and voyage related AIS information (message type 5) once. As for the global monitoring, the operations should go back to nominal mode within 24 hours after then end of the digital bent pipe mode. The satellite provider should specify how often the digital bent pipe can be used.

This can now be summarized as follows:

- The satellite should be able to provide a duty cycle of 25% per orbit for the nominal SDR operation mode.
- The satellite should provide a duty cycle of 100% for 12 consecutive hours in the global SDR monitoring mode.
- The satellite should provide a duty cycle of 7% during one single orbit for the digital bent pipe (DBP) mode.
- After the global SDR monitoring mode or the DBP mode, the payload can be turned off for up to 24 hours if needed.

6.3.1 Mission timeline

Spacecraft operations are designed to support a highly autonomous, lights out concept during routine operations. This allows operations costs to be reduced, and operational flexibility and reliability to be maximised.

During LEOP, and non-routine operations, autonomy is used to support a predominantly manual operation concept. Autonomy is used to support routine operations, while all critical operations involve an operator in the loop. This concept provides maximum mission safety and operational visibility during critical periods in the mission.

AIS is designed for a 2 year operational mission lifetime, excluding early operations, and end of life phases. Figure 6.2 shows the nominal top-level mission timeline, and Table 6.3 describes the activities undertaken during each mission phase.

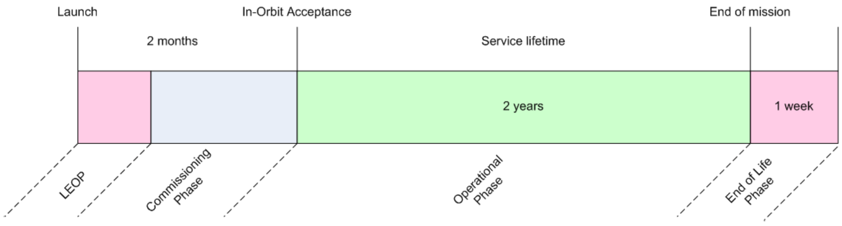


Figure 6.2 Mission Timeline

Phase	Duration	Description
Launch and Early Operations (LEOP)	1 Week	Launch and separation of spacecraft from launcher. Initial signal acquisition and platform testing. Attitude acquisition and stabilisation and placement of the spacecraft into a controlled attitude.
Commissioning & In-Orbit Test Phase	2 Months	Completion of platform testing Payload checkout.
Operational Phase	2 Years	Routine mission operations.
End Of Life Phase	1 Week	Platform passivisation.

Table 6.3 Mission Phases

The overall concept is outlined below for LEOP, Commissioning and Nominal operations phases of the mission.

LEOP and Commissioning

Launch preparations are part of the AIT and launch campaign phases. After launch and separation, the satellite autonomously activates and initiates detumbling and safe-mode control. At this stage, the spacecraft Operators can take control of the satellite during passes and begin spacecraft bus checkout. After the bus is checked and commissioned, the payload commissioning begins.

Nominal Operations

At this preliminary stage it is assumed that a mission planner is necessary to generate the schedule of operations for the payload (duty cycles). The data is acquired, forwarded, processed and archived automatically in the main data archive.

6.3.2 Operations

A single mission interface tool provides mission planning, and archived data access for mission operators. Mission schedules are loaded to the on-board computer payload software where they are expanded to produce the platform and payload commands required to perform AIS data acquisition. All safety critical operations are commanded via the on-board safety task to ensure that mission operations are performed within the safe operating limits of the spacecraft.

AIS data is transferred into the data storage system (SSDR) where it is stored pending download to the ground. The system is capable of near real-time data transfer with (HSDR option), in which case the data is transferred to the ground with minimal delay.

AIS data downlink operations are conducted via the X band transmitters. Payload data is received in the ground station before being passed to the Mission Control Centre for processing and archiving.

The operational scenarios consider 3 AIS transponders contemporarily active:

- Target scenario
- Goal scenario
- Experimental scenario

Scenario	Mode	Characteristics
1. Target	Mode-1	Software Defined Radio (SDR) 25% duty cycle Data rate (3 x modems) = 10.35 MB/orbit
2. Goal	Mode-1	Software Defined Radio (SDR) 100% duty cycle for 12 orbits (required) Data rate (3 x modems) = 41.42 MB/orbit
3. Experimental	Mode-2	Digital Bent pipe (DBP) 7% duty cycle Data rate (3 x modems) = 300 MB/orbit

Table 6.4 Scenario Definition

Nominal operations strictly depend on power availability, but an example of orbital timeline for the Target scenario is provided in Figure 6.3. The timeline is equal to the orbital period of 95 min. After an initial phase when the payload and the GPS are Off, the GPS is initialised (10 min) and the time synchronised with the on board computer. Once the synchronisation has been achieved the payload is switched on. The AIS data are acquired and stored on board. At the same time the AOCS data are captured. This will enable the antenna performance reconstruction on ground depending on the spacecraft attitude. The diagram assumes instantaneous On/Off transitions.

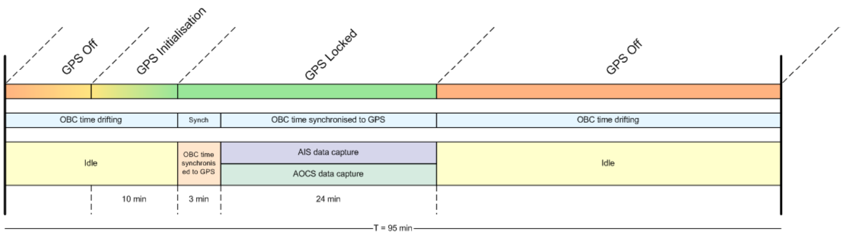


Figure 6.3 Orbital Timeline

6.4 Orbit selection

The operational orbit has been selected as Sun Synchronous with 15 ground tracks daily repetition. This leads to an operational altitude of 561,0 [km] with an inclination of 97.6° and an orbital period of 5752 sec (95.2 min).

In order to optimise the sun light exposure, the Local Time of Ascending Node (LTAN) has been set at 08:00 AM.

6.4.1 Lifetime

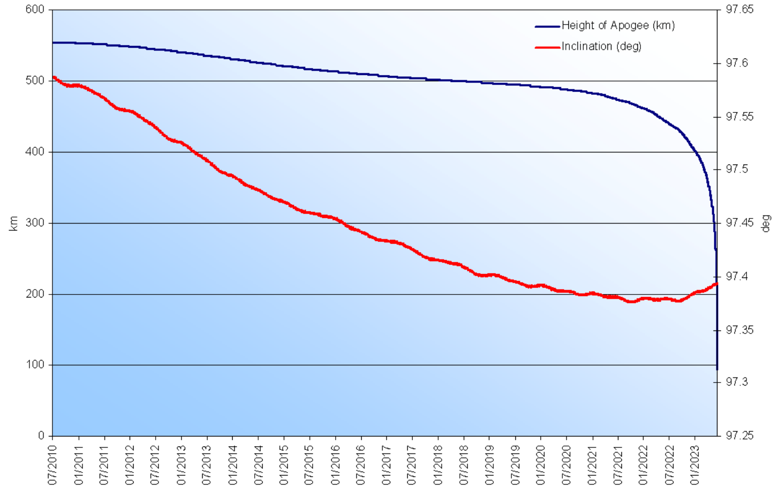


Figure 6.4 Lifetime

The design of the platform does not incorporate any ability for de-orbiting the spacecraft at the end of its service life.

The natural decay for a ballistic coefficient of 60 kg/m^2 is guaranteed in less than 15 years.

6.4.2 β-angle Variation

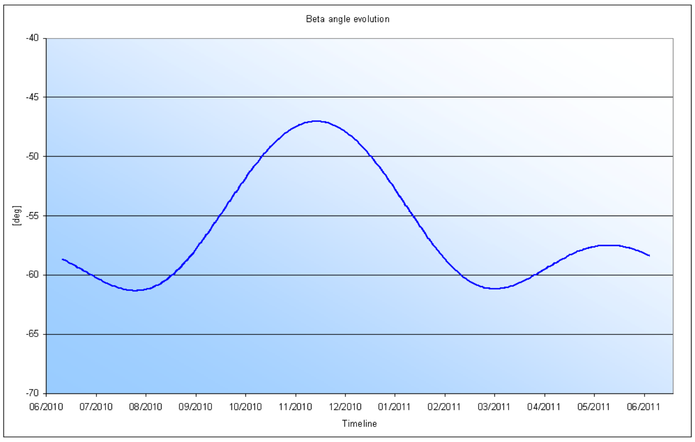


Figure 6.5 Beta Angle

Beta angle	MAX (worst) min (best)	-47.01 [deg] -61.3 [deg]	06/12/2010 15/08/2010

6.4.3 Eclipse

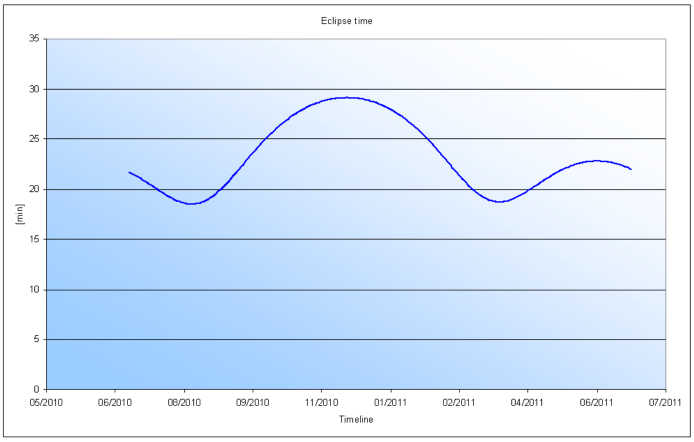


Figure 6.6 Eclipse Duration

Eclipse time	Max Min Average	29.1 [min] 18.5 [min] 23.2 [min]	06/12/2010

6.4.4 Radiation Analysis

In order to determine the impact of the radiation environment a set of simulation has been performed at different altitude in the range 500 km - 600 km.

The output of the analysis, summarised in Figure 6.7, lead to the following considerations:

- The total shielding thickness of boxes, structure, and arrays considered is equal to 3 mm of Al.
- Radiation dose over 2 years = 3 kRad.

In the light of these results, for the selected orbits the total radiation dose accumulated over an operative life of two years is compatible with COTS components approach which is compatible with total dose less than 5KRads.

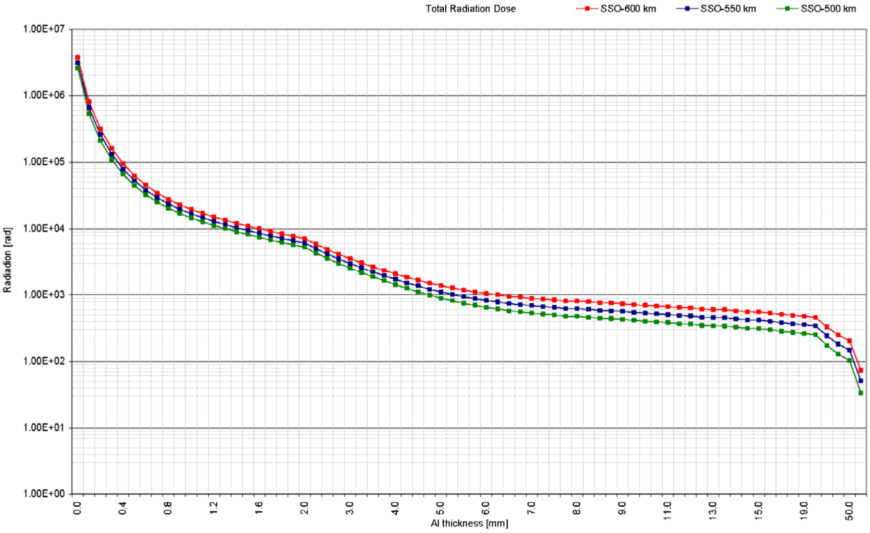


Figure 6.7 Total Radiation Dose

6.5 Ground Station Trade Off

The volume of data collected and the ground segment delivery intervals are driving factors to determine:

- On-board mass memory
- The necessary data transmission rate

A selection of ground stations distributed over the globe at different latitudes and longitudes has been considered as an initial trade off step.

As an initial step a set of potential ground stations has been selected. The results of number and duration of ground contacts is summarised in Figure 6.8. The data present the accesses time for each of the selected stations during 24 hours. The simulation has considered 15 orbits each of them identified by the white/blue vertical sector.

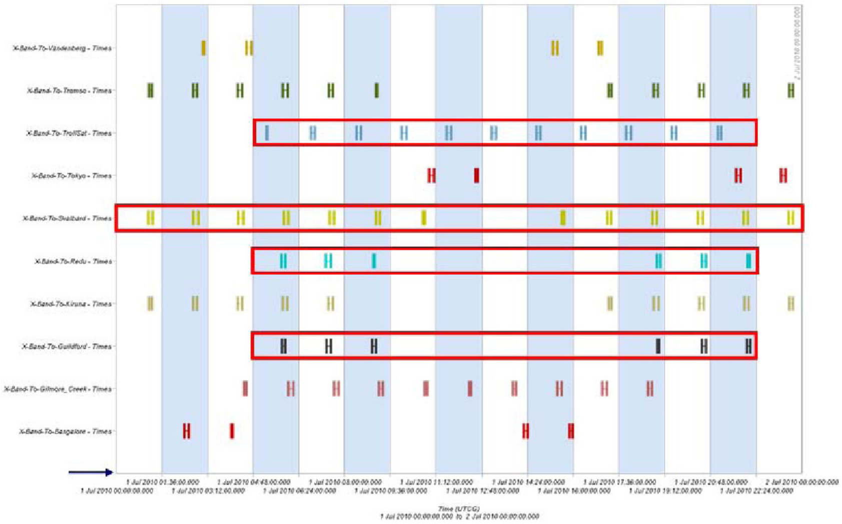


Figure 6.8 Ground Station Trade-off

In the light of SSO orbital characteristics and the number and frequency of ground contacts, the following stations have been down-selected. The selection process highlights the Artic (Svalbard) and Antartic (TrollSat) stations as fundamental for daily coverage. Norwegian Ground stations have been preferred where possible. Central Europe Redu has been selected in the ESA net as support ground station for the demonstrator mission. Guildford represents an option as supporting station during early phases or in case of Redu unavailability. Figure 6.9 shows some characteristics of the selected ground stations.

