The digitalisation of maritime communications

Study of the evolution of maritime communications: from voice to e-Navigation

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Contents

1. Introduction

This book gathers together all the information that we collected during a comprehensive study on maritime communications and the conclusions that can be drawn from that study.

The emergence of new technologies in the early twentieth century caused a sharp increase in maritime trade, which led to more traffic and the consequent need to monitor such traffic. This was the backdrop to the appearance of the first communications systems for improving maritime safety, protection of the marine environment and/or the adjacent coastal area, and navigation efficiency. Whilst communications needs were initially met using beacons and other light-signalling devices, these systems were subsequently replaced by voice communication systems. Meanwhile, the passage of time and the consequent advances in technology led analogue communications to migrate to a digital scenario, which is where we can place today's systems, such as AIS, Satellite AIS, DSC and VDES.

Today there is also a concern to engage in communications that are less trivial than the inconsequential or personal messages from a vessel to the members of the crew or passengers just mentioned. Such concerns mean that we must constantly review these ever-evolving communication systems.

Our aim was to perform a study of communications at sea and collate all the available information related to this sector. In the chapters that follow, we aim to address all matters related to the various standards, guidelines and communications plans published to date, covering the most technical aspects to provide the reader with an overview. In addition, we will look at the different systems and technologies developed in this context, as well as the various projects concerning safety at sea, navigation and preserving the marine environment, to show clearly just how much communications have changed since digitalisation occurred.

The organisations responsible for regulating the context of maritime communications include the ITU, IALA, IMO and COSPAS-SARSAT. Coordination and cooperation between these bodies is essential to ensure an effective approach to maritime communications and support their various developments.

- The ITU is the specialised telecommunications agency of the United Nations Organisation (UNO) tasked with regulating telecommunications internationally among the various administrations and regulators.
- The IALA is a non-governmental organisation that groups together the Lighthouse Services of most maritime countries worldwide, which are responsible for the supply and maintenance of lighthouses, buoys, radio-navigation systems and other aids to navigation.
- The IMO is the world authority responsible for setting standards for safety, protection and environmental behaviour to be observed in international maritime transport.
- Cospas-Sarsat is an element of the International Maritime Organization's Global Maritime Distress Safety System and is of great importance in search and rescue operations.

This book has been prepared by GRADIANT with the collaboration of CELLNEX, both of which have prior experience and have made efforts in R&D in the maritime field.

CELLNEX TELECOM is Europe's leading operator of wireless telecommunications and broadcasting infrastructures and classifies its activities into four areas: mobile telephony infrastructures, audiovisual broadcasting networks, security and emergency service networks and solutions for smart urban infrastructure and services management (Smart Cities and the "Internet of Things" (IoT)).

CELLNEX has specialised in mobile, voice and data communications networks, aimed at closed groups of users or fleets that require reliable service with a high level of availability. To achieve this, it uses both analogue (PMR) and digital (DMR, TETRA) technologies and avails its clients of over 9,000 sites distributed throughout Spain as well as specialised technical personnel and capacity for around-the-clock supervision of centres for the efficient management of this type of communications, even in crisis situations.

The company therefore has extensive experience in managing safety and emergency communications networks and services, and its mobile radio systems serve more than 80,000 police officers, firefighters, forest rangers and healthcare personnel throughout Spain.

In September 2017, CELLNEX and the Spanish Maritime Rescue Company signed the "*Provision of services within the Global Maritime Distress and Safety System*" for the Safety of Human Life at Sea. Having won this contract through public tender, the company has continued to provide the service, which was initially awarded in 2009.

CELLNEX provides this service through its network of shore stations to guarantee a 24/7 permanent listening service on the maritime frequency bands. The contract covers receiving automatic alerts and distress calls, to be sent immediately to Maritime Rescue coordinators, as well as transmitting information for maritime safety and meteorological information.

In 2009 the company installed and started up a communications network between the Maritime Radio Communications Control Centres (CCRs), shore stations and Rescue Coordination Centres (CCS's) of the *Sociedad de Salvamento y Seguridad Marítima* (Maritime Rescue and Safety Company).

The services offered by CELLNEX TELECOM within the mobile communications framework are: planning engineering, network design, operation and maintenance and supply and installation of equipment.

As a Telecommunications Technology Centre, GRADIANT provides vision and knowledge in telecommunication technologies to the processes and products that companies develop.

In the communications field, GRADIANT has extensive experience in the application of signal processing techniques, both in analogue and digital radiofrequency subsystems. The Centre works in research, design and implementation of satellite communication systems; developing technologies aimed at solving the various challenges of the next generation of mobile systems; and modelling, analysis and efficient operation of the electromagnetic spectrum.

The subsystems designed at GRADIANT make it possible to operate in different media, both wireless and guided, terrestrial and satellite, to solve the needs linked to the communications that arise in the different sectors. Likewise, the Centre performs activities related to implementing solutions for positioning and navigation systems and designs on-board systems based on programmable devices, embedded platforms and sensors.

Another of the challenges facing GRADIANT is the increasing demand for the radio spectrum. Of importance in this context is their work on cognitive radio and *spectrum holes* (white spaces) in the UHF band, which include implementing spectrum monitoring schemes and developing geo-referenced databases in the television band. Also of note are the technologies related to signal analysis and monitoring and interference.

GRADIANT's work extends beyond communications and signal processing to cloud computing, data analysis, security and privacy, IoT (Internet of Things) and biometrics. Thus, the Centre is clearly positioned as a spearhead in terms of technological progress and R&D+I.

Both CELLNEX TELECOM and GRADIANT have several years' experience in R&D in the maritime communications sector, participating in key projects such as ONDADA and POLARYS, which will be mentioned in later chapters.

The ONDADA project was run by a consortium comprising the companies RETEVISIÓN (CELLNEX group), EGATEL and SCIO, plus two research organisations: GRADIANT and the Integrated Engineering Group from the University of A Coruña. This consortium was supported and funded by the CDTI (Spanish Centre for Technological and Industrial Development) through the FEDER-INNTERCONECTA-2011 programme (ITC-20113042). The main objective of the project, which ran from January 2012 to December 2014, is to increase the coverage of the AIS network using repeaters to allow a larger number of vessels to benefit from the system. In turn, this will facilitate greater use of this system, making it useful not only for the safety of vessels, but also for people.

The POLARYS project was developed by a consortium led by RETEVISIÓN, with the participation of BASTET SEGURIDAD TECNOLÓGICA, EGATEL, INSITU and SCIO, as well as the CINAE and GRADIANT technology centres. The project ran for three years (2016-2018) and obtained the support and financing of the CDTI through the FEDER INNTERCONECTA-2016 programme (EXP 00091271/ITC - 20161120). The aim of the project is to enhance maritime safety while increasing efficiency in shipping and emergency management by developing a VDES (*VHF Data Exchange System*) transceiver to exchange maritime safety information from one ship to another and between ships and infrastructures. The development of this transceiver has a direct and immediate impact on the limitations observed in the AIS platform while opening the door to the development of new applications that previously seemed infeasible.

The contents to be covered throughout the following chapters are set out below. After this brief introduction, Chapter 2 reviews the first communications systems and explains why there is a need to modernise GMDSS. Chapter 3 presents the AIS, Satellite AIS and DSC systems, which are evolutionary developments of the initial systems, and describes each one. Chapter 4 describes the problems of AIS and the consequent appearance of VDES and sets out the characteristics of this latter standard. Chapters 3 and 4 provide comments on some of the results of tests performed in the POLARYS project to facilitate a better understanding of the systems described through reference to real cases. This last section also introduces the e-Navigation concept and the state of the art in this field, defining how far we want to advance and the necessary starting point in order to achieve it. Finally, Chapter 5 presents some conclusions concerning the analysis performed.

2. The beginnings: analogue communications

2.1. Context

As we mentioned in the introduction, the emergence in the twentieth century of new technologies such as radar (1935) and the LORAN system (1942) revolutionised maritime trade. The considerable increase in traffic and the need for some kind of monitoring mechanism were to lead to the first VTS (*Vessel Traffic Services*) in 1949. A VTS is based on a more or less extensive network of radars, together with as much information as possible about the area concerned (electronic chart, meteorological and oceanographic data, characteristics and conditions in which monitored vessels are located, etc.) and a VHF-FM (*Very High Frequency - Frequency Modulation*) voice communications network providing periodic reporting by each vessel on its position and the reception of data by the info station. The main objectives of a VTS were to improve maritime safety, protection of the marine environment and/or the adjacent coastal area, and efficiency of navigation.

2.2. First analogue communications systems in the maritime field

The maritime domain uses multiple communications technologies across the radio spectrum to support safe navigation, efficient operations and trade aspects. Below are listed the first communications systems used in this context and their main characteristics.

2.2.1. LORAN-C

LORAN-C is a system of transmitting stations several hundred kilometres apart linked in chains. One station within a chain is designated as the main (master) station and the others are secondary stations. Each chain contains at least one master station and two secondaries to provide two position lines. While LORAN-C is now obsolete, other systems such as *e-Loran* and research projects are underway to evaluate the use of the LF spectrum.

Enhanced LORAN, also known as e-Loran, is the latest system to be developed, and makes full use of 21st century technologies for low-frequency navigation. This system provides the modulated data channel in the approximately 100 kHz signals. Two formats, known as *Eurofix* and *9th Pulse,* are currently available for this data channel. Both techniques offer data rates below 100 bps, although higher rate concepts have been proposed.

Figure 1: Example of LORAN-C Furuno receiver, extracted from [1]

2.2.2. Voice communications in MF/HF

These types of communications provide a range from hundreds to thousands of kilometres. These communications systems offer the possibility to initiate, receive, attend and maintain telephone and radio conversations from both fixed equipment and mobile terminals.

General voice communication takes place in ship-to-ship, ship-to-shore and shore-to-ship modes of operation across the band 1.6-26.5 MHz. Channel bandwidths are typically 3 kHz.

2.2.3. VHF voice communications

Voice communication using the VHF band (156.025-162.025 MHz) is prevalent, with ship-to-shore, shore-to-ship and ship-to-ship communication also operating. Channel spacing is currently 25 kHz although the use of 12.5 kHz channels on an interleaved basis is allowed. In this case the range is of the order of tens or hundreds of kilometres.

It is used for distress, safety and general communications. Primary channels 6, 13 and 16 are used for safety and distress communications.

Figure 2: Example of Garmin 300i VHF fixed station, extracted from [2]

2.2.4. Locating Beacon

The principle of operation of a radio beacon is simple: When activated, the device sends intermittent signals with the information that makes it possible to locate people or vessels in an emergency.

The frequency 121.5 MHz is an aeronautical emergency frequency. 121.5 MHz radiobeacons were developed in the mid-seventies for installation on aircraft, as Emergency Locator Transmitters (ELTs). However, they can also be used on board ship as part of Emergency Position-Indicating Radio Beacons (EPIRBs) or in Personal Locator Beacons (PLBs).

Figure 3: Example of automatic McMurdo SmartFind G8 emergency beacon, taken from [3]

2.2.5. Voice communications in UHF

Manual and fixed UHF radios are normally used in vessels for on-board communications, among crew members, port workers or operators with related posts. These radios are usually limited to radiating less than 2 W in the 450 470 MHz band and are used for voice and data communication.

Figure 4: Example of UHF radio for TechBrands internal communications, extracted from [4]

2.2.6. Radar

Radar systems typically operate in two bands: S-band from 2.9 to 3.1 GHz and X-band from 9.2 to 9.5 GHz. The radars are used for target detection and to support identification and for coastal and port navigation. These bands are also used by radar transponders for search and rescue (RACON, SART) RACONs are maritime radar signal transponders that are used to improve object detection. SART radars are devices for locating ships in distress through the creation of a series of points on the radar screen of a rescue ship.

Figure 5: Example of Rescuer 2 SART Plastimo transponder, extracted from [5]

2.3. Other communications systems

Although the main communication systems are discussed in Section 2.2 to contextualize and address the various systems related to maritime safety and distress communications, others are mentioned here to allow the reader to appreciate more clearly the advantages of the technologies described later in chapters 3 and 4.

2.3.1. NAVTEX

NAVTEX is an automated system for instantly distributing Maritime Safety Information such as maritime navigational warnings, weather forecasts and warnings, search and rescue notices and similar information to ships.

The frequency of NAVTEX messages varies by language used. Messages are broadcast in English on 518 kHz, while 490 kHz and 4209.5 kHz are used to broadcast in English and/or local language. The messages are coded and the time of broadcasting is internationally coordinated by areas to share the same frequency.

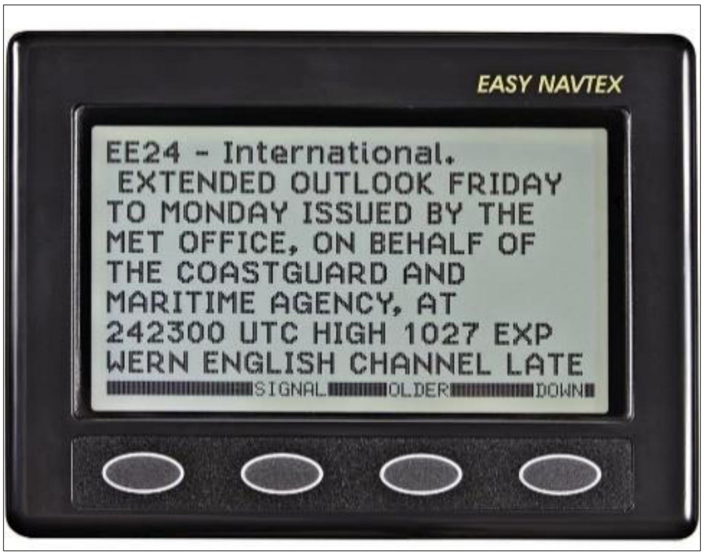


Figure 6: Example of NASA Easy NAVTEX receiver, extracted from [6]

2.3.2. NBDP

NBDP (also known as radio telex) is a technique which automates radio signals to telegraphy. It is FSK modulated onto HF channels of 0.5 kHz and supports low speed data transmissions (100 bps) in the maritime mobile service bands within 1.6-26.5 MHz.

NBDP is an element of GMDSS and can be used as the text-based distress follow-up communications and general communications between ship-to-ship, ship-to-shore and shore-to-ship, especially to overcome the language difficulties. The use of NBDP for general communication is declining and is now used for position reporting from ships and promulgation of meteorological warnings and forecasts from shore stations. The IMO has indicated that radio telex may no longer be considered a required system within GMDSS.

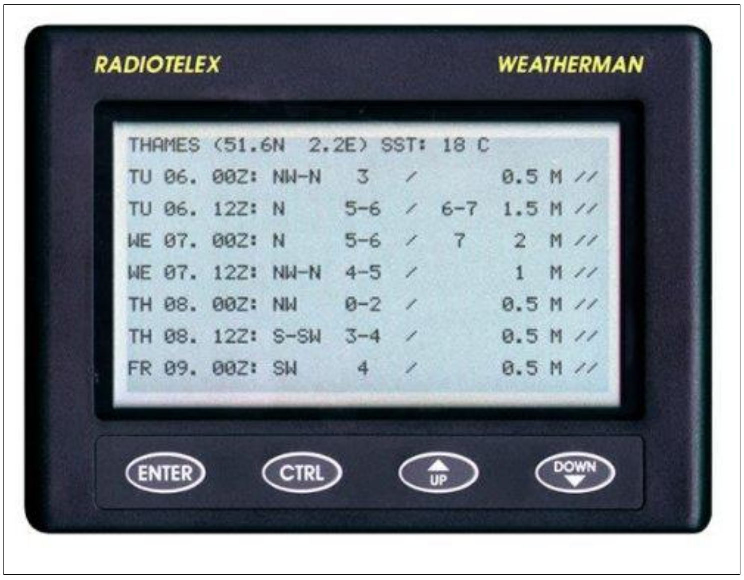


Figure 7: Example of NASA radio telex, extracted from [7]

2.3.2. Summary Tables

Tables 1, 2 and 3 show a summary of all the systems discussed in this chapter, both in this and the previous section, together with the most significant characteristics of each one.

System	Band	Channel frequency	Bandwidth data rate	Service	Purpose
MF/HF voice communications	MF/HF	2,182 kHz 4,125 kHz 6,215 kHz 8,291 kHz 12,290 kHz 16,420 kHz	3 kHz	Mobile to mobile. Mobile to fixed. Fixed to mobile.	Distress Communication
VHF voice communications	VHF	156,300 MHz 156,650 MHz 156,800 MHz	25 kHz	Mobile to mobile. Mobile to fixed. Fixed to mobile.	Distress Communication
Locating Beacon	VHF	121,5 MHz		Mobile to mobile.	Location
SART		9.2 - 9.5 GHz		Mobile to mobile.	Location of objectives

Table 1: Main systems for distress communications in the maritime field [8]

System	Band	Channel frequency	Bandwidth data rate	Service	Purpose
HF voice communications	MF/HF	1.6,25.5 MHz	3 kHz	Mobile to mobile. Mobile to fixed. Fixed to mobile.	General voice communications
VHF voice communications	VHF	156.025 MHz	25 kHz	Mobile to mobile. Mobile to fixed. Fixed to mobile.	General voice communications
NBDP	MF/HF	1.6,25.5 MHz	0.5 kHz	Mobile to mobile. Mobile to fixed. Fixed to mobile.	General text communication
On-board communications	UHF	457.5125 – 457.5875/ 467.5125 MHz		Mobile to mobile. Internal communication	On-board communications

Table 2: Main systems for general communications [8]

System	Band	Channel frequency	Bandwidth data rate	Service	Purpose
NAVTEX	MF/HF	518 kHz 490 kHz 4,209.5 kHz	0.5 kHz	Fixed to mobile.	Receipt of maritime safety information
NBDP	HF	4,210 kHz 6,314 kHz 8,416.5 kHz 12,509 kHz 16,806.5 kHz 19,880.5 kHz 22,376 kHz 26,100.5 kHz	0.5 kHz	Mobile to mobile. Mobile to fixed. Fixed to mobile.	Receipt of maritime safety information
LORAN	LF	90 kHz		Fixed to mobile.	Positioning
VHF voice communications	Mobile VHF	156.025 MHz	25 kHz	Mobile to mobile. Fixed to mobile. Mobile to fixed.	Communication for navigational and safety related purposes
Radar S Band		2.9-3.1 GHz		Mobile and fixed	Collision avoidance, Navigational aid.
Radar X Band		9.2-9.5 GHz		Mobile and fixed	Collision avoidance, Navigational aid.
RACON		2.9-3.1 GHz 9.2-9.5 GHz		Fixed	Navigational aid

Table 3: Main systems for the promulgation of Maritime Safety Information [8]

2.4. Need to modernise GMDSS

The challenge facing radio communication in the maritime sector is the need to relay more information, which puts pressure on the availability of spectrum. As a finite resource, spectrum is under increasing demand from all users globally.

The current GMDSS system was designed at the end of the nineteen seventies and, until just a few years ago, there was no intention to review it. The technology has developed significantly in that time, and elements within the GMDSS have also evolved, although the initial functions remain unchanged.

In these circumstances, there is a need to switch from analogue to digital and from voice to data to allow the effective and efficient sharing of large amounts of data by a great many users.

Therefore, to maintain all the priorities and uses for radiocommunications that are still required, as is the case for distress alerts and warning messages or emergency and safety communications, the modernisation of GMDSS focuses on the following aspects:

On the one hand, the idea is to simplify drafting of the documentation, to facilitate the compression of GMDSS for seafarers, crew members and coastal authorities, and to any entity directly or indirectly linked to the maritime sector.

On the other hand, it seeks to introduce into the system any emerging and new technologies that may appear in the future, to integrate mobile satellite systems such as Iridium or Thuraya and lay the foundations of the e-Navigation concept to run it.

Another issue involved in the modernisation of GMDSS is reviewing the definition of the marine area.

3. Present: digital communications

3.1. Evolution of initial systems

The fact that communications are made by voice has led to serious accidents over the years. Statistics estimate that between 75% and 96% of total maritime accidents are the result of human error [9]. Radars, on the other hand, also have inherent limitations that cause a small number of disasters. They become less effective in adverse conditions and they do not provide an effective response to obstacles such as an islet or a rock.

These circumstances, and the intention to renew the GMDSS system, caused the IMO to study the need for a complementary autonomous system that also provides the ability to communicate between ships, in addition to the radiocommunications to the land station, leading to AIS.

3.2. AIS

3.2.1. Introduction

AIS is a broadcast communications system operating in the VHF band assigned to maritime mobile services (156.025 MHz-162.025 MHz). This technology allows exchanges of navigation information both ship-to-ship and ship-to-shore control stations. AIS uses an open protocol for the exchange of navigation data in the access to the medium is provided as variants of TDMA.

The information exchanged between the various entities is transmitted over 26.66 ms slots, which corresponds to 256 bits (guard intervals + flags + data) at a bit rate of 9.6 kbps. This value is more than sufficient, since the type of data transmitted corresponds to basic parameters such as speed, position, identification or direction.

One of the greatest advantages of AIS over radar technology is the possibility to contact a ship with which there is no direct vision, since it can avoid obstacles. Furthermore, the data received do not give rise to false positives (rocks, waves, etc.). Despite this, AIS is always considered as a complementary, rather than a supplementary technology.

The AIS system emerged as an attempt to improve maritime safety. However, its applications have been shown to help improve navigation efficiency and environmental protection.

An example of an AIS network is shown illustratively in Figure 8.

3.2.2. Applications

At present, the main applications of AIS are:

- Providing weather and navigation information.
- Improving port planning.
- Facilitating communications.
- Enabling efficient navigation.
- Providing support to assistance systems in search and rescue or accident investigation.
- Environmental protection.

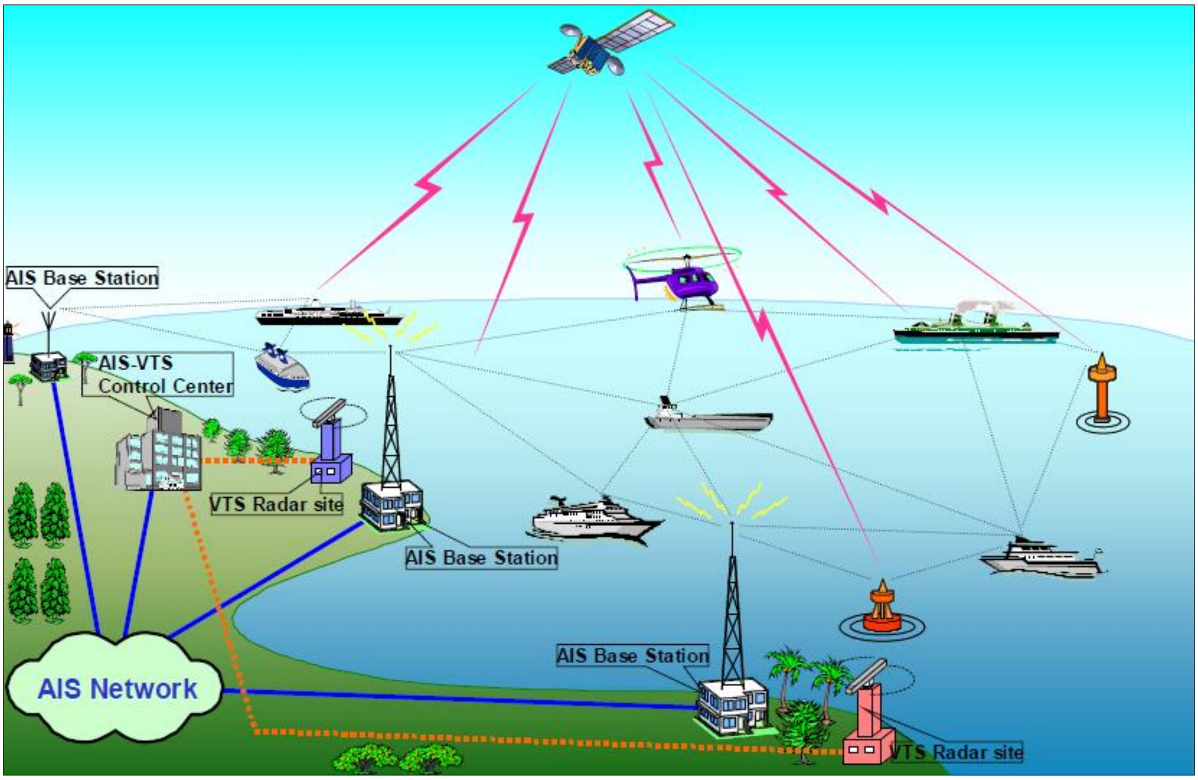


Figure 8: Example of an AIS network [10]

3.2.3. Mandatory use

Numerous international organisations such as IMO, IALA, ITU and IEC worked together to help design the AIS system, which took place in the mid-1990s. In addition, great contributions were made by entities from Sweden and Finland, which were fundamental for the development of the SOTDMA mode.

In subsequent years, to improve safety in maritime transport, the IMO established requirements related to cargo type and tonnage to the effect that all vessels meeting these requirements install the AIS system on a mandatory basis. These requirements, extracted from [11], are as follows:

- **For ships built from 1 July 2002:** AIS must be fitted aboard all passenger ships, cargo ships of 300 GT and upwards engaged on international voyages and cargo ships of 500 GT and upwards not engaged on international voyages.
- **For ships built before 1 July 2002 and engaged on international voyages:** passenger ships and tankers are granted 1 year for installation (not later than 1 July 2003) and cargo ships from 2 to 5 years depending on gross tonnage (1 July 2004 for 50,000 GT and over and 1 July 2007 for those between 300 and 3,000 GT).
- **Ships engaged on international voyages built before 1 July 2002:** 1 July 2008 is the deadline for the installation of AIS.

In 2012, around 70,000 ships were equipped with AIS worldwide and it was estimated that the future figure would reach 150,000 [12].

3.2.4. System overview

Next, we shall describe in detail the salient aspects of the AIS system, while providing an overview at the same time.

3.2.4.1. Classes of AIS stations

There are several classes of AIS devices or stations, which are grouped into two categories:

- **Mobile stations:** These are generally devices located on ships. Various types of stations fall within this classification:
  - **Class A:** equipment on ships meeting IMO requirements. They have minimal equipment, such as a keyboard and a screen. Transmit output power is 12.5 W.
  - **Class B:** devices compatible with those in Class A but installed on vessels that do not comply with IMO restrictions (for example, pleasure craft). Two variants have been defined depending on whether the media access mode is CSTDMA (Class B 'CS') or SOTDMA (Class B 'SO'). Their transmit output power is 2 W, and therefore they have a lower range than Class A equipment. The market price is also lower.
  - **SAR:** station used by an aircraft in a search and rescue situation.
  - **SART:** device designed to transmit only. An example of this is the emergency beacon (MOB or Man-Over-Board scenario).
  - **AIS receiver:** a cheaper option for “non SOLAS” vessels wishing to monitor AIS traffic. They have only receiver circuits, so they cannot be seen by the other AIS stations.
- **Fixed stations:** These are installed in a fixed location, such as on shore or on a buoy. There are several types:
  - **Base station:** used by the competent authorities for the efficient management of the VDL (*VHF Data Link*).
  - **AtoN:** a device designed to improve safety and efficiency in navigation. They range from signalling beacons to buoys that report sea conditions: meteorology, waves, etc.
  - **Repeater:** an element used to extend the range of other AIS stations.

