Acquisition Directorate
Research & Development Center

Report No. CG-D-02-21

Very High Frequency Data Exchange System (VDES) Technology Roadmap

Distribution Statement A: Approved for public release; distribution is unlimited.

January 2021

Homeland Security

N O T I C E

This document is disseminated under the sponsorship of the Department of Homeland Security in the interest of information exchange.

For use outside the United States Government, the Government assumes no liability for its contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report.

Mr. Robert Riley
Information Technology & Networks Branch Chief
United States Coast Guard
Research & Development Center
1 Chelsea Street
New London, CT 06320

Technical Report Documentation Page

1. Report No.	2. Government Accession Number	3. Recipient's Catalog No.
CG-D-02-21		

4. Title and Subtitle	5. Report Date
Very High Frequency Data Exchange System (VDES) Technology Roadmap	January 2021
	6. Performing Organization Code Project No. 8703
7. Author(s) Irene Gonin, Gregory Johnson, James Spilsbury, Sophie Ordell, and Michael Wurl	8. Performing Report No. RDC UDI # 1861
9. Performing Organization Name and Address U.S. Coast Guard Research and Development Center 1 Chelsea Street New London, CT 06320 Serco, Inc. 1 Chelsea St., Suite 200 New London, CT 06320	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Contract # HSCG23-15-D-R00151
12. Sponsoring Organization Name and Address COMMANDANT (CG-761) US COAST GUARD STOP 7331 2703 Martin Luther King Jr Ave SE Washington, DC 20593	13. Type of Report & Period Covered Interim 14. Sponsoring Agency Code Commandant (CG-761) US Coast Guard Stop 7331 Washington, DC 20593

15. Supplementary Notes

The R&D Center's technical point of contact is Irene Gonin, 860-271-2694, email: Irene.M.Gonin@uscg.mil

16. Abstract (MAXIMUM 200 WORDS)

The Automatic Identification System (AIS) is a ship-to-ship collision avoidance system that allows for communication of position, speed, and other ship data via a Very High Frequency (VHF) data link network. The volume of marine vessels using AIS has been steadily increasing and is resulting in overload of the two channels that carry the AIS transmissions. The next generation AIS – called the VHF Data Exchange System (VDES) is under development. VDES preserves the original function of AIS and provides four additional channels for communication. The primary benefits of transitioning from AIS to VDES are:

- Increased capacity for data communications with VDE-Terrestrial (up to 32 times the capacity of AIS).
- Increased coverage area provided by VDE-Satellite, including the Arctic.
- Ability to layer in cyber-security.
- Provides a backup Positioning Navigation and Timing or Global Navigation Satellite System-denied environments and the ability to de-spoof AIS.

This report summarizes the VDES technology, standards, timeline for completion, and provides example use cases of how VDES will benefit and improve safety of navigation for the United States Coast Guard and other mariners. It also describes the state of equipment development, field-testing (both previous and that planned by the USCG), and challenges to implementation.

17. Key Words	18. Distribution Statement
Automatic Identification System, AIS, Very High Frequency Data Exchange System, VDES, Application Specific Messages, ASM, VHF Data Exchange, VDE Terrestrial, VDE-Ter, VDE Satellite, VDE-Sat, Use Cases, VDES Benefits, VDES Challenges, United States Coast Guard, USCG	Distribution Statement A: Approved for public release; distribution is unlimited.

19. Security Class (This Report)	20. Security Class (This Page)	21. No of Pages	22. Price
UNCLAS//Public	UNCLAS//Public	58	

(This page intentionally left blank.)

EXECUTIVE SUMMARY

The Automatic Identification System (AIS) is a ship-to-ship collision avoidance system that allows for communication of position, speed, and other ship data via a Very High Frequency (VHF) data link network. Mariners worldwide use AIS and it has proved to be an effective system enabling effective ship-to-ship collision avoidance at sea and increased Maritime Domain Awareness. However, the volume of marine vessels using AIS has been increasing since its inception in 2000. This increase is resulting in overloading of the two channels that carry the AIS transmissions.

In response to this overloading of AIS, international organizations like the International Telecommunication Union (ITU), the International Maritime Organization (IMO), and the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) are developing the next generation AIS – called the VHF Data Exchange System (VDES). VDES is designed to support the IMO electronic navigation (e-Navigation) goals with multiple subsystems within one device. VDES retains the original AIS channels, but then adds two new channels for Application Specific Messages (ASMs), and also adds the higher speed VDE Terrestrial (VDE-Ter) and VDE Satellite (VDE-Sat) channels.

The primary benefits of transitioning from AIS to VDES are:

- Increased capacity for data communications with VDE-Ter.
- Increased coverage area provided by VDE-Sat, including the Arctic.
- Ability to layer in cyber-security.
- Provides a backup PNT for GNSS-denied environments and the ability to de-spoof AIS.

These benefits directly support the USCG strategic focus areas of *Increasing Maritime Commerce and Emerging Cyber Risks to the Maritime Transportation System*. Five different use-cases of VDES are presented that highlight these primary benefits: Vessel Traffic Service (VTS)/Route Exchange, Enhanced Maritime Safety Information (eMSI), Search and Rescue (SAR), Sensitive But Unclassified (SBU) Tactical information Exchange and Display System (STEDS), and Ranging (R-Mode). For each use-case the mission and current state with AIS are described, and the benefits of moving to VDES are presented.

The primary challenge to achieving the benefits of VDES is that it is an emerging system with some aspects still under development. The VDES system and equipment standards are available in draft form and are on track to be finalized in 2021 or 2022. Several manufacturers have developed and tested first generation equipment based on the draft standards and are upgrading their equipment as the standards evolve. Other challenges include frequency availability, adjacent channel concerns, and the required shore infrastructure (processes, procedures, and information infrastructure) that will be needed to effectively use VDES.

Since VDES is an emerging system, the authors have reviewed the relevant international standards and its status is documented in the report. A market survey was conducted to identify the availability of VDES equipment; there are four venders with equipment available now or potentially in the near future. There have been a number of tests conducted internationally over the past 6 years, which have helped to guide standards development and assess performance of prototype hardware.

A next step is to conduct field tests of VDES. Two tests are planned: one test to assess the feasibility and benefits of transitioning USCG messaging from AIS to the ASM channels, and a second test to assess the performance of VDES and to identify issues that need to be resolved for potential operational implementation. These issues include how to manage the bulletin boards and channel management between adjacent base stations with overlapping coverage, including those on International borders.

(This page intentionally left blank.)

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AES	Advanced Encryption Standard
AIS	Automatic Identification System
APNT	Assured Position Navigation and Timing
ASM	Application Specific Message
AtoN	Aid to Navigation
BFT	Blue Force Tracking
bps	bits per second
CD	Committee Draft
CISM	Co-site Interference Mitigation System
CRC	Cyclical Redundancy Check
CSTDMA	Carrier Sense Time Division Multiple Access
dB	decibel
DLR	German Aerospace Center (Institute for Communication and Navigation)
DSC	Digital Selective Calling
ECDIS	Electronic Chart Display and Information System
ENC	Electronic Nautical Chart
eMSI	enhanced MSI
e-Navigation	electronic Navigation
ETA	Estimated Time of Arrival
FATDMA	Fixed Access Time Division Multiple Access
FCC	Federal Communications Commission
FEC	Forward Error Correction
FOC	Full Operational Capability
GIS	Geographic Information System
GMDSS	Global Maritime Distress and Safety System
GMSK	Gaussian Minimum Shift Keying
GNSS	Global Navigation Satellite System
GUI	Graphical User Interface
HDLC	High-level Data Link Control
HF	High Frequency
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IEC	International Electrotechnical Commission
IHO	International Hydrographic Organization
IMO	International Maritime Organization
IS	International Standard
ITDMA	Incremental Time Division Multiple Access
ITU	International Telecommunication Union
kHz	kilo Hertz
kbps	kilo bits per second
ksps	kilo symbols per second
LE	Law Enforcement
LEO	Low Earth Orbiting

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

MARAD	Maritime Administration
MDA	Maritime Domain Awareness
MEDEVAC	Medical Evacuation
MET/HDRO	Meteorological and Hydrological
MF	Medium Frequency
MITDMA	Multiple Incremental Time Division Multiple Access
MHz	Mega Hertz
ms	millisecond
MSC	Maritime Safety Committee
MSI	Marine Safety Information
NAIS	Nationwide Automatic Identification System
NAS	Navigational Assistance Service
NAVDAT	Navigation Data
NAVTEX	Navigation Text
NBDP	Narrowband Direct Printing
NMEA	National Marine Electronics Association
NOAA	National Oceanic and Atmospheric Administration
OOW	Officer of the Watch
OSC	On Scene Commander
PAS	Publicly Available Standard
pfd	power flux density
PI	Presentation Interface
PNT	Positioning Navigation and Timing
PORTS	Physical Oceanographic Real-Time System
PS	Product Specification
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RATDMA	Random Access Time Division Multiple Access
RDC	USCG Research and Development Center
RCC	Rescue Coordination Centre
R-Mode	Ranging Mode
RTCM	Radio Technical Commission for Maritime Services
SAR	Search and Rescue
SBAS	Satellite-based Augmentation Service
SBB	Satellite Bulletin Board
SBU	Sensitive But Unclassified
SINS 2	Scalable Integrated Navigation System version 2
SMC	SAR Mission Coordinator
SOLAS	international convention on Safety of Life at Sea
SOTDMA	Self-Organized Time Division Multiple Access
SRU	SAR Response Units

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

STEDS	SBU Tactical information Exchange and Display System
TOI	Target of Interest
TBB	Terrestrial Bulletin Board
TDMA	Time Division Multiple Access
TOS	Traffic Organization Service
UHF	Ultra High Frequency
US	United States
USACE	US Army Corps of Engineers
USCG	Unite States Coast Guard
VDE	VHF Data Exchange
VDES	VHF Data Exchange System
VDE-Sat	VHF Data Exchange Satellite
VDE-Ter	VHF Data Exchange Terrestrial
VDL	VHF Data Link
VHF	Very High Frequency
VOS	Voluntary Observing Ship
VTC	Vessel Traffic Centers
VTS	Vessel Traffic Services or Vessel Traffic Systems
WG	Working Group
WRC	World Radio Conference

1 INTRODUCTION

The Automatic Identification System (AIS) is a ship-to-ship collision avoidance system that allows for communication of position, speed, and other ship data via a Very High Frequency (VHF) data link (VDL) network. Mariners worldwide use AIS to ensure safety at sea. The Nationwide Automatic Identification System (NAIS) is a nationwide network of land-based AIS receivers and transmitters operated by the United States Coast Guard (USCG). It was designed to increase Maritime Domain Awareness (MDA) in United States (U.S.) coastal and territorial waters. Numerous NAIS sites along the coast "listen" to transmitted maritime AIS activity. This data is consolidated and disseminated to the USCG and other government agencies[1] to support maritime safety and security, maritime mobility, national defense, and protection of natural resources in U.S. coastal waters.