Station				
Guildford	LAT	+51.2 deg	Min Duration	60 sec
	LON	-0.6 deg	Max Duration	596 sec
			Mean Duration	444 sec
TrollSat	LAT	-72.0 deg	Min Duration	61 sec
	LON	+2.0 deg	Max Duration	610 sec
			Mean Duration	495 sec
Svalbard	LAT	+78.2 deg	Min Duration	60 sec
	LON	+15.4 deg	Max Duration	602 sec
			Mean Duration	477 sec
Redu	LAT	+50.0 deg	Min Duration	61 sec
	LON	+ 5.1 deg	Max Duration	597 sec
			Mean Duration	445 sec

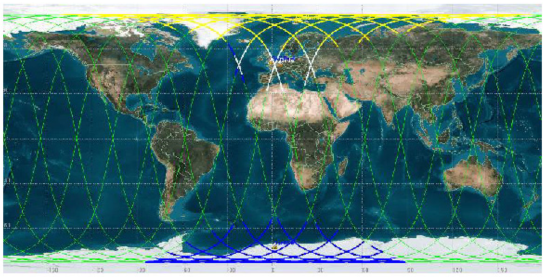


Figure 6.9 Characteristics of selected ground stations

6.5.1 Svalbard

The Svalbard-3 (SG-3) antenna provides S-band transmit and S- and X-band receive capability. Svalbard Satellite Station (SvalSat) is operated by Kongsberg Satellite Services AS (KSAT) and is located near Longyearbyen. Due to its far northern position, it is the only satellite station that can track all orbits of polar-orbiting satellites, such as ERS-2 and ENVISAT.

The 13-metre antenna terminal is located in the Svalbard Satellite Station (SvalSat) complex, at 78.229772°N, 15.407786°E, and at an elevation of 501.3 metres. Svalbard is on the island of Spitsbergen, a part of Norway, in the Arctic Ocean. Its administrative centre is the town of Longyearbyen.

6.5.2 TrollSat

As of March 1st 2007, the TrollSat ground station facility in Antarctica was completed and ready for operations. TrollSat and SvalSat together constitute the KSAT Pole-to-Pole service whereby satellite tracking and data reception is available from Antarctica and the Artic within the same ground network.

The main TrollSat LEO system includes:

- One 7.3m S-band and X-band LEO antenna installed in radome
- Complete backend chains for TT&C operations. The station is equipped with primary and secondary chains of Cortex CRT systems for multimission support. Space Link Extension (SLE) is offered as well as mission specific protocols. KSAT can support onsite integration of mission specific TT&C equipment as defined by the user.
- Complete backend chains for X-band data reception. Data reception up to 2x400 Mbit is supported through. The ground station includes generic multi-mission demodulators as well as multi mission Front End Processors (FEP). KSAT can support onsite integration of mission specific TT&C equipment as defined by the user.

The ground station is collocated with the Norwegian Polar Institute (NPI) research facility and located at 72°S and 2°E. The facility is permanently manned all year around.

6.5.3 Redu

Redu station provides ESTRACK tracking capabilities in S- and Ka-band, and supports in-orbit testing (IOT) of telecommunication satellites. Redu supports ESA's Artemis and Integral missions as well as Proba. The site hosts multiple tracking antennas operating in a variety of frequency bands, and is located in the Ardennes region of Belgium.

The coordinates of the REDU-1 antenna are 50.000456° North and 5.145344° East. This reference point is 386.6 metres above sea level with respect to the WGS-84 reference ellipsoid, a mathematically-defined reference surface that approximates the Earth's geoid surface.
Redu station is sited about 1 km from the village of Redu, in the Belgian province of Luxembourg.

Redu has been expressly asked for by ESA even if it doesn't't' have X-band capabilities. It will help as a secondary S-band operational ground station for S-band communications.

6.5.4 Ground station coverage

Figure 6.10 indicates the stations' field of view and satellite coverage from the ground.

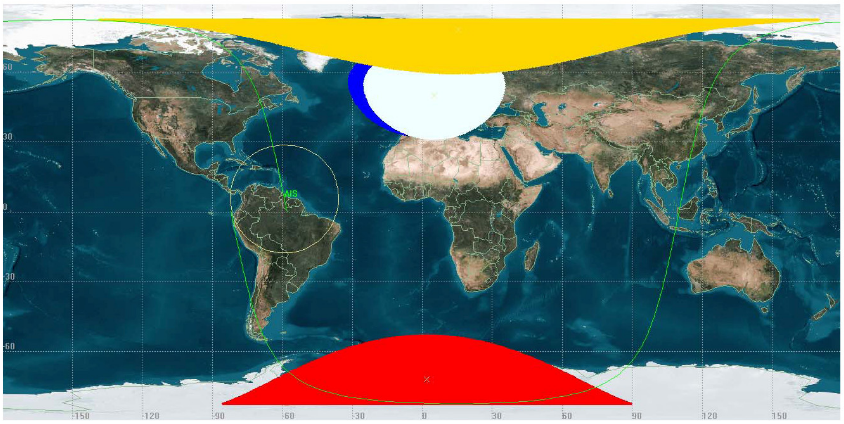


Figure 6.10 Ground Station Coverage

Table 6.5 and Figure 6.11 present a one- day scenario. The simulation has been performed considering a minimum 5 deg masking angle and a minimum of 60 seconds contact time. The results highlighted an average of 30 ground contacts with 1 Arctic contact and 1 Antarctic contact for each pass.

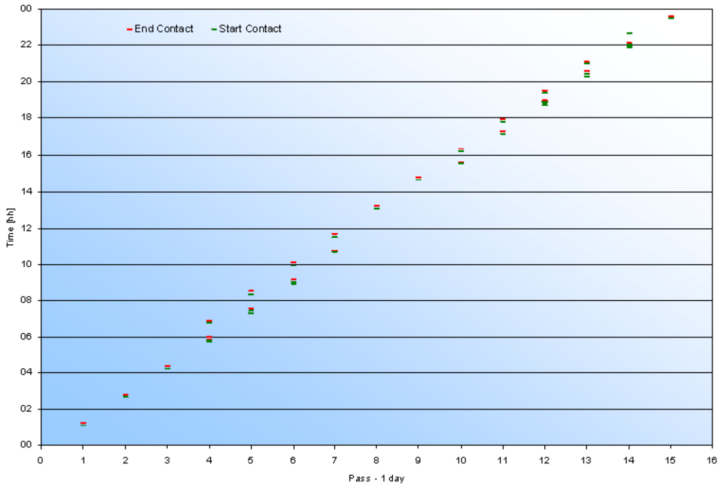


Figure 6.11 Daily Contact Sessions

Pass	Start Contact	End Contact	Duration (sec)	Object	Pass	Start Contact	End Contact	Duration (sec)	Object
1	01:04:00	01:13:45	584.585	Svalbard	9	14:38:10	14:46:36	505.812	TrollSat
2	02:38:30	02:48:22	591.523	Svalbard	10	16:11:48	16:21:00	552.021	TrollSat
3	04:13:12	04:23:13	601.12	Svalbard	10	15:30:50	15:35:32	282.071	Svalbard
4	05:44:54	05:51:02	368.251	Guildford	11	17:45:53	17:55:49	596.409	TrollSat
4	06:45:11	06:52:51	459.306	TrollSat	11	17:06:08	17:13:33	445.526	Svalbard
4	05:48:24	05:58:16	591.66	Svalbard	12	18:51:28	18:55:00	212.607	Guildford
4	05:43:27	05:50:54	446.442	Redu	12	19:21:01	19:30:47	585.996	TrollSat
5	07:17:08	07:27:02	593.723	Guildford	12	18:41:25	18:50:32	546.75	Svalbard
5	08:20:02	08:29:43	581.123	TrollSat	12	18:50:19	18:57:01	402.002	Redu
5	07:24:26	07:33:28	542.054	Svalbard	13	20:23:58	20:33:52	593.255	Guildford
5	07:16:36	07:26:29	593.175	Redu	13	20:57:46	21:05:40	473.287	TrollSat
6	08:53:52	09:00:56	423.694	Guildford	13	20:16:37	20:26:31	593.722	Svalbard
6	09:55:01	10:04:58	597.001	TrollSat	13	20:24:03	20:33:59	596.332	Redu
6	09:01:28	09:08:46	437.654	Svalbard	14	21:59:22	22:07:22	479.561	Guildford
6	08:55:05	08:59:11	245.886	Redu	14	22:37:43	22:38:59	75.445	TrollSat
7	11:29:50	11:39:05	554.973	TrollSat	14	21:51:40	22:01:42	601.4	Svalbard
7	10:39:33	10:44:03	270.611	Svalbard	14	22:00:06	22:06:10	363.902	Redu
8	13:04:17	13:12:44	507.408	TrollSat	15	23:26:30	23:36:22	591.167	Svalbard

Table 6.5 Daily Contacts

6.6 Satellite Overview

As result of the trade-off, the SSTL-100 has been selected as heritage baseline. Figure 6.12 shows the satellite designed in the stowed and operative configuration.

The first image shows the deployable panel and the three antennas in stowed position in order to provide an overview about the spacecraft in launcher configuration. The proposed solution is characterised by an extremely compact design which allows easy fairing accommodation as a piggy-back payload.

The second view presents the platform in the operative configuration with the appendages fully deployed and the high performance solar array in final position with a slant angle of -140°.

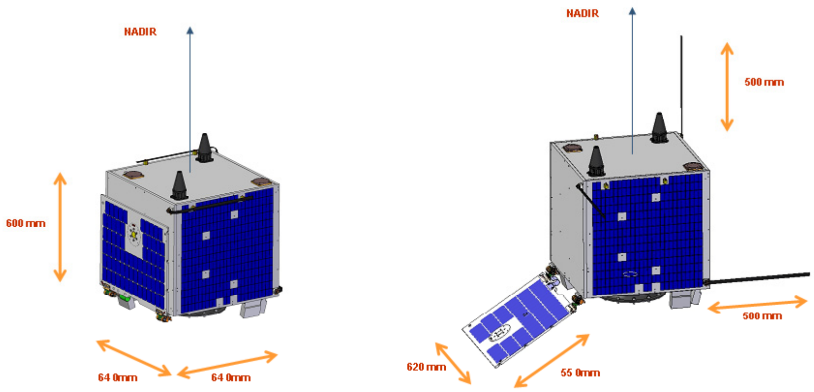


Figure 6.12 Platform configuration: Stowed & Deployed (transparent deployed solar panel)

Figure 6.13 summarises the spacecraft block diagram. The spacecraft design has been split into six main areas:

- OBDH and CAN BUS: computer and CAN BUS interface represents the backbone of the platform design.
- Low rate communication: for S-band communication dedicated to platform telemetry and telecommand.
- Power: including the electronics, the solar array and the battery.
- Payload chain: is defined as the payload data storage and downlink. The payload is interfaced with the OBC via CAN BUS and via RS422 with the X band transmitters.
- AOCS: it comprises the attitude electronic interface module, attitude sensors and actuators and the GPS navigation system.
- Payload: the module is entirely dedicated do the payload electronics and payload antennas.

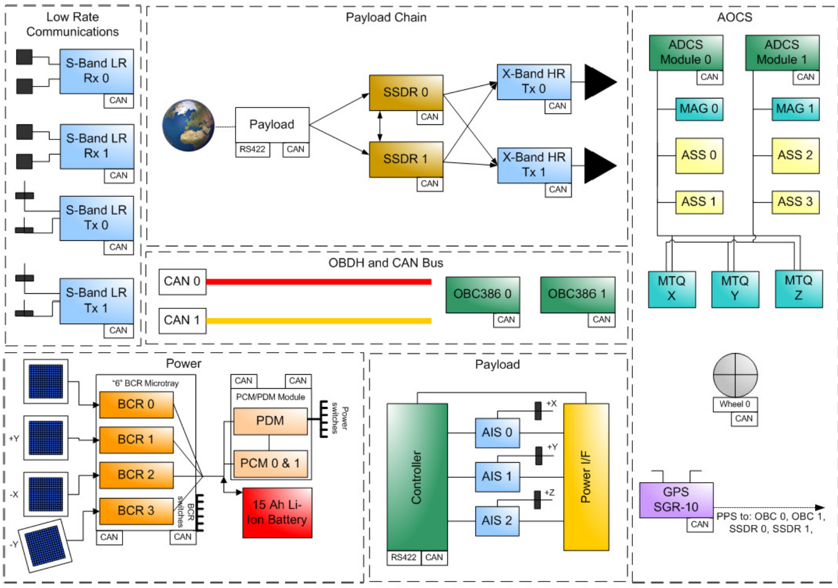


Figure 6.13 Platform Block Diagram

6.6.1 Attitude Determination and Control

A 3-axis attitude estimator is used to calculate the spacecraft attitude to a level of accuracy that is good enough to support the pointing requirement. This estimator can be updated with one or more unit vector measurements.

These measurements would normally be the direction to the Sun or the local direction of Earth's magnetic field. During periods of eclipse the attitude estimate can be maintained using only magnetic field measurements.

The GPS receiver can also provide phase-difference measurements from the antenna pair. These can be used to generate a single-baseline attitude measurement as an alternative to the Sun Sensor measurement to improve performance during periods of eclipse.

Two magnetometers are considered the primary attitude sensor and three magnetorquers as the primary attitude actuators.

The secondary attitude sensors and actuators are the standard SSTL sun sensors and one SSTL MicroSat wheel, controlled by the AOCS Interface Module (AIM).

Given the relaxed pointing requirement, the simplest possible form of attitude control is desirable.

Magnetorquers can provide sufficiently large torques to suppress disturbance torques but can only provide 2-axis control at any one time. To supplement this, a single wheel is used to provide some gyroscopic rigidity about the pitch axis, which is aligned to the orbit angular momentum.

The wheel speed is set to a constant level and is not used to control the attitude directly. In this way it is possible to achieve 3-axis attitude control with only the magnetorquers being used as the closed-loop control actuators.

The 3 magnetorquer rods are initially used for detumbling after separation, and once coarse Nadir pointing has been achieved and the wheel commissioned, the torque rods are used primarily for wheel momentum desaturation.

6.6.1.1 Navigation

The SGR-10 GPS receiver provides accurate position, velocity and time information. It can be used for time-stamping payload data and for updating the on-board orbit ephemeris estimates.

6.6.1.2 Attitude Control Modes

There will be three attitude control modes: De-tumble, Y-Thomson and Normal Mode. The normal mode will be the standard operating mode, with the other modes used to move towards 3-axis stabilisation in a controlled manner.

DE-TUMBLE MODE
This mode damps the rotational energy using the magnetorquers. The moments applied will be in proportion to the apparent rates of change in the Earth's magnetic field direction, as measured by one of the magnetometers.

In this way the rotation is slowed until the attitude rates are small. This mode of operation has extensive heritage on SSTL microsatellites.

Y-THOMSON MODE
This mode is used to put the satellite into a stable configuration after the attitude rates have been suppressed. A magnetometer is used to estimate the attitude rates and the magnetorquers are used to place the spacecraft in a controlled spin around the pitch axis.

The pitch axis MicroSat reaction wheel can be used to provide additional stability if necessary. This mode of operation has extensive heritage on SSTL microsatellites.

NORMAL MODE
This is the standard, 3-axis stabilised operating mode used to support payload operations. In this mode the pitch axis momentum wheel is used to provide some gyroscopic rigidity to allow 3-axis stabilisation using the magnetorquers. The momentum wheel is operated at a constant speed of 300rpm. A similar mode of operation was previously used on SSTL's SNAP-1 nanosatellite.

This mode is acquired from the Y-Thomson configuration by absorbing the spacecraft angular momentum about the pitch axis onto the momentum wheel. The resulting wheel speed will initially be higher than the nominal 300rpm but this can be reduced to the desired level through additional magnetorquer actuation.