3.2.4.2. Types of information and transmission periods

AIS messages may contain the following types of information, each with its corresponding transmission rate:

- **Static**: information associated with parameters that do not change over time, such as the name of the ship, its dimensions, etc. Sent every 6 minutes or when requested by another station.
- **Dynamic:** data provided by the ship's sensors (speed, direction, turning rate, latitude and longitude, etc.). Tables 4 and 5 show the transmission slots for this type of information according to the type of station and speed.
- **Voyage related:** information on the navigation status (destination, estimated time of arrival, type of cargo, draught, etc.). Follows the same shipping period as static information.
- **Safety-related:** ASCII text to warn of any anomaly or danger. Transmitted whenever necessary.

Dynamic changes in vessel movements	Nominal transmission period
At anchor or moored and speed <3 knots	3 min
At anchor or moored and speed >3 knots	10 s
Speed between 0-14 knots	10 s
Speed between 0-14 knots and changing course	3.33 s
Speed between 14-23 knots	6 s
Speed between 14-23 knots and changing course	2 s
Speed >23 knots	2 s

Table 4: Transmission period for a Class A vessel [13]

Station conditions	Nominal transmission period
Class B 'SO' with speed <2 knots	3 min
Class B 'SO' with speed between 2-14 knots	30 s
Class B 'SO' with speed between 14-23 knots	15 s
Class B 'SO' with speed >23 knots	5 s
Class B 'CS' with speed <2 knots	3 min
Class B 'CS' with speed> 2 knots	30 s
Search and Rescue aircraft	10 s
Aids to navigation	3 min
AIS base station	10 s

Table 5: Transmission period for another type of station [13]

3.2.4.3. Mode of operation

With the exception of devices designed solely to transmit or receive, every AIS station must be able to receive simultaneously from two channels in parallel and transmit alternately on those channels. This mechanism is known as *dual channel operation*. This requires two receiver circuits and one transmitter[1].

Alternating transmissions between two channels mitigates the harmful effects of RF interference and balances the load between those channels.

Because AIS is a simplex service, as TDMA techniques do not allow transmitting and receiving simultaneously on the same channel, transmission is prioritised over reception.

3.2.4.4. Frequency aspects

For the AIS service, the ITU has defined two worldwide channels within the maritime VHF band (156.025-162.025 MHz). These channels are AIS 1 and AIS 2, centred on 161.975 MHz and 162.025 MHz respectively, with a bandwidth of 25 kHz.

Simplex and duplex channels are assigned within this frequency band[2]. Duplex channels comprise two frequencies - one for transmissions from ships (reception by the shore station) and the other

[1] Some AIS stations have a third receiver, used to receive DSC (*Digital Selective Calling*) commands. The DSC standard (channel 70) is the core of GMDSS and complements the services offered by AIS.

[2] A device is said to operate on a simplex channel when it uses the same frequency for transmitting and receiving information. Whereas a device operates on a duplex channel when the frequency at which it transmits is different from the frequency at which it receives the information.

for transmission from the shore station (reception by ships). For example, marine VHF channel 87 consists of frequencies 157.375 MHz and 161.975 MHz, for transmissions from ships and shore stations respectively (see Annex 4 of [14]).

This explanation serves as a link to clarify the numbering method used when a duplex channel is used for a simplex service, such as AIS, where channels AIS 1 and AIS 2 correspond to the shore frequencies of channels 87 and 88. Following this approach, the procedure determines that AIS 1 can be numbered as 2087 or 87B and AIS 2 as 2088 or 88B. If the frequencies of the simplex channel were associated with transmissions from ships, the prefix '20' would be replaced by '10' and the suffix 'B' with 'A'. See Figure 9.

In summary, AIS stations should be designed to operate across the entire VHF maritime mobile band, although two simplex channels have been assigned by default for the international use of AIS. Both channels have a bandwidth of 25 kHz:

- AIS 1 (Channel 87B, 161,975 MHz) (numbering 2087): primary channel.
- AIS 2 (Channel 88B, 162,025 MHz) (numbering 2088): secondary channel.

Should one of these two channels be unavailable, either because the local authorities have assigned it to another service or because interferences make it impossible to use, then alternative channels must be selected using channel management techniques.

One frequency-related characteristic is stability in the carrier frequency. This parameter must be lower than ± 500 Hz, both for the transmitter and the receiver.

CHANNEL NUMBER			FREQUENCY A		FREQUENCY B	
First 25 kHz Channel	Interleaved 12.5 kHz Channel	Second 25 kHz Channel	SHIP	SHIP & COAST	COAST	
		60	156.025		160.625	
	260		156.0375		160.6375	
01			156.050		160.650	
		87	157.375		161.975	AIS 1
	287		158.3875		161.9875	
28			157.400		162.000	
	228		157.4125		162.0125	
		88	157.425		162.025	AIS 2

Figure 9: Excerpt from the frequency table of Rec. ITU-R M.1084-5

3.2.4.5. Physical layer blocks

This section contains the essential aspects associated with the blocks of the physical layer:

- **Data encoding:** Encoding is NRZI type. An NRZI signal transits between voltage levels when the bit to be transmitted is a '1' and remains at the same level when the bit is a '0'. No additional FEC techniques are used, nor other physical layer blocks such as bit interleaver or bit scrambler.

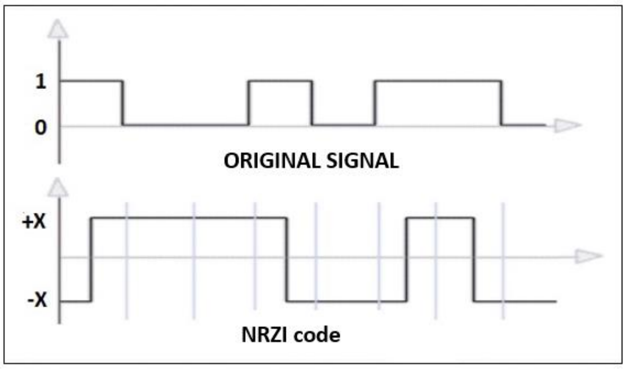


Figure 10: NRZI coding example

- **Modulation:** GMSK/FM is used. A Gaussian low pass filter is placed before the frequency modulator to compact the MSK spectrum. The MSK modulation index: h = 0.5 is used.

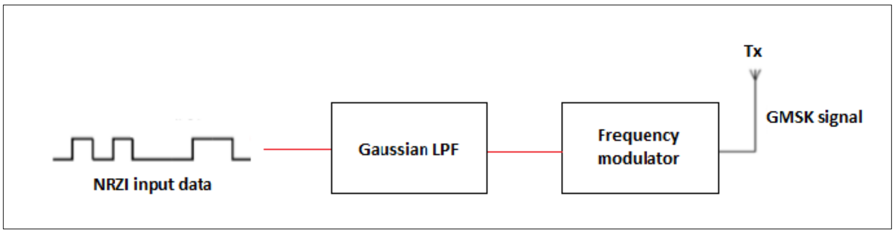


Figure 11: Block diagram of a GMSK-FM modulator

- **BT (*Bandwidth x Time*) product**: the relation between the bandwidth of the Gaussian filter at -3 dB and the bit rate. The values used in AIS are BT = 0.4 for the transmitter and BT = 0.5 for the receiver.
- **Binary rate→** The binary rate for AIS is 9.6 kbps ± 50 ppm.
- **Transmit output power→** 1 - 12.5 W depending on the device. Carrier power tolerance must be in the range ± 1.5 dB.
- **Spectrum mask →** The characteristics of the spectrum mask are: -25 dBc @ ±10 kHz y -70 dBc @ ±25 kHz.

3.2.4.6. Format of an AIS package

An AIS package consists of 256 bits (guard intervals + flags + data) and its structure is inherited from the HDLC protocol [15]. The format in Figure 12 corresponds to that used to transmit most messages. However, there are scenarios (Class B 'CS' devices, long-range transmissions, messages that need more than 1 slot, etc.) where package fields are adapted to meet the particular context.

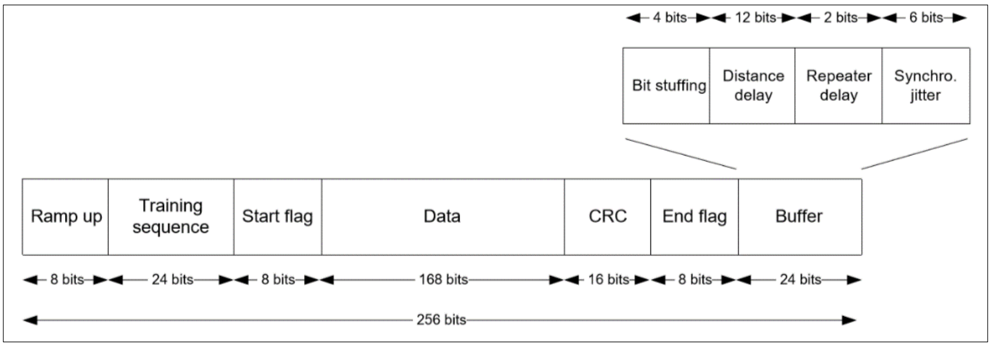


Figure 12: Default format of an AIS package

3.2.4.7. AIS messages

27 messages have been defined in the current AIS specification [13] for the operation of the system. These messages carry the four possible types of existing information discussed in Section 3.2.4.2: static, dynamic, voyage related and safety.

Each of the 27 messages is briefly specified in Table 6. For a more detailed explanation, please see Annex 8 of [13].

Number	Message	Purpose
1 – 3	*Position reports*	Position messages to be sent periodically by Class A mobile stations.
4	*Base station report*	A message sent periodically by the base station to inform about its position and temporary data.
5	*Ship static and voyage related data*	A message used by Class A equipment and SAR aircraft to report static or voyage related data.
6	*Addressed binary message*	A message addressed to a specific station to warn of certain information. The length of this type of message varies between 1 and 5 slots, which translates into a maximum of between 8 and 117 bytes of binary data.
7	*Binary acknowledge*	A message used to agree to one or more '6' messages. It must be transmitted on the same channel through which that message was received.
8	*Binary broadcast message*	Similar to message '6', but for broadcast transmissions .
9	*Standard SAR aircraft position report*	A message used by aircraft in SAR situations. By default, it is sent every 10 seconds.
10	*UTC and date inquiry*	A message used when one station requests temporary information from another.
11	*UTC and date response*	Response to message '10'. Shares format with message '4'.
12	*Addressed safety related message*	A message similar to '6' for sending safety related text.
13	*Safety related acknowledgement*	A message used to agree to one or more '12' messages. It must be transmitted on the same channel through which that message was received.
14	*Safety related broadcast message*	Similar to message 12, but for broadcast transmissions.
15	*Interrogation*	A message for requesting information other than that requested by message '10'. The response must be transmitted on the same channel through which the request is received.
16	*Assigned mode command*	A base station can assign to another AIS station a transmission schedule different to the one it already has. The new schedule must have been previously reserved by the base station through message '20'.
17	*GNSS broadcast binary message*	A message transmitted by that base station that is connected to a DGNSS signal, allowing the rest of the stations to calculate their position more accurately.

Number	Message	Purpose
18	*Standard Class B equipment position report*	A message similar to '1', '2' and '3', but for Class B devices.
19	*Extended Class B equipment position report*	A backup to message '18', with a longer period.
20	*Data link management message*	A message used by base stations to notify of slots already occupied by stations that have a fixed transmission schedule.
21	*Aids-to-navigation report*	A message used by an AtoN station to report its functionality.
22	*Channel management*	A message transmitted by a base station to notify the VHF radiocommunications parameters assigned to a specific geographical area.
23	*Group assignment command*	A message allowing a base station to assign a set of operating parameters to a specific class of AIS stations.
24	*Static data report*	A message that allows any AIS station to associate an MMSI to its name, which is 20 6-bit characters maximum in length.
25	*Single slot binary message*	A message similar to '6' and '8', but length is limited to 1 slot.
26	*Multiple slot binary message with communication state*	A message allowing the transmission of up to 5 slots with binary data to be planned.
27	*Long-range AIS broadcast message*	A message similar to '1', '2' and '3', but for long-range applications such as Satellite AIS. It is oriented to Class A equipment.

Table 6: List of AIS messages

3.2.4.8. TDMA access modes

As mentioned above, AIS devices operate on two channels of the VHF maritime mobile band. By default, these channels are AIS 1 (161.975 MHz) and AIS 2 (162.025 MHz). TDMA (Time Division Multiple Access) techniques are used to allow access to multiple users, with a duration for each slot of 26.66 ms. This figure means 2,250 slots per channel per minute. A group of 2,250 slots comprise a frame (see Figure 13).

The access period required for each station will depend on the type of information to be transmitted, and varies from two seconds for dynamic information (messages 1 - 3) in scenarios in which the ship sails at more than 14 knots, up to six minutes when the information is static or voyage type (message 5).

Synchronisation at slot and frame level is required to correctly access the medium. This is achieved thanks to two factors:

- A precise time reference such as GPS or another GNSS system.
- The 'communication state' field information present in some messages.

If it has no direct access to the time reference, the AIS device must synchronise to another device that does, or failing that, to the AIS station (which could be a base station) with the largest number of incoming connections (known as a semaphore).

Because part of the AIS devices operate outside the coverage range of the base station controlling them, for example out to sea, the first TDMA technique designed was SOTDMA (Self-Organizing TDMA). Equipment uses this mode to create its slot reservation schedule The underlying premise for establishing this scheme is to prevent its transmissions from colliding with those of other devices within range. This technique is used mainly in Class A equipment.

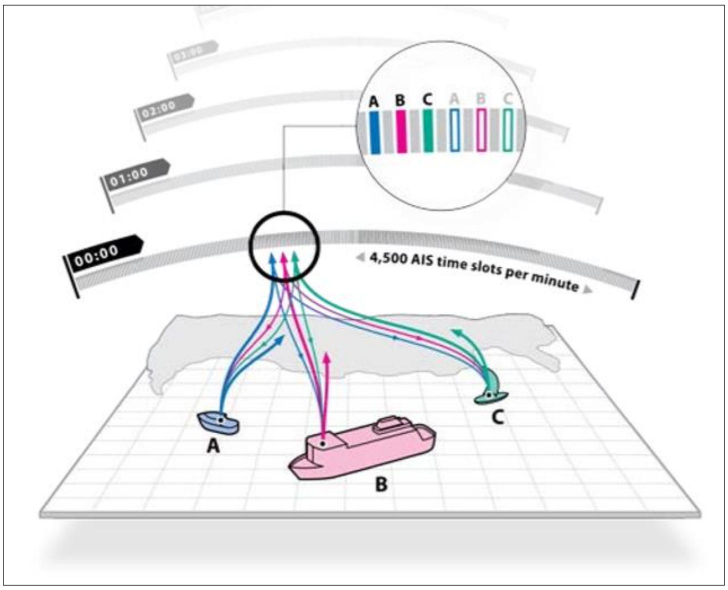


Figure 13: AIS TDMA system [16]

Other access methods interoperate with SOTDMA and are used in different types of AIS devices. These methods are:

- RATDMA (Random Access TDMA).
- ITDMA (Incremental TDMA).
- FATDMA (Fixed Access TDMA).
- CSTDMA (Carrier Sense TDMA).
- Modified SOTDMA.

Before we introduce these different schemes, we would like to refer to two related concepts that make them easier to explain later on: mode of operation and candidate slot.

3.2.4.8.1. Mode of operation

An AIS device can work in three modes of operation:

- **Autonomous or continuous**: the station determines its own schedule for transmission and should therefore automatically resolve scheduling conflicts with other stations.
- **Assigned**: In certain scenarios, the competent authority, through the base station, may decide that a device should transmit under a specific transmission schedule, specified using message 16. In this mode of operation, a Class A device will report its position with message 2, rather than with message 1.

- **Polled:** As a coastal monitoring measure, a station can be interrogated via message 15 about the type of ship and its cargo. The response should be transmitted on the channel where the interrogation message was received and should never conflict with the integrity of the other two modes. This response is made using messages 3 and 5.

Not all types of AIS stations allow all three modes of operation (see the following Table).

Station type	**Class A**	**Class B 'SO'**	**Class B 'CS'**	**AtoN type 1**	**AtoN type 2**	**AtoN type 3**	**Base station**	**Repeater**	**SART**	**SAR**	**Limited base station**
Mode of operation											
Autonomous	C	C	C	C	C	C	C	C	C	C	C
Assigned	C	C	C	N	N	N	N	N	N	C	C
Polled	C	C	C	N	N	N	C	N	N	C	C
C = Allowed in any configuration. N = Not allowed.											

Table 7: Relationship between the types of stations and the modes of operation [17]

3.2.4.8.2. *Candidate slot*

Stations that present one of the schemes mentioned at the beginning of the section require a phase for monitoring both AIS channels. The aim is to determine their activity, participating users, position, assignment of slots and the existence of shore stations. This information is used to create a dynamic memory (slot map) to store the status of slots, providing a starting point to establish the transmission scheme of each station.

The slots used for transmission are chosen randomly from a set of special slots, known as candidate slots, belonging to the selection interval. This interval consists of a series of consecutive slots whose duration varies according to the TDMA method used. For example, for RATDMA the selection interval is set to 150 slots (4 seconds).

While candidate slots are being selected to broadcast on one channel, the activity of the other channel is also taken into account. First, all slots free on both channels are determined as candidate slots. Next, if fewer than four slots meet this condition, the station should intentionally reuse slots. The reason for intentionally reusing slots to maintain a minimum of four candidate slots is to provide a high probability of access to the radiocommunications, while relieving congestion. In this process, the state of each slot has an influence on both channels and the limit of 120 nautical miles from the base station. Reusing slots reduces the size of the AIS cell, ensuring that the position messages from the nearest ships (those that are really relevant for safe navigation) are not affected.

If slot reuse is required, the candidate slots must meet any of the five conditions or rules defined for this process (sub-section 4.4.1 of Annex 2 of [13]), to be applied in descending order of priority until four candidate slots are complete or until the slots of the selection interval have been used.

3.2.4.8.3. *Self-Organizing TDMA* - SOTDMA

SOTDMA is the most complex access scheme of all those defined for AIS. The aim of this mode is to offer an access algorithm to resolve possible collisions without the intervention of a central station. To do this, each SOTDMA station announces in advance which slots future transmissions will be made in. This allows the rest of the stations to be consistent with that reservation pattern.

By and large, the messages transmitted under this access mode are of a periodic nature and inform about the position of the ship.

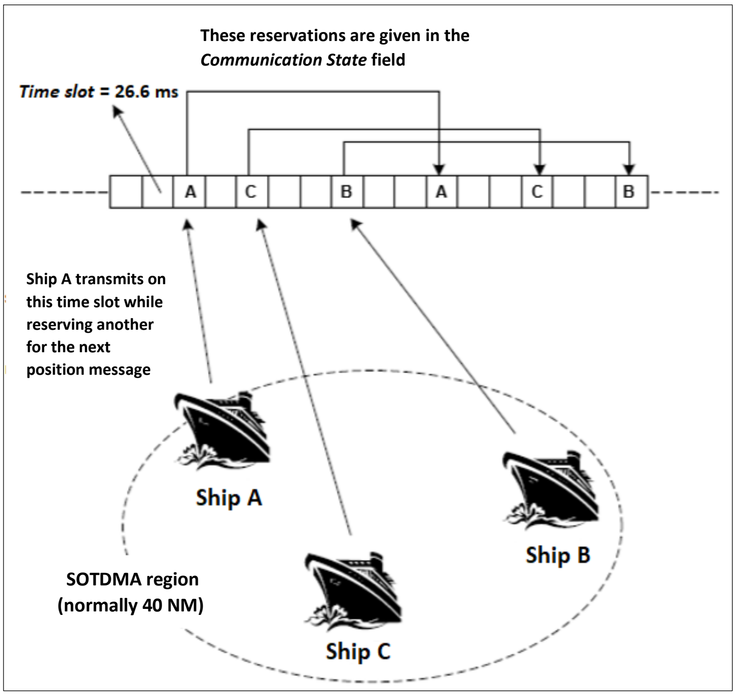


Figure 14: Access and reservation of slots for SOTDMA equipment

3.2.4.8.4. *Random Access TDMA* - RATDMA

This access mode is used when a slot that has not been previously announced needs to be reserved. Examples of this are reserving the first slot when entering the network of a SOTDMA device and transmissions of non-periodic messages (text messages or retransmissions from a simplex repeater).

RATDMA is not suitable for periodic transmissions because it would produce a significant number of collisions, since the rest of the stations do not know what slots are reserved by RATDMA equipment.

3.2.4.8.5. *Incremental TDMA* - ITDMA

ITDMA is used when a station needs to report a temporary change in the dissemination rate of its periodic messages, notify the intention to transmit a specific (non-periodic) message, such as security-related messages, or in the network entry phase[3]. This allows the device to inform the rest of the stations of its slot reservations.

3.2.4.8.6. *Fixed Access TDMA* - FATDMA

AIS devices that operate according to FATDMA transmit in a series of predefined slots only. These slots are assigned by the competent authorities and sent to the rest of the system via the base stations using message 20.

[3] During this phase, the first slot must be reserved using RATDMA.

The rest of the stations will indicate these slots as busy; this means they cannot be used by these entities to reserve slots whenever, in addition to message 20, they receive message 4 from the same base station and verify that they are within 120 nautical miles of it.

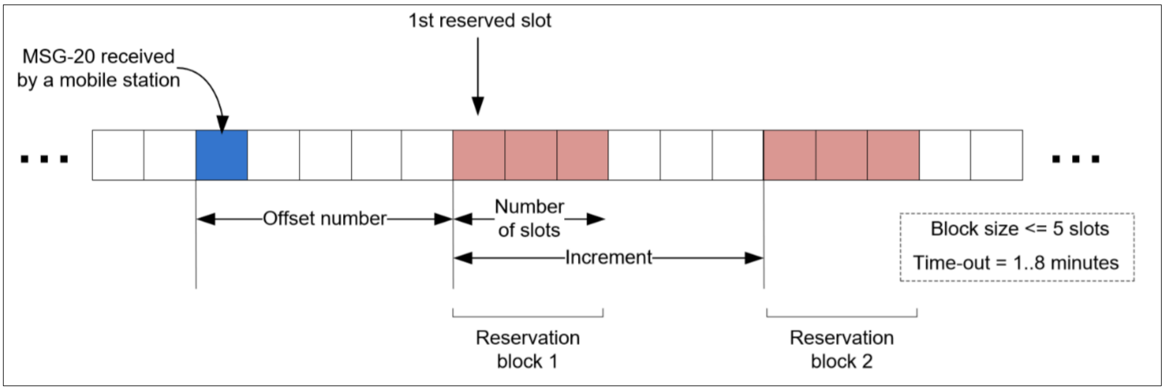


Figure 15: Example of the parameters used in a FATDMA reservation

3.2.4.8.7. *Carrier Sense TDMA* - CSTDMA

The CSTDMA access mode has been designed for Class B 'CS' AIS stations to allow cheaper devices than those in Class A (SOTDMA). This scheme is based on listening to the AIS network and transmitting only when it is determined that it is free of activity. Thus, CSTDMA stations can interoperate with SOTDMA transmissions but not interfere with them, as they are a priority.

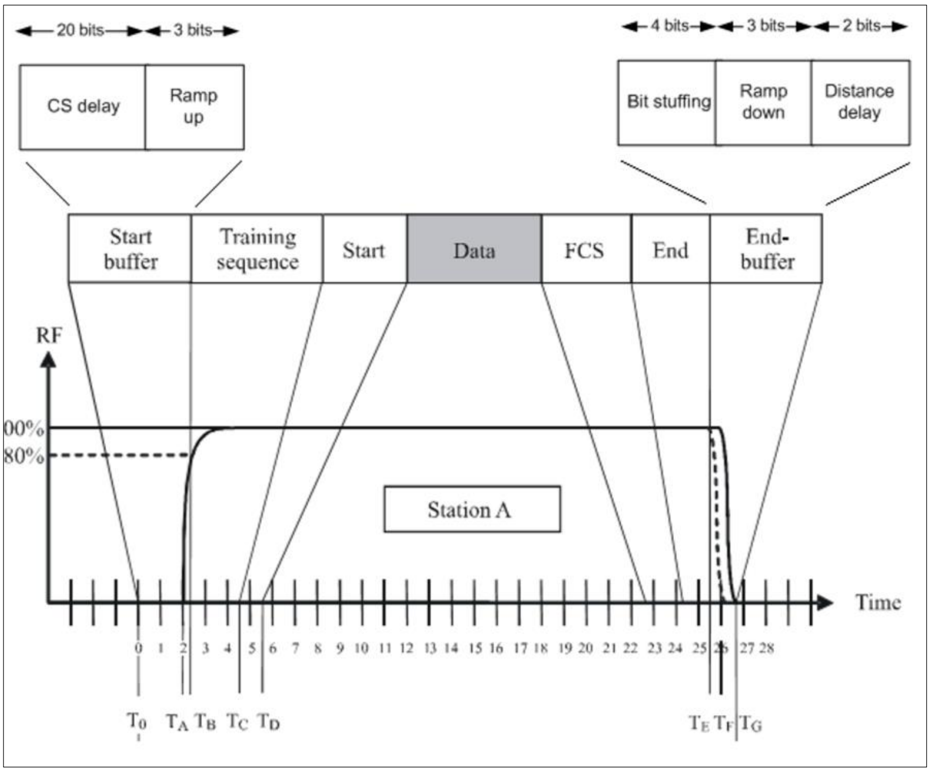


Figure 16: Format and timing of the transmission for CSTDMA [13]

3.2.4.8.8. *Modified SOTDMA*

This scheme was defined for simple devices that transmit information only. It has specific application in emergency beacons such as AIS Search and Rescue transceivers (SART).

Stations operating with modified SOTDMA transmit messages in 'bursts' of 8 slots per minute (in non-consecutive slots). This ensures successful transmission when the device is operating near the surface of the sea and may be blocked from reception by periodic swell. The pattern set for each message group is repeated over a period of 8 minutes. Therefore, during 8 frames it is transmitted over the same 8 slots.