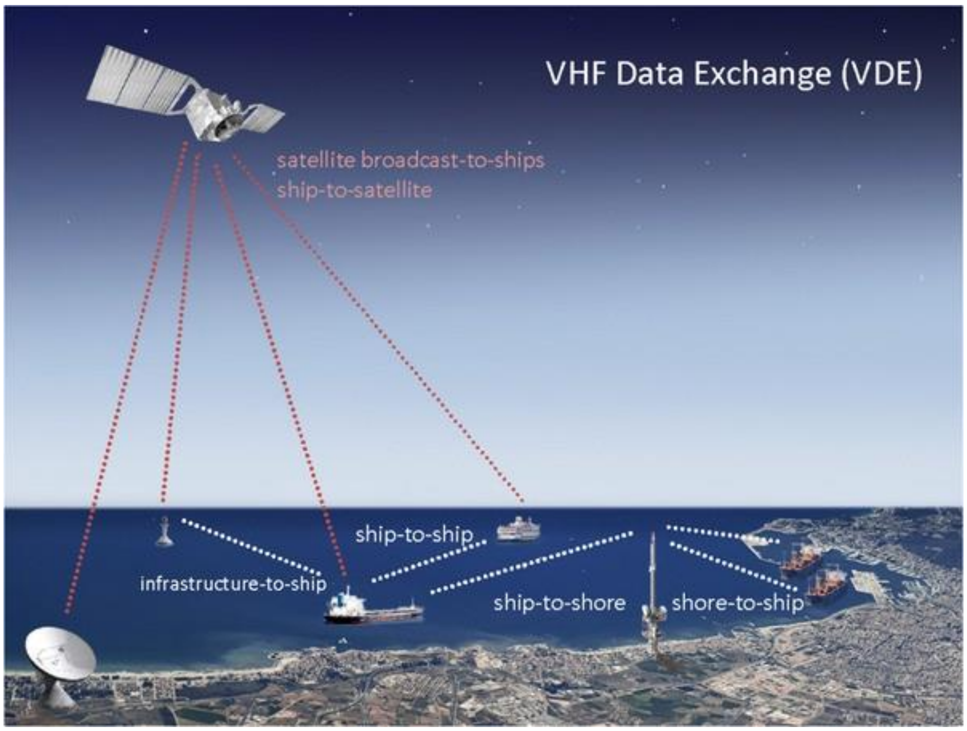


Figure 1. VHF Data Exchange (VDE) concept; image from [1].

AIS and NAIS have been used successfully in the U.S. since 2004. AIS has proved to be an effective system enabling ship-to-ship collision avoidance at sea and increased MDA for the USCG. However, an increase in the volume of marine vessels using AIS, as well as, an increase in data transmission over AIS, has resulted in overloading of the two AIS channels. In response, international organizations such as the International Telecommunication Union (ITU), the International Maritime Organization (IMO), and the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) are developing the next generation AIS – called the VHF Data Exchange System (VDES). VDES is a technological concept utilizing terrestrial and satellite radio communication links in the VHF maritime mobile band to facilitate globally interoperable digital data exchange between ships, between ships and shore, between shore and

[1] https://www.navcen.uscg.gov/?pageName=NAISvsAIS

ships, between ship and satellite, and between satellite and ships (see Figure 1). It will also increase the bandwidth available for these communications by using a greater number of VHF channels.

The USCG is looking to the future to determine the next steps in improving maritime safety and domain awareness. This report discusses the capability of VDES as it pertains to USCG mission needs. It is based upon a review of USCG Research and Development Center (RDC) reports and open literature as well as market research on VDES equipment and current and developing international standards. The goal of this effort is to determine the benefits of VDES and the path to implementation of VDES to support USCG operations.

2 VDES OVERVIEW

2.1 VDES as a Key Component of e-Navigation

In 2005, "Development of an e-Navigation Strategy" was introduced as an input paper at the 81st Session of the IMO Maritime Safety Committee (MSC) [2]. It described a clear need to equip the master of a vessel, and those responsible for the safety of shipping ashore, with modern proven tools to make marine navigation and communications more reliable and thereby reduce errors. This paper provided the impetus to create a series of committees, subcommittees, and working groups to develop a strategy and implement standards to support electronic navigation (e-Navigation). The creation of VDES is one of the key components within the e-Navigation framework and falls fully under the communication and ship components shown in Figure 2. For the shore component, VDES includes the hardware to transmit and receive the communications; it does not include the creation, authentication, or management of the information for dissemination on VDES. This key part of the shore component needs to be developed and implemented by the various authorities as part of their e-Navigation system.

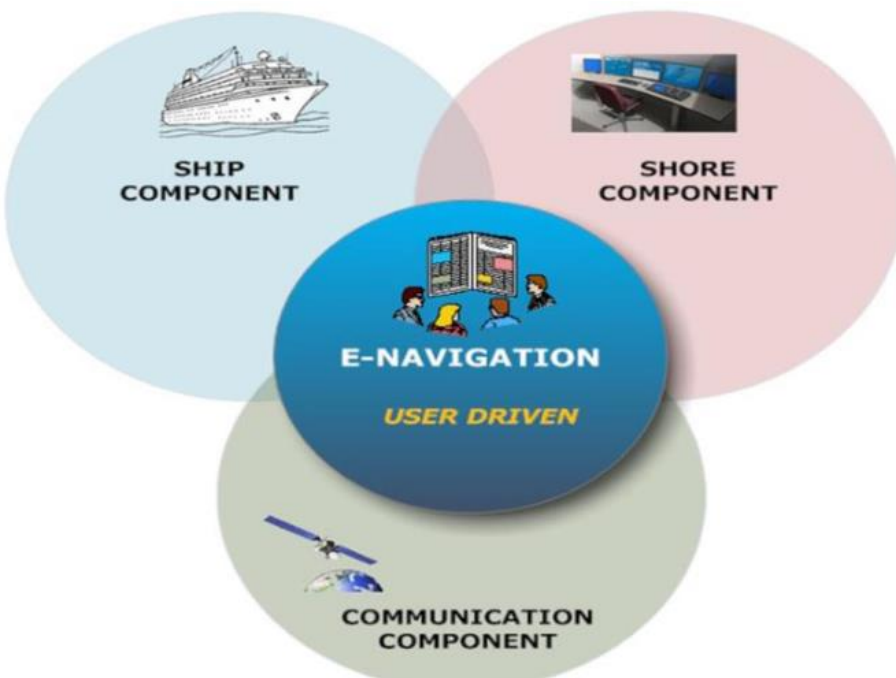


Figure 2. Key components of e-Navigation; image from [3].

VDES is seen as an effective and efficient use of the VHF radio spectrum. In particular, it builds on the capabilities of AIS and addresses increasing requirements for data exchange between ships and shore. Newer modulation techniques used by VDES provide higher data rates than those used for AIS. In addition, the VDES network protocol is optimized for data communications so that each VDES message is transmitted with a high confidence of reception. VDES also provides access to the Maritime Cloud[2]. Users of VDES include mariners, Vessel Traffic Systems (VTS), port authorities, maritime authorities, regulatory authorities, scientific, environmental, educational and industrial organizations, and other service providers for the maritime industry.

In 2017, RDC published a report on Marine Safety Information (MSI) Systems [4] that included a section on VDES. Since the MSI Systems report publication, there has been a large amount of effort expended internationally to further define the VDES system and document the communications modulations, protocols, and procedures in the standards. The initial frequency allocation (for the terrestrial component) was made by the World Radio Conference in 2015 (WRC-15). The final frequency allocation (for the satellite component) was authorized at WRC-19[3] [5]. Figure 3 shows the frequency allocations for each service as well as the VHF channel numbers from the Radio Regulations, Appendix 18 [6, 7]. The primary VDES standard, ITU Recommendation M.2092, "Technical Characteristics for a VHF Data Exchange System in the VHF Maritime Mobile Band" [8] is being updated consequential to the decisions of WRC-19. This and other relevant standards are discussed in Section 7. In addition, several authors have written their own summaries of the VDES system [1, 9-11], which provide some additional information. In this report, some details of the system and its components will be included for ready reference in the following section.

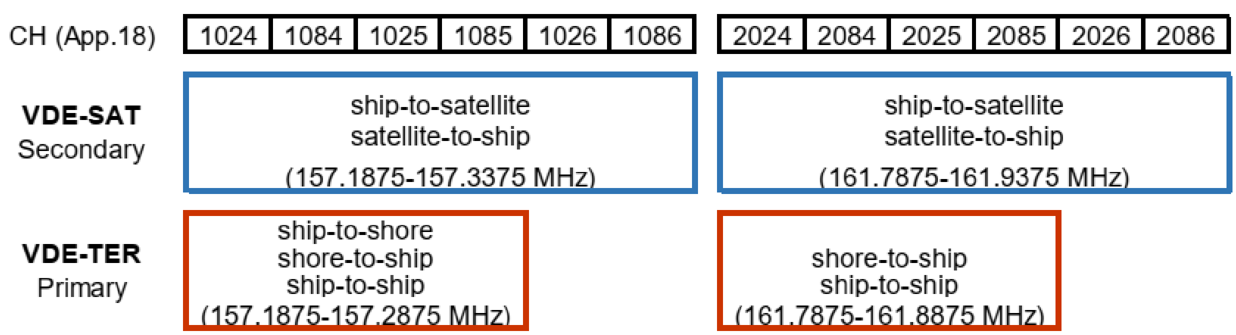


Figure 3. VDES frequency plan adopted by WRC-19; image from [5].

3 VDES COMPONENTS

VDES is designed to support the IMO e-Navigation goals with multiple subsystems within one device. It has four individual components/ capabilities/ subsystems, each described in the subsections below. These four components are: the original AIS, two new channels for Application Specific Messages (ASMs), and the higher speed VDE Terrestrial (VDE-Ter) and VDE Satellite (VDE-Sat) links (see Figure 4). The frequencies allocated to each component are listed in Table 1. The mapping of frequencies to functions are

[2] The Maritime Cloud is defined as "A communication framework enabling efficient, secure, reliable and seamless electronic information exchange between all authorized maritime stakeholders across available communication systems." IMO NCSR 1/INF.X, 22 April 2014

[3] WRC-19 revised the International Radio Regulations to facilitate VDES terrestrial and satellite components. FCC rules are being revised accordingly, since VDES, which subsumes AIS, is an international system, now recognized by IMO.

shown visually in Figure 5, Figure 6, and Figure 7. The color coding of the frequencies bands is the same in all figures and matches the row shading in Table 1.

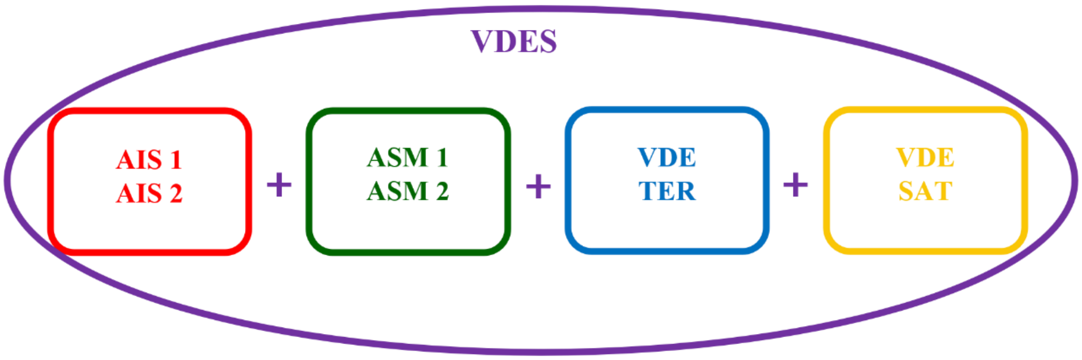


Figure 4. VDES components.

Table 1. VDES frequencies and usage.