6.6.1.3 Simulation Results & Performance

The normal mode of operation has been assessed using a simulation of the heritage baseline, UK-DMC-2. This simulation has been used to assess performance and determine what momentum wheel speed is suitable to support 3-axis stabilisation. Figure 6.14 to Figure 6.16 below show that for wheel speeds above 400rpm there is little or no benefit in performance. Furthermore there is some evidence that for much larger wheel speeds the performance becomes worse, most likely because it is difficult to damp out precession of the larger momentum with the magnetorquers.

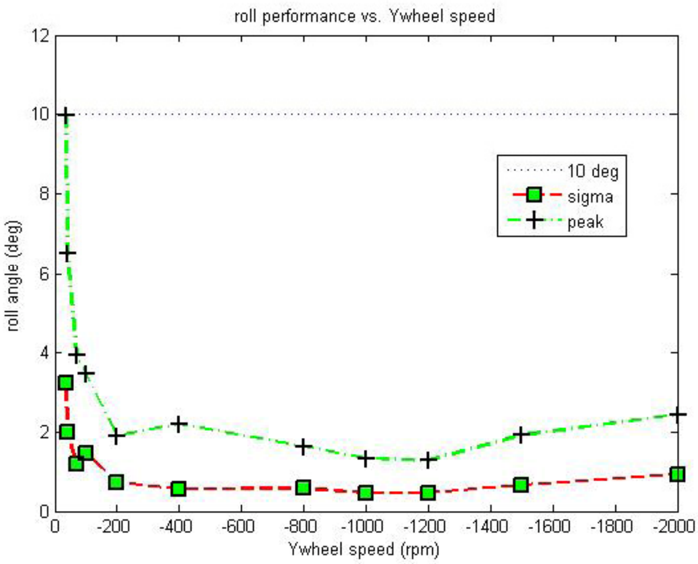


Figure 6.14 Affect of pitch wheel speed on roll error

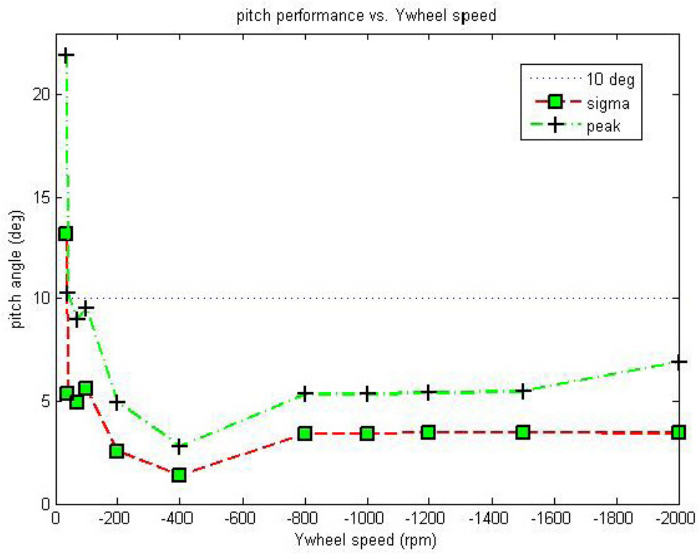


Figure 6.15 Affect of pitch wheel speed on pitch error

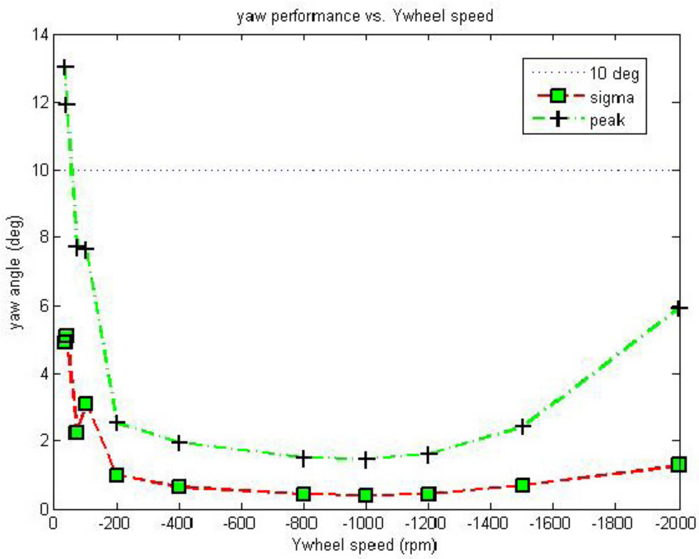


Figure 6.16 Affect of pitch wheel speed on yaw error

It was determined that setting the MicroSat pitch wheel speed to around 300rpm provides most of the benefit of the momentum stabilisation with minimal power consumption.

6.6.2 TMTC Subsystem

The Telemetry & Telecommand (TTC) System enables ground-based operators to monitor and control the functions and behaviour of the microsatellite in orbit throughout its mission.

The Telemetry & Telecommand System comprises the following functions:

- Fixed hardware Telemetry encoder & command decoder
- Distributed Controller Area Network (CAN) with programmable nodes for local Telemetry encoding and command decoding
- Software and communications protocols
- S-Band RF up/down links

The spacecraft will be capable of:

- Downlinking housekeeping data
- Downlinking payload data
- The High Rate S Band transmitter will be replaced with a second X Band transmitter and a second Low Rate transmitter
- The X Band Transmitters will downlink payload data at 20 Mbps

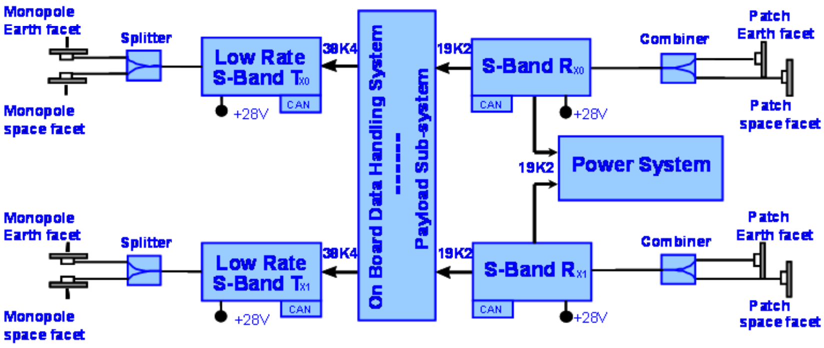


Figure 6.17 Platform Uplink and Downlink

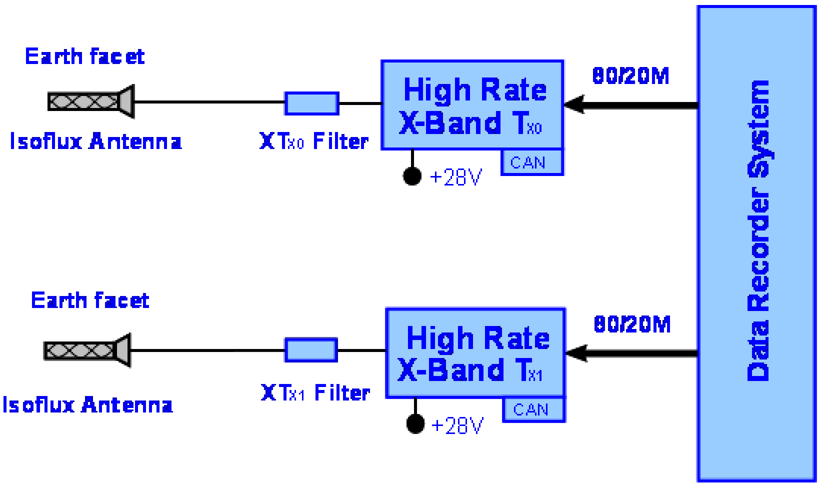


Figure 6.18 Payload Downlink

6.6.3 SSDR

The data recorders will consist of two 2GB SSDR modules connected to the payload controller, S-Band receivers, X-Band transmitters, OBC and GPS PPS.

The SSDR is characterised by asynchronous and synchronous data interfaces.

The payload interface consists of several separate physical links that connects to the payload processor. In summary these are the SSDR's inputs:

- Six 20Mbit/s synchronous serial input streams into the SSDR
- Signals are transmitted over an LVDS hardware layer

On the other side the data storage unit interfaces with the RF transmitter. The purpose of this interface is to send captured AIS messages, payload data and OBC housekeeping data to the RF transmitters.

The SSDR has two transmitter interfaces; one to the RF S-Band transmitter and another to the RF X-Band transmitter with the following output features:

- One 8Mbps synchronous serial output streams to the RF system
- One 20/40 Mbps synchronous serial output streams to the RF system
- Both signals are transmitted over an LVDS hardware layer

6.6.4 Thermal Subsystem

The Thermal Control System (TCS) is required to maintain all equipment and structures at acceptable temperatures throughout the mission. The process is one of design, with demonstration by analysis that temperature predictions for all equipment and structures fall within an acceptable temperature range agreed upon with the equipment provider. An allowance is made for modelling uncertainty in the temperature predictions.

The general approach is one of conductive transfer of heat away from dissipating units, and rejection to Space via radiators. External heat inputs (Sun, Earth, Albedo) are managed by choice of external surface properties.

The purpose of the thermal subsystem is to;

- Keep all units within operating and non-operating temperature limits during all nominal phases of the spacecraft mission.
- Ensure battery mission average temperature is not exceeded (to ensure battery lifetime).

6.7 Mass Budget

The mass budget is presented in the following table. The forecast presented in Figure 6.19 and Table 6.6 is for a launch mass of 60 kg.

Sub-system	**Total mass [kg] NO margin**	**Total mass [kg] Margin**
AOCS	5.4	5.5
Power	11.0	11.3
Comms	11.0	11.4
Propulsion	0.0	0.0
OBDH	4.8	4.9
Environment	0.4	0.4
Structure	9.4	9.9
Harness	5.0	5.3
Payload	5.2	5.7
Sub-system total	52.1	54.4
System margin (10%)	-	5.4
Dry mass	52.1	59.8
Propellant	0.0	0.0
Launch mass	52.1	**59.8**

Table 6.6 Platform Mass Budget

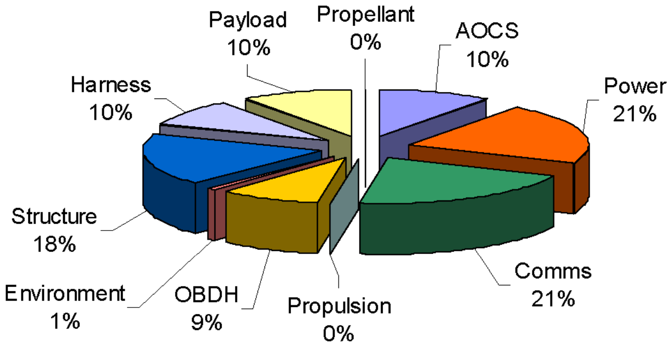


Figure 6.19 Platform Mass Budget in percent

6.8 Power Budget

The main parameters considered in order to derive the power budget are:

	Single junction		Triple junction	
BOL cell efficiency	19.2	% at 28°C	27.5	% at 28°C
Lifetime	5	Years	5	years
Radiation loss	1.5	%	2.5	%
EOL cell efficiency	18.91	% at 28°C	26.14	% at 28°C
EOL cell efficiency	17.34	% at 65°C	23.33	% at 70°C
BOL cell efficiency	22.08	% at -40°C	32.06	% at -40°C
Worst case (EOL, max temp.)	16.42	%	21.7	%
Best case (BOL, min temp.)	21.16	%	29.81	%

Table 6.7 Drivers for power budget

The following paragraphs present the results obtained considering the requirements defined in Section 6.3.2. Three operational scenarios have been analysed:

- Target scenario
- Goal scenario
- Experimental scenario

The next three sections present the power budget associated to the worst operative conditions with a detailed breakdown for each subsystem. Each scenario is divided into three operative modes:

- **Nominal operation**: Considers the platform in nominal mode. In this condition the payload in switched off and the link with the ground station is not active.
- **AIS**: Represents the payload operative mode.
- **Downlink**: Identifies the ground contact activity when TM and SSDR content are down linked and TC received from ground.

A fourth column is added in order to provide the results of the Orbit Average Power consumption averaged over 15 orbits.

For each of the operative modes, the Mode duty cycle (%) is identified. This will ease the reading of the results in order to verify compliance with the mission requirements.

The last three rows of the table identify respectively:

- **Total power**: Represents the total power require by the platform in order to operate under the selected conditions with the defined duty cycles.
- **Power generated**: This is the power generated by the solar arrays in the selected configuration (3x single junction panels, 1x triple junction panel with -140° slant angle). The generated power is the same for the three scenarios due to the fact that the platform configuration is the same.
- **Margin**: Is the margin on top the system margin (10%) as balance between the power generated and the power required.

6.8.1 Target Scenario Power Profile

	1	2	3	Orbit
Description	Nominal Ops	AIS	Downlink	
Mode duty cycle (%)	66.9	25.0	8.1	
Sub-system	**Mode 1 average power (W)**	**Mode 2 average power (W)**	**Mode 3 average power (W)**	**Orbit average power (W)**
AOCS	6.1	12.6	6.1	**7.7**
Power	5.8	5.8	5.8	**5.8**
Comms	2.7	2.7	2.7	**2.7**
Propulsion	0.0	0.0	0.0	**0.0**
OBDH	4.18	4.18	4.18	**4.2**
Environment	0.0	0.0	0.0	**0.0**
Structure & Harness	0.0	0.0	0.0	**0.0**
Payload	0.0	25.0	71.2	**12.0**
Sub-system total	18.8	50.3	90.0	**32.4**
System margin (10%)	1.9	5.0	9.0	**3.2**
Total power	20.7	55.3	99.0	**35.7**
Power generated				**64.9**
Margin	(on top of system margin)			**82.0%**

Note: The X-band is defined as part of the PL. The GPS is defined as part of the AOCS

Table 6.8 Target Scenario Power Budget

The payload Mode-1 in Software Defined Radio configuration with an operative duty cycle of 25% is satisfied with an overall margin (on top of system margin) of 82%.