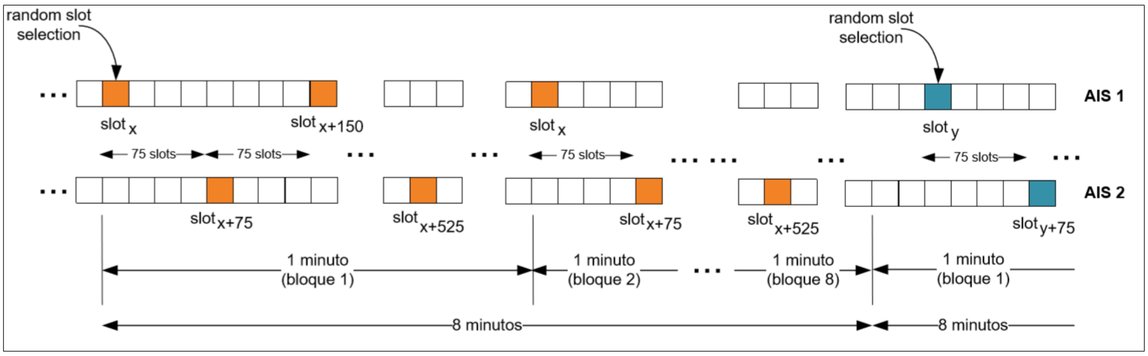


Figure 17: Transmission scheme for modified SOTDMA mode

3.2.4.9. Hardware features required for the various access modes

Below is a summary of the minimum hardware equipment necessary to support the various TDMA modes. These requirements are grouped into three points:

- **Transmission and reception circuitry:** An AIS device generally has two receivers and one transmitter that can operate on the maritime VHF band. However, devices whose access is modified FATDMA or SOTDMA do not require the receiving circuits, since they function as information transmitters only.
- **GPS receiver:** All schemes except CSTDMA require the GPS signal directly or indirectly. This signal provides the necessary time reference for synchronisation.
- **RAM memory:** SOTDMA, RATDMA and ITDMA modes require a memory to store a map with the use of slots. This memory must be sufficient to store at least five minutes of activity of the two AIS channels [16], which is equivalent to a memory that can hold the status information corresponding to 5 x 2 x 2,250 = 22,500 slots. To do this, the equipment operating with one of the three modes mentioned above requires an AIS message decoder circuit to access the content of the '*communication state*' field.

3.2.5. Issues

Although the appearance of AIS has spelt a great technological leap forward within the maritime field, this system suffers from a series of setbacks and limitations that need to be overcome to achieve greater safety and efficiency in navigation.

3.2.5.1. Malicious attacks

The fact that AIS uses an open protocol[4] has led to several malicious attacks on the system over the years, the most prominent of which were:

[4] The protocol used by AIS is not intended to offer secure communications.

- ***Spoofing***: changing messages from other vessels to alter their position or even to add one or more fake ships to the network.
- **Replay attacks**: Messages are stored to be retransmitted at a later time.
- ***Man-in-the-water***: fake "man overboard" (MOB) distress alerts. According to maritime regulations, this type of alert must be attended by any type of vessel.
- ***Fake CPA***: CPA (*closest-point-of-approach*) messages are created near another ship. The vessel will receive this alarm and change its route to avoid an alleged collision.

3.2.5.2. Coverage

Like most VHF terrestrial systems, the maximum range of AIS communications is normally governed by line-of-sight and diffraction mode propagation mechanisms. Assuming typical technical parameters of AIS equipment, maximum reliable ship-to-ship radiocommunications over sea water is in the range of 20-25 nautical miles. Shore stations, with their high antennas, can reliably receive AIS messages from ships at distances of up to 20 to 35 nautical miles, depending on antenna heights above sea level. As discussed in the introductory chapter, this problem has been addressed in the ONDADA project to extend and improve the coverage of the AIS service through repeaters.

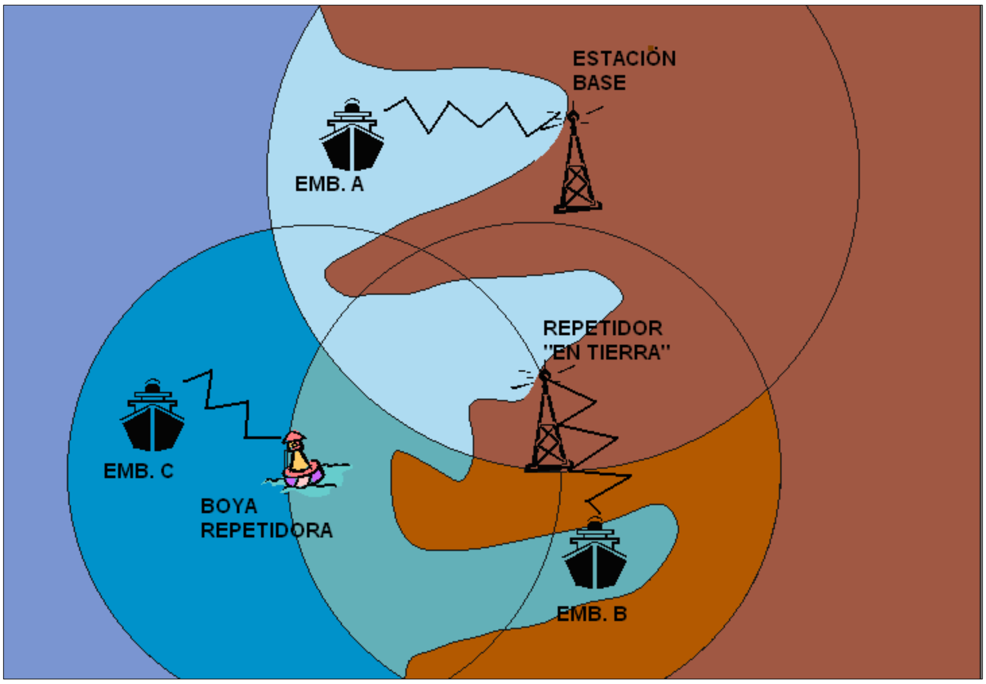


Figure 18: AIS coverage extension scheme using duplex repeaters

3.3. Satellite AIS

3.3.1. Introduction

Satellite AIS was created as a low-cost solution for VTS, providing the individual position of each vessel registered in the network, the activities it performs and the type of cargo carried.

Monitoring maritime traffic from shore stations is limited by the range of VHF radios, which is about 40 nautical miles. A growing interest in extending the area monitored led to the deployment of several satellite constellations for this purpose.

Small low earth orbit (LEO) satellites are often used in these constellations since a satellite takes approximately 90 minutes to circle the Earth and therefore it is a simple solution. Since it takes sixteen days to pass through the same point again, a constellation of a number of[5] satellites is required.

The footprint of an LEO satellite is about 6,000 kilometres in diameter and, since SOTDMA cells have a radius of approximately 40 nautical miles, several hundred SOTDMA cells that are not synchronised with each other are included within the FoV of each satellite. In addition, the standard defines that the method of access to the medium for AIS-S is RATDMA, which comprises the main problem of Satellite AIS reception[6].

The task of these satellites is to receive messages with the identifier '27'[7] of the AIS standard, in some cases to decode them and, finally, download them to the earth station so that they are delivered to the final client. As already specified above, the ITU defines in [18] two channels within the maritime VHF band reserved exclusively for the operation of AIS: AIS 1 (161.975 MHz) and AIS 2 (162.025 MHz). The AIS-S service has two independent AIS 1 and AIS 2 channels for proper operation - channels 75 (156.775 MHz) and 76 (156.825 MHz).

3.3.2. Issues

Receiving AIS messages on a satellite poses a series of problems mentioned below:

- **Package collision:** SOTDMA cells ensure the transmission of a single AIS message per slot inside the cell. However, there is no relation between the different cells. A satellite's footprint includes multiple SOTDMA cells and several packets could collide within the same slot.

  The difference in delays that messages may suffer in reaching the satellite should not be a problem of collisions between messages transmitted in different slots, since the difference in delays between the point in the vertical of the satellite (minimum delay) and the limit of its FoV (maximum delay) is about 8 ms, below the guard level of 9 ms in AIS standard message 27.

[5] Ships do not need to be monitored at all times, just every few hours, since their position changes progressively and slowly over time.

[6] Ship-satellite communication cannot be synchronised to avoid message collision without communication between ships (infeasible because they are outside each other's Field of Vision) or without a return link from the satellite.

[7] Type of message for long-distance communications. These can be transmitted only by AIS Class A equipment; the content is similar to messages 1, 2 and 3, but it has been shortened to support propagation delays typical of long-distance communications.

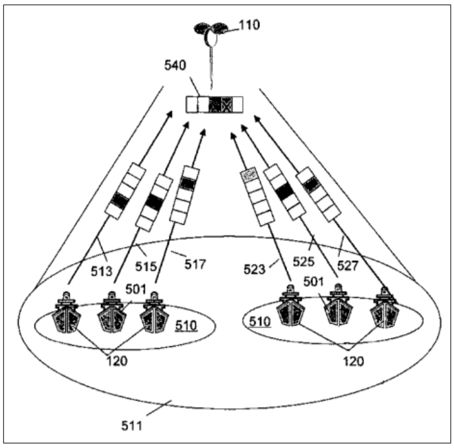


Figure 19: Collision between two-cell SOTDMA messages [19]

- **Signal diversity:** since a satellite covers a wide area, the changes that will occur to the signals as they travel from the ship to the satellite will vary depending on the relative position of the ship with respect to the satellite, the atmospheric conditions, relative speeds, etc.
- **Signal strength:** The gain of both transmitting and receiving antennas varies according to the elevation angle to the satellite. Free space loss is four times greater on the satellite's horizon than on its vertical. Multipathing also impacts the level of signal received by the satellite, and both constructive and destructive interference may occur [20].
- **Doppler effect:** As shown in Figure 20, for a satellite with LEO orbit, the Doppler deviation ranges between -3.7 kHz and 3.7 kHz, with the maximum (absolute) deviation around the horizon in the path traced by the satellite, [20].

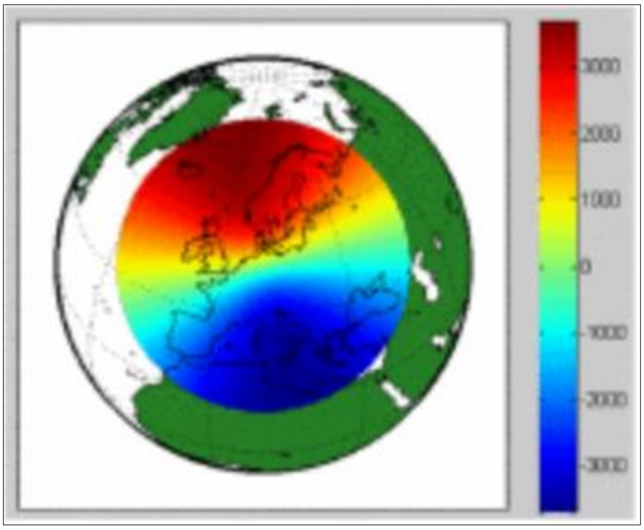


Figure 20: Doppler effect on AIS messages received by a satellite [20]

- **Polarisation:** AIS transmissions use vertical polarisation in all directions. On its path to the satellite, polarisation of these signals undergoes a rotation due to the Faraday effect. Since this effect is considerable in the VHF band, the waves will rotate several full turns before reaching the satellite.

3.3.3. Solutions

Problems concerning diversity of the signal also affect other types of systems, such as GPS, and there is already a mature technology to address them satisfactorily [20]. The main issue to address is collision of messages from different SOTDMA cells. The solutions can be divided into the following groups:

3.3.3.1. Problem minimisation

In [21], [22] and [23], we propose various measures to minimise the number of collided messages that reach the satellite. Below is a list of the ones proposed and implemented in [13] Rev. 4:

- Creating a specific message, message 27, for satellite reception. This message is shorter in duration: 96 bits instead 256 bits. This increases the guard interval between slots, allowing a longer propagation delay.
- Defining a 3-minute retransmission period for message 27, instead of the repetition periods described in Tables 2 and 3 of [24]. Limiting which stations can issue message 27 only to Class A[8] and excluding Class A stations within the range of a shore station.
- Reserving another pair of channels for the transmission of AIS message 27. The only globally defined frequencies in the maritime VHF band, apart from AIS 1 and AIS 2, were channels[9] 16, 70, 75 and 76. Since channels 16 and 70 are safety frequencies, it was decided not to use these to bring in the new service and, when it was determined that the transmission of 17 ms messages repeated every three minutes with a power of 12.5 W did not cause any considerable interference in voice communications on channels 75, 16 and 76, these were allocated for transmission of Satellite AIS messages. With the exception of AIS, the output power of maritime mobile service communications is limited to 1 W on these channels.

3.3.3.2. Collision recovery

Several proprietary solutions have been implemented and are in use to address this problem, as described in [25], from exactEarth®:

- **OBP:** This consists of applying very selective frequency filters to the signals received by the satellite to separate the messages. It uses the various frequency shifts experienced by signals from different points to decode them and stores them for later transmission to earth. This method does not require any additional processing, so the latency caused is very low. The downside is that it is effective only in low-density areas such as the centre of the Pacific Ocean.
- **SDP:** This requires the use of complex algorithms to successfully decode AIS messages. These algorithms are also very costly in computational terms, therefore it is necessary to store the collected RF data and transmit them to the earth stations to process, retrieve and decode the messages. This method offers a high possibility of detection, even in areas with high ship density.

[8] Equipment with better features, causing fewer synchronism problems.

[9] Channel 50 is already used solely for transmitting DSC communications. Channels 75, 16 and 76 (adjacent and ascending frequency, in that order), are for transmitting voice over radio.

There are also other solutions oriented more towards the physical layer that consist of cancelling interferences as in [26] or in [27]. Other solutions resort to configurations of arrays of antennas, as in [20].

3.3.4. Clients and applications

Implementing Satellite AIS involves a large investment, therefore a prior study is required to find out which clients may be interested in the service:

- **Institutional users, port authorities, coastguards, etc**.: the interest of Satellite AIS for such institutions revolves around questions such as control of fishing vessels or port management beyond the areas already covered by shore stations.
- **Commercial users, legal shipping companies, yacht clubs, insurance companies, etc.:** these users may be interested in applications like fleet tracking or resource optimisation.
- **Defence or security users, coastal security and defence agencies and bodies, Port Police, Border Police, Immigration Authorities, etc.:** a clear application of this service is global monitoring of vessels, control of border waters or tracking the routes followed by one or more vessels.

Other uses being made of Satellite AIS are:

- Disaster response: for example, monitoring ship movements in the path of a hurricane.
- Search and rescue: knowing the route taken by a ship facilitates search operations.
- Environmental response and protection: for example, evaluating the contamination risk profile of a specific vessel.
- Risk modelling.

3.3.5. Operation

Several companies and governments are currently running programmes to operate Satellite AIS. This section analyses the hardware and the software underlying the service, as well as the companies that offer it.

3.3.5.1. Satellites

As a fundamental part of the system, a lot of work has been conducted in recent years to develop satellites specialised in receiving AIS. There has been a trend to develop small satellites dedicated exclusively to receiving messages, although AIS receivers have also been placed in large satellites as a secondary payload.

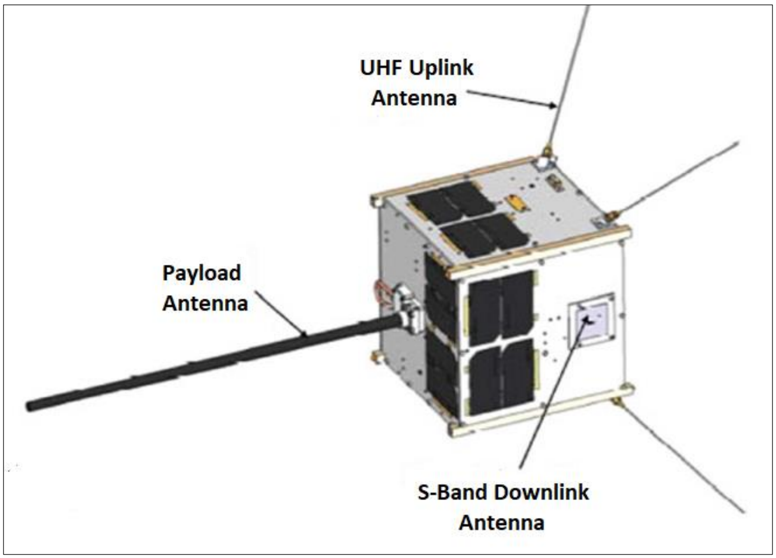


Figure 21: Nanosatellite designed for AIS reception [21]

The role these satellites play in the system can vary from one case to another. Some are limited to receiving the signals from the vessels, storing them as raw data and broadcasting them to the base stations when the link is available. Others perform slightly more complex tasks, ranging from simple decoding of the AIS message, discarding some messages that cannot be decoded, to the processing needed to retrieve messages that have collided with others.

Some satellites and/or constellations of satellites linked to the reception of AIS-S are listed below:

- AprizeSat.
- PAZ.
- ADS1B.
- ResourceSat-2.
- M3MSat.
- AISSat 1 – 3.
- VesselSat 1 – 2.

3.3.5.2. Algorithms

In most cases, satellites intended for receiving AIS messages (or incorporating equipment for this purpose), implement algorithms to retrieve all possible information from the signal received. These are usually proprietary patented algorithms, of which [27] and [28] are two examples.

3.3.5.3. Companies

A leading company in this sector is called *exactEarth*. Its services include tracking maritime vessels in real time from their location using Satellite AIS technology. Other companies of interest are:

- FleetMon.
- Norwegian Space Centre.
- ORBCOMM.

3.3.6. POLARYS project tests

A series of tests were performed during the POLARYS project to validate the use of the Satellite AIS component, the results of which may be of interest for ratify the use of AIS-S transmission.

HISDESAT, a partner from exactEarth which helps to manage the maritime satellite traffic information system, helped to verify this group of tests. The Radiomaritime Communications Centre from A Coruña was also contacted to check and compare the operation with them.

The equipment developed by EGATEL, connected to a multiband antenna located in the offices of GRADIANT, was used for the various tests performed. All transmissions used the maximum power output defined in the recommendation [29]: 12.5 W. These tests can be summarised in the points mentioned below:

- Transmission of messages 18 and 27 with default values with different power levels over one hour.
- Transmission of message 14 once every minute for one hour.
- Transmission of messages 18 and 27 with real values with maximum power over two hours.
- Transmission of messages 18 and 27 with real data once every three minutes for 24 hours.
- AIS transmission of messages 1 and 3 in autonomous mode over six hours.

The conclusions drawn from the results obtained are as follows:

- Messages with default or out-of-range values proposed by [29] are filtered and do not allow the possibility to verify that transmission and reception are correct.
- Satellite reception depends entirely on the time at which it is made and on the fact that the satellite's footprint coincides with the position from which it is transmitted.
- Message 27 is properly received once real data regarding position, speed, course, etc. are included.
- The system can work for long periods of time.
- The number of messages received and the position of the satellites at a given time influences the congestion of the area and therefore affects the number of collisions.

It is important to note that the results of these tests do not contain measurements and information regarding the quality of the received signal. However, in light of the numerous tests performed and the fact that certain messages can be filtered, we can affirm that Satellite AIS reception is functional and operational.

3.4. DSC

3.4.1. Introduction

DSC is a digital communications system within GMDSS which allows point-to-point or point-to-multipoint transmissions[10]. The purpose of this standard is to send digital alert messages.

DSC was developed to replace conventional calling systems, as it provides a more stable signal and lower bandwidth, allowing communication over greater distances (up to 25% more) at greater speed. The system is designed to send distress alerts quickly, since the equipment has the MMSI and the position of the ship, obtained from the GPS equipment.

[10] A point-to-point transmission consists of a shore-to-ship, ship-to-ship or ship-to-shore transmission. A point-to-multipoint transmission is aimed at a group with a common interest or to a geographical area.

DSC transmissions can be both semi-duplex (only one frequency is used, which would allow only receiving or broadcasting, but not both at the same time); or full-duplex (can be transmitted and received simultaneously on different frequencies).

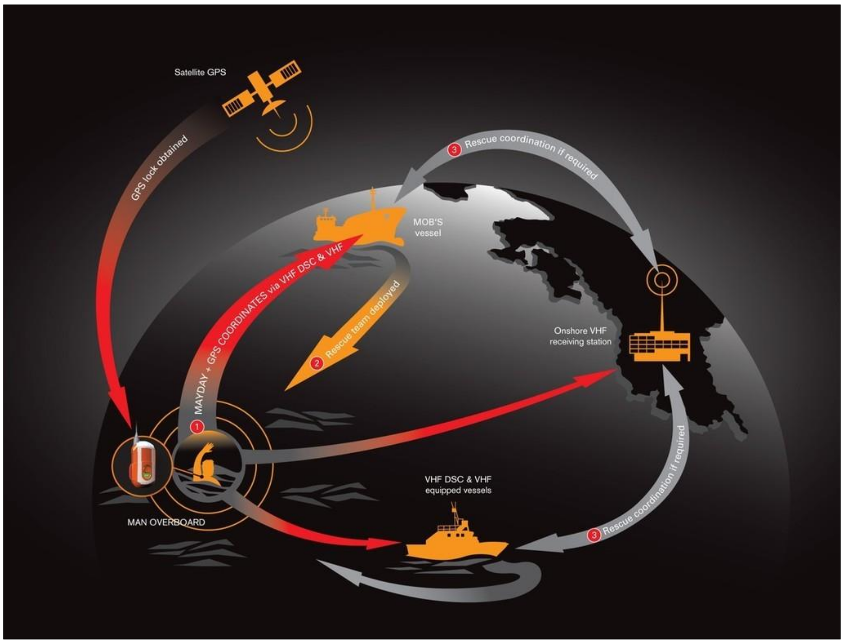


Figure 22: GMDSS in the case of a "man overboard" distress alert

3.4.2. System overview

DSC can operate in the MF, HF and VHF bands of the maritime mobile service. The medium can be accessed freely whenever a transmission is needed. The equipment itself must incorporate the necessary mechanisms to determine whether the channel is free before starting a transmission.

DSC transmissions are known as calls, call sequences or sequences. These sequences consist of a header string, a set of messages and an end string. The information transmitted by the DSC sequences are preset messages that include distress, safety or emergency alerts, or are simply intended to establish communication with one or more DSC stations. Transmission rates are extremely low due to the small amount of information exchanged between stations, but they are sufficient for the purpose they serve. A bit rate of 100 bps is used in the MF and HF bands, and 1,200 bps for the VHF band.

3.4.2.1. DSC equipment classes

DSC equipment can be classified into four types according to its characteristics:

- **Class A:** includes all the features recommended by the IMO GMDSS for the MF, HF and/or VHF bands.
- **Class B**: meets the minimum requirements imposed by the GMDSS for on-board equipment in the HF and/or VHF bands. This equipment is valid for vessels where Class A equipment is not required.
- **Class D:** devices include the minimum characteristics for making and receiving DSC calls, but without necessarily complying with the minimum requirements imposed by GMDSS for devices in the VHF bands.

- **Class E:** like Class D equipment, it offers the minimum characteristics for making and receiving DSC transmissions, but does not necessarily meet the minimum requirements of GMDSS for equipment in the MF and HF bands.

Class A and Class B equipment allow the service to be used semi-automatically/automatically.

3.4.2.2. Minimum requirements

The IMO imposes minimum equipment requirements according to the area of operation of the vessels. The state to which each vessel belongs is then responsible for regulating the type of equipment to be used in each case. The GMDSS equipment required by the IMO depending on the area of operation is:

- **Zone A1:**
  - Distance: 20 - 50 nautical miles from the coast (within the reach of shore stations in VHF).
  - Band, frequency: VHF, 156.525 MHz (DSC).
- **Zone A2:**
  - Distance: 50 - 400 nautical miles from the coast (within MF range of shore stations).
  - Bands, frequencies: MF and VHF, same as zone A1 plus 2,187.5 kHz (DSC), 2,182 kHz (radiotelephony), 2,174.5 kHz (NBDP) and 518 kHz (NAVTEX).
- **Zone A3:**
  - Distance: between 70º N and 70º S, within the geostationary satellite range (INMARSAT).
  - Bands, frequencies: HF/satellite, MF and VHF, the same frequencies as zone A2 plus all HF frequencies or the 1.5 to 1.6 GHz band (INMARSAT).
- **Zone A4**:
  - Distance: North of 70º N and south of 70º S, beyond the geostationary satellite range (INMARSAT).
  - Bands: MF, HF and VHF.

3.4.2.3. Types of calls

The ITU defines two types of calls with different priority levels and different assigned frequencies:

- **Distress, safety and emergency**: These are the highest priority calls and have exclusive frequencies for transmission. They are intended for all ships that have a DSC device.
- **Routine:** these are low priority calls, and have three different types of recipients:
  - A specific ship or a single shore station.
  - A group of ships with a common interest (same company, same owner, etc.) within a geographical area.
  - All ships.

3.4.2.4. Frequency aspects

The ITU has defined a wide range of frequencies internationally that are reserved for DSC transmissions, ranging from MF to VHF and are classified according to the purpose of the call:

3.4.2.4.1. Distress, safety and emergency transmissions

The frequencies in Table 8 are designated by the ITU for transmission of distress, safety and emergency calls only. They may not transmit voice signals or DSC messages that do not correspond to these categories. In this case the communications are semi-duplex.

VHF channel 70 also allows transmissions for other purposes and is the only channel reserved for this purpose in the VHF band, but is also not allowed to transmit voice signals.

3.4.2.4.2. Transmissions for other purposes

Table 9 lists the frequencies that the ITU assigns for "routine" category DSC transmissions, although if emergency frequencies were not available, it would also be possible to transmit distress, emergency and safety calls on these frequencies.

The frequencies in Table 9 correspond to transmission frequencies, with listening possible on any of the channels. Figure 23 shows a semi-duplex communication between two ships where both transmit and receive on the same frequency. Figure 24 shows the case in which both use different listening and transmission frequencies, which allows full-duplex communication. Finally, Figure 25 shows a full-duplex communication between a shore station and a ship.

The frequencies designated by the ITU and listed in Tables 8 and 9 are the international frequencies of first choice for transmitting DSC calls, but it is preferable to transmit routine calls over national DSC channels if known.