Channel	Center Frequencies (BW)	Radio Regulations channel number	Usage					
			Ship Xmt	Ship Rcv	Base Xmt	Base Rcv	Sat Xmt	Sat Rcv
AIS 1	161.975 (25kHz)	87B	X	X	X	X		X
AIS 2	162.025 (25kHz)	88B	X	X	X	X		X
AIS LR 1	156.775 (25kHz)	75	X					X
AIS LR 2	156.825 (25kHz)	76	X					X
ASM 1	161.950 (25kHz)	2027	X	X	X	X		X
ASM 2	162.000 (25kHz)	2028	X	X	X	X		X
VDE lower	157.200 (25 kHz) 157.225 (25 kHz) 157.250 (25 kHz) 157.275 (25 kHz) 157.2125 (50 kHz) 157.2625 (50 kHz) 157.2375 (100 kHz)	1024 1084 1025 1085 1024+1084 1025+1085 1024+1084+1025+1085	X	X	X	X	X	X
VDE lower	157.300 (25 kHz) 157.325 (25 kHz)	1026 (Sat only) 1086 (Sat only)	X	X			X	X
VDE upper	161.800 (25 kHz) 161.825 (25 kHz) 161.850 (25 kHz) 161.875 (25 kHz) 161.8125 (50 kHz) 161.8625 (50 kHz) 161.8375 (100 kHz)	2024 2084 2025 2085 2024+2084 2025+2085 2024+2084+2025+2085	X	X	X		X	X
VDE upper	161.900 (25 kHz) 161.925 (25 kHz)	2026 (Sat only) 2086 (Sat only)	X	X			X	X

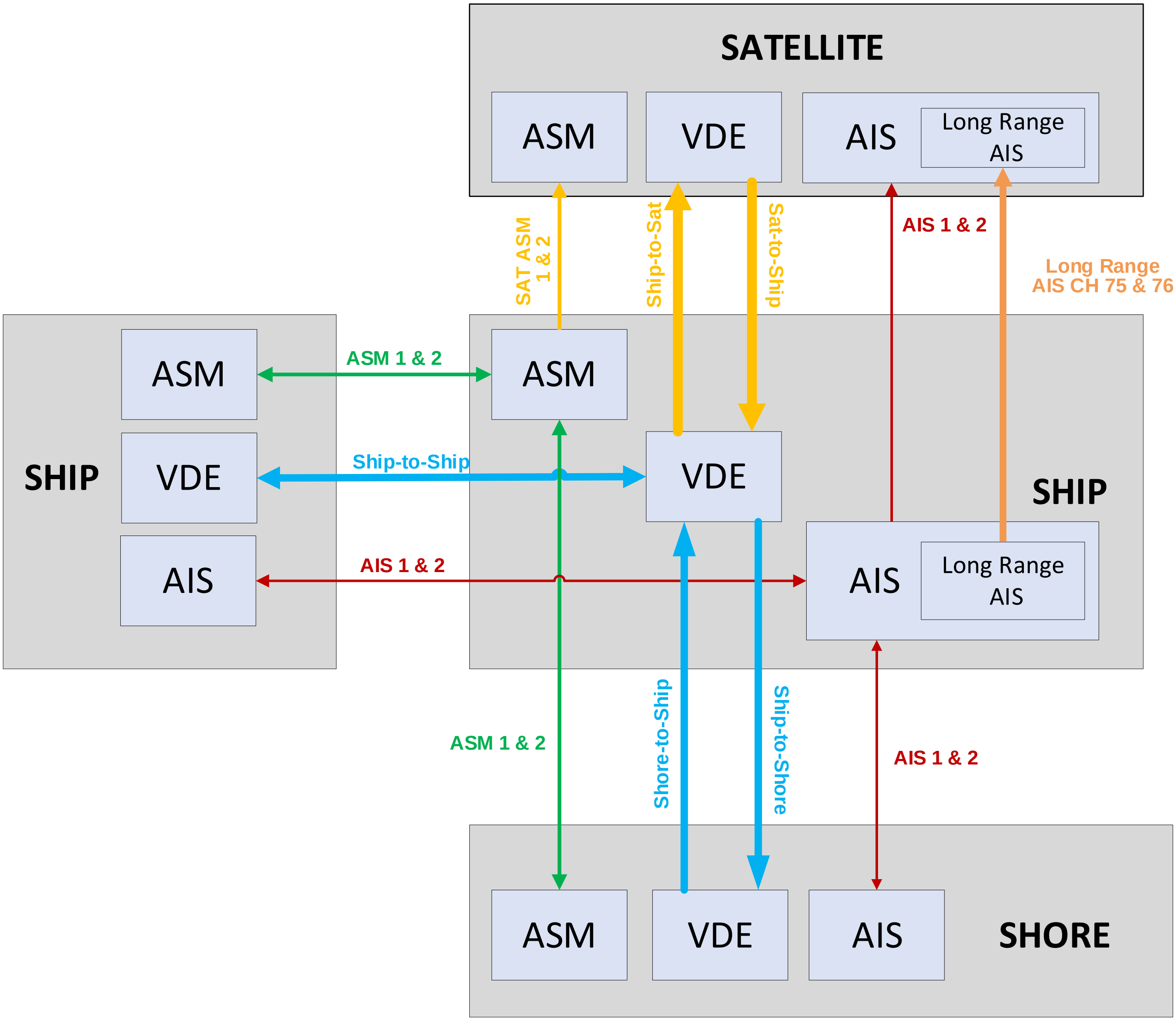


Figure 5. VDES communications links.

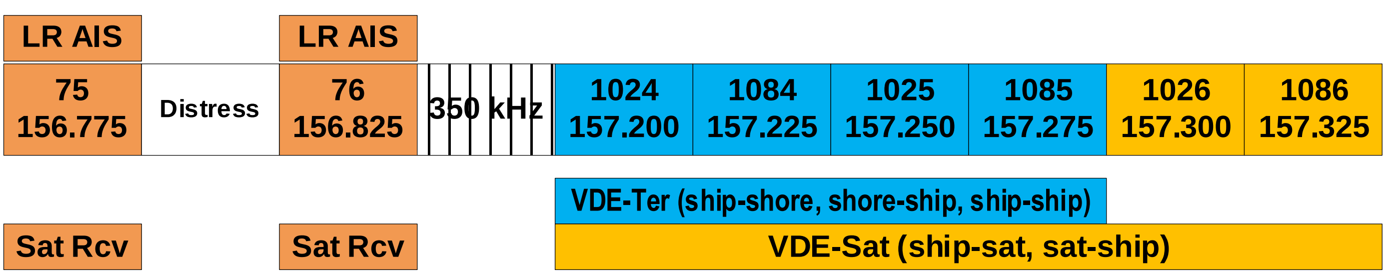


Figure 6. VDES functions and frequency usage lower bank.

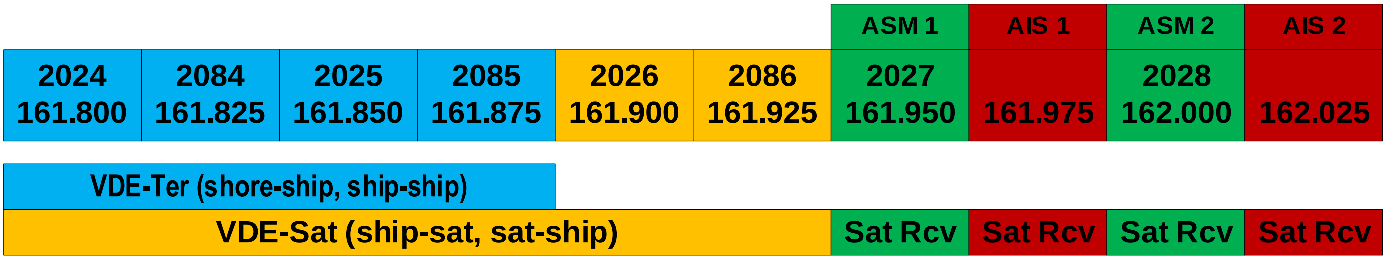


Figure 7. VDES functions and frequency usage upper bank.

3.1 AIS

AIS remains the same, as defined in ITU Recommendation M.1371 [12]. It transmits data at 9,600 bps using Gaussian Minimum Shift Keying (GMSK) on two 25 kHz wide channels, AIS1 and AIS2. Each channel has frames of 2,250 slots per minute (26.667 ms per slot) and channel access can be done using Random Access Time Division Multiple Access (RATDM), Fixed Access Time Division Multiple Access (FATDMA), Incremental Time Division Multiple Access (ITDMA), Carrier Sense Time Division Multiple Access (CSTDMA), or Self-Organized Time Division Multiple Access (SOTDMA). The basic packet structure is shown in Table 2; this is for a single slot message. The data field can be expanded up to about 1,000 bits taking up to five slots to transmit.

There are also two additional 25 kHz channels used for long range AIS, that are used for ship transmissions (and satellite reception) only; these are channels 75 and 76. Ships broadcast a shorter AIS message (Message 27) on these channels when outside of a base station service area.

Table 2. AIS packet structure (from ITU-R M.1371[12]).

	Bits	Description
Ramp up	8	
Training sequence	24	Alternating 0's and 1's.
Start Flag	8	Standard High-level Data Link Control (HDLC) flag (01111110).
Data	168	For single slot
Cyclical Redundancy Check (CRC)	16	The CRC only includes the data field
End flag	8	Identical to start flag
Buffer	24	Distance delay and jitter
Total	**256**	

3.2 ASM

The frame structure and channel access modes are the same for the ASM channels as for the AIS channels with the addition of the Multiple ITDMA mode (MITDMA). MITDMA is used to chain together up to 15 slots to accommodate longer messages (otherwise messages are limited to 3 slots). The main difference is that the ASM channels modulate at 19,200 bps using pi/4 Quadrature Phase Shift Keying (QPSK) and the packet structure is slightly different (see Table 3). In addition to a longer training sequence there is a link ID instead of HDLC type start and stop flags. The packets also include Forward Error Correction (FEC), interleaving, and bit scrambling. Due to the FEC and overhead in the packet structure, the overall information rate is not double that of AIS even though the modulation rate is double.

Table 3. ASM packet structure (from IALA G.1139[13]).

	Symbols	Description
Ramp up	4	
Training sequence	27	Necessary for synchronization
Link ID	16	Decoded from (32,6) bi-orthogonal code; ASM channel configurations as defined in Link ID table; Note that the Link ID will identify how many slots make up the message.
Data	1 slot: 176 2 slot: 432 3 slot: 688 SAT: 616	The symbol count and the information bits vary according to coding rate as defined by the Link ID field
CRC	16	The CRC only includes the data field
FEC termination bits	6	Set to zero when not used
Ramp Down	4	Distance delay and jitter
Guard Time	TER: 7 SAT: 79	Distance delay and jitter
Total	**1 slot: 256** **2 slot: 512** **3 slot: 768**	

3.3 VDE Terrestrial

While the frame structure (2,250 slots per minute) is the same as for AIS and ASM channels, VDE-Ter has a variety of options: channels of 25, 50, or 100 kHz bandwidth, modulations of pi/4 QPSK, 8-PSK (8 state phase shift keying), and 16-QAM (16 state quadrature amplitude modulation), and different FEC techniques. The bit rates range from 38.4 kbps (25 kHz channel with pi/4 QPSK) up to 307.2 kbps (100 kHz channel with 16-QAM). While the number of slots per minute remains the same across these physical channel options, the number of bits per slot varies.

The packets also include FEC, interleaving, and bit scrambling. Similar to the ASM channels, the effective information rate is less than the bit rate due to the FEC and the packet structure overhead. Some of the bandwidth is also reserved to transmit the terrestrial bulletin board (TBB) information, which describes the channel structure and slot maps being used. Figure 8 shows the default slot mapping taken from the latest draft of ITU-R M.2092-1. The 2,250 slot frames are divided into six Time Division Multiple Access (TDMA) channels (labeled TDMA0 to TDMA5). TDMA0 is used for signaling, with the first 3 slots of every group of 15 reserved for the transmission of the TBB.