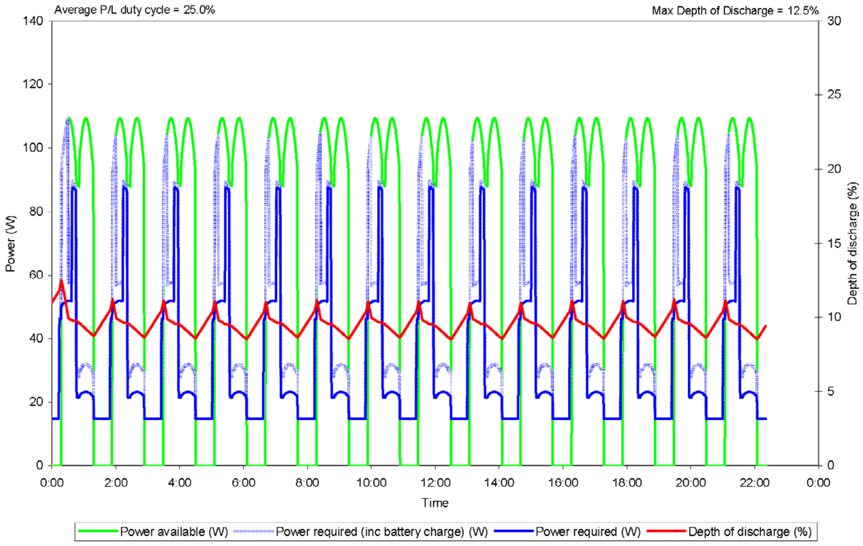


Figure 6.20 Target Scenario – Power and depth of discharge profile

6.8.2 Goal Scenario Power Profile

	1	2	Orbit
Description	Nominal Ops	AIS + downlink	
Mode duty cycle (%)	0.0	100.0	
Sub-system	**Mode 1 average power (W)**	**Mode 2 average power (W)**	**Orbit average power (W)**
AOCS	0.0	12.6	**12.6**
Power	3.2	4.9	**4.9**
Comms	0.0	3.2	**3.2**
Propulsion	0.0	0.0	**0.0**
OBDH	0.00	4.18	**4.2**
Environment	0.0	0.0	**0.0**
Structure & Harness	0.0	0.0	**0.0**
Payload	0.0	30.1	**30.1**
Sub-system total	3.2	55.0	**55.0**
System margin (10%)	0.3	5.5	**5.5**
Total power	3.5	60.5	**60.5**
Power generated			**64.9**
Margin	(on top of system margin)		**7.4%**

Note: The payload is always On. Downlink during payload operations.

Table 6.9 Goal Scenario Power Budget

The payload Mode-1 in the Software Defined Radio configuration with an operative duty cycle of 100% is satisfied with an overall margin (on top of system margin) of 7.4%. This implies that the AIS mode is the only mode active for the entire orbit.

Nominal operations (when the payload is off) are not foreseen in the GOAL scenario. The downlink has been included into the payload operations budget.

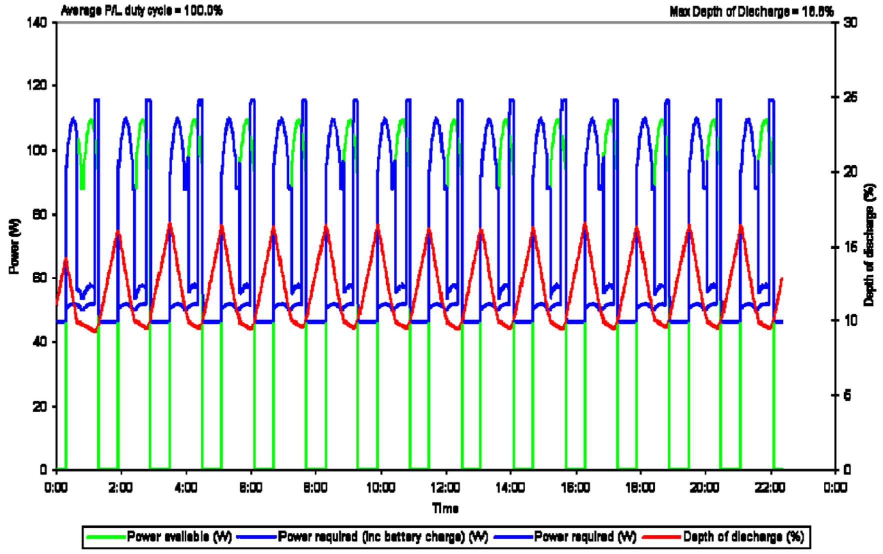


Figure 6.21 Goal Scenario – Power and depth of discharge profile

6.8.3 Experimantal Scenario Power Profile

	1	2	3	Orbit
Description	Nominal Ops	AIS	Downlink	
Mode duty cycle (%)	84.9	7.0	8.1	
Sub-system	**Mode 1 average power (W)**	**Mode 2 average power (W)**	**Mode 3 average power (W)**	**Orbit average power (W)**
AOCS	6.1	12.6	6.1	**6.6**
Power	6.8	6.8	6.8	**6.8**
Comms	2.7	2.7	2.7	**2.7**
Propulsion	0.0	0.0	0.0	**0.0**
OBDH	4.18	4.18	4.18	**4.2**
Environment	0.0	0.0	0.0	**0.0**
Structure & Harness	0.0	0.0	0.0	**0.0**
Payload	0.0	25.0	71.2	**7.5**
Sub-system total	19.7	51.2	90.9	**27.7**
System margin (10%)	2.0	5.1	9.1	**2.8**
Total power	21.7	56.3	100.0	**30.5**
Power generated				**64.9**
Margin	(on top of system margin)			**113.1%**

Table 6.10 Experimental Scenario Power Budget

The payload Mode-2 in the Digital Bent Pipe configuration with an operative duty cycle of 7% is satisfied with an overall margin (on top of system margin) of 113.1%.

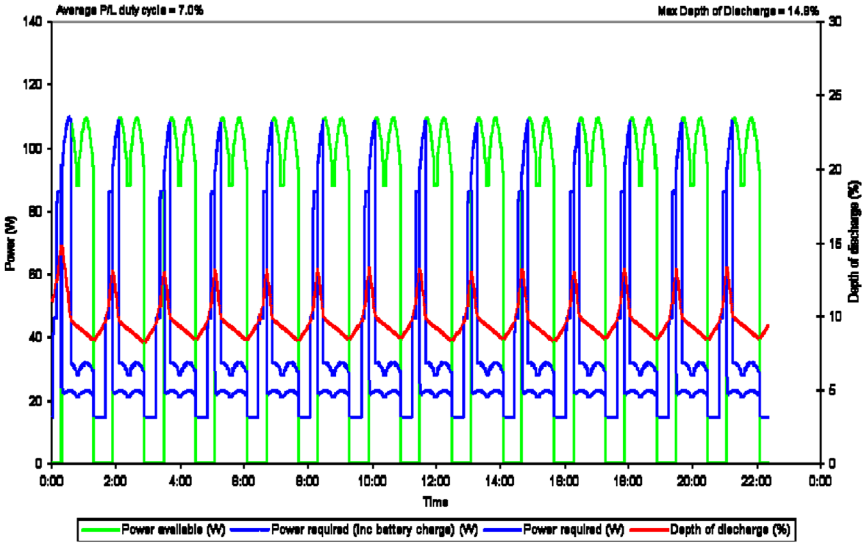


Figure 6.22 Experimental Scenario – Power and depth of discharge profile

6.9 Launch

One of the requirements identified for the launch provider selection entails that the platform needs to be compatible with at least two launchers.

The first step in the launcher selection has been the identification of the launch configuration as highlighted in Figure 6.23.

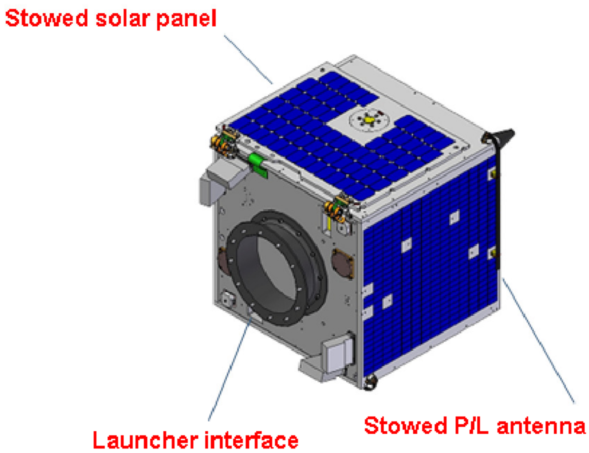


Figure 6.23 Launch Configuration

In order to investigate a wider spectrum of opportunity, four launch vehicles have been selected as potential options:

- Vega
- Dnepr
- Rockot
- PSLV

SSTL's approach to spacecraft structural design is to provide compatibility with a wide set of launcher options identifying a worst case scenario in terms of loads level.

On the other hand, the reduced size and mass of the proposed spacecraft allows a piggy back launch as secondary payload with the guarantee of an easier access to space.

The main characteristics for each launcher are summarised in Table 6.11.

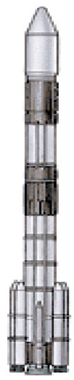
Launcher	VEGA	DNEPR	ROCKOT	PSLV
Launcher view				
Mass to AIS orbit	1500 kg	1500 kg	1100 kg	1500 kg
Fairing dimensions	Diameter: 2.38 m MAX Length: 5.50 m MAX	Diameter: 2.70 m MAX Length: 5.16 m MAX	Diameter: 2.38 m MAX Length: 6.00 m MAX	Diameter: 2.90 m MAX Length: 5.40 m MAX
Launch Vehicle Adapter	Clampband, Ø937 Custom	Depending on launch configuration	Clampband, Ø937	Clampband, Ø937 IBL-298
Injection accuracy	1 sigma Altitude: 5 km Inclin: 0.05 deg RAAN: 0.1 deg	Altitude: ±5.5 km Inclination ±0.045 deg RAAN: ±0.060 deg	3 sigma Altitude: ±1.5% Inclination: ±0.05 deg RAAN: ±0.05°	3 sigma Altitude: 35 km Inclination: 0.2 deg

Table 6.11 Launch Options

6.10 Mission verification scenario

With several new European SAR systems being launched, a verification scenario should test the received AIS signal together with a campaign of SAR imaging of the targeted area, and other possible sources of ship activity. This could include the vessel monitoring system for fishing, Long Range Identification and Tracking if it is operative, and AIS information from coastal base stations, from airborne AIS receivers and if available, already existing space based AIS receivers.

It should be envisaged three main measurement campaigns. A first should cover the Barents Sea, which is reasonably well covered and where the vessel density is low. This would ensure that the system is working to specification.

The second measurement campaign should cover the Mediterranean. This will show the potential in this important European sea area, and also indicate the limitations of the system.

The third campaign should look at passes over the North Sea, to understand the true limits of the system. Here and probably also for the Mediterranean, the DBP mode should be used, enabling processing of data on ground, where competing algorithms can be given the chance to prove their worth in mitigating the problem of message collisions.

Looking at the probability of detection in the North Atlantic, several vessels going in shuttle traffic between Europe and America should be monitored for several weeks to get an estimate of detection probability.

In addition to what is commented here, the approach to meeting the demonstration requirements is given in Table 6.1.

6.11 Preliminary mission requirements for demonstration concept

Based on the results of the study, the following preliminary mission requirements for an AIS demonstration concept have been identified.

DMR-ID	Description	Requirement
DMR-001	Attitude determination	Must be able to achieve attitude control better than +/- 10 degrees.
DMR-002	Attitude control	+/- 10 degrees
DMR-003	Orbit maintenance	The orbit shall ensure at least two years operational lifetime. As long as other mission requirements are met, the reception of AIS signals requires no orbit maintenance.
DMR-004	Orbit inclination	Between 80 and 100 degrees
DMR-005	Orbit altitude	Preferably 600 km or lower
DMR-006	Antenna FOV	To the horizon
DMR-007	Antenna size	Three orthogonal monopoles at opposite corners of the spacecraft.. Each less than 50 cm long.
DMR-008	Antenna mass	Three orthogonal monopoles each less than 1 kg including the harness.
DMR-009	Payload GMSK decoding technique	Optimal coherent receiver
DMR-010	Payload Power Consuption	Less than 15W operating all three receivers.
DMR-011	Receiver mass	Less than: • 1.5 kg – electronics • 1.2 kg – aluminium housing
DMR-012	Receiver size	150x250x150 mm (3 receivers)

DMR-ID	Description	Requirement
DMR-013	Mass memory	In it is given that the DBP option gives 2 Mbits/sec/receiver of data. Operating over 6 minutes with 3 receivers produce ~ 300 MByte of data. Including some margin, the mass memory should be 1 GByte or large.
DMR-014	Payload thermal	The payload should be able to operate in a temperature environment between -20C and +50C
DMR-015	Radiation	It is shown that the expected total radiation dose inside 3 mm Al after 2 years is 3 kRad. All equipment should be able to function after a reset under these environment conditions.
DMR-016	Vibration	The vibration requirement will depend on the final choice of launcher.
DMR-017	S/C position determination	The spacecraft should be able to determine its own position in order to use e.g. Doppler as a way of estimating where an AIS signal is sent from.
DMR-018	Operational modes	Three main operational modes are foreseen: 1. Nominal SDR operations with a duty cycle of 25 %. 2. Global mapping with SDR used with a 100 % duty cycle for 12 consecutive hours 3. Digital bent pipe for on-ground processing with a duty cycle of 7%.
DMR-019	Launch	The spacecraft should be able to be launched as an auxiliary payload.
DMR-020	Commissioning time	A maximum of 10 weeks from launch should be needed for commissioning of spacecraft
DMR-021	Backup S/C	Plans for a backup spacecraft should be established in case of launch failure.
DMR-022	End-of-life	According to space debris mitigation recommendations [25] the spacecraft orbit shall be such that the natural decay ensures re-entry into the atmosphere within 25 years of end-of-life.

DMR-ID	Description	Requirement
DMR-023	Ground Station Location	The suggested locations are Svalbard, TrollSat, Guildford and Redu.
DMR-024	MCC location	The mission control centre should be run by ESA for a demonstration mission.
DMR-025	MCC Data processing	The mission control centre must be able to implement new data processing algorithms to test on data received during DBP operations.
DMR-026	MCC Database	The mission control centre must be able store all payload data received in a database and also have a mirrored back-up database.
DMR-027	Metadata	In addition to the AIS messages, metadata such as time of reception, Doppler shift, direction of incoming signal ID of message received, ID of satellite and position of satellite at the time of reception should be stored in the MCC Database.
DMR-028	Data distribution scheme	A secure data distribution scheme to potential users of space-based AIS data for European maritime security should be established and tested during the demonstration mission.
DMR-029	User Validation	A user validation scheme shall be set up to make sure the AIS data is only distributed to approved users.
DMR-030	Secure Network	Secure network solutions shall be used for distribution of data from ground station to MCC and from MCC to end users.
DMR-031	Uplink capacity	For a demonstration mission, the uplink capacity is not assumed to be critical. Still, to enable updates of FPGA images within reasonable time, it should be at least 10kbps.
DMR-032	Downlink capacity	The downlink rate should be at least 8 Mbps.
DMR-033	Coding	Error detecting and correcting coding should be implemented in the up-link and down-link communication in order to improve the link budgets.

DMR-ID	Description	Requirement
DMR-034	Encryption	Encryption should be used to ensure the integrity of the received AIS data.
DMR-035	Bent-pipe	A "digital bent pipe" option should be implemented in order for AIS message decoding techniques to be tested on ground.
DMR-036	Redundancy	With three antennas and three receivers there is already some redundancy included. Triple voting should be considered in the FPGA programming.

Table 6.12 Demonstration Mission Requirements.