MF	2,187.5 kHz
HF	4,207.5 kHz
	6,312 kHz
	8,414.5 kHz
	16,804.5 kHz
VHF	156.525 MHz (Channel 70)

Table 8: International DSC frequencies for distress, safety and emergency purposes

	Ship station	Shore station
MF		455.5 kHz
	458.5 kHz	
	2,177 kHz (between ships only)	2,177 kHz
	2,189.5 kHz	
HF	4,208 kHz	4,219.5 kHz
	4,208.5 kHz	4,220 kHz
	4,209 kHz	4,220.5 kHz
	6,312.5 kHz	6,331 kHz
	6,313 kHz	6,331.5 kHz
	6,313.5 kHz	6,332 kHz
	8,415 kHz	8,436.5 kHz

	Ship station	Shore station
	8,415.5 kHz	8,437 kHz
	8,416 kHz	8,437.5 kHz
	12,577.5 kHz	12,657 kHz
	12,578 kHz	12,657.5 kHz
	12,578.5 kHz	12,658 kHz
HF	16,805 kHz	16,903 kHz
	16,805.5 kHz	16,903 kHz
	16,806 kHz	16,904 kHz
	18,898.5 kHz	19,703.5 kHz
	18,899 kHz	19,704 kHz
	18,899.5 kHz	19,704.5 kHz
	22,374.5 kHz	22,444 kHz
	22,375 kHz	22,444.5 kHz
	22,375.5 kHz	22,445 kHz
	25,208.5 kHz	26,121 kHz
	25,209 kHz	26,121.5 kHz
	25,209.5 kHz	26,122 kHz
VHF	165.525 MHz (Channel 70)	165.525 MHz (Channel 70)

Table 9: International DSC frequencies for purposes other than distress, safety and emergency

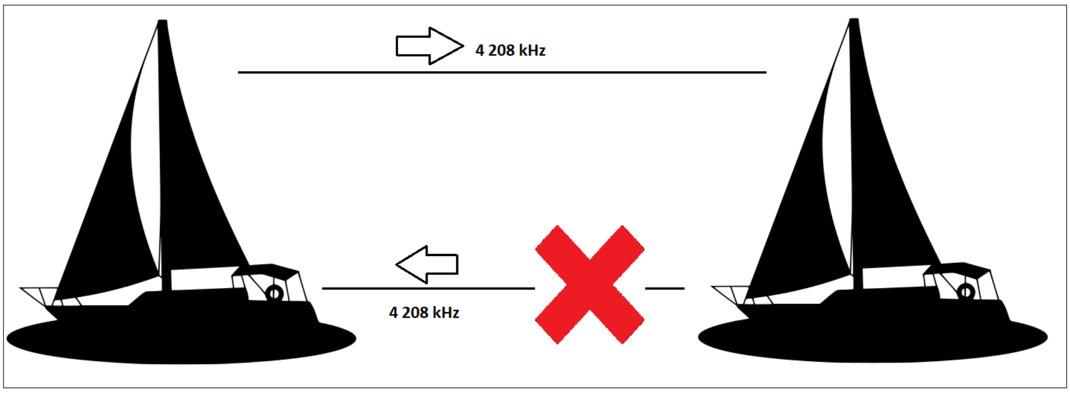


Figure 23: Routine semi-duplex DSC communication between two ships

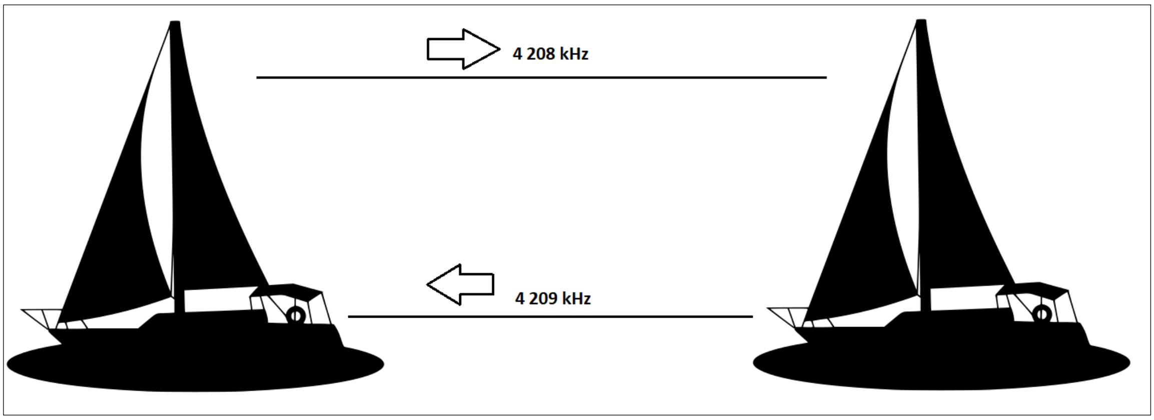


Figure 24: Routine full-duplex DSC communication between two ships

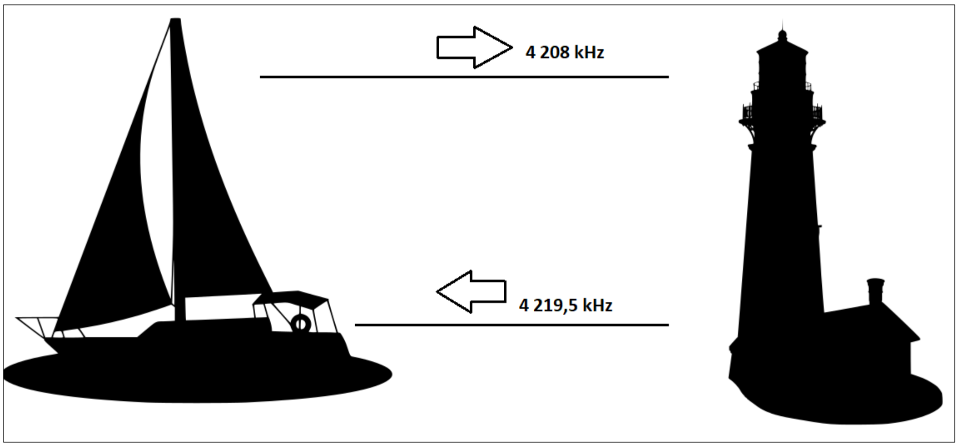


Figure 25: Routine full-duplex DSC communication between a ship and a shore station

3.4.2.5. Physical layer blocks

This section defines the blocks related to power, bandwidth and modulation for the DSC system.

- **Power and bandwidth:** The DSC standard stipulates that all equipment must offer the option of transmitting the sequences either at a low level, with a transmitted power of between 0.1 and 1 W, or at a high level, with a transmitted power of between 6 and 25 W. This choice is mandatory for all channels, except 70, where it will always be transmitted at a low level.

  In the MF and HF bands, channelling is 500 Hz and the bandwidth of the J2B modulated signal is 170 Hz. In the VHF band, channelling of maritime services is 25 kHz, although sometimes it can be subdivided into 12 kHz and the bandwidth of the G2B modulated signal is 1.6 kHz. As can be seen, DSC transmissions, both in MF and HF and VHF, are narrowband.

- **Modulation:** The DSC standard documentation includes two types of modulation according to the frequency band used in the transmission: F1B6, J2B for the bands MF and HF and G2B for band VHF.

3.4.2.6. Sequences

As we explained in the general description, messages are known as calls, call sequences or simply sequences. Each sequence comprises a series of elements made up of one or more characters. A character is a set of 10 bits that form an error detection code.

In addition to error protection provided by the error detection code, the DSC standard provides time diversity to each character by transmitting it twice with a separation of four characters between them, corresponding to a time difference of 400 ms in the MF and HF bands and 33.33 ms in the VHF band.

A complete DSC sequence would follow the structure described in Figure 26.

Series of points	DX/RX Phasing sequence	A Format specifier 2 identical characters	B Called user address 5 characters	C Category 1 character	D Self-identification 5 characters

E Telecommand message 2 characters	F Frequency message 3 characters	G Frequency message 3 characters	H End of sequence 3 identical DX characters 1 RX character	I Error checking character 1 character

Figure 26: Technical format of a routine call sequence [30]

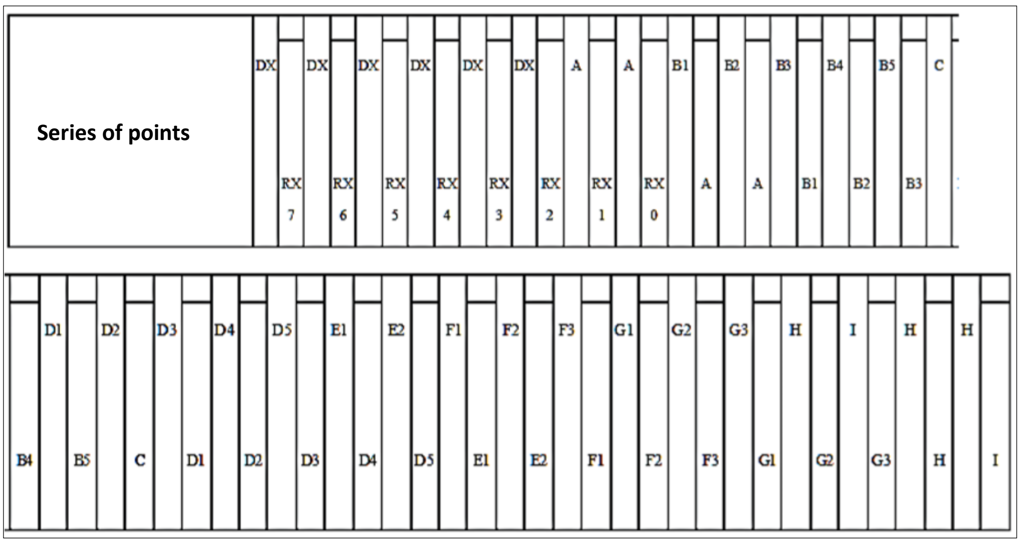


Figure 27: Transmission sequence [30]

3.4.2.7. DSC messages

The messages included in a DSC call sequence depend on the purpose of the call. Not only does the content of the messages vary, but so also does their number.

3.4.2.7.1. Distress alert

Distress information is contained in four messages whose format is specified in Table 4.1 of [30].

Message No.	Contents
1	Indicates the nature of the danger coded according to Table 3 of [30].
2	Indicates the coordinates of the distress site. The coordinates are coded using 10 digits, 5 characters, where the first digit corresponds to the geographical quadrant, the following four digits to the latitude in degrees and minutes and the next five to the longitude in degrees and minutes. If the coordinates are unknown or have not been updated in the last 23 hours, all figures must be transmitted as “9”.
3	Indicates the time when the coordinates were valid. It is coded with 4 digits, 2 characters, with the first two indicating hours (in hours) and the other two the fraction of hours (in minutes). If the time cannot be included, the number “8” must be inserted four times.
4	Indicates in a single character according to Table 3 of [30] what type of communication is preferred by the station in danger for subsequent exchanges of distress traffic.

Table 10: Distress alert messages

3.3.2.7.2. Retransmission of distress alerts, acknowledgements of distress alerts and retransmission of distress alerts

In these cases, the information on the danger is included in five messages described in Tables 4.2 to 4.4 of [30].

The first message is the MMSI of the ship in danger. The following four messages are identical to those in Table 10.

3.3.2.7.3. Other types of calls

The rest of the DSC call sequences include three messages, the formats of which can be found in Tables 4.5 to 4.10.2 and Figures 2 and 3 of [30].

Message No.	Contents
1	Indicates the telecommand information, which consists of two telecommand characters coded according to Table 3 of [30]. It is possible to transmit one, two or no telecommands.
2	It can contain two frequency or channel elements, each of 3 characters, or the position of the ship, in 6 characters. If the first character is 55, the remaining 5 characters represent the position of the ship as described in the second message of distress calls. Otherwise, if the first digit is '3', the following five digits indicate an MF/HF channel; if it is '9', the following five digits indicate a VHF channel and, if it is less than '3', it indicates the frequency in multiples of 100 Hz.

3	The third message, when a station on a ship initiates a call that requires a semi-automatic or automatic connection, contains the telephone number to be called.

Table 11: Messages for other types of calls

3.3.2.7.4. Error control

As already explained, the DSC system has three protection systems: the error detection code, time diversity and an error check character.

The standard requires all this information to be used in order to correctly decode the sequences, and no action can be taken until the last character of the sequence has been decoded and the integrity of all data checked.

3.4.3. Commercial equipment

States are responsible for legislating on what equipment is required in each case and for approving the equipment on the market. The body that performs these functions in Spain is the Directorate-General for Merchant Shipping (DGMM).

Numerous manufacturers of VHF radio equipment incorporate DSC, but they are mostly Class D, type-approved as "*DSC non-SOLAS*"[11] by the DGMM. Only three companies manufacture equipment approved as "DSC *SOLAS*": Furuno, JRC and Thrane & Thrane. These manufacturers offer type-approved VHF[12], HF and MF[13] equipment.

Figure 28: Example of Furuno FM-8900S semi-duplex radiotelephone, extracted from [31]

[11] DSC equipment, but which the DGMM does not consider to comply with all features of GMDSS.

[12] Four models that include radiotelephone and DSC services.

[13] Nine models: eight include radiotelephone, DSC and radiotelex; One includes only radiotelephone and DSC.

Figure 29: Example of JRC JSS-2150 equipment without radiotelex, extracted from [32]

Figure 30: Example of Thrane & Thrane SAILOR TT-6310 equipment, extracted from [33]

3.5. Other communications systems

As we stated previously, this book aims to provide an overview of maritime communications. Starting from this premise, we have run through this sector from its origins, describing the first technologies that emerged in this domain, showing their evolution and digitalisation up to the new systems in use today. The various chapters emphasise the voice communications systems that emerged for the maritime sector, their evolution to AIS and DSC and the presentation of VDES and introduction of the concept of e-Navigation.

However, there are many more communications systems within the maritime environment and, although they will not all be described, it is worth mentioning at least a few of them.

3.5.1. Inmarsat

Inmarsat is a maritime mobile satellite system. The system has an inherent capacity, known as *SafetyNET*, which uses enhanced group calls (EGC) to broadcast messages to selected groups of ship stations located anywhere within range of satellite coverage. Four geostationary satellites provide almost worldwide coverage for *SafetyNET*, with the exception of the polar regions.

SafetyNET and NAVTEX are the main means for disseminating maritime safety information. *SOLAS* vessels operating outside areas covered by NAVTEX must carry an Inmarsat *SafetyNET* receiver.

3.5.2. Iridium

Iridium is a constellation of non-geostationary satellites designed to provide mobile satellite services with global coverage. The aim of the system is to provide voice and data communication through portable devices in areas outside the coverage of traditional communication systems (fixed/mobile telephony).

3.5.3. Thuraya

Thuraya is a geo-synchronous mobile satellite system that provides access to satellite and GSM services from the same phone. As a communications operator, it offers voice, fax and data services at a bit rate of 9.6 kbps. Coverage is not worldwide - mainly Europe, North and Central Africa and the entire Middle East.

3.5.4. LRIT

LRIT is a system required by the IMO through which all passenger and cargo ships and mobile offshore drilling units engaged on international voyages must report their position on a regular basis (at least four times a day) to their flag state administration.

By and large, satellite communications are used as a method of transmitting these reports, which are received and authenticated by an authorised service provider before being sent to the data centre. Data sent by the ship can be complemented with additional information from the coastal authorities. Other states may have the right to request this information from the flag state administration.

Figure 31: Example of Inmarsat IsatPhone 2 satellite phone, extracted from [34]

Figure 32: Example of Iridium 9575 Extreme satellite phone, extracted from [35]

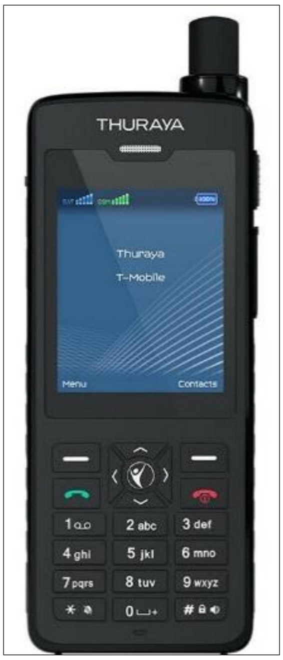


Figure 33: Example of Thuraya XT Pro satellite phone, extracted from [36]

4. Future: VDE and e-Navigation

4.1. AIS saturation and appearance of VDES

AIS is a very important, useful and effective technology as a navigation assistant, but it is not appropriate for data transfer. For that reason, the increasing number of registered vessels and the inclusion of new applications (AIS SART, AIS MOB, EPIRB AIS, AtoN, ASM, etc.) have resulted in a significant increase in the VDL load in transit zones, causing saturation and the consequent degradation of the AIS and Satellite AIS system.

Despite its success as a support service for safety and maritime emergencies, the AIS system suffers a series of shortcomings that are intended to be remedied or mitigated with the introduction of a new technological concept known as VDES. VDES will substantially improve the possibilities of AIS, integrating new channels, AtoN and VTS services, which will be able to cope with the growing number of new applications.

These shortcomings are listed below to provide an overview of the limitations of AIS that led to the birth of the VDES system:

- **Overload:** a study carried out by the ITU in 2013 revealed that in certain parts of the world where maritime traffic is high, the critical threshold [37]of 50% load for SOTDMA access mode has been exceeded [38]. In 2014, loads of 64% were detected in the Gulf of Mexico and 40% in Korea and Japan [39]. This increase in system load corresponds to the rising number of AIS stations and to the greater number of services integrated within the system, which inherently already constitutes an overload.

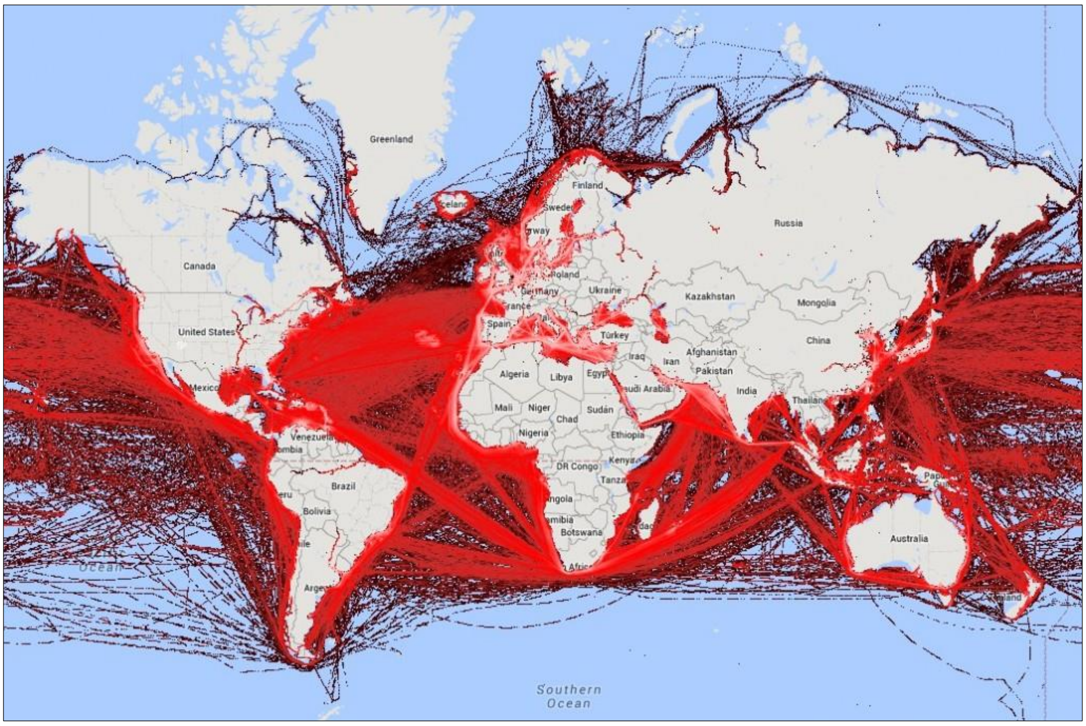


Figure 34: Global vessel traffic with AIS devices (2016) [40]

- **Security:** As already mentioned in previous sections, AIS is an open system, which means that broadcasts are not encoded and can be received (or generated) by any equipment that meets the system specifications. This makes the system highly vulnerable.
- **Rate**: The AIS system, which has a transmission rate of 9.6 kbps, was not designed to support sending the amounts of information required for new applications (such as e-Navigation) in maritime radiocommunication services. Its purpose, which is still valid today, is as a means of tracking ships under SOLAS worldwide, providing position reports, alert and security notices and SAR services.

4.2. VDES

4.2.1. Introduction

The VHF data exchange system (VDES) integrates the functions of VHF data exchange (VDE), application specific messages (ASM) and the automatic identification system (AIS) in the VHF maritime mobile band (156.025-162.025 MHz). The figure below (Figure 35) shows its entire operational concept.

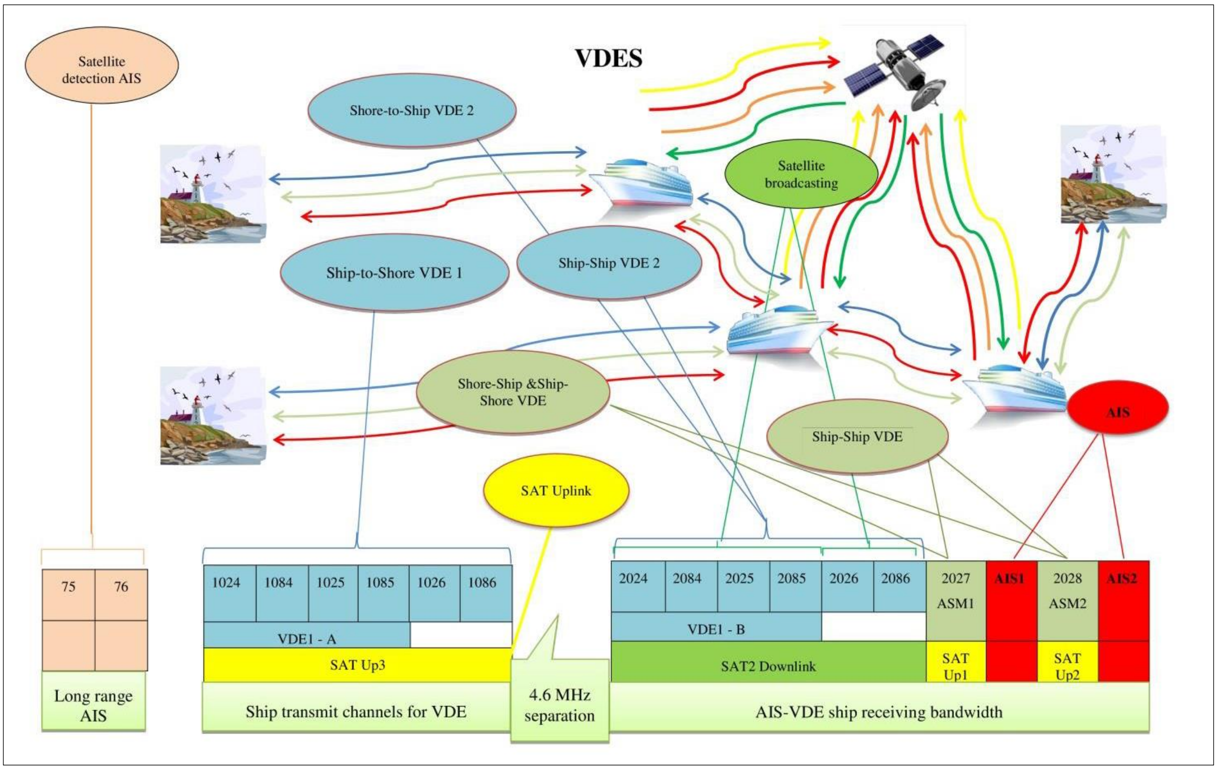


Figure 35: VDES system operational concept [39]

To meet the growing need to increase the capabilities and uses of the AIS system, VDES offers support for:

- The exchange of safety, emergency, efficiency improvement and environmental protection data.
- Interoperability and global availability dedicated to maritime safety communications.

- e-Navigation.
- Maritime data links and modernisation of the GMDSS service, without interfering in any way with the DSC (Channel 70) or distress, safety and calling voice communications (Channel 16).
- New applications that cannot be developed on AIS.

The aforementioned increase in capacity includes:

- Higher bit rates supported, making it possible to increase the amount of information transmitted.
- Increased operational range thanks to the definition of the satellite component for its integrated services.
- Relieving pressure on the AIS system, since transmitting certain contents is now the task of other components of the VDES system, which helps to protect service provision.
- The ability to integrate new services and applications within the system.
- The possibility to encrypt information, thereby increasing security against malicious attacks.

The VDES system is still in the development and implementation phase, since the necessary regulatory framework for standardising its use is not currently defined. Figure 36 shows a timeline indicating the milestones for development.

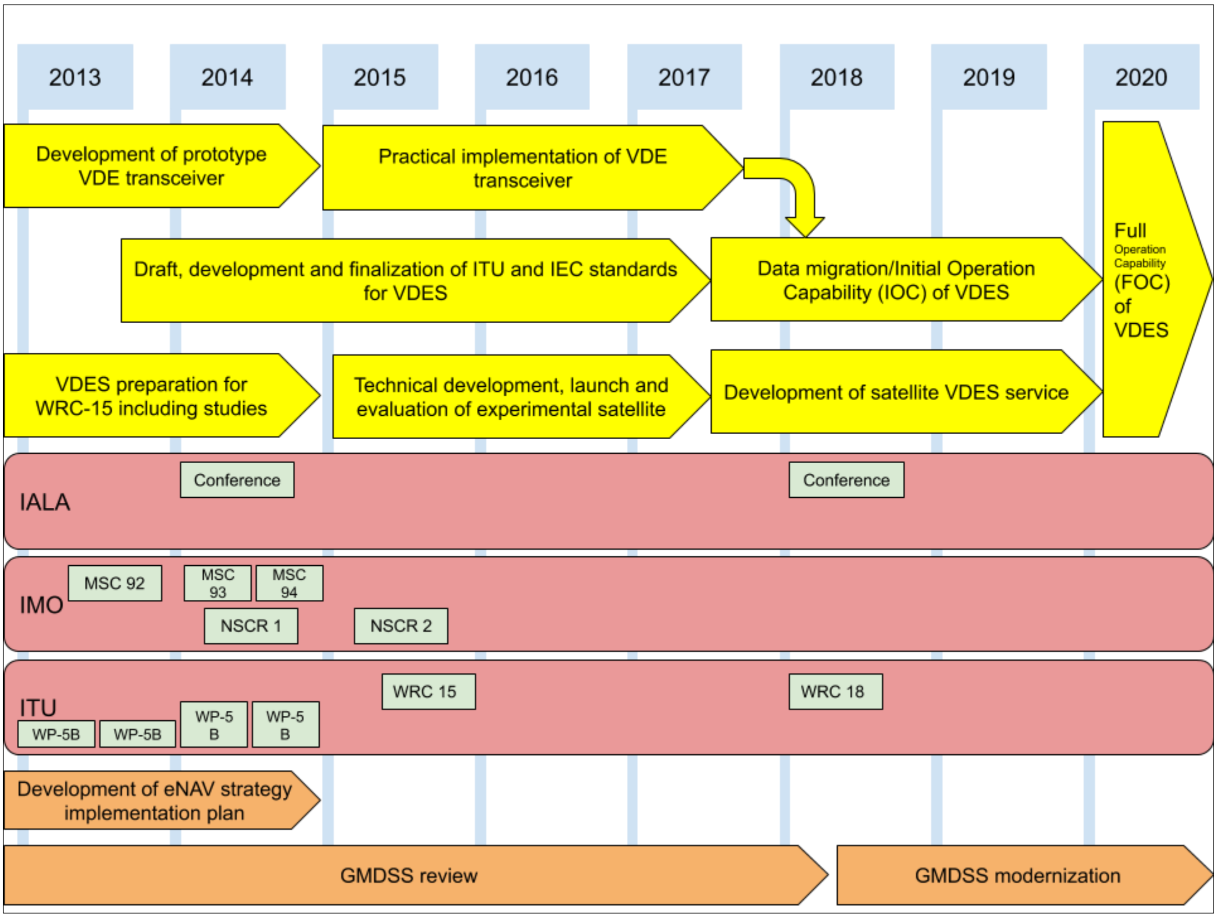


Figure 36: Timeline for development of the VDES system [39]

4.2.2. System overview

The general characteristics of the VDES system are described in the following subsections.