(yellow)	Bulletin Board Signalling Channel
(green)	Random Access Signalling Channel
(pink)	Announcement Signalling Channel
(orange)	Data Signalling Channel
(blue)	Data Channel
s	Slot number
L	Logical Channel Number

TDMA 0		0 0	6 0	12 0	18 1	24 1	30 1	36 1	42 1	48 1	54 1	60 1	66 1	72 1	78 1	84 1
TDMA 1		1 2	7 2	13 2	19 2	25 2	31 2	37 2	43 2	49 2	55 2	61 2	67 2	73 2	79 2	85 3
TDMA 2		2 4	8 4	14 4	20 4	26 4	32 4	38 4	44 4	50 4	56 4	62 4	68 4	74 4	80 4	86 5
TDMA 3		3 6	9 6	15 6	21 6	27 6	33 6	39 6	45 6	51 6	57 6	63 6	69 6	75 6	81 6	87 7
TDMA 4		4 8	10 8	16 8	22 8	28 8	34 8	40 8	46 8	52 8	58 8	64 8	70 8	76 8	82 8	88 9
TDMA 5		5 10	11 10	17 10	23 10	29 10	35 10	41 10	47 10	53 10	59 10	65 10	71 10	77 10	83 10	89 11

TDMA 0		90 0	96 0	102 0	108 1	114 1	120 1	126 1	132 1	138 1	144 1	150 1	156 1	162 1	168 1	174 1	...
TDMA 1		91 2	97 2	103 2	109 2	115 2	121 2	127 2	133 2	139 2	145 2	151 2	157 2	163 2	169 2	175 3	...
TDMA 2		92 4	98 4	104 4	110 4	116 4	122 4	128 4	134 4	140 4	146 4	152 4	158 4	164 4	170 4	176 5	...
TDMA 3		93 6	99 6	105 6	111 6	117 6	123 6	129 6	135 6	141 6	147 6	153 6	159 6	165 6	171 6	177 7	...
TDMA 4		94 8	100 8	106 8	112 8	118 8	124 8	130 8	136 8	142 8	148 8	154 8	160 8	166 8	172 8	178 9	...
TDMA 5		95 10	101 10	107 10	113 10	119 10	125 10	131 10	137 10	143 10	149 10	155 10	161 10	167 10	173 10	179 11	...
	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
TDMA 0	...	2160 0	2166 0	2172 0	2178 1	2184 1	2190 1	2196 1	2202 1	2208 1	2214 1	2220 1	2226 1	2232 1	2238 1	2244 1	
TDMA 1	...	2161 2	2167 2	2173 2	2179 2	2185 2	2191 2	2197 2	2203 2	2209 2	2215 2	2221 2	2227 2	2233 2	2239 2	2245 3	
TDMA 2	...	2162 4	2168 4	2174 4	2180 4	2186 4	2192 4	2198 4	2204 4	2210 4	2216 4	2222 4	2228 4	2234 4	2240 4	2246 5	
TDMA 3	...	2163 6	2169 6	2175 6	2181 6	2187 6	2193 6	2199 6	2205 6	2211 6	2217 6	2223 6	2229 6	2235 6	2241 6	2247 7	
TDMA 4	...	2164 8	2170 8	2176 8	2182 8	2188 8	2194 8	2200 8	2206 8	2212 8	2218 8	2224 8	2230 8	2236 8	2242 8	2248 9	
TDMA 5	...	2165 10	2171 10	2177 10	2183 10	2189 10	2195 10	2201 10	2207 10	2213 10	2219 10	2225 10	2231 10	2237 10	2243 10	2249 11	

Figure 8. Default slot map for lower leg of VDE; image from ITU-R M.2092-1 draft.

According to the evolving draft of ITU Recommendation M.2092-1, “VDE-Ter may operate in either duplex or simplex mode. VDE-Ter may operate in duplex mode by using the lower leg channels for ship-to-shore and the upper leg channels for shore-to-ship and ship-to-ship digital messaging. VDE-Ter may operate in simplex mode by using the lower leg channels for ship-to-shore, shore-to-ship and ship-to-ship digital messaging.” Note that this is not true duplex mode though in that communications cannot take place simultaneously.

3.4 VDE Satellite

The satellite service is intended to provide coverage beyond the reach of terrestrial base stations for ship-to-shore and shore-to-ship communications (see Figure 9). VDE-Sat is layered on top of VDE-Ter (sharing much of the same bandwidth) using spread spectrum modulation and a power flux density (pfd) mask in order to alleviate interference between the two. Within terrestrial base station service areas, communications are expected to be conducted using VDE-Ter; the satellite signals will not interfere by design, but will not in general be useable except in the two 50 kHz blocks of frequencies that are reserved for satellite communications only.

VDE-Sat uses the same frame structure as the other VDES components. Like VDE-Ter, VDE-Sat also has a variety of options: 50 to 150 kHz channels and symbol rates of 2.1 to 56.4 ksps. The packets also include FEC, interleaving, and bit scrambling. As with VDE-Ter, the actual information rate is less due to the FEC and packet overhead. VDE-Sat also reserves some of the bandwidth for a satellite bulletin board (SBB) which performs the same functions as the TBB; it defines the physical channels and slot maps to be used in the satellite service areas.

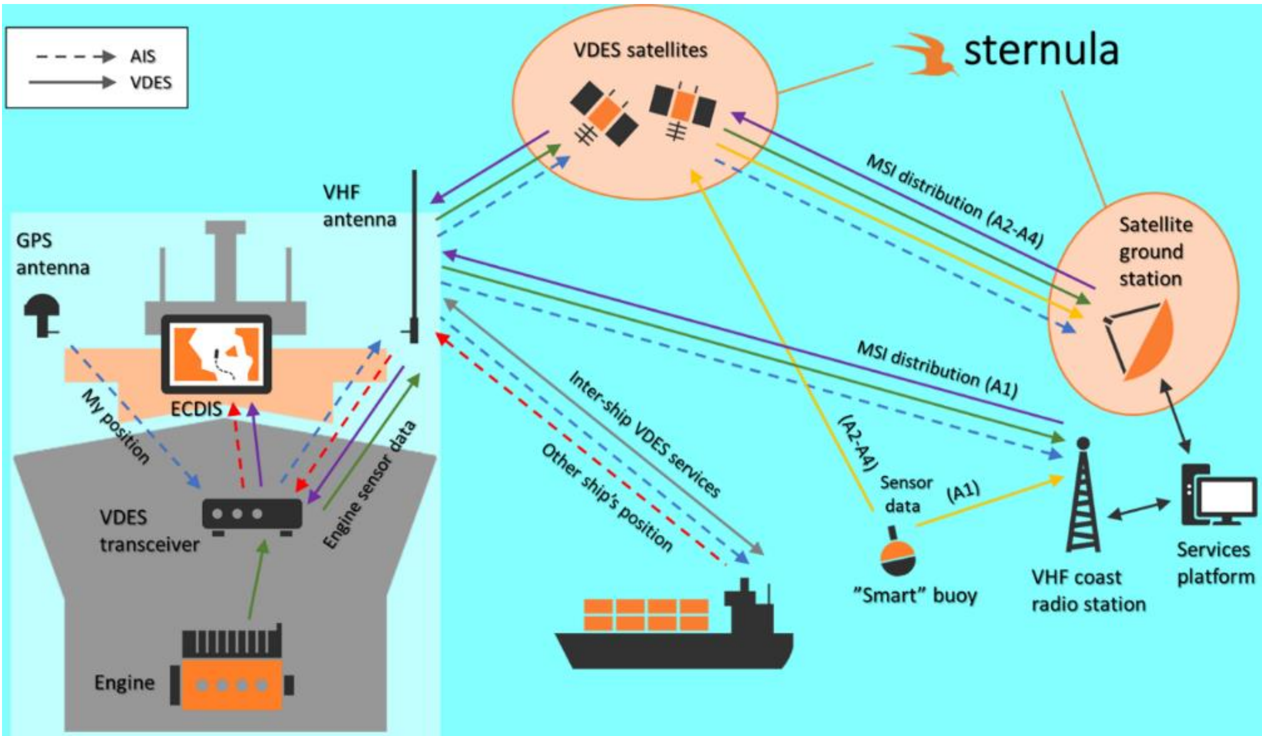


Figure 9. VDE-Sat system concept; image from Radio Technical Commission for Maritime Services (RTCM) Assembly 2020 presentation.

There are no operational VDE-Sat services at this time, although some companies have flown test satellites. One company (Sternula) has proposed a satellite service with phased launches over time providing increasing service area as more satellites are launched (see Figure 10).

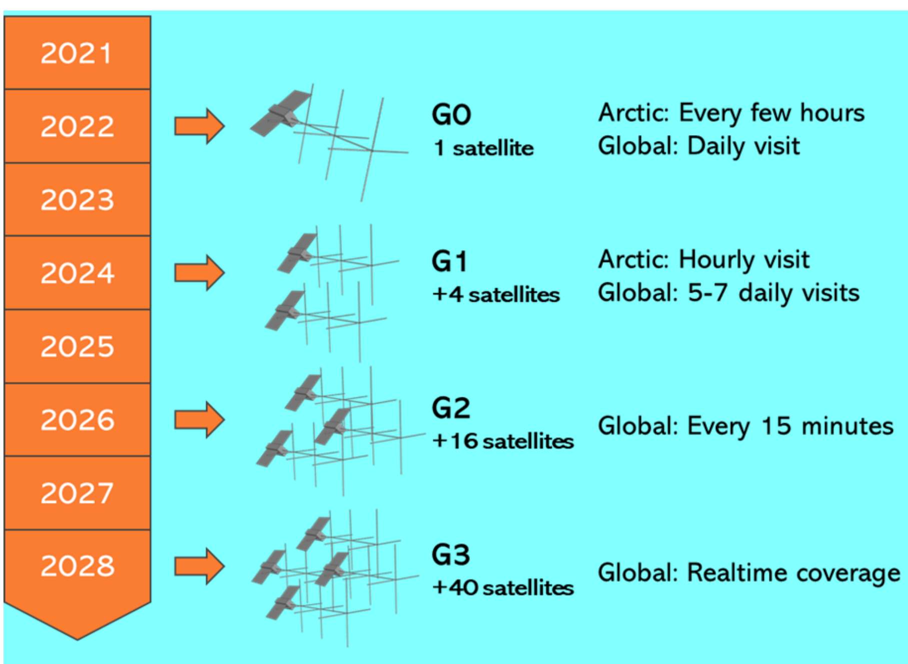


Figure 10. VDE-Sat satellite launch schedule; image from RTCM Assembly 2020 presentation.

4 VDES BENEFITS

The primary benefits of transitioning from AIS to VDES include:

1. Increased capacity for data communications with VDE-Ter (up to 32 times the capacity of AIS).
2. Increased coverage area provided by VDE-Sat, including the Arctic.
3. Ability to layer in cyber-security.
4. Provides a backup Positioning Navigation and Timing (PNT) for Global Navigation Satellite System (GNSS)-denied environment and the ability to de-spoof AIS.

These benefits directly support the USCG strategic focus areas of *Increasing Maritime Commerce and Emerging Cyber Risks to the Maritime Transportation System*[4]. A set of use-cases (described in Section 6) have been selected to highlight the benefits of VDES in the context of certain mission areas. These use-cases are summarized in Table 4. For each use-case, the table provides an example, an indication of the primary communications links used, what the benefits of VDES over AIS are, and which S-100, Universal Hydrographic Data Model, product specifications (described below) are relevant.

Table 4. VDES use cases summarized.

Use Case	VTS	eMSI	SAR	STEDS	Ranging (R)- Mode
VDES Use Case Examples	Route exchange	Ship weather Ice maps	SAR Comms Search Patterns	BFT TOI Search Patterns	Assured Positioning, Navigation and Timing (APNT) for ships position verification
VDE Satellite (Ship-shore and Shore-Ship)	Can be used in this mode, but less likely than terrestrial	Primary mode – especially for longer range	Can be used in this mode, but most SAR is close to coast	STEDS will be used in all three modes	N/A
VDE Terrestrial (Ship-Ship)	Primary mode	Can be used in this mode but is less important	Can be used in this mode but is less important		Potentially could be used in this mode. But is less important
VDE Terrestrial (Ship-Shore and Shore-Ship)		Primary mode	Primary mode		Primary mode
Improvement over AIS	Longer, more detailed routes. More route exchanges.	More complex and rich data, including geographic and graphic More data exchange. Increased coverage range.			More accurate ranges/positions.
Cyber	Encryption and authentication are possible				
S-100 Product Specification	S-125, S-127, S-210, S-211, S-212	S-101, S-102, S-104, S-111, S-121, S-122, S-124, S-125, S-126, S-129, S-201, S-411, S-412, S-413, S-414	S-124, S-125	S-5xx (to be developed)	To be Developed
USCG Strategic Plan	Collaborate on the development of vessel routing measures to support future capacity of the Marine Transportation System (MTS). Promote a Safe, Secure, and Resilient MTS infrastructure by reducing cyber threats and manage maritime risks[5]				

[4] Commandant's Strategic Intent 2015 – 2019 America's Coast Guard
[5] Coast Guard Strategic Plan 2018-2022 and the USCG's Vision for Operating in the Western Hemisphere, September 2014

S-100, the Universal Hydrographic Data Model, was adopted by the International Hydrographic Organization (IHO) as on official standard in January 2010. It was developed as the replacement to the existing S-57 standard for digital hydrographic data and is intended by IMO to be the data standard for e-Navigation developments. It was designed to overcome the limitations of S-57, by being flexible and able to support a wider range of hydrographic data such as imagery, gridded data and time-varying data. The current version of S-100 (version 4) was published in 2019 [14]. S-100 is a data model; specific Product Specifications (PS) are then defined under the model (see Table 5 for a list relevant to VDES) to describe how the data is to be defined, categorized, and formatted for exchange between systems; for example, S-101 is the new Electronic Nautical Chart (ENC) PS being developed by IHO.