B.11 Operational Concept

WP 260 Development Plan and Cost Estimates
RES-260-10 Development Plan and Cost Estimation
Date 10.04.2008

7 Operational Concept

The objective was to have an operational system for receiving AIS messages from space in order to improve maritime security. Based on the user requirements, the main objectives can be summarized as follows:

- Global mapping of class-A vessels transmitting AIS information in areas not covered by coastal base stations.
- Updated vessel information several times per day.
- Short delay from data acquisition until data is available to the different users
- Have an operational system which can be trusted to provide data to the users.
- Have a secure system, where the integrity of the system is high and where the system is secured against misuse of data. The system should improve maritime security, not spread information which could worsen it.
- The system should be cost effective and based on small satellite technology.

This chapter looks at a possible architecture of an operational constellation.

7.1 Payload concept

7.1.1 Receiver

As shown in Table 4.3, KSX has found that a software defined radio (SDR) (Figure 7.1) is the best concept for an AIS receiver in space as it offers the highest flexibility. This flexibility opens for different uses of the SDR, where one also can look at various modes used at certain times, e.g. one mode for areas with low vessel density and one for areas with high vessel density.

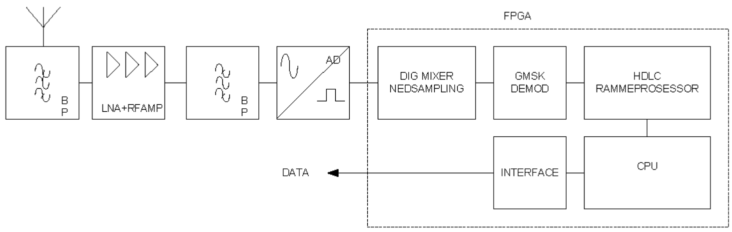


Figure 7.1 SDR receiver block diagram

In areas with low vessel density and corresponding high detection probability, simple algorithms in the onboard SDR will be able to decode most of the AIS messages and forward the information to the main computer for downlink at first contact with a ground station. This requires some processing on-board but gives the least strain on the downlink capacity. It is an obvious choice in the low vessel density areas.

Additional signal processing will be required in areas with high vessel densities to decode the AIS messages. This can be the combination of signals from different antennas and sophisticated signal processing to extract the data of one or several messages arriving at the same timeslot. While some of this may be handled by the processing power available to the payload on-board the S/C, much more processing power could be used if it was done on the ground.

To be able to do signal processing and extraction of AIS signals on ground, two solutions are available. The best solution, which introduces the least changes to the original received signal, is to use a bent pipe solution where the received signal is filtered, amplified and up-converted to a downlink frequency for direct downlink to a ground station where all the processing is done. The main requirement for this solution is that the satellite must have contact with a ground station at the same time as the AIS messages are received. While this may be problematic at the high seas, it could be a possible solution while the satellites are passing over European high density areas like the North Sea and the Mediterranean. For an operational system, this option should probably be disregarded because of the concern about the information being open and spread to everyone within the downlink antennas field of view.

The last option is to use a sample, store and forward solution, where the baseband is sampled and stored for downlink at first opportunity. While some information may be lost in the sampling process on-board, careful design should still enable on-ground signal processing of the sampled signal. This solution is the most flexible, but would also increase downlink bandwidth requirements, especially if the baseband from several antennas should all be downloaded. To lower the bandwidth requirements a solution could be to only sample one of the AIS channels. While all vessels should transmit alternately on the two channels, this could still cause a lower detection probability since only half of the messages from each vessel will be available for reception.

To find the requirements of storage capacity in one can look at the store and forward mode, also called digital bent pipe (DBP). For a DBP, a single two channel AIS receiver will produce 2Mbps of data. The system should normally have ground station access several times per orbit, but the storage capacity should at least be able to handle two full orbits. Assuming ~100 minutes per orbit, this will imply a storage capacity of 3GBytes per receiver.

Assuming onboard processing and decoding of signals, only 19.2 kbps of AIS data will be generated from one receiver. With 3 GB storage capacity this would mean storage of more than 24 hours of continuous operations.

Internally the communication rate between the sensor and the storage must be between ~20 kbps for the simplest solution and up to ~6 Mbps for the solution of three receivers using DBP.

7.1.2 Antenna

No perfect solution for the antenna was found for a global satellite based AIS system. The recommendation is therefore to await results from a technology demonstration mission using three orthogonal monopoles, and use this knowledge together with what is shown to be achievable through advance signal processing before a final choice is made for antennas in a constellation. However, with the knowledge gained through this study, Figure 7.2 shows that the double Yagi will give the best performance for a system covering ocean areas near Europe with high vessel density.

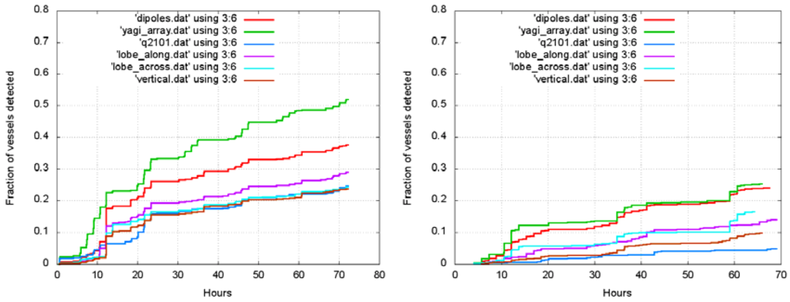


Figure 7.2 Comparison of detection probability in the North Atlantic (left) and North Sea (right) for a simple receiver on a single satellite with different antenna configurations.

7.2 Satellite constellation

The user requirements specify hourly updates of ship positions and that the area covered should stretch from the Mediterranean at ~30°N up to the Barents Sea at ~ 80°N. To achieve this, a constellation of satellites will be needed.

A large swath width would enable a constellation of fewer satellites to achieve the user requirements than a narrow swath width. The swath width is increased by raising the orbit altitude of the satellite and increasing the antenna FOV. On the other hand, a large swath width would lower the detection probability because it increases the number of AIS message a S/C receives simultaneously. This limits the choice of orbit altitude and FOV.

A third factor influencing the choice of orbit altitude is the mission lifetime. SSTL has looked at expected lifetimes for a generic S/C for different altitudes. Considering a lifetime of 5 years, an orbit altitude of 600 km is chosen as the design target. At 600 km the orbital period is approximately 97 minutes. Knowing that the circumference of the Earth at the equator is ~ 40,000 km this can be used together with the swath width to calculate a theoretical minimum number of satellites needed to achieve the user requirement of hourly updates north of 30°N. Table 7.1 shows the swath width at the equator and the corresponding minimum number of satellites needed for the different antenna options at an altitude of 600 km.

Antenna solution	Swath width (equator)	Minimum # satellites
Double Yagi antenna	3500 km	12
Quad Helix antenna	5000 km	8
Three orthogonal antennas	5000 km	8

Table 7.1 Swath width at the equator and theoretical minimum number of satellites needed for a constellation at an orbit altitude of 600 km

Because orbits are not entirely stable, it is better to look at Walker constellations which will require more satellites than the absolute minimum in order to have system that will meet the user requirements. The Walker is a configuration that is useful in providing uniform coverage over the Earth's surface from a LEO satellite system. A common task in system design is to determine what values for the parameters of a Walker Constellation yield the best coverage.

The Walker code, when combined with the constellation altitude and inclination parameters, which are the same for all satellites in the constellation, facilitates rapid analysis of a large number of constellation configurations.

The relative positions of many satellites within a Walker pattern are computed from a simple three-number code. This code is stated as T/P/F.

T - is the total number of satellites
P - is the number of orbital planes
F - is a measure of the relative positions or phasing of the satellites in any two adjacent planes.

There are an equal number (T/P) of evenly spaced satellites in each orbital plane.

The nature of the phasing parameter F is sufficiently non-intuitive that a brief discussion is warranted. The offset or phase difference between adjacent planes is measured in "Pattern Units" or PU, where 1 PU is equal to 360° divided by T, the total number of satellites in the constellation.

The offset between any plane and the next plane to the east equals the product of F multiplied by PU. The Globalstar™ constellation uses T/P/F = 48/8/1. Since T = 48, PU = 7.5°, and since F =1, the offset between corresponding satellites in adjacent planes is 7.5° of arc.

The Globalstar™, Iridium ™, and GPS ™ constellation use Walker delta patterns.

7.2.1 Area Target Definition

The requirement on geographical coverage imposes a need to define a target area with a wide range in latitude. The required coverage area has to include the whole Mediterranean basin, the Atlantic Ocean in proximity of the European coastline, the North Sea, the Baltic Sea and the Norwegian Sea. This is reflected in a latitude range varying from 34° N to 70.5°N and longitudes from 12°W to 43°E.

Boundary points of the selected marine area are detailed in Table 7.1.

Geodetic-Lat	Geodetic-Lon
34.00	-12.00
30.00	18.00
30.00	36.00
40.00	43.00
48.29	37.90
47.86	29.60
42.85	26.31
42.28	21.01
47.43	13.57
39.49	-4.89
41.70	-6.47
42.99	-0.17
45.85	1.40
47.57	-0.89
50.29	3.98
52.58	8.85
53.30	14.86
53.73	22.01

Geodetic-Lat	Geodetic-Lon
61.66	34.32
61.66	25.02
62.95	23.59
64.95	26.45
67.39	24.88
59.96	14.00
60.66	13.14
61.52	8.42
68.25	18.86
69.10	28.45
66.10	32.17
62.95	35.18
64.00	43.00
70.50	43.00
70.50	14.00
63.00	-12.00
53.00	-12.00
34.00	-12.00

Table 7.1 Area Target Boundary Point

The resulting area is highlighted the surface bounded by the blue outline in Figure 7.3.

Figure 7.3 Area Target Definition

7.2.2 Walker 48/8/1, FOV = 120°, 600 km

A Walker constellation at 600 km in the configuration 48/8/1 has been selected. The antenna is characterised by a FOV = 120°.

A further analysis of the coverage performance is provided in the next section. The data are presented by means of a set of charts.

- *3D configuration of the constellation*
  - It provides a three dimensional representation of the constellation. The satellites populating the scenario are presented along the selected Walker's orbits. The green cones identify the antenna FOV pattern and their projection on ground.
  - The "European_Sea" area target is identified by the blue line surrounding the European coasts.
- *Coverage time - % per day*
  - Coverage Time measures the amount of time during which grid points are covered. Because Coverage Time does not have a dynamic definition, no time-dependent information is computed.
  - The percentage of time during which a point is covered: computed as 100x(TotalTime)/ (CoverageInterval).
  - It defines the percentage of coverage during a 24 hours simulation. The key legend presents fading colours form RED, for minimum percentage coverage (0%), to BLUE, for maximum percentage coverage (100%). Each shading zone of the target area reflects how good the constellation coverage is. Different colours are associated to different quality level of coverage.
  - The key legend is divided in 10 steps of 10% each.
- *Total coverage time*
  - The amount of time (over the entire coverage interval) during which a point is covered.
  - It defines the total coverage time during a 24h simulation. The key legend presents fading colours form RED, for minimum time coverage (0 hrs), to BLUE, for maximum time coverage (24 hrs). Each shading zone of the target area reflects how good the constellation coverage is. Different colours are associated to different duration of coverage. The key legend is divided in 24 steps of 1 hour each.
  - Total Coverage Time is an indicator of coverage during the entire simulated period, thus not representing a punctual representation of the quality of the service.
- *Time Average Gap*
  - It expresses (in minutes) the duration of the gaps. Gaps are defined as time periods without coverage by any constellation element.
- *Coverage Definition*
  - The chart presents a diagram of the constellation coverage over the area target. The coverage quality has been expressed in terms of percentage during the 48 hrs simulation, where 100% means 24/7 coverage.

The orbital plane inclination has been selected in order to guarantee the coverage at highest latitude coastlines with the imposed antenna FOV. Therefore the selection of inclination has been driven by the sensor characteristics, which represents the most stressful constraint in the orbit trade-off.

In order to achieve the coverage of the northern portion of European coastal zones the nominal inclination has been set at 65°. Table 7.2 describes a constellation of 48 elements distributed along 6 planes. Based on Walker constellation distribution this means 6 satellites in each plane equally spaced at 45° in each orbit.

T	P	F	PU	e	h	I	FOV
48	8	1	7.5°	0	600 km	65°	120°

Table 7.2 Walker 48/8/1, Constellation Parameters

Figure 7.4 provides a 3D sketch of the operational scenario. The 8 planes can be easily recognized, each of them identified by a dedicated colour.

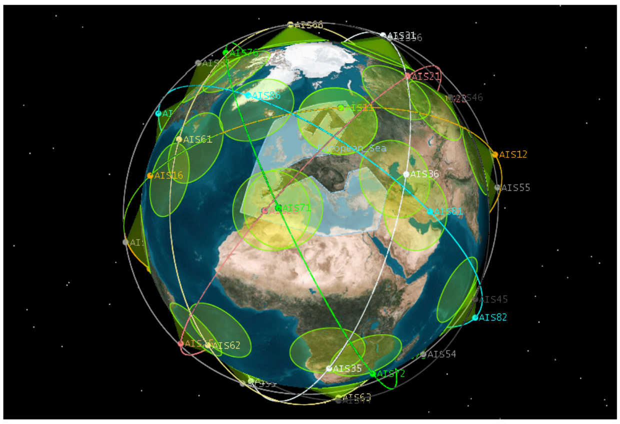


Figure 7.4 Walker 48/8/1, 3D Configuration

The satellite IDs consist of:

- Name of the mission: AIS
- Progressive plane number in the constellation: 1-8
- Progressive satellite number in the plane: 1-6