4.2.2.1. Requirements

The document defining the technical characteristics of the VDES system [41] sets out a series of requirements to be met, as listed below:

- It should give its highest priority to the AIS position reporting and safety related information.
- It should be capable of receiving and processing the digital messages and interrogating calls specified by the Recommendation
- It should be capable of transmitting additional safety information on request.
- The system installation should be able to operate continuously while under way, moored or at anchor.
- It should use for the terrestrial links time-division multiple access (TDMA) techniques, access schemes and data transmission methods in a synchronised manner as specified in the Recommendation.
- It should be capable of various modes of operation, including the autonomous, assigned and polled modes.
- It should provide flexibility for the users in order to prioritise some applications and, consequently, adapt some parameters of the transmission (robustness or capacity)
- An automatic stop and alert procedure that acts if the transmitter keeps transmitting for more than two seconds must be enabled. This stop procedure must be independent of the software control.

Likewise, all VDES stations must be uniquely identified. A suitable numerical identifier may be used for identification purposes, for example the Maritime Mobile Service Identity (MMSI) defined in the most recent version of [42].

4.2.2.2. Integrated services

The VDES system can be broken down into three main subsystems or services: VDE, ASM and AIS, all of which have a terrestrial and a satellite segment, although this segment is bidirectional only in the case of VDE. Below are the most significant characteristics of the three subsystems:

4.2.2.2.1. VDE

VDE (*VHF Data Exchange*) provides an effective link for data transfer. It enables a series of key applications for the maritime community to be incorporated which the AIS system alone would not be able to support. As its structure is different to the AIS and ASM messages, the transmission rates provided by VDE are higher than in the other two services.

- **Terrestrial VDE:** Data transmission is made in the VHF maritime mobile band. Data transmissions are made within the spectrum allocated for the VDE1-A and VDE1- B[14]. The spectrum may be used as 25 kHz, 50 kHz or 100 kHz channels.

  The typical range of a terrestrial VDE link is usually between 20-50 nautical miles, slightly higher than the 25 to 40-mile range provided by the AIS system.

[14] VDE1-A comprises the set of channels used for shore-to-ship and ship-to-ship communications using VDE. VDE1-B is the set of channels used in ship-to-shore communications, also using VDE.

Simplex mode is used for simple transmissions between vessels, while duplex mode is used in ship-to-shore and shore-to-ship transmissions, in which the low and high parts of the assigned spectrum are used respectively and only one of the ends transmits at a particular moment (semi-duplex).

Control stations are an important element within the VDE earth component. These stations are coastal base stations that transmit bulletin boards, in this case terrestrial ones (TBBs). Bulletin boards make it possible to assign the main operating environment parameters to the service area of a control station. This includes the frequencies in use and the dimensions of the service area, among other technical details. Monitoring the TBB allows vessels to determine whether they are within a service area of the control station.
Control stations can transmit a bulletin board through the service area. The content of the TBB applies only to vessels within the area of the corresponding control station.

While vessels are within an area belonging to a station, all data session transmissions between vessels must be made through the control station. Ships outside the service area of the station can communicate directly. In this case, AIS receptions can be used to determine if a vessel is within range.

The TBB is authenticated to provide protection to the communication environment. The authentication confirms that the TBB has been transmitted by a trusted entity.

To increase security, a public key infrastructure (PKI) can be set up with IMO as the top trusted entity. The idea is to attach a digital signature to the bulletin board issued by a control station to authenticate the station issuing the TBB. This increases protection and establishes a measure to thwart possible malicious attacks (spoofing, replay attacks, man-in-the-water, fake CPA, etc.).

To achieve this, ships need a PKI unit dedicated to their connection system or to build the functionality into the VDES equipment. This unit provides cryptographic services to general network and connection applications and requires a smart card for tamper-proof storage of the security network.

The user will be notified if the signature verification fails in the VDES mobile station. The system will continue to run as if the signature had been verified.

The cryptographic algorithm for digital signatures of end-entities is the The Elliptic Curve Digital Signature Algorithm (ECDSA). The public key will be 256 bits. With this size, RFC 5480 recommend that the minimum security number must be 128 bits.

Communication with a separate PKI unit will be based on the network protocol.

- **Satellite VDE:** Satellite VDE provides a communications link beyond the coverage of the shore stations or at points where there is no station.

Its downlink supports multi-packet and multicast data transfer and shore-originated unicast multi-packet data transfer via satellite (shore stations). Its uplink supports information gathering from VDES stations and long-range ship-to-shore communications.

4.2.2.2.2. ASM

Binary messages 6, 7, 8, 12, 13, 14, 25 and 26, used by the AIS system for the transmission of ASMs (Application Specific Messages), are a burden for this [38] [39].

The ASMs defined in Annex 5 of [29] are binary messages in which content is defined by the application. Therefore, they are an ideal medium for integrating new applications that use them to transmit meteorological, navigation, port management, information, etc. This is also a threat to the AIS system, as new applications could further overload the system. It has therefore been proposed to remove them from the AIS channels and assign channels 2027 and 2028 (169,950 and 162,000 MHz) for use in the ASM service using a different modulation (π/4 QPSK) both in its terrestrial and satellite (uplink) component. This proposal was accepted and in 2015 it was incorporated into the ITU document that defines the technical characteristics of the VDES system [41].

- **Mode of operation:** Like AIS, the ASM service must be able to simultaneously receive two channels in parallel and transmit alternately on two independent channels.
- **Application identification:** the binary messages that are directed and broadcast must contain a 16-bit application identifier, structured as indicated in Table 12.
- **Definition of functional messages (FM):** Each unique combination of application identifier (AI) and application data results in a functional message. Functional messages can be international or regional in nature. These messages can be consulted at [29] and [43].

Bit	Description
15 – 6	Designated Area Code (DAC). This code is based on the maritime identification digits (MID). Exceptions are 0 (test) and 1 (international). Although the length is 10 bits, the DAC codes equal to or above 1 000 are reserved for future use.
5 – 0	The meaning should be determined by the authority which is responsible for the area given in the designated area code.

Table 12: Defining the Application Identifier (AI) for binary ASM messages [29]

4.2.2.2.3. AIS

As already stated, AIS is a broadcast communications system operating in the VHF band assigned to maritime mobile services (156.025 MHz-162.025). It uses an open protocol for the exchange of navigation data in the access to the medium is provided as variants of TDMA.

Its incorporation into the VDES system does not change its purpose in any way, it only serves to reduce its operational load and thus better perform the function for which it was designed: to exchange information related to ship identification, position and tracking reports and search and rescue support.

The Satellite AIS service is a technology that provides added value to various sectors: environmental, fleet management, maritime safety, fight against piracy, etc. This is possible because it is a low cost solution for VTS.

4.2.2.3. Priority of services

The VDES system must respect and protect the original function of the AIS system. Since a VDES mobile station with a single antenna will suffer decreased receiver sensitivity when transmissions occur, care must be taken to respect the AIS transmission as the highest priority. With this in mind, four priority levels are defined:

Priority	Type of messages
1	Critical link management messages
2	Safety related messages
3	Interrogation and responses to interrogation
4	All other messages

Table 13: Service priority levels

Messages will be attended in order of priority both in transmission and reception. Messages with equal priority are processed in FIFO order[15].

4.2.2.4. Frequency aspects

In 2014, IALA recommended in [44] the use of the A Frequency Plan of [45], according to the technical requirements that the system must meet. This frequency allocation plan ensures that VDES coexists with VHF and DSC voice services.

For system operation, the ITU approved the frequency assignment for it within the maritime VHF band (156.025-162.025 MHz) in WRC-15 [46] (and subsequently incorporated into the RR and the technical description of VDES [41]).

Currently the only frequencies that have not been assigned correspond to the VDE satellite component although they have been proposed and are awaiting approval by the WRC-19.

Table 14 shows the assignment of frequencies to be used.

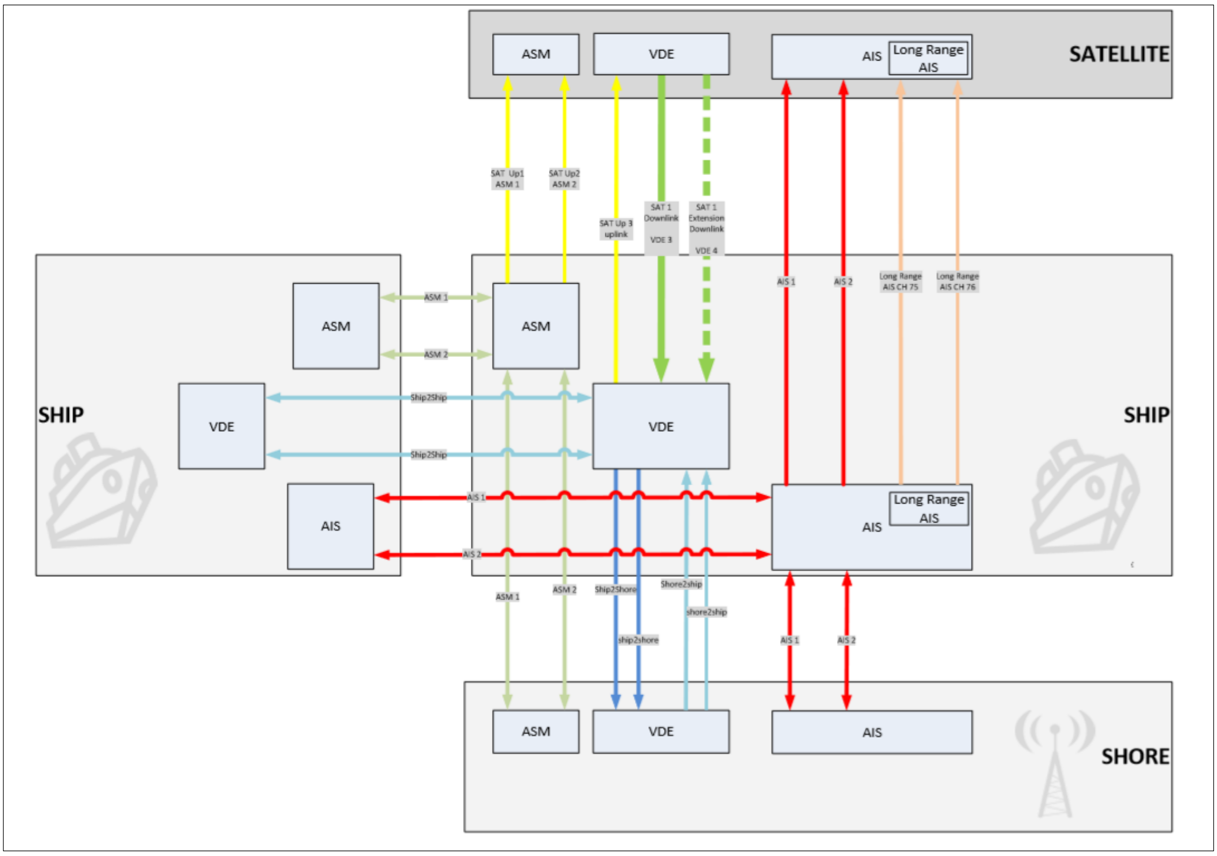
Both simplex and duplex channels are assigned within the maritime VHF band. These latter comprise two frequencies, one for transmissions from ships (reception by the shore station) and another for transmission from the shore station (reception on ships).

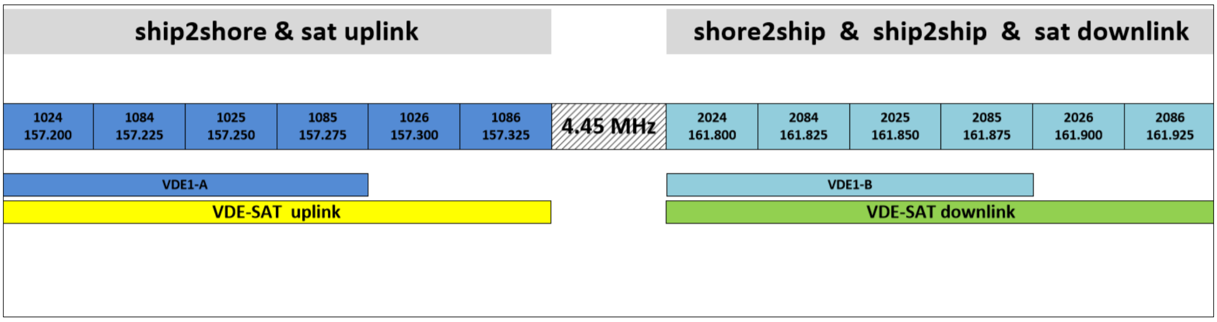
Component	Channels
Terrestrial	AIS 1 (channel 2087) and AIS 2 (channel 2088) are the channels used by the AIS system.
	ASM 1 (channel 2027) and ASM 2 (channel 2028) are the channels assigned for application-specific messages (ASM).
	VDE1-A (channels 1024, 1084, 1025 and 1085) has been assigned for ship communications to shore stations using VDE.
	VDE1-B (channels 2024, 2084, 2025 and 2085) has been assigned for communications from shore stations to ships or between ships (simplex mode) using VDE.
Satellite	AIS 1 (channel 2087) and AIS 2 (channel 2088) are AIS terrestrial channels that can also be used as an uplink for the satellite component of AIS.
	Channels 75 and 76 have been assigned as the uplink of the Satellite AIS service.

[15] For a FIFO order, the first one entering the warehouse must be the first one to be sent out.

Component	Channels
	SAT Up1 (channel 2027) and SAT Up2 (channel 2028) have been assigned as the uplink of the ASM satellite service (shared with the earth component).
	SAT Up3 (channels 1024, 1084, 1025, 1085, 1026 and 1086) has been assigned as the uplink of the VDE satellite service.
	SAT Downlink (channels 2024, 2084, 2025, 2085, 2026 and 2086) has been assigned as the downlink of the VDE satellite service.

Table 14: Assignment of channels for the different services in the terrestrial and satellite components





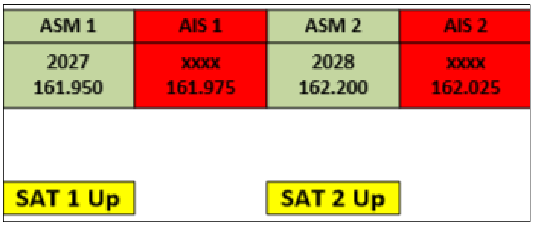


Figure 37: VDES system frequency assignment diagram [41]

4.2.2.4.1. Mode of operation

At power on, a station should monitor the TDMA channels for one minute to determine:

- Channel activity;
- Other participating member IDs;
- Current slot assignments, and possible existence of shore stations;

During this time period, a dynamic directory of all stations operating in the system should be established.

A frame map should be constructed, which reflects TDMA channel activity. After one minute has elapsed, the station may be available to transmit ASM messages according to its own schedule.

Three operating modes are defined for the VDES system, leaving open the possibility of including additional modes (without deleting the three defined). These are:

- **Autonomous mode:** A station operating autonomously should determine its own schedule for transmission. The station should automatically resolve scheduling conflicts with other stations.
- **Assigned mode:** A station operating in the assigned mode takes into account the transmission schedule of the assigning message when determining when it should transmit. In certain scenarios, the competent authority, through the base station, may decide that a device should transmit under a specific transmission schedule.
- **Polled mode:** A station operating in polled mode should automatically respond to interrogation messages. Operation in the polled mode should not conflict with operation in the other two modes. It should be noted that the response must be transmitted on the channel through which the interrogation message was received and not by another.

The default mode of operation (autonomous) is also defined and it is a requirement that it can be switched to other modes from these.

4.2.2.5. TDMA access modes

4.2.2.5.1. General

VDES uses TDMA access mode with a duration for each slot of 26.66 ms. This means 2,250 slots (a frame) per channel per minute.

These access modes will work continuously, and in parallel, on the same physical data link. All of them will comply with the rules established by TDMA and, as already mentioned, the VDE and ASM services must give priority to the AIS system when accessing the physical data link.

The slots used for transmission are chosen randomly from a set of special slots, known as candidate slots (Section 3.2.4.8.2), belonging to the selection interval (SI).

The selection interval consists of a series of slots with a duration set to 150 slots (4 seconds), formed mainly by free slots of the AIS and ASM services. The candidate slot selection process also has to consider time periods reserved for the reception of the bulletin board. The available slots are as defined in [29] and must only be taken from the most distant station(s) within the SI.

There should be, at minimum, a set of four candidate slots to choose from. If the candidate slot set contains less than four slots, additional candidate slots can be obtained by using the following rules and order:

- **Rule 1:** available slot on an AIS channel and free on all other AIS and ASM channels.
- **Rule 2:** available slot on both AIS channels and free on all ASM channels.

When selecting candidates for messages longer than one slot, a candidate slot should be the first slot in a consecutive block of slots that conform to the selection criteria stated above.

If the station cannot find a sufficient number of candidate slots, the station should not transmit and should re-schedule the transmission.

The purpose of maintaining a minimum of four candidate slots within the same probability of being used for transmission is to provide high probability of access to the link.

VDES inherits the access modes used by the AIS system.

4.2.2.5.2. AIS

As explained in Section 3.2.4.8, the main method of accessing the medium in AIS Class A devices is SOTDMA. The other modes of access that interoperate with it are:

- RATDMA (Random Access TDMA).
- ITDMA (Incremental TDMA).
- FATDMA (Fixed Access TDMA).
- CSTDMA (Carrier Sense TDMA).
- Modified SOTDMA.

4.2.2.5.3. ASM

In ASM, access to the medium is managed and controlled by four variants of the TDMA mode: ITDMA, RATDMA, SCTDMA and FATDMA.

4.2.2.5.4. VDE

Access to the medium under VDE is available as follows, depending on the service offered:

- **Ship-to-shore and shore-to-ship communications:** reservation through ITDMA from an ASM.
- **Ship-to-ship communications:** initially by CSTDMA for the first transmission in a frame, followed by ITDMA.
- **Downlink VDE-SAT:** FDMA (channels 2026 and 2086) or TDMA (FATDMA, CSTDMA and AMDTI).
- **Uplink VDE-SAT:** FDMA or TDMA.

It should be remembered that VDE transmissions should not exceed five adjacent slots.

4.2.3. Technical characteristics

Throughout this section and its corresponding sub-sections, we shall provide a general overview of the various aspects of a technical nature concerning the VDE, ASM and AIS components, both terrestrial and satellite. For a more detailed description, we recommend you consult [41].

4.2.3.1. General

This section defines a series of characteristics that must be fulfilled for all the terrestrial and satellite components of the VDES system.

4.2.3.1.1. OSI model

According to the document defined in [41], the VDES system must use layers 1 to 4 of the open systems interconnection (the physical, the link, the network and the transport layers) illustrated in Table 15.

Application layer
Presentation layer
Session layer
Transport layer
Network layer
Link layer
Physical layer

Table 15: Seven layer OSI model [41]

- **Physical layer:** The transmission and reception of raw bit streams are processed on this layer. Then, the signal modulation and the filter previous to the transmission and amplification, filtering, synchronization, demodulation and decoding upon reception are applied.
- **Link layer:** This layer ensures reliable transmission of data frames between ships, ship and shore, and ship and satellite.
- **Network layer:** This layer is responsible for the management of priority assignments of messages, distribution of transmission packets between channels and data link congestion resolution.
- **Transport layer:** This layer ensures reliable transmission of the data segments between ships, ship and shore, and ship and satellite, including segmentation, acknowledgement and multiplexing. For VDE, existing Internet protocols should be supported, including TCP, UDP, SNMP, Secure File Transfer Protocol (SFTP) and Simple Mail Transfer Protocol (SMTP).
- **Presentation Layer:** For VDES transceivers, data can be entered through the presentation interface for transmission by the VDES station. The data received by the VDES station must be output through the presentation interface. The formats and protocol used for the data flow to be presented in the presentation interface are defined in the IEC 61162 series.

4.2.3.1.2. Channels

VDES uses several channels to carry data. These channels are separated into Physical and Logical channels.

The physical channels (PC) are determined by the centre frequency and bandwidth. The logical channels (LC) are divided into signalling and traffic channels and are described in the sub-sections of this section.

The default centre frequency of the physical channel is located at the centre of each VDE1 leg (157.2375-161.8375 MHz) and the default bandwidth is set to 100 kHz.

Logical channel definitions can be made based on the physical channel and message time information (frame hierarchy, start time, etc.). define

A slotmap defines the logical channel of all slots in a frame. Each physical channel of VDES will have a defined slotmap. When monitoring the TBB, ships determine if they are within the service area of the control station and adopt the physical channel and the slotmap from the bulletin board. In the absence of a bulletin board, they adopt the default physical channel and slotmap.

In the case where the ship is outside the service area of the control station, the receiving ship must be able to assign a logical channel to another ship after receiving a resource request message. The LC should be assigned by randomly selecting a free channel from the logical channels usage map.

The default logical channels for the lower and upper phases of VDE are defined as shown in the following Figures:

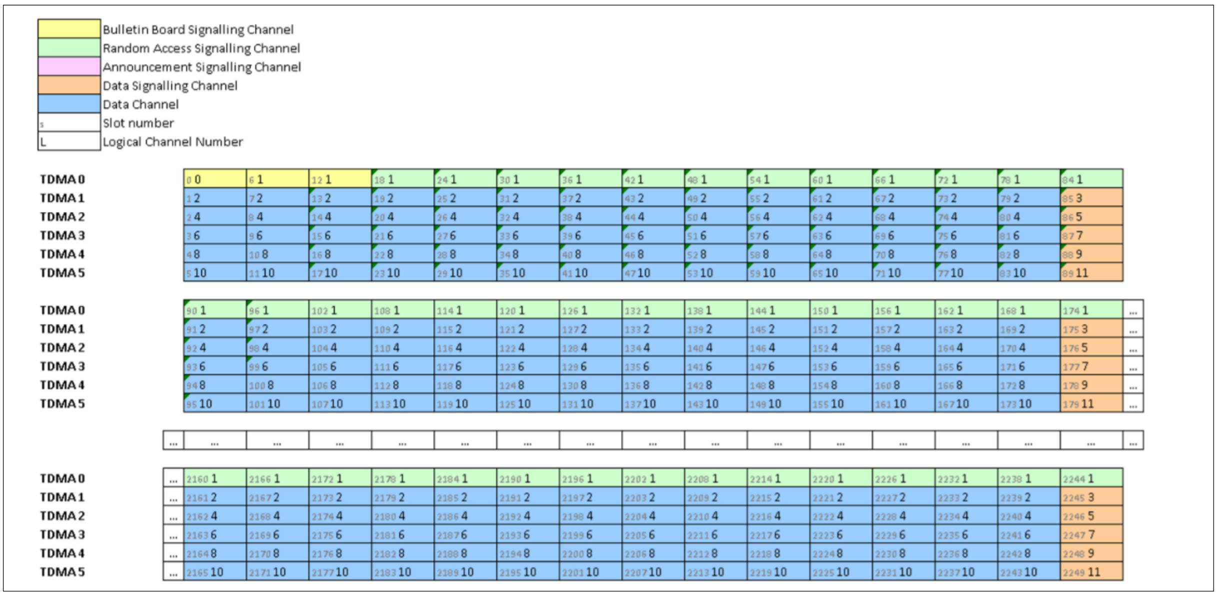


Figure 38: Ship-to-Shore default slot to logical channel mapping (lower leg)

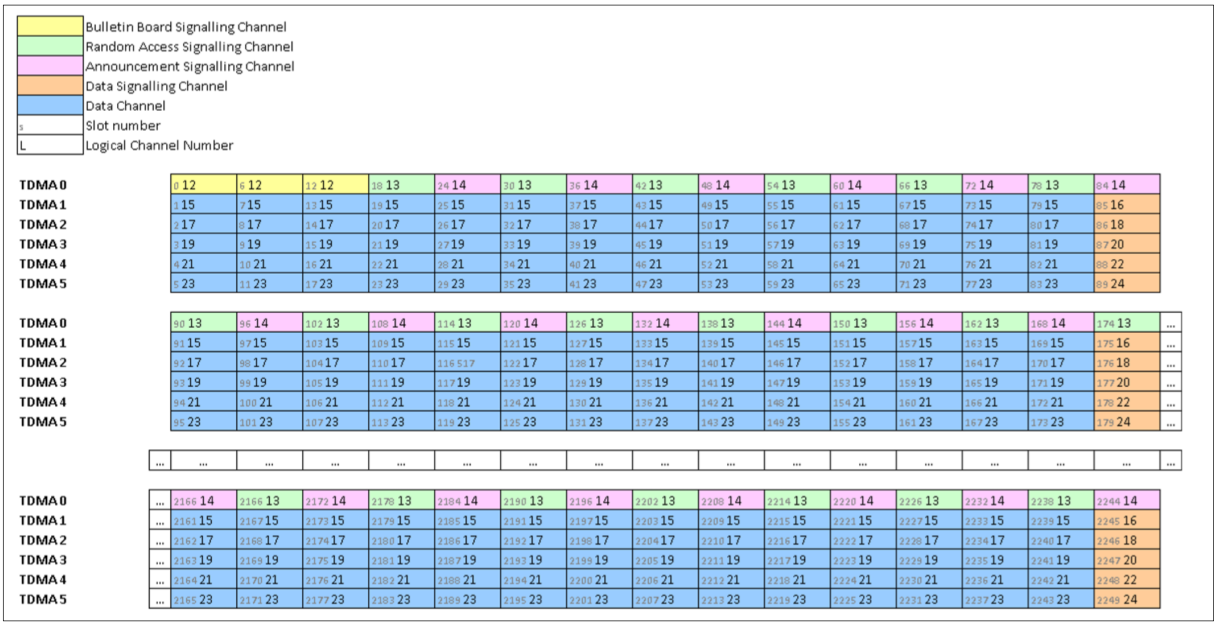


Figure 39: Ship-to-Ship default slot to logical channel mapping (upper leg)

4.2.3.1.2.1. Signalling channels

All signalling channels use the most robust modulation and coding scheme.

- **Terrestrial bulletin board signalling channel (TBBSC):** Each VDE shore station should employ a fixed logical channel for the TBB.

  All TBB logical channels will be based on one of a number of predefined structures of the frame hierarchy 50 kHz shore to ship physical channel (2024 and 2084 combined). These are defined to occupy only a portion of the frame (60 seconds, 2,250 slots) to permit possible spectrum and temporal sharing with satellites.

  The TBB defines the network configuration parameters such as signalling channels (control channels) and data channel(s), protocol versions and future network configuration.

  The TBB takes precedence in the allocation of spectrum (logical channel) resources. This may be co-ordinated with the satellite bulletin board signalling channel to facilitate sharing of mutual spectrum resources.

  The TBB information includes the area of applicability. The TBB does not change often and should be transmitted in regular intervals.

  The logical channels are normally repeated based on the VDES frame hierarchy. The VDE terrestrial channel usage for the service area of VDE shore station is defined by the TBB.

- **Bulletin board signalling channel (BBSC):** The BB defines the network configuration parameters such as signalling channels (control channels) and data channel(s), protocol versions and future network configuration. Satellite parameters and network ID are also provided, plus information about other satellites and networks.