Table 5. S-100 product specifications relevant to VDES.

PS Number	Description
S-101	ENC
S-102	Bathymetric Surface
S-104	Water Level Information for Surface Navigation
S-111	Surface Currents
S-121	Maritime Limits and Boundaries
S-122	Marine Protected Areas
S-124	Marine Navigational Warnings
S-125	Marine Navigational Services
S-126	Marine Physical Environment
S-127	Marine Traffic Management
S-129	Under Keel Clearance Management
S-201	Aids to navigation Information
S-210	Inter-VTS Exchange Format
S-211	Port Call Message Format
S-212	VTS Digital information Service
S-411	Sea Ice information
S-412	Weather Overlay

4.1 Increased Capacity

As described in Section 3.3, the VDE-Ter service will provide data rates up to 307.2 kbps (using a single 100 kHz channel); this is 32 times the data rate of AIS (9.6 kbps). Both VDE-Ter and AIS have two channels each at these rates. Messaging on AIS is also limited to 5 slots per message maximum (per the current Standard) although the use of more than 3 slots per message is not recommended. VDE-Ter can accommodate much longer messages which will allow the transmission of images such as ice maps.

4.2 Increased Coverage

The VDE-Sat service is intended to be supported by one or more satellite service providers using Low Earth Orbiting (LEO) satellites. These LEO satellites are typically in inclined orbits that provide coverage of the entire Earth (including the poles) over time. A constellation of sufficient number of satellites can provide coverage over the entire Earth at the same time (refer back to Figure 10). This is planned to be a two-way satellite service thus providing real-time (or near real-time) communications to and from ships world-wide. By comparison, satellite AIS services are receive only, and are not optimized for satellite communications (other than the Long Range AIS messages on channels 75 and 76), so satellite reception is much less than

100% of the messages transmitted (percentage received is a function of traffic density in the satellite reception footprint).

4.3 Cyber

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

- 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.

The VDES standards include the ability to both encrypt messages and to provide authentication of messages. Both of these features are essential to providing a more robust and secure messaging service for maritime use.

4.4 Assured PNT

The greatest cyber vulnerability is PNT, on which all data exchange with ships relies and without which identification and location of ships is not possible and the synchronization of data transmissions is lost. VDES R-Mode ensures that PNT is maintained, even when GNSS is denied due to intentional or unintentional causes. On ship, an R-Mode receiver provides the ability to determine the ship's position independently of GNSS if there are sufficient VDES base stations in range, or at least a range that can be used to verify the GNSS position (protecting against spoofing) if only one base station is available. On shore, an R-mode receiver at the base station can provide a range to verify the ship's transmitted position (protecting against spoofing or faulty equipment onboard). If multiple base stations or R-Mode receivers can receive the ship's transmissions then a GNSS-independent position of the vessel can be determined, protecting against jamming and spoofing.

5 VDES CONCERNS/CHALLENGES

The primary challenge to achieving the benefits of VDES outlined in the previous section is that VDES is an emerging system with some aspects still under development. The VDES system and equipment standards (Section 7) are available in draft form and are on track for final status in 2021 or 2022. Standards for vessels will need to be developed to ensure communication is clear [9]. Several manufacturers have developed and tested first generation equipment (Section 8, 9) based on the draft standards and are upgrading their equipment as the standards evolve. The use of VDES will also require upgrades to marine vessel radios. All of this will take time to develop and roll out and for the market to mature.

Several use-cases for VDES have specific challenges for implementation as outlined below and additional specific challenges are addressed in the following sections.

5.1 Use Case Challenges

5.1.1 VTS / Route Exchange

With VTS being a 24/7 service critical to safely managing traffic in congested areas, any upgrades on ship or shore infrastructures to VDES will need to have forward and backward compatibility with legacy AIS and VTS systems to ensure continuity of VTS [15].

5.1.2 R-Mode

R-Mode capability has not been built into any of the existing AIS or VDES radios. It has also not been fully detailed technically. However, this is an opportunity for trials to be conducted using prototype receivers to assess the achievable accuracy and operational implementation details. Two other topics of research are time synchronization and standardization. The German Aerospace Center (DLR) R-Mode Baltic web site[6] defines these:

> *Time synchronization of R-Mode transmitter is a crucial issue for a terrestrial backup system because the transmitters must operate with a mutual time accuracy of a few 10ns. The project will analyze the performance of currently available time comparison methods and station clock alternatives, and will suggest a suitable r-mode timing infrastructure. Furthermore, self-synchronization of r-mode will be studied. A proof-of-concept of a transnational cost-efficient time synchronization solution with suitable hold over clocks at the transmitter sites will be developed and demonstrated.*
>
> *R-Mode standardization is a prerequisite for the distribution of r-mode technology because maritime radio beacons and AIS base stations are designed to meet international standards, recommendations and guidelines of IALA, IMO, ITU, International Electrotechnical Commission (IEC) and others. Therefore, the implementation of R-Mode technology on these stations requires the change or at least amendment of existing international standards. The project team will forward to, communicate with and encourage various standardization committees and international organizations to improve and broaden the scope of existing PNT standardization by the implementation of the R-Mode technology.*

5.1.3 STEDS

In order to transition Sensitive But Unclassified (SBU) Tactical Information Exchange and Display System (STEDS) messages to VDES, the USCG shore infrastructure to support the creation, display, and delivery of STEDs messages will need to be built out, and cutter and boat radios upgraded.

5.2 Frequency Availability

Although the VHF channels for VDES have been approved for worldwide use by the WRC in 2015 and 2019, in the U.S. the situation is more complicated. The VHF channels allocated for VDES have been licensed by the Federal Communications Commission (FCC) to MariTEL; this license was recently extended for another 10 years. The U.S. government will need to either recover the frequencies from MariTEL or enter into a public-private partnership to support the implementation of VDES.

[6] https://www.dlr.de/kn/en/desktopdefault.aspx/tabid-4308/6940_read-52591/

5.3 Adjacent Channel Issues

There have been concerns raised about the use of VDE-Ter (specifically transmitting on the upper bank of frequencies) interfering with the reception of AIS traffic. This is not a concern for ships as they cannot transmit and receive at the same time on any of the frequencies (single antenna installations) so they must schedule transmissions to avoid expected AIS receptions (based upon the slot map). Shore installations can have separate transmit and receive antennas so this can be a concern; however, solutions exist. The harmonized draft revision of ITU-R M.2092 also addresses this concern by allowing for a simplex mode for shore sites that cannot engineer a solution.

The concern for sites using separate transmit and receive antennas is that there needs to be sufficient isolation between the two antennas otherwise a transmission on one channel can negatively impact reception on other channels. The primary concern is adverse impact by VDES transmissions on the reception of AIS traffic. Isolation can be achieved by frequency separation, physical distance between antennas, polarization, etc. The lower bank of VDES frequencies is separated by ~4.5 MHz from the AIS channels so is not a concern (simplex mode uses just these frequencies). The upper bank of VDES frequencies is only 100 kHz away from AIS1 so that can be a concern. The transmission mask specified by the VDES standard [13] only requires 70 dB reduction relative to the peak so additional isolation is necessary to stay under the allowable interference levels of the receiver. This issue has been investigated by Canada [16] and their testing demonstrates sufficient vertical separation is probably not feasible, horizontal separation would be needed as well. This will require the transmit and receive antennas to be located on separate towers, unless some other interference reduction measure is used. The USCG has an active Co-site Interference Mitigation System (CIMS) at the Rescue 21 towers which provides the extra isolation to allow transmit and receive antennas to be located on the same tower. This also allows the AIS and ASM channels (which are only 25 kHz apart) to not interfere with each other.

5.4 AIS Base Station Replacement

The USCG currently has a network of AIS base stations providing coverage along the U.S. coast (the NAIS system). These base stations are nearing their end-of-life and will need to be replaced at some point in the future. Since VDES (at least the terrestrial components) will be ready for operational implementation in the near future, it would make sense to procure replacement base stations that are VDES base stations (which includes AIS), or at least have the capability of being upgraded to include all of the VDES functionality in the future. The market trends support this approach; new AIS base stations from major venders are planned to be VDES base stations. These base stations could be drop-in replacements for the existing AIS base stations. If the existing base stations were to be replaced with new AIS-only units, then the USCG would be faced with either a long delay in VDES implementation or additional expense (or both).

5.5 Information Infrastructure

In addition to the VDES components, a shoreside information infrastructure will also be needed to support the information exchange. This infrastructure will include the transmitters, receivers, hardware, and software necessary to generate, process, and control the flow of information.

In any information technology, many parts or components make up the technology.

1. Creation of the data (e.g., from sensor or the competent authority).
2. The type of data:
    - Data from a depth or air gap sensor, chart update, etc.

   - Informational – weather forecast, planned route, emergency notification, etc.
3. The format of the data:
   - Binary.
   - National Marine Electronics Association (NMEA).
   - S-100.
   - Graphic.
   - Geographic.
4. The infrastructure or shore network to move the data to radios or satellites.
5. Radio or satellites need a network for the data to travel to ships.
6. Hardware to receive and software to decipher the data.
7. Software to manage and portray the data.
8. Graphical User Interface (GUI) for the user to "see" and "use" the data.

The shoreside information infrastructure must include all of these elements. Ship-to-ship communications must also include these elements although the network in this case would be the ship's local network.

Figure 11 shows the flow of data from creation to a vessel. Note that many of the components required to collect and manage the data are not part of VDES. The other parts of the overall system (acquiring and managing the information - represented in green) are necessary and will need to be implemented as part of any VDES implementation otherwise VDES (represented in blue) will be an empty communications capability. The final component for deciphering and portraying the data is represented in purple.

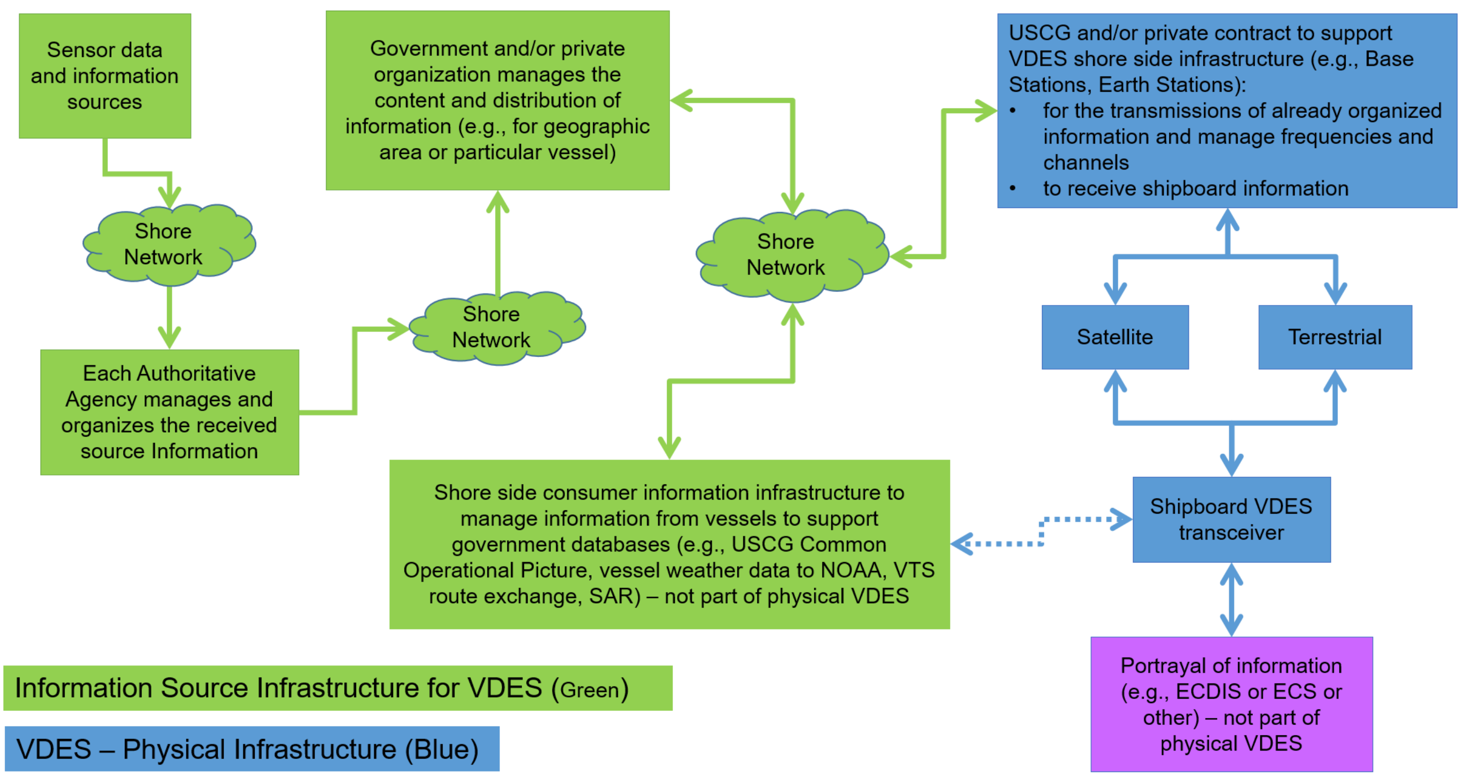


Figure 11. Data flow from source to user.