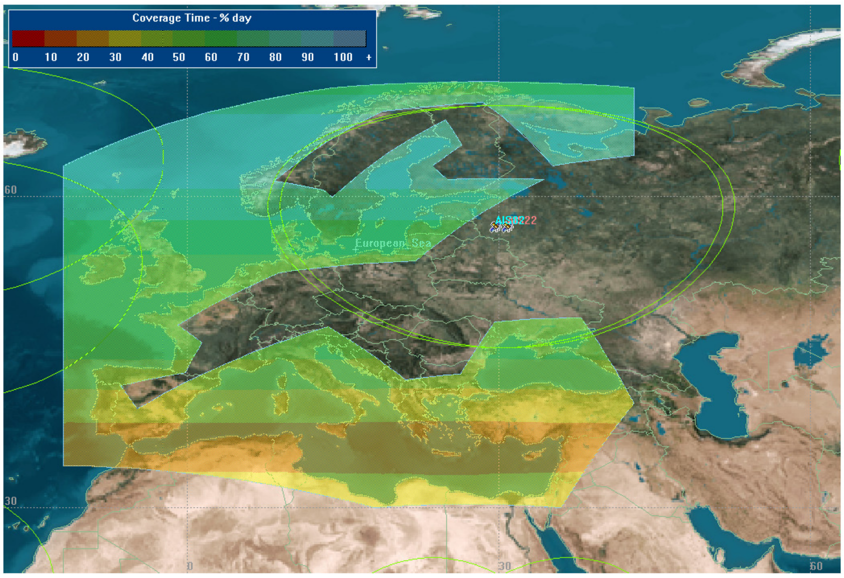


Figure 7.5 Walker 48/8/1, Coverage Time - % Day

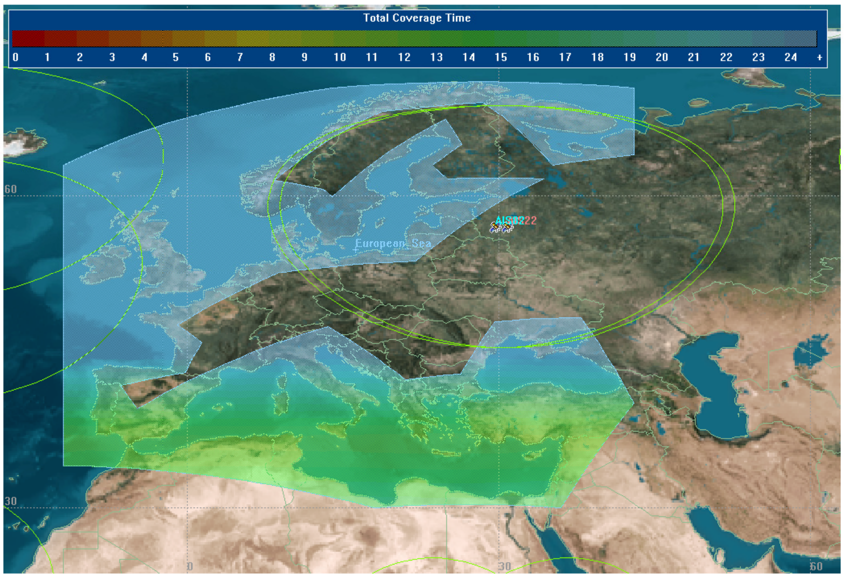


Figure 7.6 Walker 48/8/1, Total Coverage Time

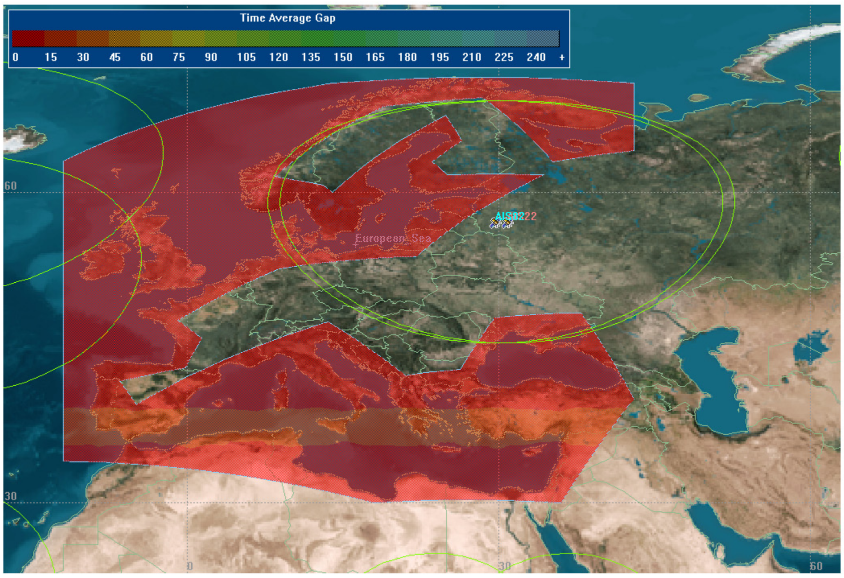


Figure 7.7 Walker 48/8/1, Time Average Gap

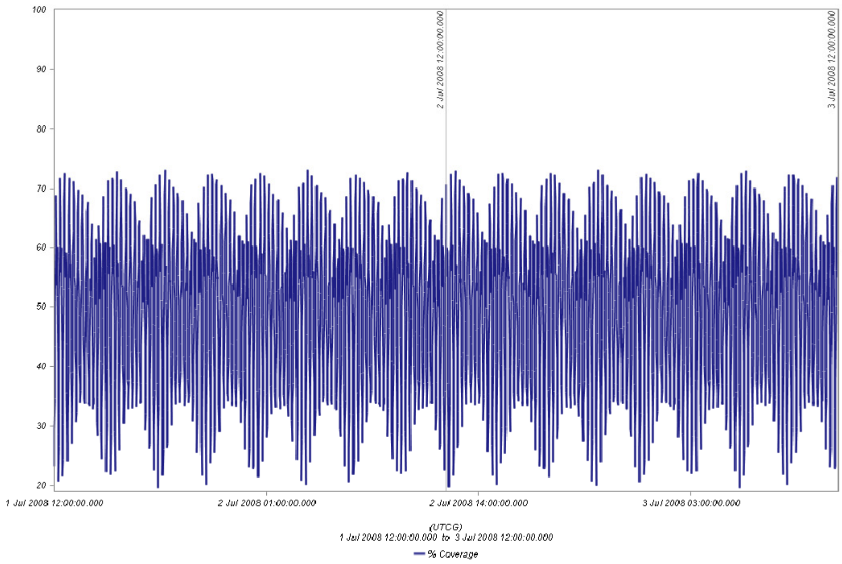


Figure 7.8 Walker 48/8/1, Coverage Definition

As highlighted in Figure 7.7, the Time Average Gaps plot reveals that the constellation design selected is compliant with the timeliness requirement. UR-02 highlights that hourly updates of the AIS system information are accepted by the user community.

The plot reveals gaps in the range 0'-15' for the majority of the European Sea area. Due to the orbital configuration of the constellation, a narrow band in latitude range between 39°N and 35°N is affected by longer gaps in the range of 15'-30'.

7.2.3 Target Access

In order to evaluate the constellation coverage a group of target points has been selected.
Next is the list of the selected marks (from South to North):

- Cairo
- Tunis
- Athinai
- Lisboa
- Istanbul
- Marseille
- London
- Oslo
- Helsinki
- Murmansk

Figure 7.9 Access Target Points

Table 7.3 summarizes the information about minimum and maximum Access/Gaps obtained for the selected targets.

		Cairo	Tunisi	Athenai	Lisboa	Istanbul
Access	Min duration [sec]	68	65	12	4	1
	Max duration [sec]	514	408	448	466	532
	Mean duration [sec]	367	323	372	374	396
Gaps	Total gaps	494	428	12.279	438	506
	Min duration [hh:mm:ss]	00:08:31	00:09:43	00:00:43	00:00:01	00:00:00
	Max duration [hh:mm:ss]	00:11:03	00:56:04	00:54:44	00:14:01	00:21:07

		Marseille	London	Oslo	Helsinki	Murmansk
Access	Min duration [sec]	5	5	30	180	13
	Max duration [sec]	593	498	438	442	372
	Mean duration [sec]	400	372	389	393	306
Gaps	Total gaps	604	742	1037	1036	1276
	Min duration [hh:mm:ss]	00:00:16	00:01:50	00:01:40	00:01:37	00:00:04
	Max duration [hh:mm:ss]	00:11:26	00:09:24	00:01:55	00:01:38	00:04:19

Table 7.3 Gaps and Access

As demonstrated by the charts in Section 7.2.2, the constellation has the tendency of a better coverage for Northern regions.

7.3 Ground segment

The number and distribution of ground stations is determined by the amount of data which needs to be uplinked or downloaded, the capacity of the uplink/downlink communication channels, the orbits of the satellite constellation and the timeliness of data user requirement.

Meeting the user requirement of 30 minutes from data acquisition until the decoded data are available to the user will be very difficult if not impossible on a world-wide basis. Restricting this requirement to only be necessary for areas around Europe will limit the need for ground stations to mainly be concentrated in Europe. Using inclinations between 80-100 degrees, ground stations in the Arctic, e.g. Svalbard, and Antarctic, e.g. Troll, would increase downlink opportunities up to twice per orbit in addition to any ground stations covering passes over Europe.

Using a bent-pipe approach, the reception, signal processing and decoding must be done in the ground segment. The data will be received without delay and up to 30 minutes will be available for data treatment before it is forwarded to the users. Compared to a sample, store and forward solution, this will reduce delivery time considerably due to the possible time delay between observations and downlink in a store and forward solution. A time delay will also have to be considered for an on-board processing solution, but then the AIS signals will already have been decoded when they are received by a ground station.

The main challenge of the store and forward solution will be to ensure that the downlink capacity is large enough to downlink all received data during each contact with the ground station.

In addition to the ground station(s), the ground segment also consists of a mission control centre responsible for the operation of the service and the storage and distribution of information to the end users. This part of the architecture will be ground based and should be built around the discussion of data policy, where the European Maritime Safety Agency is mentioned as a possible candidate as an operational entity for a European space based AIS system for maritime security. This part of the architecture is currently not foreseen to introduce any technical challenges and is not discussed further here. The only part worth mentioning is that the data policy recommends encryption of the data and this will not be compatible with an analogue bent pipe solution.

7.4 Downlink communication

For the communication to ground the requirement will be for all new data to be downlinked during one ground station contact. In Figure 6.9 is shown that an average ground station contact is more than 400 seconds long. Table 7.2 shows the required downlink capacity for one-three ground stations for AIS data from a single receiver using either SDR or DBP in a full orbit.

Single orbit	100% DBP	50% DBP – 50% SDR	25% DBP – 75% SDR	100% SDR
Total data (Mbits)	12000 Mb	6057,6 Mb	3086,4 Mb	115,2 Mb
400 s (one GS)	30,00 Mbps	15,14 Mbps	7,72 Mbps	0,29 Mbps
800 s (two GS)	15,00 Mbps	7,57 Mbps	3,86 Mbps	0,14 Mbps
1200 s (three GS)	10,00 Mbps	5,05 Mbps	2,57 Mbps	0,10 Mbps

Table 7.2 Downlink requirements for pure AIS data using a single receiver in one full orbit for different combinations of SDR or DBP.

Analysis indicates that a simple receiver will cover most areas of the world and sophisticated processing is only required in some high density areas. Thus the “25% DBP – 75% SDR” choice would be the best choice. Taking also into account some overhead, e.g. telemetry and encryption of data, a downlink capacity of 20 Mbps should be enough. The option with three receivers would require up to three times that capacity.

7.5 Possible architectures

When looking at architectures that will try to meet the update rates required in all European waters of interest, the suggested constellation varies from 8 to 48 satellites. When looking at a service like space based AIS detection for maritime security, the cost of such a constellation must be manageable and thus the size and complexity of the satellites should be kept as low as possible. Nanosatellites will be too small, but micro satellite platforms less than 100 kg, should be able to handle the demand of antenna, AIS sensor and communication for such a system. The most challenging architectures in regard to this will be those utilizing a double Yagi configuration, but these are also the ones with the best detection probability. Five possible constellation architectures are described below, and a trade is done in chapter 7.6. These five architectures also represent at least one option from each of the three antenna configurations described in 4.6.

7.5.1 Mini constellation

The "mini constellation" architecture uses the minimum number of satellites which passes over European areas at least once per hour, with the simplest of the antenna solutions; a constellation of 8 satellites in 600 km sun synchronous circular orbits with the three orthogonal monopoles solution. This is the cheapest solution, though a more detailed study would need to be done before this architecture is chosen, in order to determine if the stability of the orbits is good enough to stay within the designed update rates throughout the lifetime. This solution depends strongly on very advanced signal processing being able to decode messages from all ships in areas of high vessel density. The antenna solution is the simplest but since there are three receiver chains, there is a higher power demand and there may be a higher downlink rate demand than on some of the other solutions, especially in the areas where the DBP solution is used. The constellation is shown in Figure 7.10.

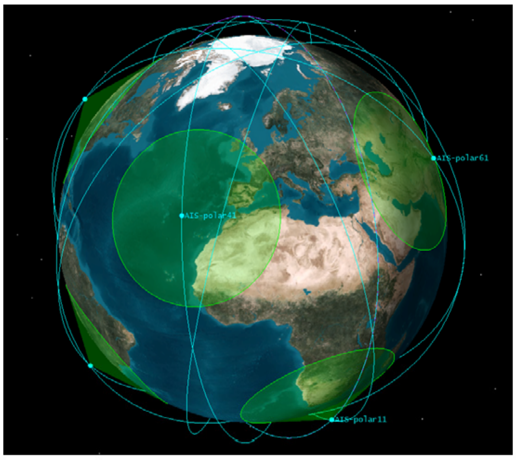


Figure 7.10 Mini constellation

7.5.2 Mix 1 constellation

The "mix 1 constellation" architecture uses the same antenna solution as the "mini constellation", but with more satellites for a more robust constellation design; 12 satellites in a 12/4/1 walker constellation with 50 degrees inclination, and 4 near polar satellites covering the high latitudes, all in 600 km circular orbits. All areas will be covered more often and the demand on detection probability from one single satellite will thus be slightly less than in the "mini constellation" for the same quality of service. The constellation is shown in Figure 7.11.

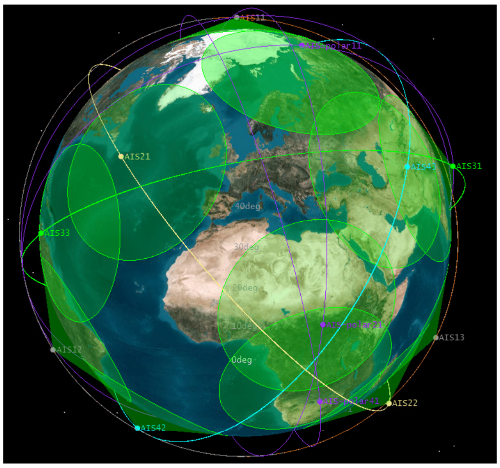


Figure 7.11 Mix 1 and Mix 2 constellations

7.5.3 Mix 2 constellation

The “mix 2 constellation” architecture is similar to the “mix 1 constellation” except that a 2.1 λ quadrifilar helical antenna is used instead of the three monopoles. This architecture will highlight the quadrifilar helical antenna solution. It will reduce the receiver complexity from 3 to 1, and reduce the power and downlink rate requirements similarly. On the contrary side, a deployable mechanism is needed for the antenna. This increases the mechanical complexity of the antenna, but the deployment of a single quadrifilar helical antenna in space is believed to be of only moderate complexity, and should be relatively easily handled on a micro satellite platform. This architecture has its downside on the detection probability. Because of the circular polarization, all messages are received, making decoding harder and lowering the detection probability of this solution. Even though the antenna has higher gain than the monopoles, accounting for side lobes still gives a swath width to the horizon. The constellation is shown in Figure 7.11.

7.5.4 Mix 3 constellation

The “mix 3 constellation” architecture is similar to the “mix 1 constellation” and “mix 2 constellation” except that a double Yagi array is used as the antenna. This represents a reduced solution compared with the “full constellation”, while using the same antenna arrangement. It will reduce the receiver complexity from 3 to 1 compared with the “mix 1 constellation”, and reduce the power and downlink rate requirements similarly. On the negative side the mechanical complexity of the antenna increases significantly and two deployable or inflatable booms will be required. The double Yagi offers a reduced FOV compared to the other two antenna options, reducing this architecture’s ability to deliver the required update rates. The main advantage is the use of both message discrimination because of Faraday rotation and reduced FOV. This enables the satellites to achieve a significantly better detection probability in areas of high vessel density. The constellation is shown in Figure 7.12.