The BBSC must be broadcast once every minute on specific VDE-SAT channels downlink (channels 2046 and 2086), starting at slot '0 and with a duration of 90 slots (2.4 seconds).

For an LEO satellite, it is sufficient that the Bulletin Board is received once per pass and a repeat rate of once per minute is sufficient for most passes.

The complete BB can be repeated every certain number of frames. The essential information of the BB must be repeated in each frame (every 60 seconds).

The ship's receiver must be able to receive BBs from up to eight different satellites. To do this, a CDMA scheme should be used to allow different satellites with overlapping coverages to transmit their BBs at the same time.

The structure of the BBSC can be found in section 3.8.1 of [41].

- **Announcement signalling channel (ASC)** This channel(s) will normally carry announcements, MAC information, VDE forward and return resource allocation, CQIs, ARQs, and ACKs.

  Announcements also include the co-ordination of unicast and multi-cast (broadcast) datagrams.

  As in the TBB, these are defined to occupy only a portion of the frame to permit possible spectrum and temporal sharing with satellites.

  The MAC information includes changes to network version, congestion control (randomisation interval (hold-off) and minimum priority level).

  The ASC defines the physical channel usage (logical channel, i.e. frequency and slot) to an individual ship following a resource request.

  The VDE shore station uses CQI information from the ship terminal to select the highest throughput format with adequate link margin.

- **Random access resource request (RQSC):** A ship uses this channel to access the network. A ship will randomly select the transmission time within the slots allocated for this channel on the Bulletin Board.

  The downlink Announcement Channel provides congestion control parameters such as retry interval and message priority.

- **Announcement response channel (ARSC):** A ship uses this channel to inform the satellite that it is ready to receive a message.

- **Acknowledgement channel (ACK):** A ship uses this channel to inform the satellite that it has received a message correctly (CRC match).

- **Automatic repeat request signalling channel (ARQSC):** A ship uses this channel to inform the satellite that it has not received a message correctly (CRC failure). The ship can request retransmission of the whole message or up to four fragments.

4.2.3.1.2.2. Traffic channels.

Traffic channels can use a combination of robust modulation and coding schemes and higher bit rate.

- **Multicast data channel (MDC)** This traffic channel is utilised to send messages to be received by a large number of ships. By default, multicast messages are addressed to all stations (i.e. broadcast).

- **Unicast data channel (UDC)** This traffic channel is allocated a specific ship for the duration of a unicast datagram. This channel is set up after a ship responds to an announcement, and the response includes received channel quality information (CQI) allowing the shore station to maximise throughput.
- **Random access short messaging channel (RADC)** This channel is used for short messages that fit in a single transmission.

  Terrestrial addressing may require up to 254 bytes, and every ship uses therefore a 2-byte look-up table at the coast earth station for address translation.

- **Assigned data transfer channel (ADDC)** This channel is assigned by the satellite following a resource request from a ship. It is intended for longer messages and is optimised to achieve a higher throughput.

4.2.3.1.2.3. Mixed.

These logical channels are different from the logical channels of the TBB.

- **Random Access Channel (RAC):** This channel has the characteristics of a slotted Aloha channel, uses a random access scheme and will be selected from a predefined list of logical channels.

  For shore-to-ship communications, a ship station uses these channels to communicate with other ship stations directly via short message.

  For ship-to-ship communications when ships are outside the control zone of a VDE shore station, the ship station uses these channels to communicate directly with other ship stations via short messages and coordinate communication with other ships for longer messages.

  These logical channels will be based on a number of predefined structures of the frame hierarchy of the ship-to-ship physical channels (2024 and 2084 combined).

Ship-to-ship random access channels should have fixed physical channel assignments and use the most robust modulation and coding scheme.

4.2.3.1.3. Frame hierarchy

The VDES system uses the Recommendation ITU-R M.1371 concept of a frame. A frame equals one minute and is divided into 2,250 slots.

Access to the data link is, by default, given at the start of a slot. The frame start and stop coincide with the UTC minute. Each frame consists of 2,250 slots (or 60 seconds, which is the same thing).

All VDES transmitters should be synchronised to this common frame structure and use a common addressing of frame constituents so that each slot can be uniquely identified per frame.

Frame 0 starts at 00:00:00 UTC, and there are 1,440 distinct frames in a day. The impact of leap second should be accounted for to avoid any propagation of error.

The components of the frame can be divided into different levels, in a format defined below:

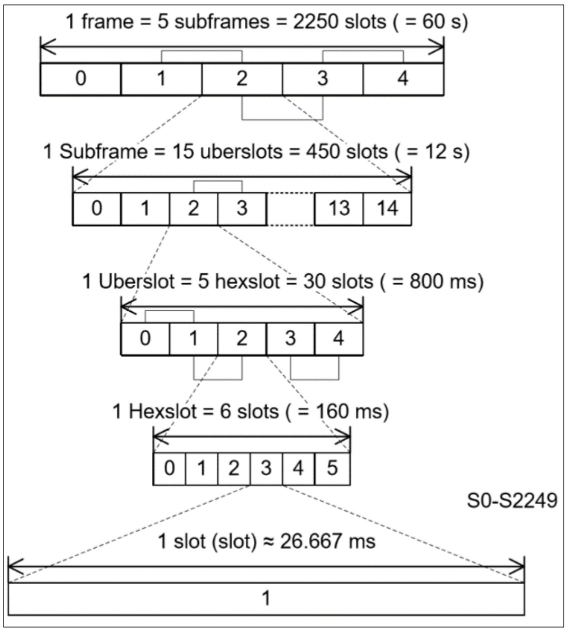


Figure 40: Frame hierarchy for shared frequency [41]

4.2.3.2. VDE

The following subsections set out the technical characteristics of VDE.

4.2.3.2.1. Terrestrial

The key points concerning the transmission parameters are listed below:

- Antennas such as those already on board many ships today can be used for VDE, but a ship antenna with a minimum gain at 0 degrees elevation of 3 dBi at the receiver input is required.
- Terrestrial VDE may share the same antenna(s) with the other subsystems AIS, ASM, VDE-SATas long as the protection of the AIS system is respected.

- The minimum ship EIRP vs elevation angle is shown in Table 16 and is based on a linear transmitter meeting the maximum Adjacent Channel Interference levels. For saturated operation the EIRP shall be 3 dB higher.
- A VDE transmitter station must have a frequency error of no more than 3 ppm for a transmit power between 1 and 25 W (± 1.5 dB normal, 2/-6 dB extreme).
- The spectrum mask to be respected varies depending on the channel bandwidth to be considered as in Figure 41.
- Spurious emissions should respect the specifications in Table 17.
- Sensitivity and Carrier to Interference Ratios for VDE vary depending on the modulation and coding scheme used. They can be consulted in Table 18.
- The transmission rates offered vary between 38.4-307.2 kbps depending on the modulation and channel bandwidth used.
- The timing accuracy of the transmit signal should be better than 5 ppm and the timing jitter should be better than 5% (peak value).
- Slot transmission accuracy at the output should be less than 100 µs peak relative to UTC reference time for the ship station and less than 50 µs peak relative to UTC reference time for the shore station.
- The operating modes to be used are: simplex for ship-to-ship communications and duplex for shore-to-ship and ship-to-shore communications.
- The system should use TDMA techniques in a synchronised manner.
- Shore-based stations should transmit a channel terrestrial bulletin board (TBB) message that defines the configuration of the VDE channels.

Ship elevation angle	**Embedded antenna gain**	**Minimum EIRP by ship with 6 W transmitter.**
Degrees	dBi	dBW
0	3	10.8
10	3	10.8
20	2.5	10.3
30	1	8.8
40	0	7.8
50	-1.5	6.3
60	-3	4.8
70	-4	3.8
80	-10	-2.2
90	-20	-12.2

Table 16: Minimum EIRP of the ship station transmitter depending on the elevation angle [41]

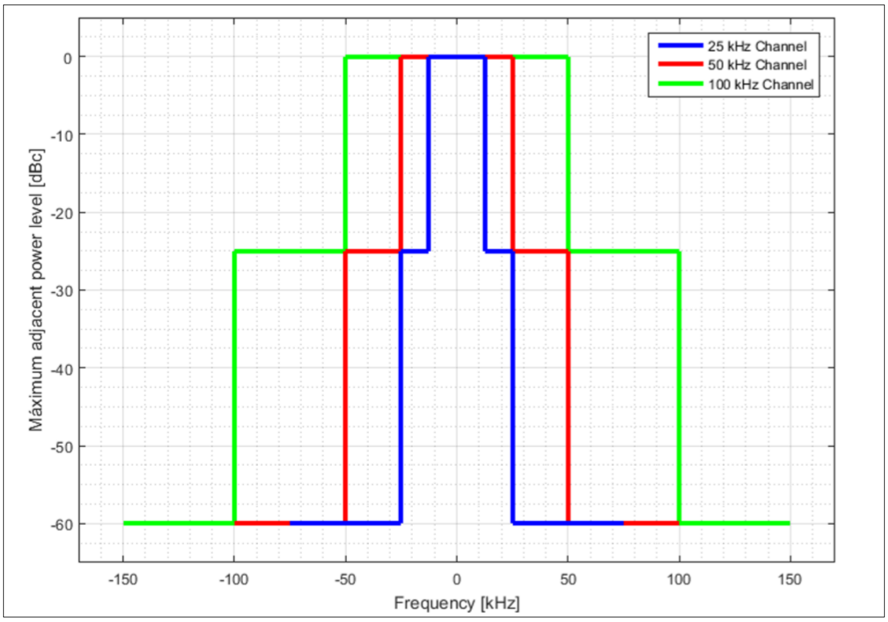


Figure 41: Maximum power levels in the adjacent channel of VDE

Requirement	Condition
Less than -36 dBm	9 kHz - 1 GHz
Less than -30 dBm	1 - 4 GHz 9.2 - 9.5 GHz

Table 17: Requirements concerning spurious emissions of VDE

Modulation and coding scheme	25 kHz		50 kHz		100 kHz	
	Sensitivity (dBm)	CIR (dB)	Sensitivity (dBm)	CIR (dB)	Sensitivity (dBm)	CIR (dB)
MCS - 1*	-110	8	-107	8	-104	8
MCS - 3*	-104	14	-101	14	-98	14
MCS - 5*	-102	16	-99	16	-96	16

Table 18: Sensitivity and Carrier to interference ratio for VDE [41]

The frame structure of VDE is illustrated in Figure 42.

Modulation: the terrestrial component of VDE is modulated according to various MCS (Modulation and Coding Schemes) by which it is possible to modify the gross channel flow rates, as well as the robustness of transmissions against errors. Currently, three MCSs have been fully defined and thirteen more have been reserved for future use. For more details about modulation schemes, see [41]. The bitmaps of the modulations used are defined in Figure 43. For n/4 QPSK, the phase of each of the subsequent transmissions is turned n/4.

Rate adaptation is obtained by puncturing the encoder output as described in Clause 5.3.1 of [47].

The characteristics of the interleaver are set out in [41].

A cyclic redundancy code CRC 0X04C111DB7 of the 32-bit polynomial of [48] is used and is calculated for all fragments of the datagram.

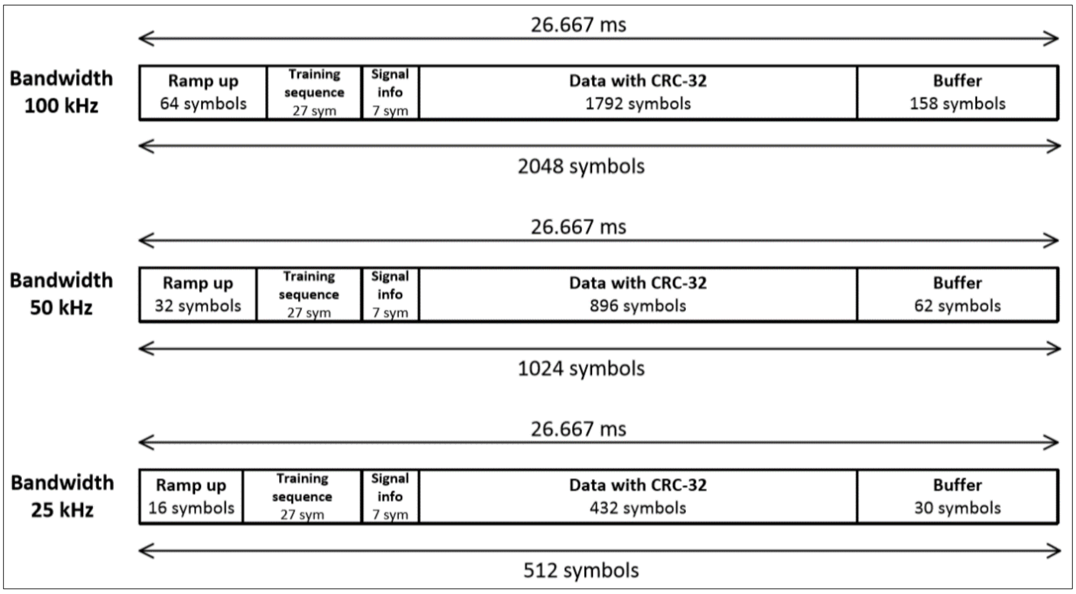


Figure 42: Frame structure for VDE [41]

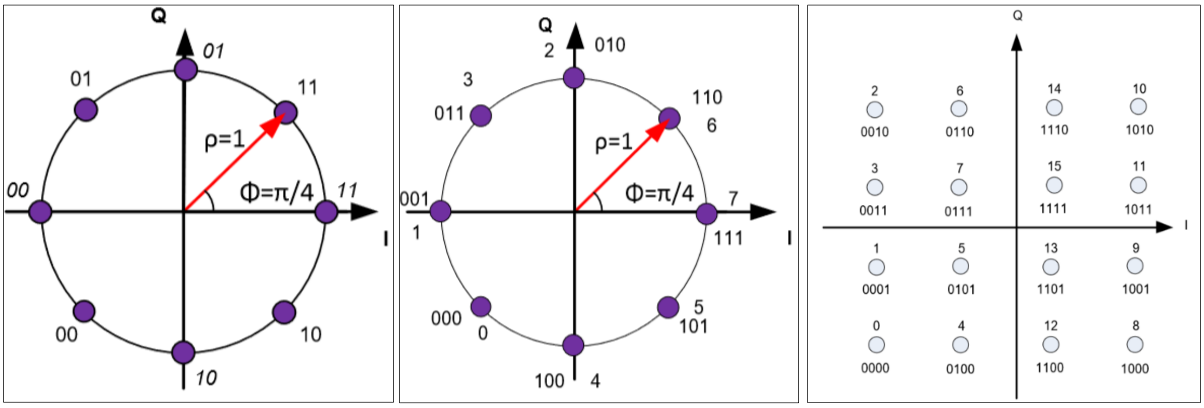


Figure 43: Bit mapping for п/4 QPSK, 8-PSK and 16-QAM [41]

4.2.3.2.2. Satellite

The emission mask, the characteristics of the on-board antenna and the transmit powers of the VDE-SAT service coincide with those defined for the VDE terrestrial component. The same applies to the correction of errors in reception and the cyclic redundancy code. However, there is no information about the application of code rate adaptation.

The use of LEO satellites is considered for the VDE satellite component, as for the other VDES satellite components. The minimum signal range is therefore equal to the orbit height (assuming the satellite in the vertical of the transceiver). For an LEO satellite at 600 km altitude the minimum range will be 600 km. This value is used to determine the minimum propagation delay time. Using a maximum range of 3,000 km, the path delay will vary from 2 ms to 10 ms, a variation of 8 ms.

The system can be configured for semi-duplex or full-duplex satellites.

In addition to the relative delays due to satellite signal propagation, there could be absolute delay due to other sources such as signal processing delay.

The frequency error, defined as the sum of the satellite transmission frequency error and Doppler and the frequency uncertainty at the receiver should be less than 1 ppm, i.e. ±160 Hz.

For the downlink, the maximum EIRP of the satellite depending on the ship elevation angle should be:

Ship elevation angle, θ (degrees)	Powerflux density on ground (dBW/m²/4 kHz)	Satellite range (kilometres)	Maximum downlink satellite EIRP (dBW at 25 kHz
0	-149	2 831	-1
10	-147.4	1 932	-2.7
20	-145.8	1 392	-4
30	-144.2	1 075	-4.6
40	-142.6	882	-4.7
50	-139.4	761	-2.8
60	-134	683	1.6
70	-133	635	2
80	-132	608	2.6
90	-131	600	3.5

Table 19: Satellite maximum EIRP vs. ship elevation angle for the VDE-SAT component [41]

The satellite coverage area and visibility time will be higher at low elevation angles. High elevation angle coverage may be sacrificed without significant system capacity loss.

The following two satellite antennas have been analysed in [41]: *Yagi* and *Isoflux*. The aforementioned document goes into greater detail concerning their characteristics.

The frame hierarchy for VDE satellite is identical and is synchronised with the rest of the components of the VDES system using the UTC time on the Earth's surface (as well as AIS).

The modulation techniques used are different in the uplink and in the downlink.

A block channel interleaver is considered on the VDE-SAT downlink in order to reduce the impact of the channel short blockage (for example due to the AIS transmission from the vessel or fast fading events). The channel interleaver is applied to the code-words at the output of the encoder.

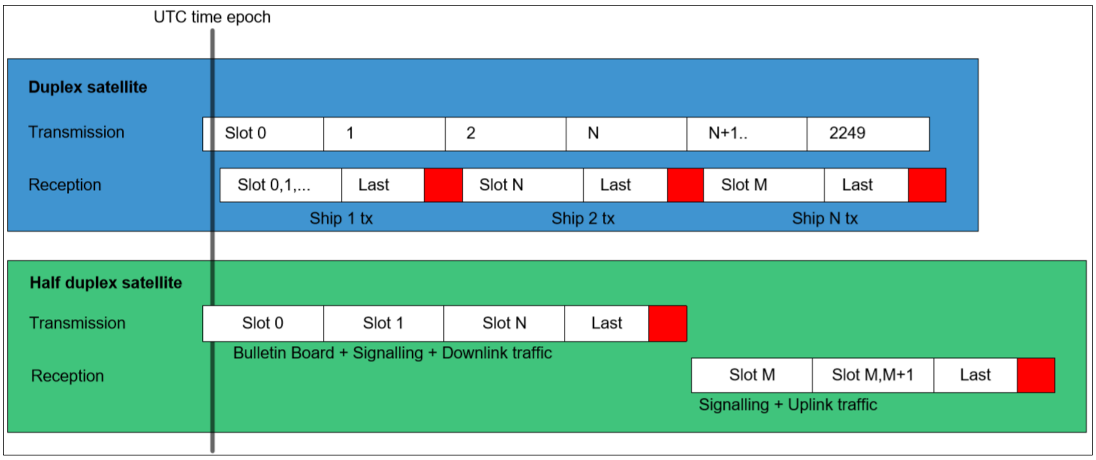


Figure 44: Operation of the full-duplex and semi-duplex satellite service [41]

	Type of modulation
Uplink	Gray encoded QPSK and OQPSK
	Gray encoded 8-PSK
	16-APSK
	Spread Spectrum with Constant Envelope
Downlink	BPSK
	Gray encoded QPSK
	Gray encoded 8-PSK
	16-APSK

Table 20: Modulations available on the uplink and on the VDE-SAT downlink [41]

4.2.3.3. ASM

The technical characteristics of ASM are detailed throughout the following subsections.

4.2.3.3.1. Terrestrial

These are most important points related to transmission parameters:

- The ASM service may share the same antenna(s) with the other subsystems AIS, ASM, VDE-SAT, taking into account the restrictions on the antenna.
- ASM requires compliance with the emission mask shown in Figure 45, with average power output between 1 W and 12.5 W and a tolerance of ±1.5 dB.
- The same is true with parameters such as transmitter output power, tolerance or sensitivity of the receiver. All these data can be consulted at [41].

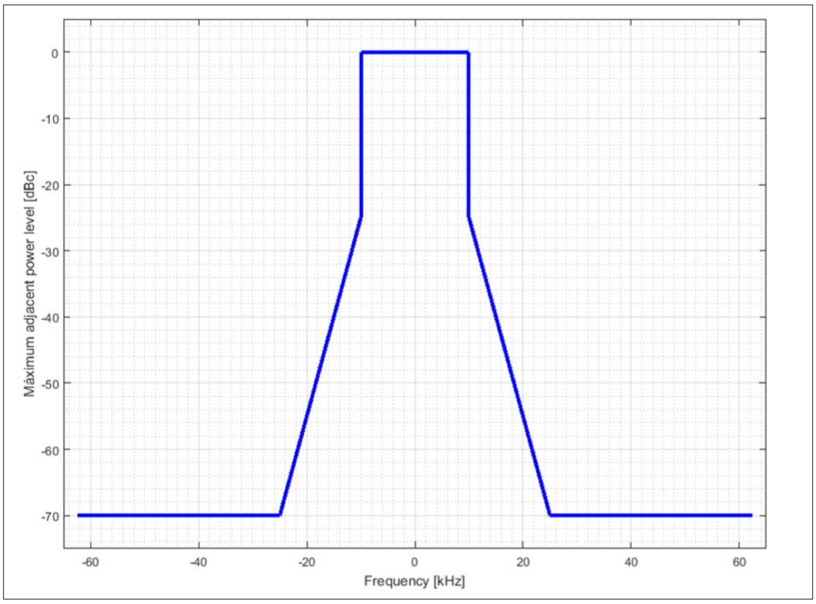


Figure 45: Maximum adjacent channel power levels in on-board transmitters of the ASM service

The frame structure is similar to that of the AIS system, but presents some significant differences. The total size of the transmission packet moves from 256 bits to 512, following the structure defined in the following Figure:

Ramp up	Training sequence	Signal Information	Data Length	Data	CRC	Buffer
16	27	7	10	380 (Maximum)	32	40

Figure 46: Default format of an ASM transmission packet [41]

The modulation scheme used by the ASM service must be quadrature phase shift keying n/4 (n/4 QPSK), both in the earth component and in the ASM satellite component. The bit mapping of this modulation appears in Figure 43.

Error correction is analogous to that mentioned in the previous sections, as is the cyclic redundancy code. An interleaver is used according to the FEC designated in the '*signal information*' field.

There is no adaptation of the code rate.

4.2.3.3.2. Satellite

The transmission parameters for the ASM satellite service are identical to those of the terrestrial component.

The uplink can be provided by the VDES device or a dedicated device that uses the Slot carrier sense TDMA (SCTDMA) access scheme to consolidate AIS communications and ASM terrestrial communications.

A constellation of Low Earth Orbit (LEO) satellites is considered as a support to this service.

Two types of frame structures are defined for the ASM satellite service depending on the access method used:

Ramp up	Pre training sequence	Training sequence	Signal information	Data length	Data field	CRC	Buffer	Total
16	100	27	7	10	166	32	154	512

Figure 47: Fields of a satellite ASM package for RATDMA, ITDMA and FATDMA

Carrier sense period	Ramp up	Pre training sequence	Training sequence	Signal information	Data length	Data field	CRC	Long-range ASM receiving system buffer	Total
56	16	44	27	7	10	166	32	154	512

Figure 48: Fields of a satellite ASM package for CSTDMA

The modulation used by the ASM satellite service is the same as that of its terrestrial component. The same applies to the interleaver, error correction and cyclic redundancy code. The code rate is not adapted.

4.2.3.4. AIS

The following subsections detail the technical characteristics of AIS.

4.2.3.4.1. Terrestrial

Some observations regarding the transmission parameters:

- The antenna to be used by the AIS system is the same as the one defined for the terrestrial VDE component.
- The AIS emission mask, as well as the transmission and reception parameters for a Class A station are identical to those of the ASM service.
- For Class B stations, the emission mask is as shown in Figure 49, while the transmission and reception parameters are to be found in [29].
- Both Class A and Class B AIS transceivers must be able to offer a rate of 9.6 kbps.

The frame structure is already described in Section 3.2.4.6 of Chapter 3. The scheme of an AIS transmission packet can be found in Figure 12. Modulation aspects are also mentioned in the chapter on AIS.

AIS does not use additional error correction techniques or adapt to the code rate.

A 16-bit cyclic redundancy code is used.

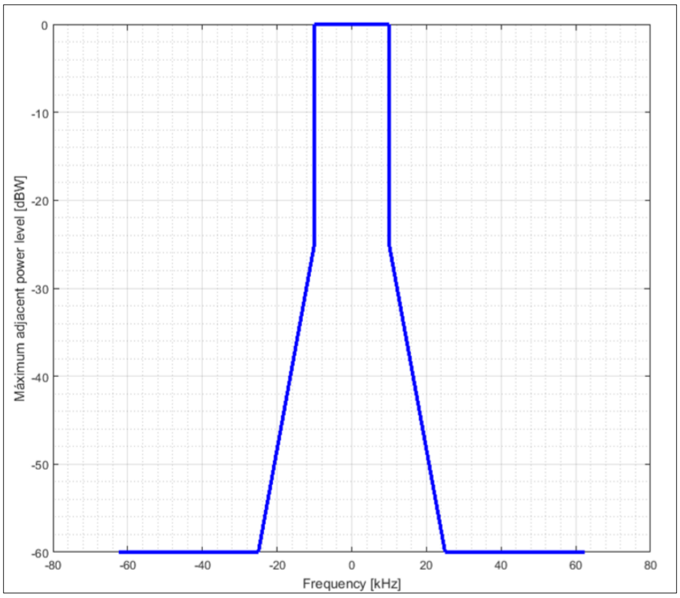


Figure 49: Emission mask for AIS Class B transmissions [29]

4.2.3.4.2. Satellite

The transmission parameters of satellite AIS are the same as those of the terrestrial component.

In satellite AIS transmissions, the signal has to travel further than the terrestrial component to reach its destination. This class of long-distance transmissions is mandatory for Class A equipment only. The access mode used is RATDMA and the transmission power is nominal.

Likewise, the structure of the AIS package needs to be changed to allow reception on satellites, as shown in the following Figure:

Ramp up	Training sequence	Start data	Data field	CRC	End flag	Long-range AIS receiving system buffer	Total
8	24	8	96	16	8	96	256

Figure 50: AIS package for long distance applications [29]

A message specially designed for these applications is inserted on this package format. This is message 27 (*Long-range AIS broadcast message*), which is a simplified version of position messages 1, 2 and 3.

The modulation used for Satellite AIS communications is the same as that of the terrestrial component, as is the cyclic redundancy code. No additional error correction techniques are used and nor is the code rate adapted.