An information infrastructure for Global Maritime Distress and Safety System (GMDSS) information using Navigation Text (NAVTEX) (government owned/operated) and satellite providers (commercial owned/operated) such as INMARSAT and Iridium exists today that could potentially be used as a basis for creating this infrastructure.

6 USE CASES

Figure 12 provides a graphic representation of all five VDES use-cases presented in this report. Each of the following sections will describe in detail each individual use-case:

- 6.1 - VTS/Route Exchange (Figure 13)
- 6.2 - eMSI (Figure 14)
- 6.3 - R-Mode (Figure 23)
- 6.4 - Search and Rescue (SAR) (Figure 24)
- 6.5 - STEDS (Figure 25)

For each use-case the mission and current state with AIS are described, and the benefits of moving to VDES are presented.

Figure 12. VDES use cases.

6.1 VTS / Route Exchange

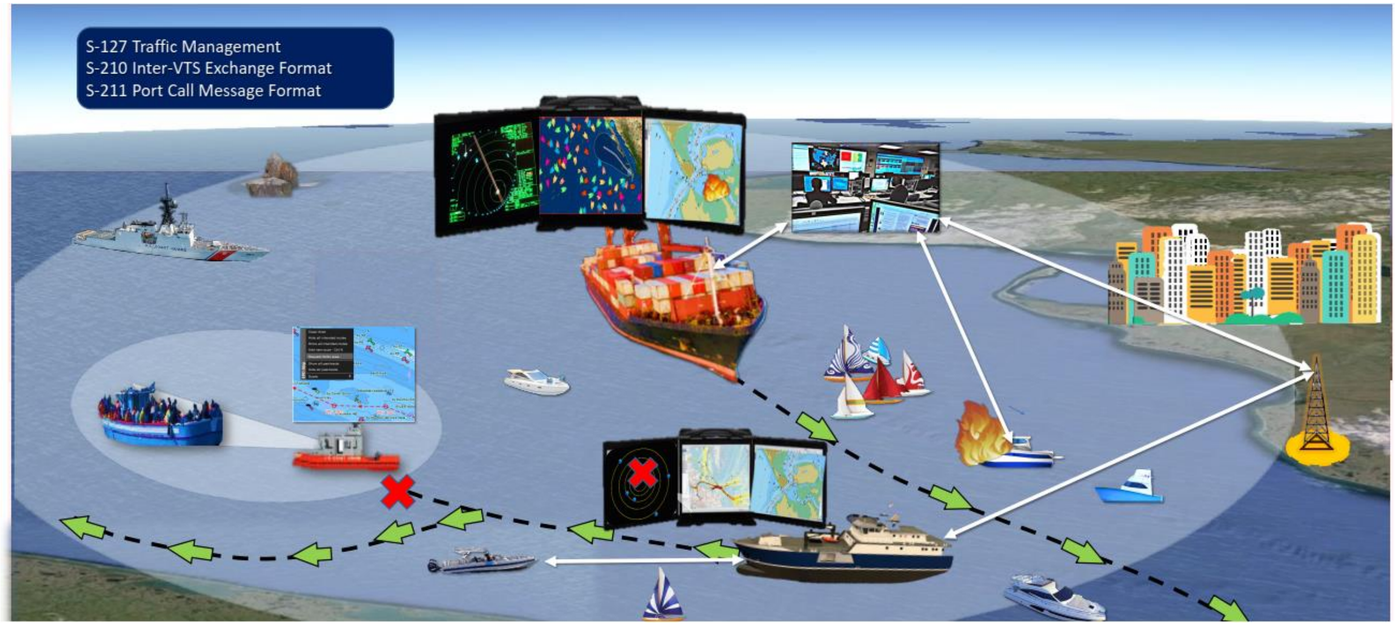


Figure 13. VTS / route exchange use case.

6.1.1 VTS / Route Exchange Description

VTSs are marine monitoring systems that keep track of vessel movements within a limited geographical area, usually high traffic ports. As defined by the Safety of Life at Sea international convention (SOLAS), "VTS helps contribute to safety of life at sea, safety and efficiency of navigation and protection of the marine environment, adjacent shore areas, work sites and offshore installations from possible adverse effects of maritime traffic." The USCG and local partners currently maintain twelve Vessel Traffic Centers (VTC) that support the VTS' throughout the U.S. (see Figure 14). These systems help facilitate safe and efficient navigation in high traffic ports. There are two main types of VTS systems[7]:

- Surveilled:
    - One or more land-based sensors (i.e. radar, AIS and closed-circuit television sites).
    - Operators monitor and manage vessel traffic movement from central location.
- Non-surveilled:
    - One or more reporting points at which ships are required to report their identity, course, speed, and other data to the monitoring authority.

[7] https://navcen.uscg.gov/index.php?pageName=vtsMain

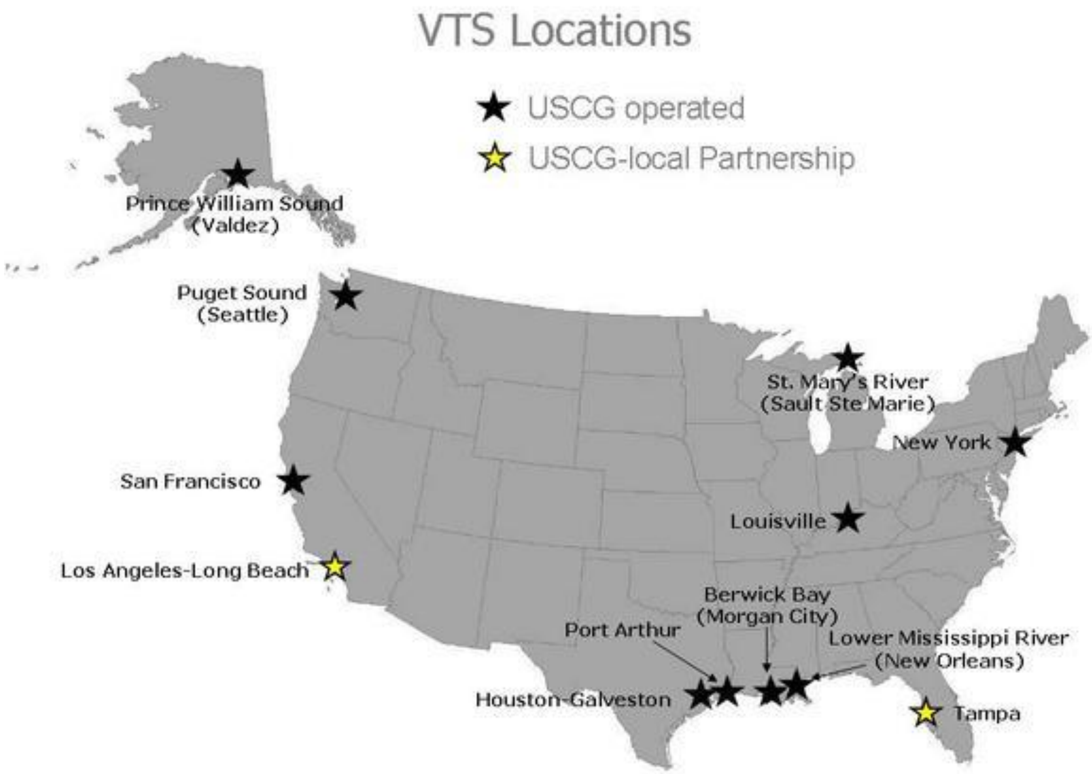


Figure 14. The USCG and local partners currently maintain twelve VTCs that support VTS' throughout the U.S.; source: https://navcen.uscg.gov/index.php?pageName=vtsMain.

Authorities use AIS data and other land-based sensors within a VTS area to monitor vessel traffic and create a traffic image (see Figure 15) that depicts vessel movements (including their intentions and factors influencing their movements). VTS authorities then use this traffic image to make decisions on managing traffic transiting within the VTS area. In a recent market survey conducted by industry, global VTS services are forecasted to grow 6.3% between 2019 and 2024, including in the U.S[8]. In ports and other maritime regions that will see increased vessel traffic and increases in autonomous shipping in the future years, VTS systems will be critical to continuing to ensure the safe and efficient navigation in these areas.

One concept that facilitates safe navigation both in and out of VTS areas is route exchange, which allows a vessel to transmit its intended route to nearby vessels. These vessels would in turn, share their intended routes. This represents an improvement over AIS position reports as it allows ships to broadcast not just their position, course, and speed to avoid collision but their intended route allowing advanced situational awareness [1], reduction in misunderstandings [15, 17], and decision support when encountering other vessels or new potentially dangerous areas. The route exchange concept thus supports safe and efficient vessel movements [15].

The use of route exchange could also assist with VTS operations, whereby information on routes can be exchanged with shore personnel. In a more advanced form, the shore facility could provide optimized routes

[8] http://www.wboc.com/story/42613257/global-vessel-traffic-services-vts-market-detailed-analysis-report-by-market-dynamics-size-growth-covid-19-impact-and-forecast-to-2024

to the ship. The ship operator could transmit their intended route from their voyage plan in their Electronic Chart Display and Information System (ECDIS). The shore system could then optimize the route by analyzing information from shore and other ships and send the new route back to the ship. The system could also continuously examine the route ahead and suggest possible route changes that could save on time or be safer.

Figure 15. VTS concept. Example schematic of a VTS port area, illustrating the diverse range of vessel traffic and various surveilled and non-surveilled systems used to create a port's "traffic image."[9]

6.1.2 Current State of VTS / Route Exchange

AIS is currently used in all VTS areas to collect data on ships' position and identity. RDC conducted several tests of transmitting additional information over AIS to vessels within port areas; primarily Meteorological and Hydrological (MET/HYDRO) data from the National Oceanic and Atmospheric Administration (NOAA) Physical Oceanographic Real-Time System (PORTS) and developed several potential architectures for integrating AIS transmit into VTS areas; however, none have been implemented. Currently, the only VTS that routinely transmits information is Sault Ste Marie.

Route exchange as envisioned with VDES does not exist currently; however, AIS Application Specific Message (ASM) route exchange, a more limited capability, is used now in circumstances where safety of navigation requires it. For example in very large ports such as Singapore and Rotterdam, where high traffic

[9] http://www.micronetsolutions.in/maritime-surveillance/

increases risk of collision, the active route of a ship is transmitted using an AIS ASM defined in IMO Circular 289 [18].