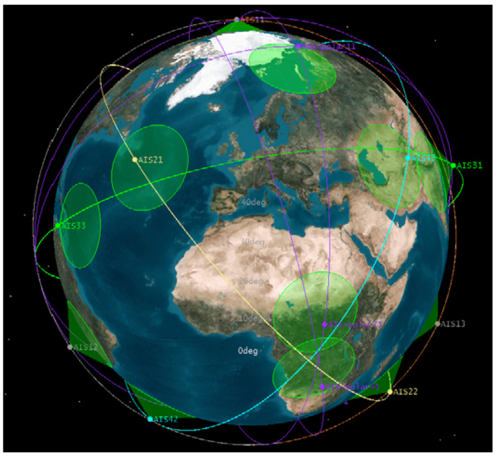


Figure 7.12 Mix 3 constellation

7.5.5 Full constellation

The "full constellation" architecture uses 48 satellites in a 48/8/1 walker constellation with a double Yagi as an antenna. This constellation is discussed in detail in chapter 7.2. The same double Yagi array as in the "mix 3 constellation" is used, which has a FOV of ~120 degrees. This constellation in 600 km with an inclination of 65 degrees gives world coverage with update rates always better than 60 minutes. The increase in satellites from the "mix 3 constellation" mitigates the reduced coverage because of reduced FOV. This is the architecture which scores highest on detection probability. While there are 3 times as many satellites as in the "mix" constellations and 6 times as many as in the "mini" constellation, the number of launches needed could be similar in all the cases if it is possible to fit all the satellites in one orbit plane into one launch. This architecture will also be least to susceptible to the failure of any one satellite. The constellation is shown in Figure 7.4.

7.6 Baseline operational architecture

Table 7.4 shows a comparison of the five different architectures described in chapter 7.5. The focus has been on the detection probability, the complexity of the constellation (size) and the power and downlink requirements.

Architecture	1	2	3	4	5
# Sat	8	16	16	16	48
Inclination	98.7°	98.7° and 50°	98.7° and 50°	98.7° and 50°	65°

Architecture	1	2	3	4	5
# Rec/Sat	3	3	1	1	1
P/L Power	15 W	15 W	5 W	5 W	5 W
Downlink	60 Mbps	60 Mbps	20 Mbps	20 Mbps	20 Mbps
Comm. access to Europe	< 65 min	< 45 min	< 45 min	< 45 min	<60 min
Det. Prob. Mediterreanean	14.49 %	28.57 %	5.92 %	34.15 %	47.71 %
Det. Prob. North Atlantic	10.60 %	7.38 %	2.46 %	25.55 %	43.76 %
Det. Prob. North Sea	1.98 %	0.46 %	0.00 %	0.36 %	4.60 %
Det. Prob. at 60°+ Lat.	84.07 %	68.41 %	40.73 %	44.29 %	69.54 %
Antenna choice	3 x Monopole	3 x Monopole	Quadrifilar	Double Yagi	Double Yagi
Antenna complexity	Low	Low	Moderate	High	High
µSat suitability	Excellent	Excellent	Excellent	OK	OK
Cost	Medium	High	High	High	Very High
Pointing req.	None	None	10 degrees	10 degrees	10 degrees

Communication access to Europe is given as the maximum delay between to satellites having access to the same spot on the European continent.
Detection probability is an average per hour probability taken over 5 hours.

Table 7.4 Comparison of architecture concepts.

As can be seen from the table, none of the architecture meets the user requirement of hourly update rates with 100 % detection probability in the chosen areas. This may be because of the conservative simulations and payload detection probability properties assumed in this project. Thus the first natural step should be to get more knowledge on actual detection probability through a demonstration project. There are also several companies who claim to have signal processing algorithms that will be able to significantly increase the detection probability of AIS from space. If these or other techniques can be demonstrated to solve the challenge of simultaneously received AIS messages from space it could make a global space based AIS service possible.

Looking at the numbers in the table, one can see that the double Yagi is the only antenna solution with significant detection probability in both the Mediterranean and the North Atlantic. The narrower field of view, which increases the detection probability, also requires more satellites in the constellation to cover the same areas as the antenna solutions with FOV to the horizon. This and the inclination is also the reason why the detection probability in areas of relatively low vessel density, like north of 60° latitude, is higher for the triple monopole solutions than for the other solutions. This would also suggest that a demonstration satellite should focus on this solution as it is the most flexible, has the simplest antenna solution, has the highest detection probability in low vessel density areas, and has a nonzero detection probability in high vessel density areas. The downside is a higher demand of power and downlink capacity, but if this is a problem, a demonstration mission does not need to operate continuously and can preserve energy for use in parts of the orbits or during a dedicated measurement campaign. A demonstration satellite could also accept to downlink data over several orbits if the downlink requirements are too difficult to achieve.

It is also clearly evident that the use of circular polarisation as in the quadrifilar helical solution gives the worst detection probability in all the given areas.

At this point in time it is really too early to decide on a mission concept for a full operational constellation. Of the options in Table 7.4, only option 5, which presumably will be the most expensive, shows detection probability rates which are high enough to be considered for a European system. This is then chosen as the baseline for the operational system in this project, but it is emphasised that this should be re-evaluated after analysis of detection probability feasibility of a dedicated space based AIS demonstration mission.

Figure 7.13 shows an illustration of the functional architecture of such a constellation, with vessels, a satellite representing the constellation, transmitting of data via ground stations to a mission control centre (e.g. EMSA) and the distribution of data to the registered and approved users.

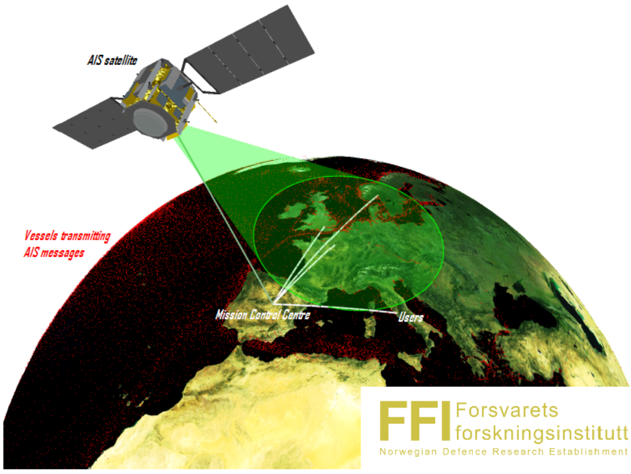


Figure 7.13 Functional architecture, European satellite based AIS system.

Figure 7.14 shows the data flow of the same architecture. It is also possible that the mission control centre is divided in two, where one is responsible for the operation of the satellites in the constellation and the other is responsible for the AIS data.

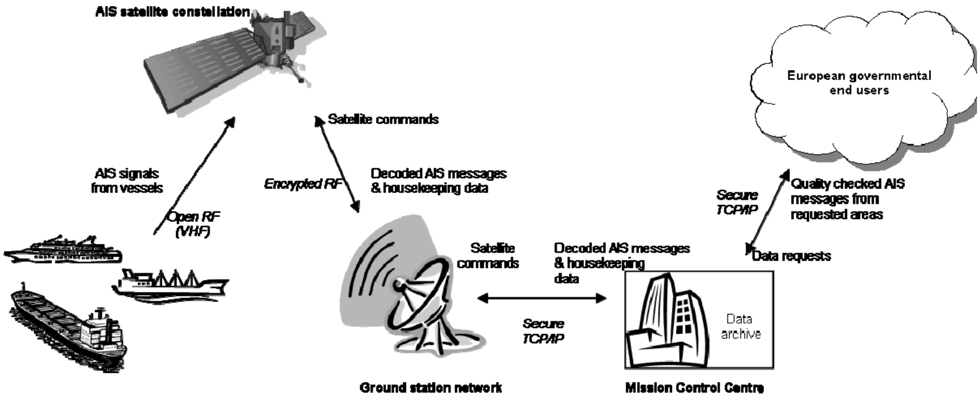


Figure 7.14 Data flow in a European satellite based AIS service.

7.7 Operational mission- preliminary mission requirements

A summary of the preliminary mission requirements identified is given in Table 7.5

MR-ID	Description	Requirement
MR-001	System segments	The system involved in the mission shall be composed by • Space segment • Ground segment • Launch segment
MR-002	Space segment coverage	The space segment should be able to receive AIS messages from all around the globe, and cover European waters from the Barents Sea to the Mediterranean at least once per hour as given in UR-01 and UR-02.
MR-003	Constellation	A constellation of satellites should be designed to meet the coverage requirement
MR-004	Inclination	The inclination of the satellites should include orbits between 80 and 100 degrees
MR-005	Altitude	Preferably 600 km or lower

MR-ID	Description	Requirement
MR-006	Timeliness	The system should enable downlink from space segment to ground segment at least once per orbit, and preferably twice per orbit in more than 50 % of the time. Especially for data from the areas around continental Europe the time from data acquisition to users should be less than 30 minutes.
MR-007	Lifetime	Each satellite in the constellation should have minimum 5 years operational in-orbit lifetime
MR-008	Radiation	The space segments shall handle the maximum radiation expected from 5+ years in low Earth orbit
MR-009	Vibration	The vibration load will be dependent on the choice of Launcher. The space segments should be designed for launch on multiple launchers.
MR-010	Backup S/C	The system shall have spare/backup spacecrafts ready for launch on short notice in case of unexpected failure of one of the operational spacecrafts in the constellation.
MR-011	End-of-life	Re-entry shall be completed in less than 25 years after operational end of life by natural decay.
MR-012	Platform	The mission shall be compatible with small satellite platforms with launch mass < 100 kg.
MR-013	Launch window	The spacecrafts shall be compatible with a daily launch window.
MR-014	Power	The receiver should operate on a 28V unregulated power line.
MR-015	Receiver mass	The receiver total receiver mass including housing should be less than 4 kg
MR-016	Receiver size	The total size of the receiver including housing should be less than 150mm x 250mm x 150mm
MR-017	Antenna size and mass	The antenna should be able to be accommodated on a micro satellite platform.

MR-ID	Description	Requirement
MR-018	Duty cycle	The payload should handle a duty cycle of 90% for an operational service, accepting some off-time or firmware upgrade when passing over large land areas.
MR-019	Mass memory	> 500 MByte. The main part of this is for data storage, which could also be handled by a separated spacecraft storage medium.
MR-020	Thermal	The payload should be able to handle temperatures between -20C and +50C
MR-021	AIS detection algorithms	As far as possible the payload should use the best detection algorithms available for decoding simultaneously received messages. The final choice of algorithm and onboard or onground processing should be based on experience from a demonstration mission.
MR-022	Attitude determination	Better than 1 degree
MR-023	Attitude control	Better than 10 degrees
MR-024	Orbit maintenance	Not foreseen as necessary. Will only be required in case the changes are affecting the constellations total feasibility of meeting the requirements of coverage, revisit time and timeliness
MR-025	GNSS	A receiver for a global navigation satellite system should be implemented to provide the AIS payload with a reference time similar to that used for the AIS system.
MR-026	Propulsion	Not foreseen as necessary at this point. Should be evaluated for the whole system/satellite constellation when/if such a system is planned.
MR-027	Uplink capacity	Enough to handle communication of commands to spacecraft and payload. A minimum of 10 kbit/sec should be able to handle this.
MR-028	Downlink capacity	>2Mbits/sec
MR-029	Coding	A coding scheme ensuring a minimum loss of data should be implemented.
MR-030	Encryption	The data should be encrypted to ensure the systems integrity, and that the information cannot be used to reduce maritime security.

MR-ID	Description	Requirement
MR-031	Ground Station location	Ground stations should be distributed around the world to best meet the user timeliness requirement of 30 minutes from data acquisition to users. There should at least be two contacts with ground stations per orbit in the majority of the orbits.
MR-032	MCC space segment control	The MCC or a dedicated space operations centre. The MCC should monitor the space segment and ground stations of the system. Be responsible for any commanding of the satellites, ensure that the system is always operational and take immediate action at any anomalies registered in the space segment or on the ground stations.
MR-033	MCC Data processing	MCC should employ the data processing necessary to convert the received AIS data to standard formats.
MR-034	MCC Database	The MCC should house a database containing all AIS messages received for 10 years.
MR-035	Mirror backup storage	The MCC Database should have a Mirror backup storage updated on a regular basis, in case the main database fails.
MR-036	Metadata	Metadata to be stored in the database should be: • ID of message received • ID of satellite which received message • Time of reception • Position of satellite at time of reception • Doppler shift • Message quality tag (e.g. duplicate vessel IDs, strange/wrong position reports etc.)
MR-037	Data distribution scheme	Correctly formatted updates of AIS data from the system should be made available on a server accessible by registered users. Users should also have the opportunity to request data from the MCC database.

MR-ID	Description	Requirement
MR-038	User Validation	All users accessing the data from the system should be pre checked and registered before gaining access, and each access should be registered to prevent misuse of the system.
MR-039	Data Encryption	To prevent unregistered use of the data, all data flow from downlink to users should be encrypted.
MR-040	Secure Network	The users should access the data from the MCC through a dedicated secure network or through secure Internet connections.
MR-041	Product Assurance	A thorough product assurance document should be produced as the first document in a mission study. The product assurance should be sufficient for a 5 year LEO orbit spacecraft. ITAR and space grade components should be limited to a minimum to keep the overall cost down. All systems used should be based on thoroughly tested components or components with space heritage. Redundancy should primarily be handled at system level.

Table 7.5 Preliminary operational system mission requirements

B.12 Conclusions and Recommendations

8 Conclusions and Recommendations

This chapter gives some comments to the status after the study and where to continue.

8.1 The technology readiness level of the design

Based on the Preliminary Electrical Schematic, Bill of Materials, the different project reports from the partners and information obtained during the various project meetings, Norspace judges the technology readiness level to be at ESA TRL3 level (Analytical/experimental critical function/characteristic proof of concept).

Norspace has also identified the following issues for the next phase:

- Kongsberg Seatex have demonstrated the feasibility of the AIS receiver with their Breadboard design , this gives a good starting point for the next phase
- the design needs to be updated taking into account Engineering and Reliability, Availability, Maintainability and Safety (RAMS) analysis (see §2.3 Space Design Process)
- EEE-parts need to be upgraded to space quality level and follow derating requirements, see details given in §2.5 AIS Receiver Components
- Mechanical housing, Electronic Power Supply (EPC), Telemetry / Telecommand (TMTC) have not been a part of the study and needs to be implemented and analysed (EMC, thermal, shock, vibration etc.)
- Constraints from possible launchers and/or satellites should be identified (EMC, thermal, shock, vibration etc.)

8.2 Demonstration mission

This document gives the first steps in establishing a demonstration mission, which later could lead to a European space-based AIS detection capability for maritime security. To continue, a phase A mission study for the demonstration mission must be started as well as a development study for bringing the payload from the current technology readiness level 3 to the desired technology readiness level 5 (needed for space demonstration). These could be started at the same time if the payload developer was included also in the mission study. The major step for the payload would be to improve the algorithm used for GMSK decoding and establishing a system of three receivers which also can handle simultaneously sampling in a DBP mode.