4.2.4. Advantages of VDES over AIS

The emergence of VDES provides a series of functionalities and improvements with respect to the AIS system, including:

- **Improved capacity of maritime communications:** the new standard allows an information rate up to ten times higher than that provided by AIS, including adaptive coding and modulation.
- **Increased security:** VDE allows data to be encrypted, enhancing security in the face of various kinds of malicious attacks. Likewise, the VDES standard allows the TBB to be signed by the control stations, allowing the sender to authenticate a message.
- **Compatibility with AIS and the new VDES standard:** AIS compatibility makes it possible to protect the use of the currently existing network, while VDES expands the capacity of maritime communications. It will also contribute to the gradual migration to VDES.
- **Adaptive Processing:** the capacity to perform various coding and modulation techniques allows communication to be adapted to the characteristics of the channel.
- **Simultaneous operation of several channels:** the capacity to adapt their bandwidth and be able to deal with possible dynamic groupings of VDE channels is allowed by the new standard.
- **Reducing the current load on AIS:** implementation of the new maritime communications system will reduce the overload of the AIS system in areas where there is service congestion.
- **Increased range of AIS:** a physical layer with advanced coding and modulation will make it possible to extend the coverage range of the terrestrial stations by 15-20 %.
- **Rolling out e-Navigation:** The benefits of this communications system open the door to developing new applications to offer innovative services to ships.
- **Global coverage:** the layout of the current satellite segment makes it possible to extend coverage to a large part of the globe.

4.2.5. Merits of VDES

As we explained previously, the VDES system is still at the development and implementation stage. Figure 51 shows a timeline of the current state of VDES presented at the ITU seminar held in St. Petersburg in June 2018 [49].

To date, no new versions of the standards or implementation guides have been published subsequent to the existing documentation (ITU R. M.2092-0, ITU-R. M.1371-5, IALA Guideline "*VHF Data Exchange System (VDES) Overview*", IALA Guideline" *The technical specification of VDES*"). However, it is known that both standards and guides are almost complete and frequencies have already been assigned, except for satellite channels, which will be decided in WRC-19.

For vessels, it has been reported that wiring and antennas can be maintained, however AIS hardware will need updating and/or replacing. Currently, there are reliable data on the "closed" VHF system and there is no cost for the messages.

Another positive development in relation to the implementation of this new system is that there is good coverage in port areas and on shore.

Although system is not fully developed as yet, VDES is already a reality and some projects are already using this technology. One example of this is the POLARYS project, mentioned in previous chapters; some ESA projects, such as VDES TESTING; development of the NORSAT-2 satellite itself, which carries a next-generation AIS receiver and a payload for VHF data exchange; the fact that numerous companies are manufacturing equipment or the long list of projects and test beds that are making the most of the e-Navigation concept.

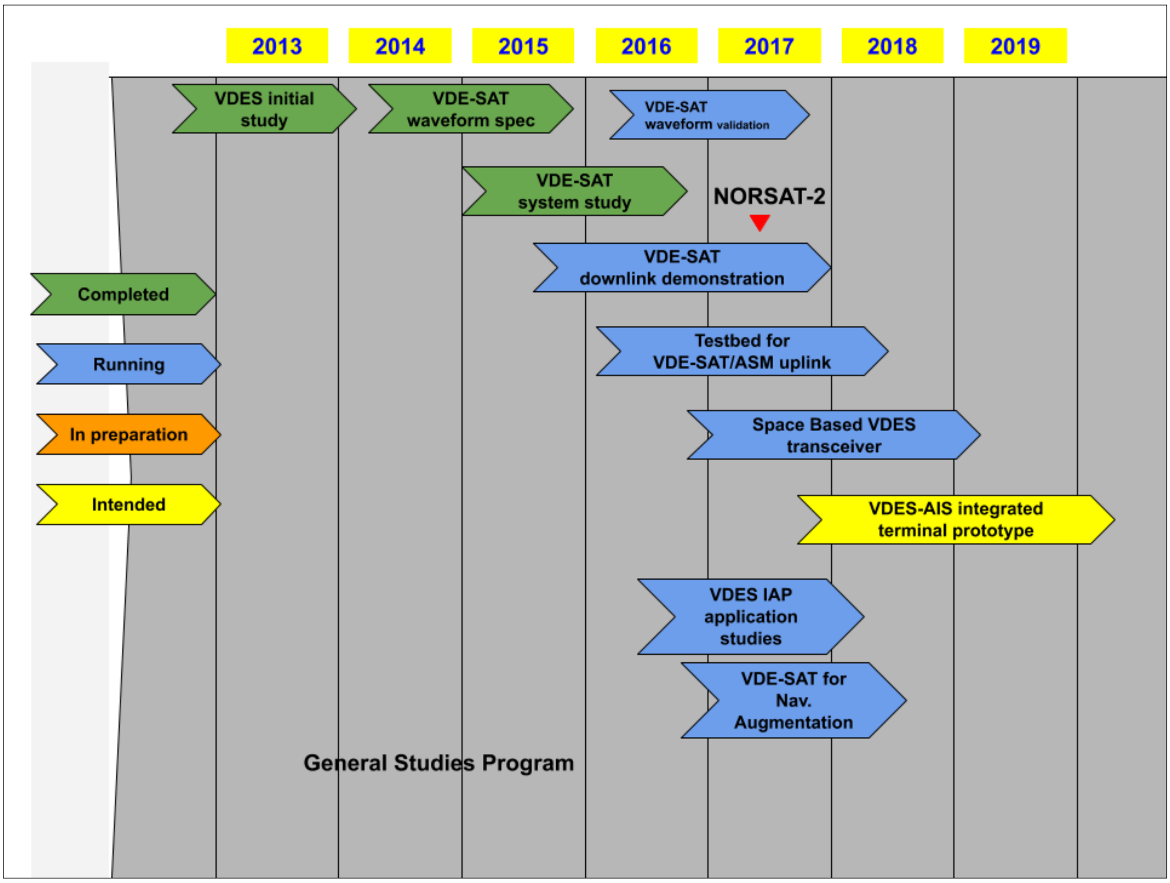


Figure 51: Time line of the state of development of the VDES system [49]

4.3. State of the art

In this section we highlight various projects developed within the VDES framework and hope to provide readers with a more practical view of the system by describing each one.

4.3.1. POLARYS project

The main objective of the POLARYS project - already presented in the introductory chapter and commented on in the section dedicated to Satellite AIS - is to increase maritime safety and efficiency in navigation and emergency management by developing a VDES transceiver and a surveillance and navigation assistance system.

The transceiver thus developed significantly expands the capacity of the AIS platform in terms of data rate and coverage, which has a direct impact on the limitations of the platform. Meanwhile, it opens the door to the development of new applications, posing an opportunity for innovation and a very significant impact on the maritime communications paradigm.

The surveillance and navigation assistance system is based on the use of on-board VDES platforms with autonomous detection capabilities. The system has all the required elements to deliver a service scenario around VDES and is based on the automatic incorporation of information relevant for navigation to the AIS/VDES platform. This includes information related to ships and other objects on the sea obtained by smart video analysis from aerial images. All information will be available in real time through a GIS 3D application designed to be used in both control and command posts, and mobile platforms that have AIS/VDES receivers. In addition, the platform will allow the inclusion of different sensors and alarms related to the maritime and physical safety of vessels, thus providing an integral on-board safety system compatible with VDES.

4.3.1.1. Architecture and system modules

Figure 52 shows an image of the overall POLARYS architecture as well as the various interfaces that communicate some modules with others. The main elements comprising the system are the VDES transceiver, the aerial vision module, the unmanned aerial vehicle (UAV) and the control centre.

Each is summarised briefly below.

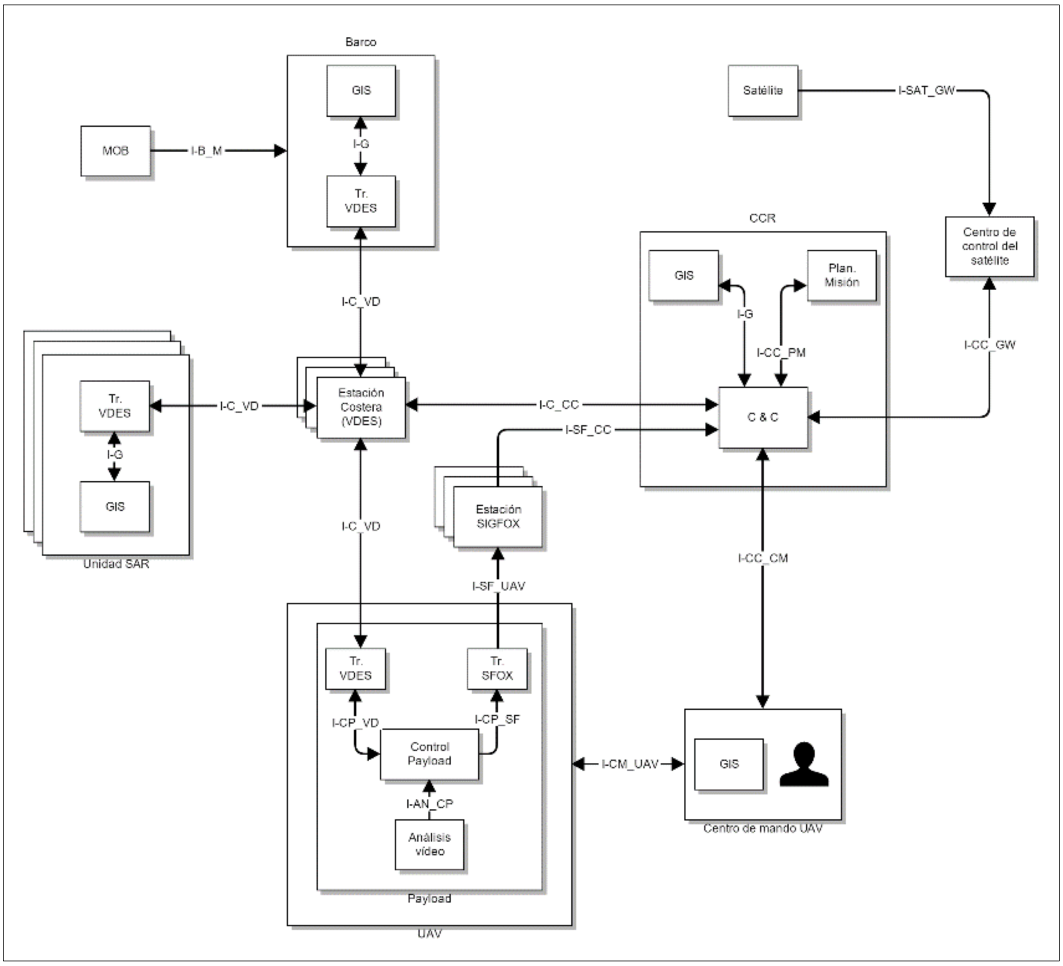


Figure 52: Overall system architecture for the POLARYS project

4.3.1.1.1. VDES transceiver

The VDES transceiver implements the functionalities of the VDES standard and can operate at any of its frequencies. It is compatible with data exchange in VHF (VDE) and with the AIS, Satellite AIS and ASM systems. Figure 53 shows a prototype of the VDES transceiver.

In turn, the transceiver is divided into two blocks: an SDR platform, for executing the VDES standard, and an RF front panel, to amplify both the transmission and reception stages.

It should be stressed that an SDR platform allows great flexibility and support when it comes to adapting to the specifications, in this case of VDES, since it offers the possibility to update the transceiver in future to adapt it to later versions of the standard in a handy and simple way.

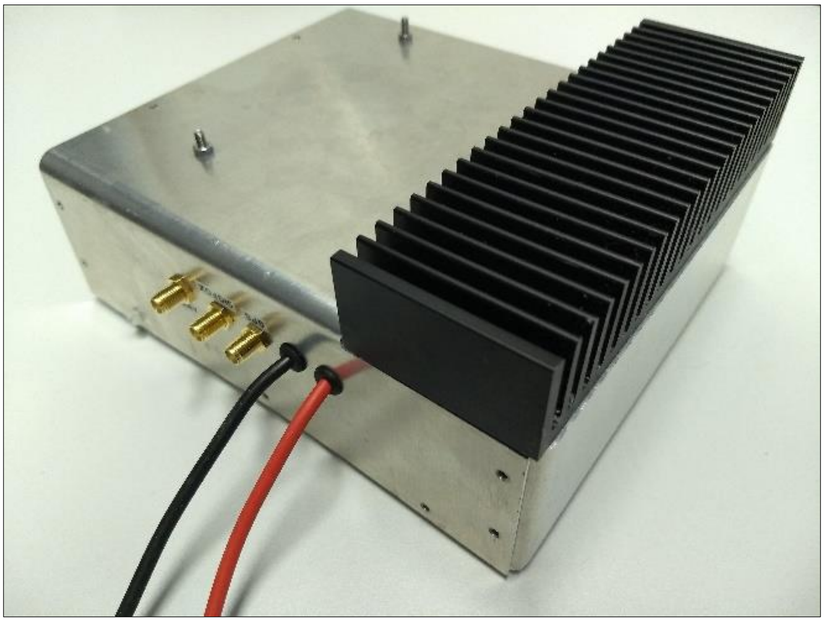


Figure 53: VDES transceiver prototype developed by EGATEL for the POLARYS project

4.3.1.1.2. Aerial vision module

The aerial vision module includes the elements developed and implemented for vessel recognition and alert generation.

Smart video analysis automatically detects objects in the sea. Information related to objects detected (identifier, coordinates, size estimation, image, time stamp, etc.) is supplied to the airborne VDES transceiver.

In parallel to the transmission of this information, a *Sigfox* transmitter integrated into the VDES transceiver generates alarms, which it introduces into the network of the same name for questions of redundancy.

4.3.1.1.3. UAV

The UAV is the unmanned aerial vehicle on which the different modules have been installed. The total flight weight of the UAV with the entire system mounted is approximately 14 kilos.

Figure 54: UAV of the POLARYS project during the tests

4.3.1.1.4. Control centre

The POLARYS control centre consists of the GIS-3D application, the mission planner and the UAV command centre.

The GIS-3D application is the cartography and control of the POLARYS system. It displays information on the status of the VDES network in a three-dimensional graphical interface.

The mission planner makes it possible to obtain the optimal flight route of the UAV based on several factors: the area to be covered, installed payload, video analysis module requirements corresponding to the mission, flight altitude, characteristics of the selected UAV, etc.

Finally, the UAV command centre is responsible for managing the flight of the vehicle based on the route calculated with the mission planner. The UAV is piloted from this centre.

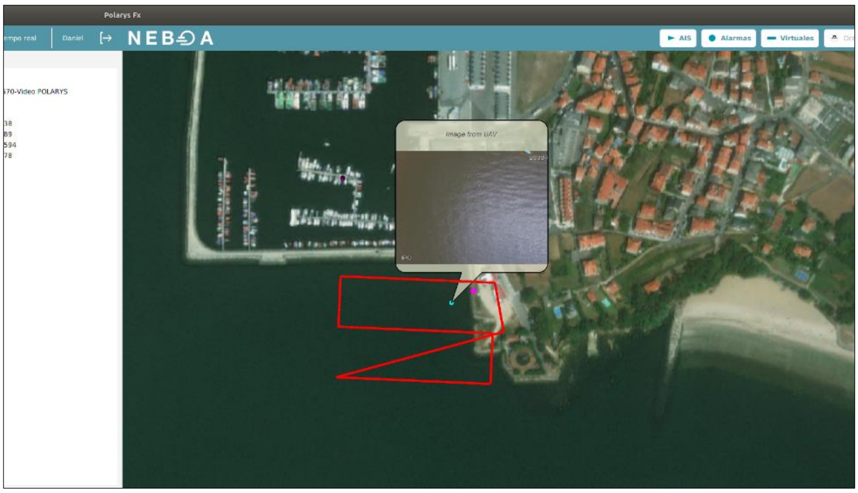


Figure 55: Screenshot of the GIS-3D application of the POLARYS project

4.3.1.2. Pilot tests

The POLARYS project pilot has taken shape through the performance of various tests that have been run incrementally: from the earliest stages to the proof of concept of the complete system with all the components. The following sub-sections explain briefly what each of these tests involved.

4.3.1.2.1. Phase one: image capture

During this phase the modules corresponding to video capture and analysis were assembled and tests carried out on real scenarios to check that they work correctly. The tests consisted of the RGB and infrared sensors acquiring video. The recorded video was then used to train image processing algorithms after the event.

4.3.1.2.2. Phase two: VDES system test

To test the operation of the VDES transceiver mounted on the UAV, test flights were carried out at various power levels and in different scenarios. These tests checked that the signal was being correctly received and that this did not affect the control and flight of the UAV. All electrical integration of the platform power systems was also checked.

4.3.1.2.3. Phase three: testing the mission control module and generating and sending alerts

Tests in this phase were performed in the laboratory, putting together several previous integrations, to make adjustments and calibrations of the various systems in a controlled environment.

4.3.1.2.4. Phase 4: proof of concept of the complete system.

This last phase involved a complete systems test. An MOB scenario was simulated with an inflatable kayak carrying a VDES receiver, an AIS receiver and GPS. A flight plan was generated and the UAV was deployed and went to the area specified by that plan. The UAV detected the kayak and took and sent photographs and videos at intervals. The relevant alarms were also generated. The information was presented in the GIS-3D application in real time.

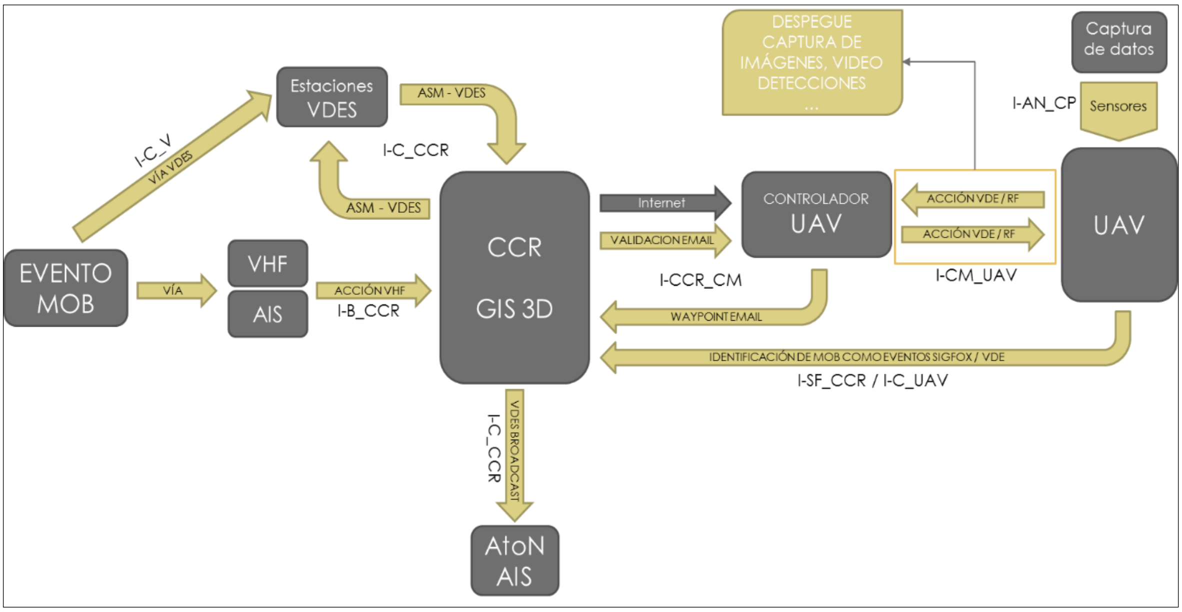


Figure 56: General outline of the POLARYS project

4.3.1.3. Conclusions

It will be possible to draw conclusions about the POLARYS project once the results of the complete system tests have been obtained.

It is clear that the VDES transceiver is able to operate within the specifications of Recommendation ITU-R. M.2092-0 corresponding to the VDES system.

In addition, the functionality of AIS and ASM was tested successfully. The satellite component of AIS is also functional and fully operational.

Regarding power issues, it was possible to transmit and receive signals with the levels defined for both AIS and ASM and for VDE.

The capabilities of the *Sigfox* technology used as a redundant channel for alarms generated was also proved.

All of the above information and the results of the various pilot tests have shown that the initial objective of the POLARYS project has been met.

4.3.2. VDES TESTING project

VDES TESTING, with reference ESA AC/2-1670/17/NL/FE, is a project developed by EGATEL, GRADIANT and ESA, additionally supported by SPACE NORWAY.

The project goal is to complement the VDE-SAT downlink measurement campaign, making independent measurements and verifying the VHF signal transmitted by the NORSAT-2 satellite and received in a real operating environment.

This involved two main tasks. The first involved identifying and recording requirements, regulatory aspects and the test plan and procedure for the VDE-SAT downlink. The second concerns the measurement campaign itself and subsequent processing of the received signal to characterise the communication channel and verify that the VDE-SAT downlink signal was detected using the transmitted data patterns.

The receiver designed in this project uses the entire sequence transmitted for different purposes (time synchronisation, equalisation, etc.). A practical receiver was implemented using the theoretical design and the decided waveform, as can be seen in Figure 57.

Part of the conclusions drawn from the measurements were presented at the *ITU 5B Meeting* in May 2018 in response to Resolution 360 of the ITU-R., for the compatibility study between the satellite component of VDES and the services established in the same and in the adjacent frequency bands. This allows possible regulatory actions to be determined in relation to the spectrum assignments for VDES applications.

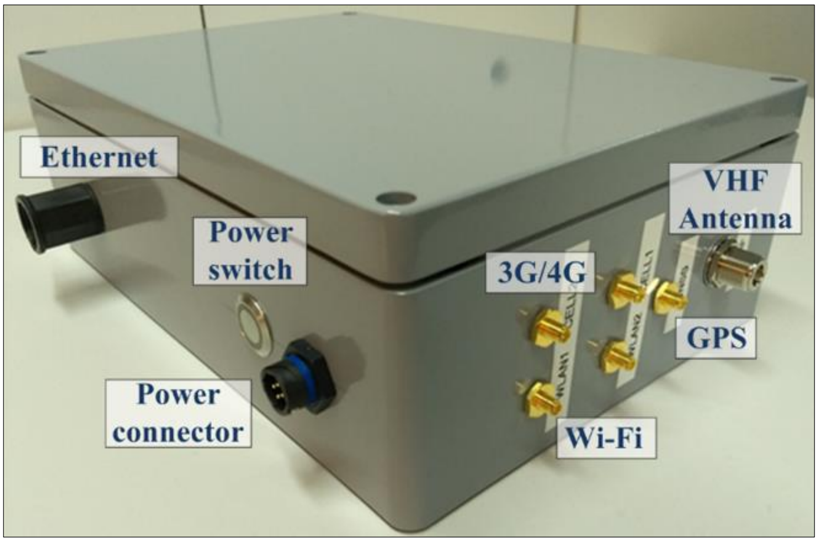


Figure 57: Receiver for the downlink of the VDES satellite component (EGATEL)

4.3.3. VDES pilot tests in Brisbane (Australia)

During the information-gathering process about the state of implementation of the VDES system, information was found concerning a pilot developed in Brisbane (Australia) in June 2015 by *IMIS Global* and *StoneThree Venture*. This pilot includes both the design of a prototype and the related laboratory and field tests.

The results of these tests are discussed below, since the conclusions may be relevant within the context of this book.

An SDR platform was used for the development of the VDE transmitter/receiver modules implementing the following features:

- π/4 QPSK, 8-PSK and GMSK modulations (these latter in comparison to AIS).
- Selectable bandwidth (channel 25, 50 or 100 kHz).

Laboratory tests [50] measured noise figure, BER curve and interference management, since these are considered fundamental measurements of the performance of the VDES prototype.

It is worth noting that the FEC techniques defined in the VDES standard were not included in the pilot.

The following results obtained concerning the theoretical performance (in laboratory) of a 'real' VDES equipment are noteworthy:

- Sensitivity.
- BER vs. $\frac{Eb}{No}$.
- Intermodulation rejection.
- Adjacent channel selectivity.
- PER vs. RSSI.
- PER vs. distance.
- Rate vs. distance.

The system architecture used for field tests is shown in the following Figure:

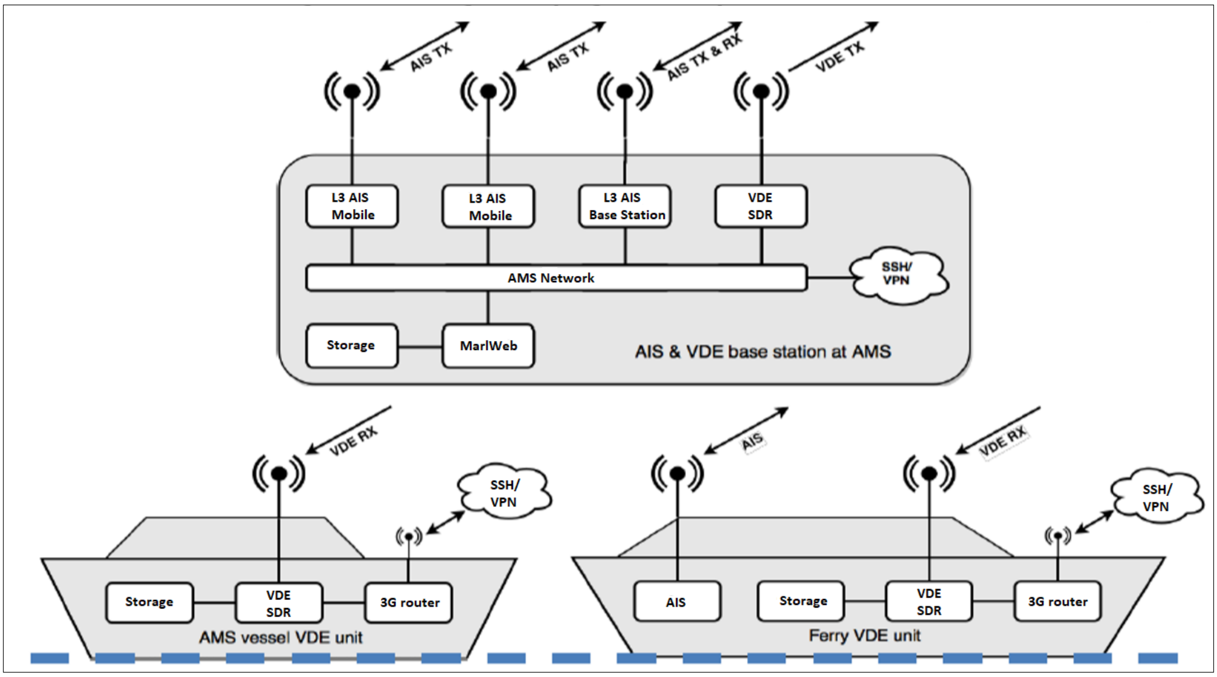


Figure 58: System architecture for VDES pilot field tests in Brisbane

As the image shows, the VDES transceiver for this pilot is characterised by:

- Independent modules for each technology (AIS, VDE).
- The base station transmits and receives AIS.
- The base station transmits VDE.
- The mobile (on-board) station transmits and receives AIS.
- The mobile (on-board) station receives VDE.

One of the two ships used made a ferry trip through the Bay of Brisbane, while the other sailed up the river to the city to characterise the effects of the multipath and LoS occlusions.

The ship moving upriver determined that fading when losing line of sight is more predominant than fading due to multipath.

In addition, the higher order modulations get the best rate at short distances. As the distance increases, more robust lower order modulations provide the best results (as expected).