6.1.3 Projected Benefits of VDES to VTS / Route Exchange

In VTS areas, vessels often navigate in close proximity to each other and frequently have navigational restrictions such as draft, height, beam, and length that restrict their ability to maneuver within these areas. In addition, their movements may be dependent on local tides, currents and other meteorological conditions that authorities and mariners need to consider when making navigational decisions. In an effort to move cargo more efficiently, some ships also have increased in size and shipping companies may increasingly move towards autonomous shipping options both of which will reduce the margin of error within VTS areas. With AIS already being an overloaded system, VDES would increase the bandwidth available to handle all of the critical AIS data within a VTS area, reducing risk of incidents in a VTS area due to lack of data capacity. Additionally, with the use of eMSI passed through VDES to all ships within the area (e.g., NOAA PORTS data), situational awareness of authorities and mariners will be enhanced[10].

"In a worldwide survey of 155 VTS participants, 97% indicated they record radar information as well as vessel position and tracks from the Automatic Identification System (AIS)…While AIS has changed the perception of the maritime world by enabling VTS to create a much more comprehensive traffic image than is possible with radar alone, AIS does not suffice to meet ever-increasing demand for data."[11]

A few scenarios have been proposed in IALA G.1117 [15] for the use of VDES:

- ***Waterway Monitoring.*** *VTS provides monitoring and other services. VDES may be used to monitor vessels and autonomously provide information to these vessels based on predetermined parameters as defined by the shore authority. In addition, VDES may enable sharing of information on synthetic VTS targets from the VTS to vessels transiting the VTS area. Information exchange may be integrated with, and portrayed on, external systems ashore and on-board.*
- ***Information Service.*** *Information Service is provided by broadcasting information at fixed times and intervals or when deemed necessary by the VTS, or at the request of a vessel. The information provided may include safety information as previously defined. Additional information could include specific limitations for navigation in the VTS area (for example maneuverability limitations; draft restrictions; channel closures; diving operations). Information exchange may be integrated with, and portrayed on, external systems ashore and on-board.*
- ***Navigational Assistance Service.*** *The navigational assistance service (NAS) is defined by IMO as 'a service to assist on-board navigational decision-making and to monitor its effects.' NAS may be provided on request by a vessel in circumstances such as equipment failure or navigational unfamiliarity. VDES could be used in the exchange of information during the provision of NAS. Information exchange may be integrated with, and portrayed on, external systems ashore and on-board.*
- ***Traffic Organization Service.*** *The traffic organization service (TOS) is defined by IMO as 'a service to prevent the development of dangerous maritime traffic situations and to provide for the safe and*

[10] https://www.gsa.europa.eu/library/case-studies/benefits-vessel-traffic-services-vts
[11] https://www.rivieramm.com/opinion/opinion/vts-and-e-navigation-roles-will-expand-31304

> *efficient movement of vessel traffic within the VTS area.' The purpose of the TOS is to prevent hazardous situations from developing and to ensure safe and efficient navigation through the VTS area. VDES could be used to exchange this information. Information exchange may be integrated with, and portrayed on, external systems ashore and on-board.*

The route exchange helps the Officer of the Watch (OOW) of a ship to plan, foresee possible dangerous situations, and reduce route detours due to traffic conditions. The route (waypoints and times) is displayed on the ship's ECDIS, allowing the OOW to see the intention of other vessels along with current position and can be used to avoid close quarters situations. It allows parties to share a common harmonized picture over a specific area. Moving this capability to VDES ASM channels would allow increased usage worldwide and reduce impacts on AIS data loading. It would also allow longer and more complex routes to be shared and allow for additional eMSI that may impact the route. The increased bandwidth would also allow more vessels to exchange routes. Route Exchange will also support future digital VTS. Some scenarios from IALA G.1117[15] are below. Graphics are from https://s3-eu-west-1.amazonaws.com/stm-stmvalidation/uploads/20160420153149/Draft-description-of-test-bed-services-and-information-needs_2015-12-10.pdf.

- ***Vessel Traffic Services and Route Exchange.*** *Ships can send their routes to shore facility (e.g., VTS) where multiple routes can be checked for proper separation, under keel clearance, violations of restricted areas and any new potentially dangerous areas. The route can then be sent back to ships signifying that it is a route optimized and mutually agreed upon between ships and the shore facility (e.g., VTS). See* Figure 16.

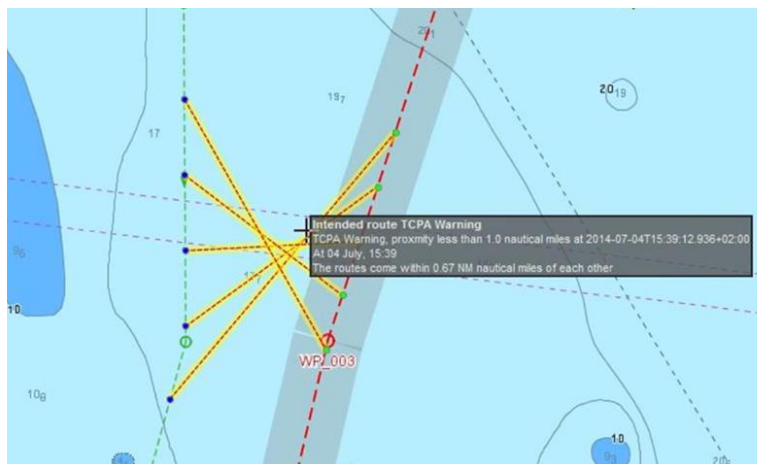


Figure 16. VTS route exchange.

- ***VTS – Ship to Shore.*** *Within a VTS area, route exchange would be used to inform shipping and other waterway users of possible hazardous situations. Shore authorities need information about the intentions of the waterway users, such as their intended route. Based on this information the authorities could organize traffic and, when needed, recommend other routes/possibilities for a safer passage, and provide information about the waterway that may affect route (e.g., speed optimization based on weather and currents, just in time arrival,*

Figure 17. Proposed route.

restrictions (e.g., military exercised or search and rescue operations) and traffic congestion). There may be some event or circumstance that impacts the normal operation of the waterway requiring urgent traffic management to ensure continuity of operations. VDES could be used to share information on the circumstance and proposed alternate routing could assist in effective movement of vessels throughout the incident. See Figure 17.

- ***VTS – Shore to Ship.*** *Before ships enter a sea area monitored by a shore authority, information about this area could be provided to assist in a safe and efficient passage. If the route of the vessel is known, information can be tailored to the route. The shore authority could link the vessel planned route with other information received, such as cargo, and adjust the information as may be required. Route plans received from ships can be used for detecting possible traffic congestions and high risk situations in advance (e.g., fatigue, weather conditions, or condition of the vessel -possible malfunction). Shore authorities can also send alternative route recommendations to ships when needed (e.g., ice). This allows ships to choose the route that is most suitable for its navigation. VDES can facilitate reception of route plans which may be integrated with, and portrayed on, external systems ashore.*

Figure 18. Shore to ship routes.

- ***Route Exchange - Ship to Ship.*** *Ship to ship route exchange would assist vessels on a transit by predicting when interactions may occur. VDES could assist in the exchange of digital data to facilitate ship to ship route exchange. In harbor approaches, the recommendation is to provide 30 minutes of a vessels intended route is exchanged with one or more vessels. This service can be of critical importance for large vessels whose course takes minutes to change due to their inertia, possibly helping in avoiding vessels collisions.*

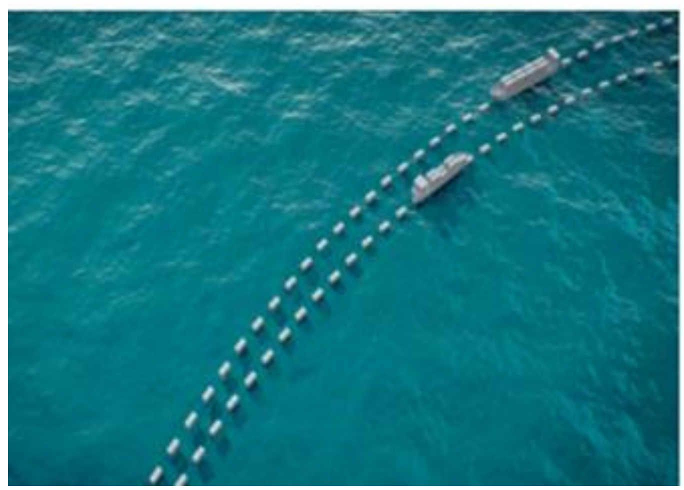


Figure 19. Route exchange.

6.2 Enhanced MSI

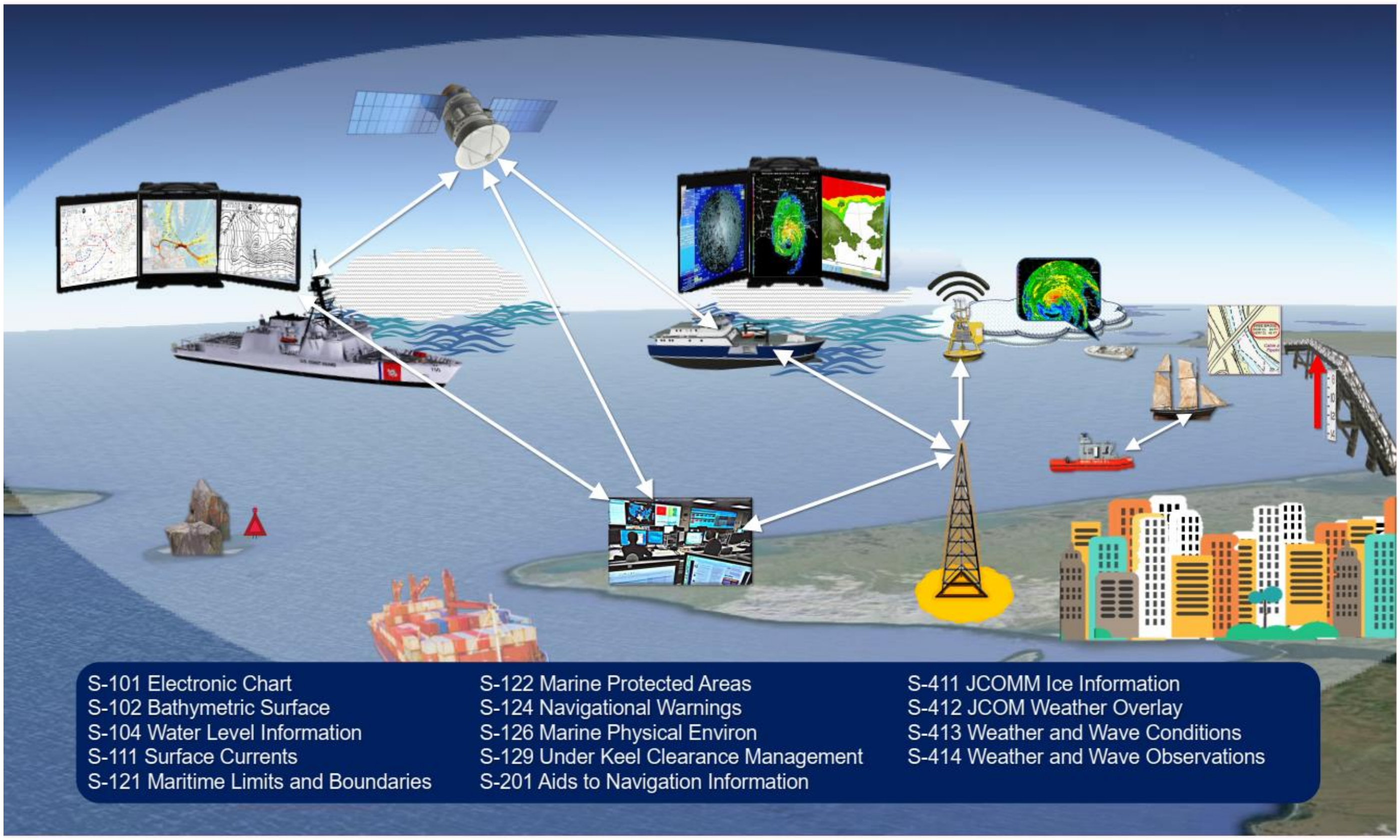


Figure 20. eMSI use case.