It is strongly recommended to go through a demonstration mission before planning a full operational system, unless someone in the meantime can prove that they have solved all problems with simultaneous arrival of AIS messages over the busy European waters. A thorough understanding of the limitations of a system is important for any user for maritime security, as the information or missing information provided by the system will effect security related decisions if the system is used operationally. Figure 8.1 shows a possible mission programmatic schedule with rough order of magnitude duration for each tasks.

ID	Task Name	Duration	Start	Finish
1	**AIS DEMONSTRATION MISSION**	**575 days**	**02/06/08**	**13/08/10**
2	**AIS payload development**	**420 days**	**02/06/08**	**08/01/10**
3	Establish preliminary design	90 days	02/06/08	03/10/08
4	Detailed design and test definition	180 days	06/10/08	12/06/09
5	Manufacturing of EQM and GTSE	90 days	15/06/09	16/10/09
6	**Validation testing**	**60 days**	**19/10/09**	**08/01/10**
7	Functional and performance tests	15 days	19/10/09	06/11/09
8	EMC tests	15 days	09/11/09	27/11/09
9	Vibration tests	15 days	30/11/09	18/12/09
10	Thermal Vacuum tests	15 days	21/12/09	08/01/10
11	S/W and F/W development	200 days	06/10/08	10/07/09
12	**Platform development**	**575 days**	**02/06/08**	**13/08/10**
13	**Phase A/B study**	120 days	02/06/08	14/11/08
14	**Phace C/D - Detailed Defintion and Production**	**425 days**	**17/11/08**	**02/07/10**
15	Final Design/ AIT Preparations	120 days	17/11/08	01/05/09
16	EGSE Upgrade	100 days	17/11/08	03/04/09
17	MGSE Procurement	75 days	17/11/08	27/02/09
18	**Assembly Integration and Test**	**295 days**	**04/05/09**	**18/06/10**
19	Electrical Integration	40 days	04/05/09	26/06/09
20	Integrated System Testing	40 days	29/06/09	21/08/09
21	Hard Slack	50 days	11/01/10	19/03/10
22	Environmental Tests	50 days	22/03/10	28/05/10
23	End to End Tests	15 days	31/05/10	18/06/10
24	**Packing/Transfer to Launch Site**	10 days	21/06/10	02/07/10
25	**Launch preparations**	30 days	05/07/10	13/08/10
26	**Launch**	0 days	13/08/10	13/08/10
27	**In orbit operations**	**581 days**	**16/08/10**	**05/11/12**
28	LEOP	6 days	16/08/10	23/08/10
29	Commissioning Phase	45 days	24/08/10	25/10/10
30	Operational Phase	524 days	26/10/10	26/10/12
31	End Of Life Phase	6 days	29/10/12	05/11/12

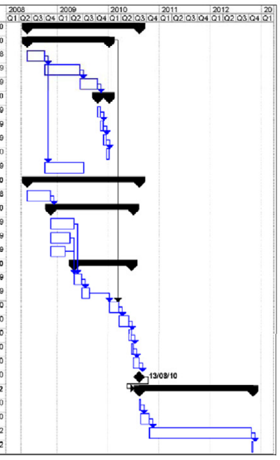


Figure 8.1 Possible project plan for a demonstration concept

8.3 Operational system

8.3.1 3rd frequency

One possible solution for obtaining global coverage is to allocate a third AIS channel [26] exclusively for space-based AIS. These messages will contain enough delay bits to avoid message collision from messages transmitted in different slots, and the nominal repetition rate will be decreased to one message every third minute. The total capacity of a space-based AIS sensor would increase to over 10,000 vessels within the spacecraft field of view. This is sufficient to achieve almost global coverage every seventh orbit as seen in Figure 8.2. There are still orbits where the detection probability falls below 90% in certain areas. Figure 8.3 shows the orbit with lowest detection probability during a 24-hour period.

One way to improve the detection rate is to specify that only vessels out of contact with a land-based AIS station shall transmit on the AIS space frequency. Fortunately, most of the coastal nations in the areas with high vessel densities either have such a system or are in the process of setting it up. Hence, a simple way to study the effect of this requirement is to remove all vessels within a fixed distance from any coastline. A part of the global vessel map is shown in Figure 8.4. It shows the vessels close to the coastline in red and vessels that would transmit on a third frequency in blue. The number of vessels transmitting on the third frequency decreases from around 52,000 to below 35,000 using the current vessel density distribution. This is most likely a conservative reduction in the number of vessels since most of the vessel distribution was derived from ocean-going ships.

Figure 8.3 and Figure 8.5 illustrate the increased performance of a space based AIS system when removing vessels close to the coastline. This simulation assumed a satellite with a vertical helix antenna, which is the antenna with the worst performance of those studied. The conclusion is that a third AIS frequency can provide global coverage from space.

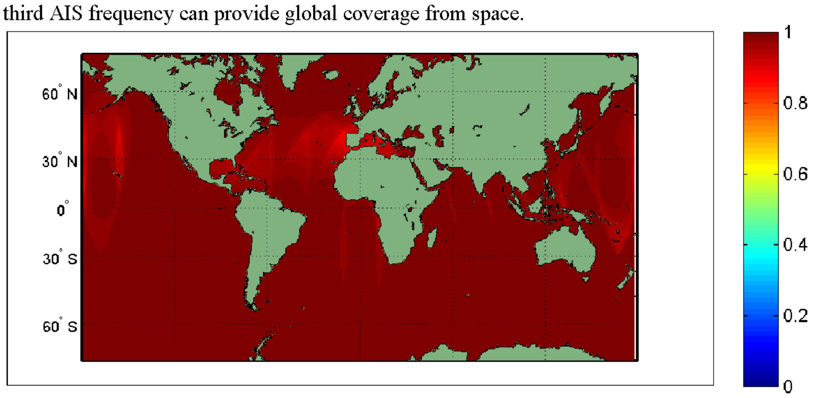


Figure 8.2 The cumulative detection probability after 7 orbits using a 3rd frequency with the

enough delay bits in the message specification to avoid collision between messages transmitted in different slots.

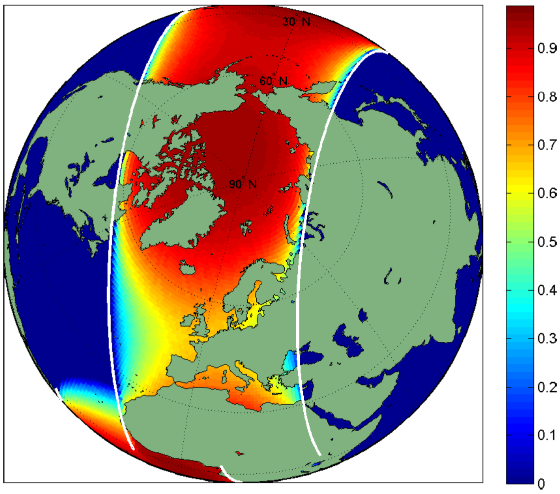


Figure 8.3 Detection probability during one orbit. The spacecraft is trajectory starts above Africa and moves north. This is the pass with the lowest detection probability during a 24-hour period.

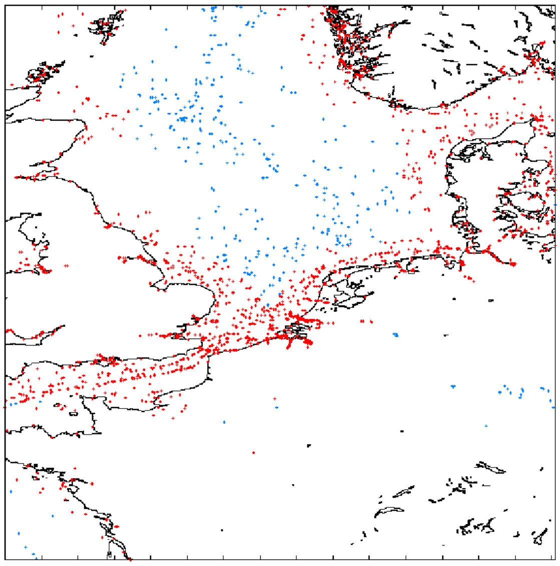


Figure 8.4 The vessels close to a coastline (red) are removed from the second simulation of a

third frequency.

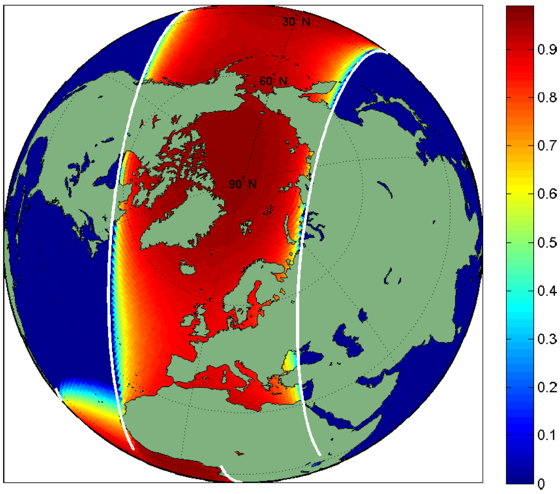


Figure 8.5 The same orbit as in Figure 8.3, but now only vessels outside the range of AIS base stations transmit on the third channel

8.3.2 Comments to user requirements

An extension of the study will investigate user requirements witih a wider perspective than what was done in the original study. A lesson learned is that care should be taken in order to get quantifiable requirements which can be used in a trade-off of design. A questionnaire or something similar should provide many alternatives where the users can give a preference to what is absolutely necessary for the data to be of interest, what would be very useful, what would be nice to have, and what is not important. This can be important information when considering a system architecture that would be acceptable to the users both in terms of predicted costs and service availability.

B.13 List of acronyms

List of acronyms

A/D	Analogue/Digital
AIS	Automatic Identification System
AISDET	AIS Detection probability program
AIT	Assembly Integration Test
AOCS	Attitude and Orbit Control system
ASP	Application Services Provider
BCR	Battery Charge Regulator
BOM	Bill of Mateerial
BP	Bent Pipe (Analogue)
CAN	Controller Area Network
CIC	Cascaded Integrator-Comb
CODE	Center for Orbit Determination Europe
CoG	Centre of Gravity
COMSAR	Sub-Committee on Radiocommunications and Search and Rescue
CORDIC	Coordinate Rotation Digital Computer)
CSP	Communications Service Provider
D/U	Received power ratio between the Desired and Undesired signal
dBi	Gain of antenna compared to an idealized isotropic antenna
dBm	Power ratio in decibel referenced to one milliwatt
DBP	Digital Bent Pipe
DG FISH	The Directorate-General for Fisheries and Maritime Affairs
DG TREN	The Directorate-General for Energy and Transport
DR	Demonstration Requirement
DSTL	The Defence Science and Technology Laboratory
e	eccentricity
EDA	The European Defence Agency
EEA	European Economic Area
EMSA	European Maritime Safety Agency
ENOB	Effective Number of Bits
EPC	Electronic Power Supply
EPPL	European Preferred Parts List
ESA	The European Space Agency
EU	European Union
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EUV	Extreme Ultraviolet Radiation
F	measure of relative offset in any two adjacent planes (Walker parameter)
FDC	France Développement Conseil

FDIR	Failure Detection Isolation and Recovery
FFI	Forsvarets Forskningsinstitutt (Norwegian Defence Research Estalishment)
FIR	Finite Impulse Response
FOV	Field Of View
FPGA	Field Programmable Gate Array
GMES	Global Monitoring for Environment and Security
GMSK	Gaussian Minimum Shift Keying
GNI	Gross National Income
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GT	Gross Tonnage
h	altitude
i	inclination
I/Q	In-phase/Quadrature signals
IALA	International Association of Marine Aides to Navigation and Lighthouse Authorities
IAPH	International Association of Ports and Harbors
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
ID	Identity
IEC	International Electrotechnical Commission
IGRF	International Geomagnetic Reference Field
ILO	International Labour Organization
IMO	International Maritime Organization
ISPS	International Ship and Port Security
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunication Union
IUU	Illegal, Unregulated, and Unreported
JSC	Joint Spectrum Center
KSAT	Kongsberg Satellite Services AS
KSX	Kongsberg Seatex AS
LAT	Lot acceptance test
LEO	Low Earth Orbit
LEOP	Launch Early Operation Phase
LNA	Low Noise Amplifier
LORAN-C	Long Range Navigation, version C
LRIT	Long Range Identification & Tracking
LTAN	Local Time of Ascending Node
MCC	Mission Control Centre
ID	Identity
OBC	On-Board Computer
MMSI	Maritime Mobile Service Identity

MOD	UK Ministry Of Defence
MoI	Moment of Ienrtia
MR	Mission Requirement
MSC	IMO's Maritime Safety Committee
MTCP	Maritime Transport Coordination Platform
NCA	The Norwegian Coastal Administration
NCG	The Norwegian Coast Guard
NEAFC	North-East Atlantic Fisheries Commission
NI	Nominal Increment
NMD	The Norwegian Maritime Directorate
NS	Nominal Slot
NSS	Nominal Start Slot
NSSDC	National Space Science Data Centre
nT	nano-Tesla
NTS	Nominal Transmission Slot
OAP	Orbit Average Power
OBC	On Board computer
OBDH	On-Board Data Handling
OCR	Optimised Coherent Re
P	Planes forming the constellation (Walker parameter)
Paris MoU	The Paris Memorandum of Understanding on Port State Control
PCM	Power Control Module
PDM	Power Distribution Module
PER	Packet Error Rate
PIANC	Permanent International Association of Navigation Congresses
PM	Progress Meeting
PSLV	Polar Satellite Launch Vehicle
PU	Pattern Unitsss
QCI	Quality Conformance Inspection
QML	Qualified Manufacturers List
QPL	Qualified Products List
RAMS	Reliability, Availability, Maintainability and Safety
RF	Radio Frequency
RMP	Recognised Maritime Picture
Rr	Report Rate
RSSI	Received Signal Strength Indication
S/C	Spacecraft
SAR services	Search And Rescue services
SAR	Synthetic Aperture Radar
SDR	Software defined radio
SEL	Single Event Latch up
SET	Single Event Transient

SEU	Single Event Upset
SI	Selection Interval
SINAD	Signal to Noise and Distortion
SNR	Signal to Noise Ratio
SOLAS	International Convention for the Safety of Life At Sea
SOMCC	Space Operations Mission Control Centre
SOTDMA	Self Organizing Time Division Multiple Access
SQM	Structural Qualification Model
SSDR	Solid State Data Recorder
SSTL	Surrey Satellite Technology Ltd
STIRES	The SafeSeaNet Information, Relay and Exchange System
T	Number of satellites in the constellation (Walker parameter)
TCS	Thermal Control System
TDMA	Time Division Multiple Access
TMTC	Telemetry / Telecommand
UN	United Nations
UR	User Requirement
USCG	United States Coast Guard
UTC	Universal Time Coordinated
VDL	Very-High Frequency Digital Link
VHF	Very High Frequency
VMS	Vessel Monitoring System
VTS	Vessel Traffic Services
WP	Work Package

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