For the ferry, the following results of rate versus range were obtained:

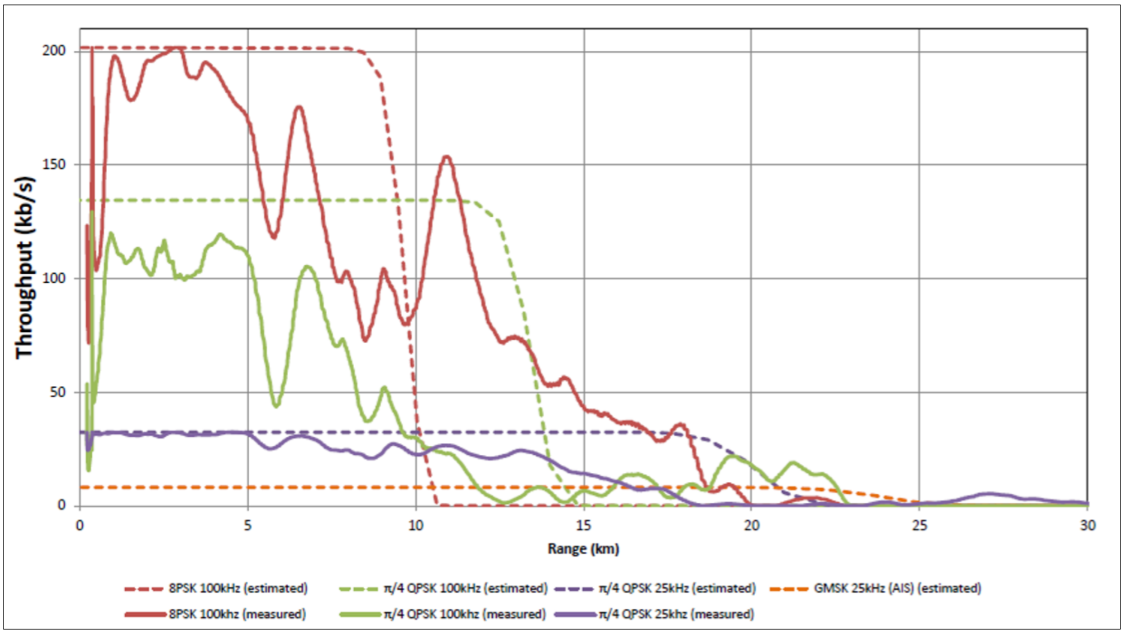


Figure 59: Rate versus range for the ferry used in the field tests of the VDES pilot in Brisbane [51]

Due to the high dynamic range, high linearity and low phase noise requirements when dealing with interference between VDES channels, the authors recommend using custom designed hardware for the VDES transceiver.

4.4. e-Navigation

4.4.1. Context

According to the IMO, the concept of e-Navigation can be defined as “the harmonised collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment.”

The e-Navigation Strategy Implementation Plan, which was approved in 2014, contains a list of tasks required to be conducted in order to address 5 prioritised e-Navigation solutions, namely:

- Improved, harmonised and user-friendly bridge design;
- Means for standardised and automated reporting;
- Improved reliability, resilience and integrity of bridge equipment and navigation information;
- Integration and presentation of available information in graphical displays received via communication equipment;
- Improved Communication of VTS.

It is expected that these tasks, when completed during the period 2015–2019, should provide the industry with harmonised information in order to start designing products and services to meet the e-Navigation solutions.

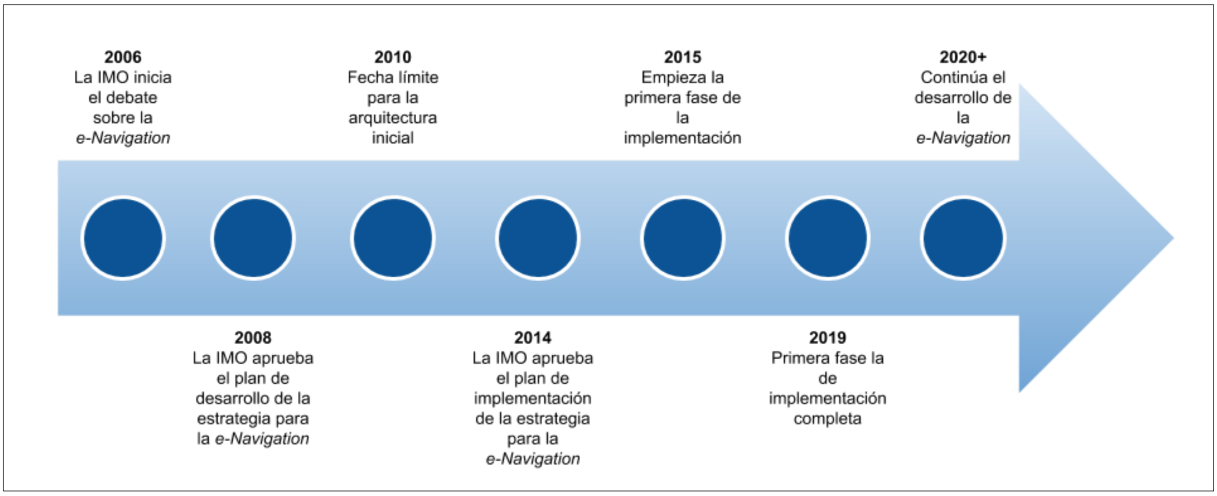


Figure 60: Timeline of the development of e-Navigation, extracted from [52]

The establishment of VDES technology as a new communications system for navigation will lead to the emergence of numerous innovation and market opportunities in the coming years. A great deal of activity is expected around the development of new systems operating under the VDES standard. These systems will have to be able to integrate into the current network, easing the burden on it and allowing the AIS network to devote itself to its main objective: vessel identification.

Assigning new channels with the arrival of VDES will not only improve the capacity of AIS, but will also offer a good opportunity to develop innovative applications in the field of electronic navigation. Of particular interest will be applications that can add value to safety in maritime environments, both in accident prevention and rescue services. New services demanded by the industry, for example those focused on logistics, could also emerge.

Another possible field of applications revolves around helping to reduce AIS vulnerabilities. One is that, as current regulations do not require the use of AIS transceivers for all active vessels, some vessels are not registered on the network, allowing them to go unnoticed, which is the case for illegal fishing (poaching). Another is that AIS is an open system, which leaves it vulnerable to malicious attacks that require nothing more than a transceiver and sufficient knowledge of the standard to perpetrate.

The e-Navigation concept is a driver for a digital concept in the maritime sector. Developments in digital communications have a profound and long-term impact on the way in which this sector operates. e-Navigation is expected to be compatible with many current and future technologies identified in this plan.

4.4.2. Goals

The arrival of e-Navigation heralds the ambition to improve communications in the maritime field. Several objectives aim to achieve this goal:

- Promoting universal standardisation, uniformity and interoperability, as well as systems integration.
- Developing training and education requirements on the one hand; and familiarisation with the processes, service provision, applications and systems on the other.
- Supporting safe navigation, traffic management and monitoring, communications and data exchange.
- Contributing to efficient logistics and shipping, in addition to effective search and rescue and disaster and incident response.

4.4.3. Implementation

The communications infrastructure should be designed to allow the authorised transfer of ships' on-board information, between ships, between the ship and the shore and between the coastal authorities and other parties.

This infrastructure must be able to support future e-Navigation applications and legacy applications. It will therefore require intensive bandwidth use and will possibly depend on certain technologies. It is important to secure the spectrum or to change its use within existing assignments for e-Navigation and other developments because of the planning deadlines involved in protecting it and extending its use.

Modern shore services require a level of on-board connectivity that is not provided by current maritime networks. Dedicated service connectivity to improve services such as the logistics chain or port arrivals and authorisations would benefit from the *network at sea* concept. This network defines a fully intertwined connectivity between all vessels and ground stations, covering direct and multi-hop connections, and is formed by a terrestrial and a satellite component. Both components are currently developed with long-range connectivity through the new VDES system.

Broadband connectivity should be developed going forward. We therefore anticipate that there will be a shore-to-ship and ship-to-ship network at sea using digital technologies such as VDES, broadband communications and satellite communications.

Spectrum allocation of the maritime mobile service should continue to be protected in the face of generalised concerns about the allocation and management of the spectrum for e-Navigation. There is also an acknowledgement of the need to develop automated processes for maritime communications making it possible to select the best technology, channel and characteristics according to vessel location and type of data to be exchanged.

The e-Navigation concept and future user requirements are developing rapidly. However, it is difficult to speculate and to estimate what systems and what spectrum will be required to fully achieve e-Navigation.

4.4.4. State of the art

This section contains a brief description of several key projects within the e-Navigation framework [53] [54] [55].

4.4.4.1. Accseas

Accseas was among the first e-Navigation projects performed and was driven by a group of organisations from Denmark, Germany, the Netherlands, Norway, Sweden and the UK.

The project was launched to improve maritime safety and environmental protection in the North Sea region on the back of development and implementation of a test bed for e-Navigation to harmonise the exchange of electronic maritime information on board and on shore. Another objective of *Accseas* was to identify key areas of congestion and limited access to ports to minimise risk in navigation.

4.4.4.2. EfficientSea2

The *EfficientSea2* project was run by the Danish maritime authorities and aimed principally to create and implement innovative and smart solutions for efficient, safe and sustainable traffic at sea through improved connectivity for ships.

The project focused on four main areas: providing services to the end user, such as monitoring sulphur emissions, services to improve emergency response in the Arctic, or route optimisation and exchange; developing and implementing platforms to support such services, ranging from web pages to data format issues; solving the challenge of weak connectivity and high-cost communication through transparent and profitable roaming between communication channels, as well as using the new VDES channel; and designing a Maritime Connectivity Platform (MCP) to allow the exchange of secure, reliable and efficient information.

The layout of the proposed maritime connectivity platform is illustrated in Figure 61. This platform makes it possible to verify identities, exchange digitally signed data, make simple use of the services and use the location as a parameter for performing all the tasks listed here.

EfficientSea2 is the successor to *EfficientSea*, another of the first projects carried out within the e-Navigation framework.

4.4.4.3. Sea Traffic Management

The *Sea Traffic Management* concept seeks to connect and update the marine world in real time with detailed information to be exchanged. Through data exchange with among ships, various service providers and shipping companies, STM is creating a new paradigm for maritime information to be shared offering tomorrow`s digital infrastructure for shipping.

Sea Traffic Management was developed during various research and innovation projects funded by the EU with a number of European partners, including maritime and port authorities, ministries, equipment suppliers, etc.

STM's aim is to create a safer, more efficient and environmentally friendly maritime sector. The goals defined for 2030 are:

- **Safety:** 50% reduction of accidents.
- **Efficiency:** 10% reduction in voyage costs and 30% reduction in waiting time for berthing.

- **Environment:** a 7% lower fuel consumption and 7% lower greenhouse gas emissions.

Through STM services such as route optimisation, exchanging routes between vessels, improved monitoring and synchronisation of calls, the personnel on-board and on-shore can make decisions based on real-time information.

The *Sea Traffic Management* concept is applied within several projects, as shown in Table 21. For further details, see [56].

Figure 61: Maritime connectivity platform scheme of the EfficientSea2 project [53]

Project	Description
STM *Validation*	Validation of the STM concept, infrastructure and services, showing its practical benefits on 300 ships, 13 ports, 5 coastal centres and 12 connected simulation centres.
Efficientflow	Efficient implementation of port calls through real-time information in Baltic ports.
Real Time Ferries Project	Connecting ferry lines with inland transport, connecting ship voyages with the transport chain.
STM *Baltic Safe*	Increased safety in Baltic Sea sailing.
STEAM	Converting a traditional port into a world-class transshipment and information centre, adopting modern digital technologies for the maritime sector.
Monalisa 2.0	*Sea Traffic Management* concept definition.
Mona Lisa	Tests on the exchange of ship-to-ship and ship-to-shore routes and of the maritime cloud.
MICE	Testing routes to land from a ship in the Arctic.

Table 21: Projects in which the Sea Traffic Management concept is developed

4.4.4.4. Smart Navigation

Smart Navigation is a project designed and organised by the Ministry of Oceans and Fisheries of the Republic of Korea to improve quality, sailing efficiency and the quality of life of sailors; contributing to the implementation of e-Navigation and fostering the growth of the maritime community through it.

The project provides various services for coordinating maritime traffic, knowledge of the surrounding area for detecting risk situations, risk prevention, monitoring and exchange of information.

4.4.4.5. Sesame Straits

The *Sesame Straits* project, run by a consortium led by *Kongsberg Norcontrol IT*, emerged from the idea of using the *e-Navigation* concept to reduce critical traffic points - busy areas with a high probability of congestion that can lead to accidents and cause delays.

This project was developed to predict these potential points and offer new strategies to avoid bottlenecks and crowding, consequently improving safe sailing and vessels to arrive on time, thereby increasing the efficiency of existing infrastructure.

An example of global ship traffic was illustrated previously in Figure 34 and shows which areas suffer the most congestion.

The success of the *Sesame Straits* test bed led to the start in early 2018 of a new project that is directly related, called *Sesame Solution II*, which seeks to develop an even completer electronic navigation system.

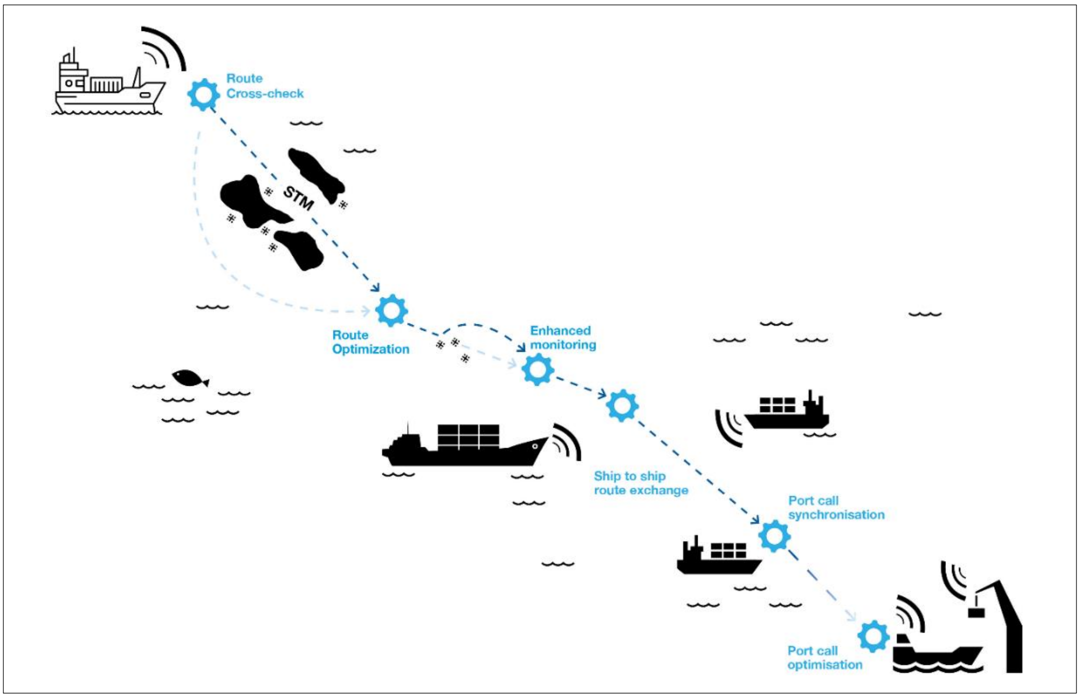


Figure 62: Sea Traffic Management Validation project services [53]

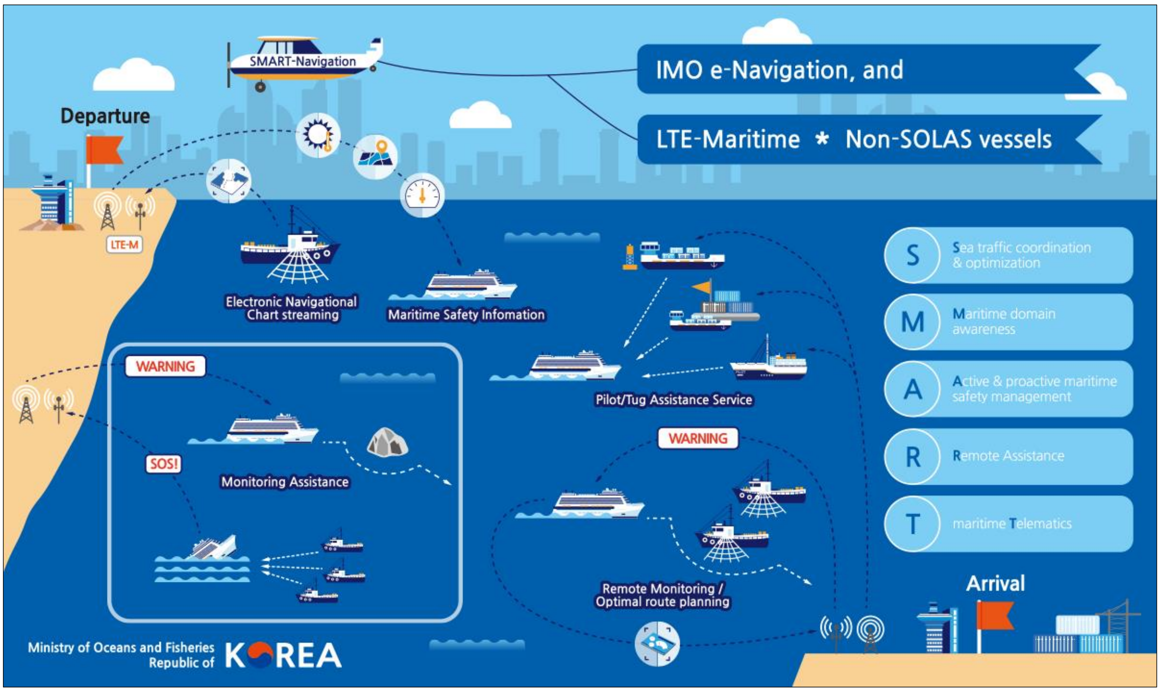


Figure 63: General outline of the Smart Navigation project [53]

4.4.4.6. Other projects

Regardless of their size, many projects have been developed to address the needs of e-Navigation. There is an extensive list in [57] specifying which test beds are currently active and which are already finished, along with descriptions of each one.

5. Future of maritime communications and conclusions

Despite the continuous evolution of technologies related to communications systems for the maritime environment, the development of the VDES standard, together with the modernisation of the GMDSS system, represent a great leap forward in this sector. It is therefore logical to wonder about the future of maritime communications for navigation, security and protection of the marine environment.

On a macro scale, e-Navigation ushered in the desire to achieve total interconnection between ships and shore stations using radio links to ensure safe sailing as well as providing the crew and coastal authorities with the relevant real-time information.

A great many efforts have been made to achieve these objectives, as well as a raft of ideas and projects put forward by the relevant authorities and organisations, all of them aiming to achieve this goal in the shortest possible time.

Various presentations were made during the radiocommunications seminars held throughout 2018 to present the latest developments in modern maritime communications and the future of e-Navigation. In anticipation of WRC-19, and based on what was presented at these events, there is a clear trend towards global connectivity by achieving full coordination of digital services. There is also a willingness to include new satellite constellations in the GMDSS system, as we stated in Chapter 1. Likewise, future developments in the COSPAS-SARSAT system will feature new Medium Earth Orbit (MEO) satellites which will cohabit with Low Earth Orbit and geostationary satellites. We are also expecting the implementation of an RLS (Return Link Service) service that will allow 406 MHz beacons to receive an acknowledgement from the Mission Control Centre (MCC) while also allowing Rescue Coordination Centres to send another acknowledgement to the beacon once the rescue activities begin.

Maritime transport is the mode most used for international trade. At present, more than 90% of world trade is shipped by sea, with maritime routes used since ancient times for that same purpose [58]. Phenomena such as the consumer society or globalisation have made this mode an ideal solution for transferring both goods and technologies. The boom in aviation has led to a significant decrease in passenger transport by sea, although it still plays a very important role in the tourism sector.

The need to communicate at sea is essential for the efficient and safe operation of the maritime domain, for whatever purpose. All ships, be they freighters, tankers, bulk carriers, cruise ships, ferries, barges or any other type of vessel, require guarantees that allow navigation to be as safe and efficient as possible.

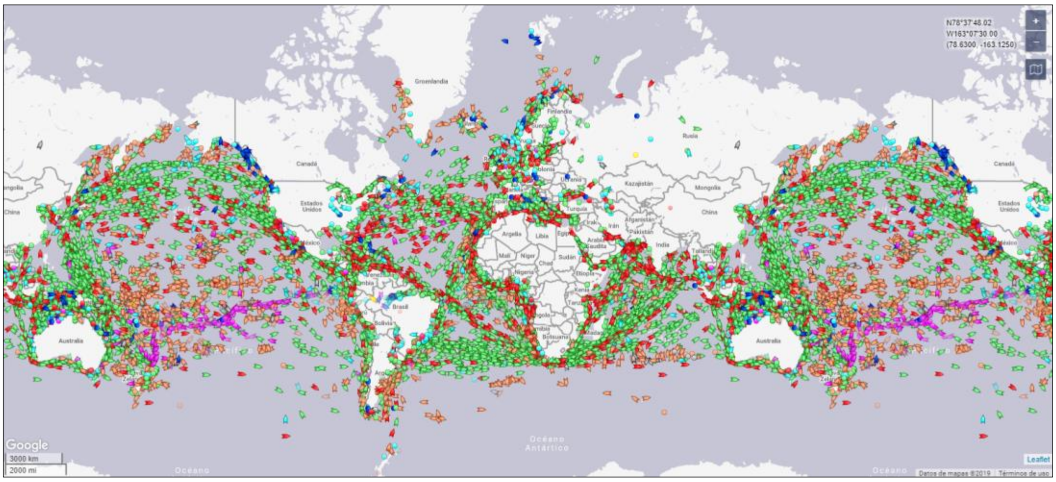


Figure 64: World maritime traffic, extracted in real time from [59]

All of these circumstances foster the appearance of various regulatory bodies and communication systems to keep track of this traffic; to prevent, identify and detect risks and hazards; to respond quickly to emergency situations and produce the least possible impact on the marine environment.

The initial systems are a first attempt to solve the problem, but they suffer limitations that make them unable to resolve everything, such as the need for direct vision. In today's fully digital era, a completely analogical scenario is inconceivable, therefore, while these systems have spelt a certain evolution of the maritime sector, the real transformation comes with its digitalisation.

As we showed in the first few chapters, the development of the AIS system has improved maritime safety and helped to increase efficiency in navigation and environmental protection. However, the system is far from definitive and still suffers a series of shortcomings (use of an open protocol, limited coverage, overload, inability to support the amount of information demanded by new applications, etc.) which means that more work is required to achieve the objectives.

Whereas the appearance of VDES really does currently mark a viable alternative for maritime communications. As we have repeatedly stated throughout this book, VDES provides increased information capabilities, enables the development of new applications, relieves congestion in the AIS system and further improves security aspects. It also fosters the roll-out of e-Navigation to ensure better prevention of risks and accidents, environmental protection and improved navigation.

The idea of a network connecting the entire maritime sector through VDES, broadband connections and the satellite component is gradually becoming more of a reality.

In short, the new VDES standard has consolidated its position as one of the main cores of e-Navigation, making it possible to develop innovative applications that seemed infeasible up to now. At the same time, e-Navigation has represented nothing less than a revolution for the maritime sector, laying the foundations for a new paradigm in navigation, transport and communications at sea.

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List of acronyms

ACK	Acknowledgement
ADDC	Assigned Data Transfer Channel
AIS	Automatic Identification System
AIS 1	161,975MHz (87B or 2087). Primary channel for the default region or in high seas.
AIS 2	162,025MHz (88B or 2088). Secondary channel for the default region or in high seas.
ARQ	Automatic Repetition Request
ARQSC	Automatic Repetition Request Signaling Channel
ARSC	Announcement Response Channel
ASC	Announcement Signaling Channel
ASM	Application Specific Messages
AtoN	Aid to Navigation
BB	Bulletin Board
BBSC	Bulletin Board Signaling Channel
BER	Bit Error Rate
CDMA	Code Division Multiple Access
CPA	Closest-Point-of-Approach
CQI	Channel Quality Indicator
CRC	Cyclic Redundancy Code
CSTDMA	Carrier Sense TDMA
DAC	Designated Area Code
DGMM	Spanish DG for the Merchant Navy
DGNSS	Differential Global Navigation Satellite System
DGM	Digital Mobile Radio
DSC	Digital Selective Calling
ECDSA	Elliptic Curve Digital Signature Algorithm
EGC	Enhanced Group Call
EIRP	Effective Isotropic Radiated Power
ELT	Emergency Locator Transmitter
EPIRB	Emergency Position-Indicating Radio Beacons
ESA	European Space Agency
FATDMA	Fixed Access TDMA
FEC	Forward Error Correction
FIFO	First-In First-Out
FMDA	Frequency Division Multiple Access
FOV	Field of View
GMDSS	Global Maritime Distress and Safety System
GMSK-FM	Gaussian-filtered Minimum Shift Keying/Frequency Modulation
GNSS	Global Navigation Satellite Service
HDLC	High-level Data Link Control

HF	High Frequency
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
ITDMA	Incremental TDMA
ITU	International Telecommunications Union
LC	Logical Channel
LEO	Low Earth Orbit
LF	Low Frequency
LOS	Line of Sight
LRIT	Long Range Identification and Tracking
MCC	Mission Control Centre
MDC	Multicast Data Channel
MEO	Medium Earth Orbit
MF	Medium Frequency
MMSI	Maritime Mobile Service Identity
MOB	Man OverBoard
MCS	Modulation and Coding Schemes
NAVTEX	Navigational Telex
NBDP	Narrowband Direct Printing
NRZI	Non Return to Zero Inverted
OSI	Open System Interconnection
PC	Physical Channel
PER	Packet Error Rate
PKI	Public Key Infrastructure
PLB	Personal Locator Beacon
PMR	Private Mobile Radio
RAC	Random Access Channel
RACON	Radar beacon
RADC	Random Access Short Message Channel
RATDMA	Random Access TDMA
RLS	Return Link Centre
RQSC	Random Access Structure Request
RSSI	Received Signal Strength Indicator
SARSAT	Search And Rescue Satellite-Aided Tracking
SAR	Search and Rescue
SART	Search and Rescue Transmitter
SCTDMA	Slot Carrier Sense TDMA
SDR	Software Defined Radio
SFTP	SSH File Transfer Protocol
SMTP	Simple Mail Transfer Protocol

SNMP	Simple Network Management Protocol
SOLAS	Safety Of Life At Sea
SOTDMA	Self-Organizing TDMA
STM	Sea Traffic Management
TBB	Terrestrial Bulletin Board
TBBSC	Terrestrial Bulletin Board Signalling Channel
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TETRA	Terrestrial Trunked Radio
UAV	Unmanned Aerial Vehicle
UDC	Unicast Data Channel
UDP	User Datagram Protocol
UTC	Universal Time Coordinated
VDE	VHD Data Exchange
VDES	VHD Data Exchange System
VDL	VHF Data Link
VHF	Very High Frequency
VTC	Vessel Traffic Services
WRC	World Radiocommunication Conference

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