6.2.1 eMSI Description

MSI is data and information delivered from shore authorities to mariners at sea to improve safety and efficiency of navigation. MSI has a very specific International definition as promulgated by the IMO. MSI consists of navigational warnings, meteorological information, and other safety-related information. Presently, MSI is disseminated in a text-based message via NAVTEX, SafetyNET, and High Frequency (HF) Narrowband Direct Printing (NBDP). GMDSS modernization includes several new communications systems for possible inclusion in the modernized GMDSS and the distribution of MSI: VDES, Iridium SafetyNET, and Navigation Data (NAVDAT). In addition, the IMO is developing the S-100 series of standards as a flexible hydrographic data standard to support imagery, gridded data and time-varying data. The ongoing GMDSS modernization plan will result in significant changes in the way that MSI is delivered and in the type of information that can be delivered by 2024. The RDC white paper in 2017 [4] provided a synopsis of the current state of MSI and the existing distribution mechanisms, an overview of the various agencies involved with MSI, and a discussion of the new technologies being pursued as part of the GMDSS modernization effort.

Enhanced MSI or eMSI is a term used to refer to the expanded delivery of information that is relevant to the mariner, to increase the safety and efficiency of navigation. This can include the electronic distribution of environmental information (wind speed, direction, tides, currents, sea states, etc.), geographic notices (warning/restricted areas due to ice, debris, shoaling, security zones, etc.) and waterways management information (lock or narrow channel procession order, lock and dam status, etc.). This can also include the collection of data from ships such as ocean weather conditions or bathymetric data. Figure 21 shows the types of data available to be transmitted to mariners from NOAA PORTS. Figure 22 shows what this data might look like on a ship's display system.

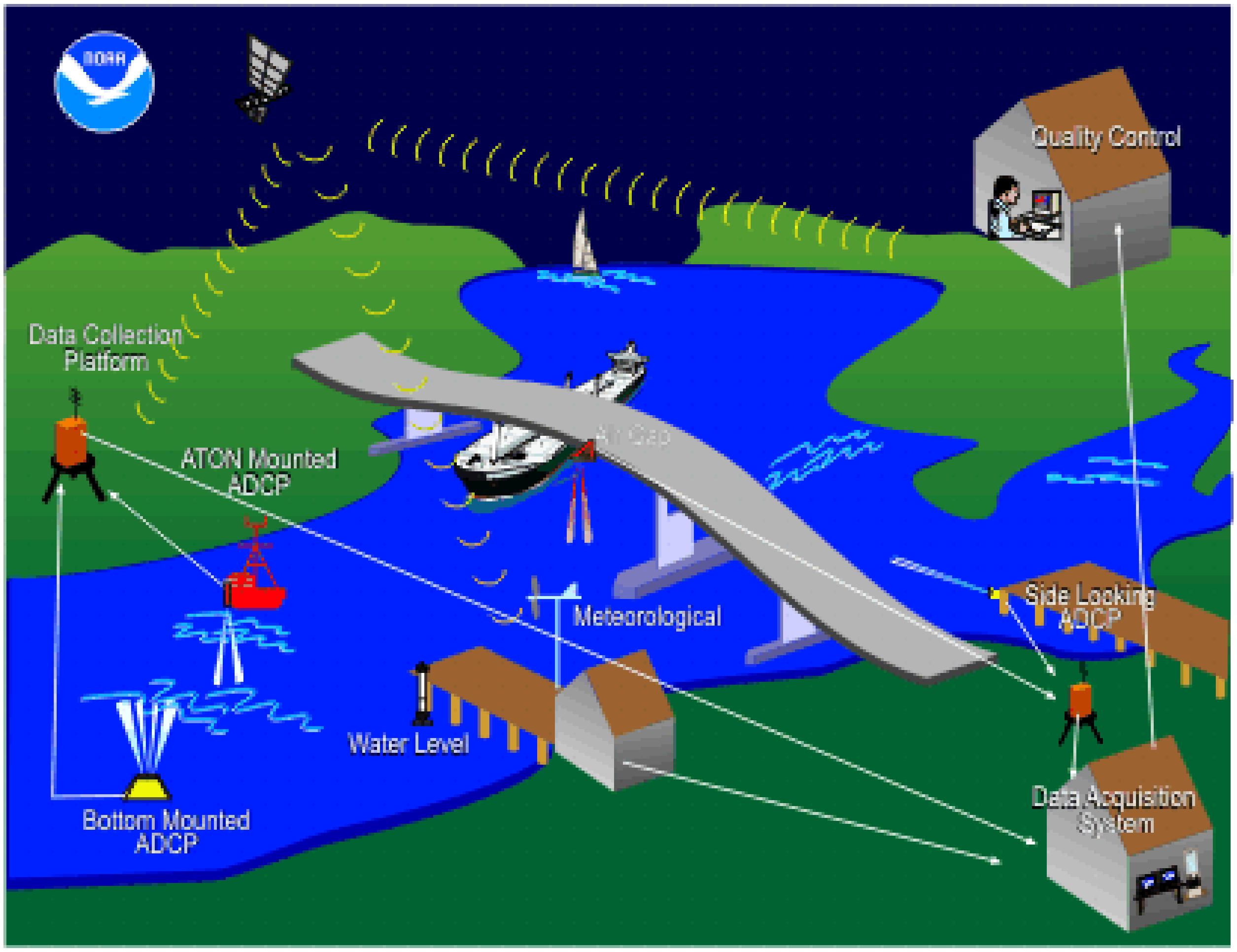


Figure 21. NOAA PORTS data is one example of eMSI that can be delivered and displayed on a shipboard ECS.

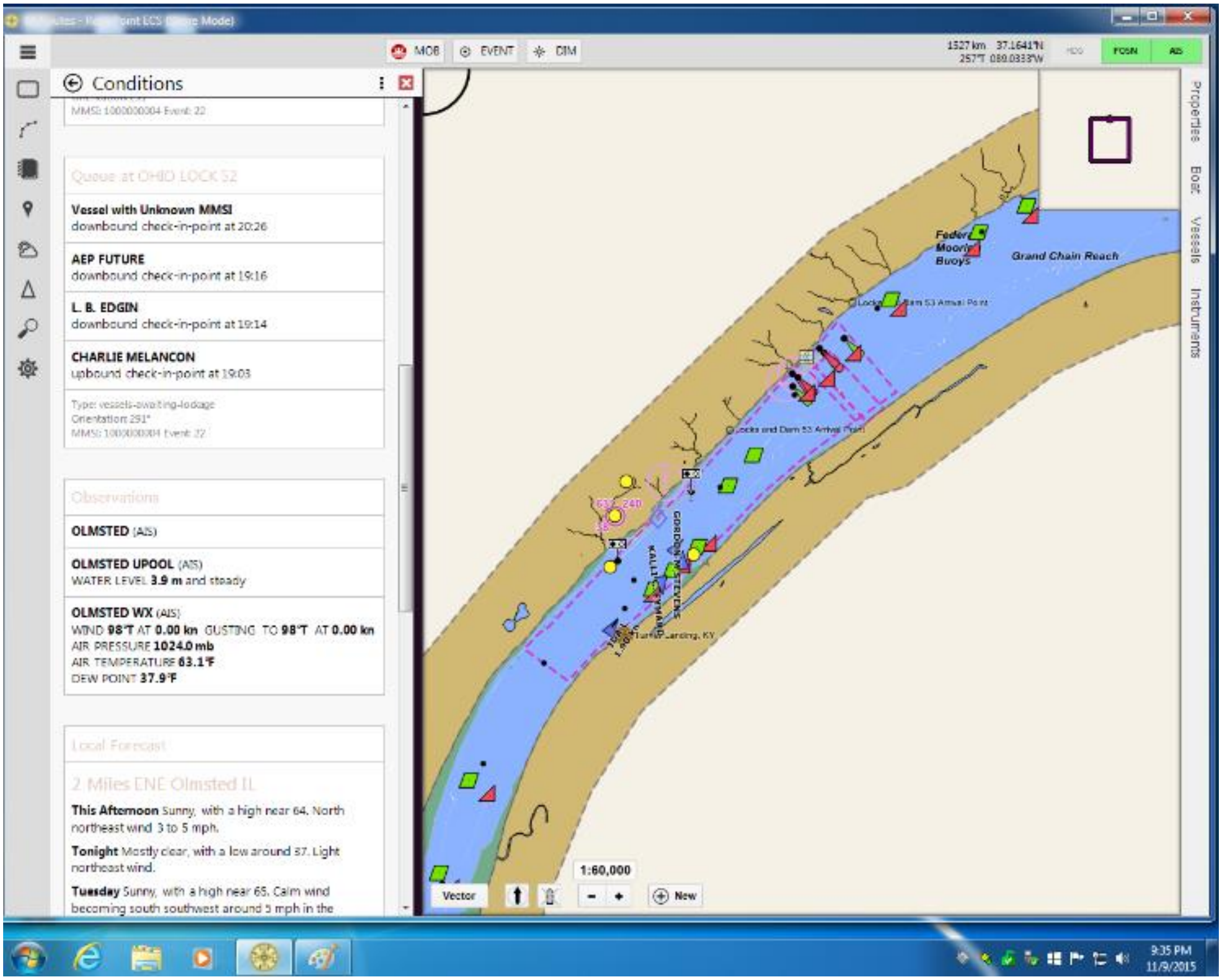


Figure 22. Screen image of an ECS showing received environmental data (data for the locations indicated by the yellow dots is shown in the sidebar).

6.2.2 Current State of eMSI

RDC started evaluating the use of AIS for transmitting eMSI in 2007 with a requirements study published in 2008 [19]. This led to the establishment of a series of test beds in Tampa Bay, Stellwagen Bank, Columbia River, and culminated in two large tests; one in the Ohio River in partnership with the US Army Corps of Engineers (USACE) [20] and one in Alaska in partnership with the Marine Exchange of Alaska [21]. During these efforts RDC and USACE developed the transmit architectures, procedures, and standards necessary to effectively use AIS as a transmit service for eMSI [22, 23]. More recently the USACE has been working with the Maritime Administration (MARAD) and NOAA on a test of collecting weather data from ships at sea using AIS [24].

6.2.3 Primary Benefits of VDES to eMSI

The primary limitation of using AIS for eMSI is the limited bandwidth available. Messages must be small (maximum of ~1,000 bits) and can only take up a small percentage of the messages in each frame in order to not interfere with navigational safety (maybe 5% of the 4,500 slots per minute). Thus, the main benefit offered by VDES is expanded bandwidth to allow for more information to be transmitted. This could be more messages or more bandwidth intensive messages such as more detailed graphic overlays, pictures, or other S-100 based information. The second main benefit for VDES is the satellite component (VDE-Sat) will increase coverage range for the transmission of data from shore to ship, and improve reception of data from ship (AIS messages via satellite AIS currently are only received <10% of the time in the Atlantic and <30% of the time in the Pacific based on USACE testing).

A few scenarios have been proposed in IALA G.1117 [15] for the use of VDES:

- ***Meteorological services and warnings / navigational warnings***. *It is important to have up to date information on the weather that can be expected along a ship's planned route. VDES could be used to facilitate information exchange relating to the route of the vessel, integrated with, and portrayed on external systems on-board.*
- ***Weather observations***. *Ships may participate in the provision of weather observations, as noted in MSC.1 Circ. 1293. This is a voluntary observing ship (VOS) scheme with information provided to the World Meteorological Organization. VDES could facilitate this reporting, with information provided directly from on-board sensors.*
- ***Ice maps***. *Information on sea ice conditions around a vessel is important to help ensure safe passage at sea. Knowledge of areas with sea ice along a ship's planned route allows ships to find the most efficient route at an early stage. Together with prognoses for expected ice movements, ice charts allow mariners to plan ahead and significantly reduce the risk of vessels becoming ice locked. VDES could be used to provide this information, which could then be integrated with, and portrayed on external systems on-board. In addition, information on the latest version of ice maps may be provided from mobile station to mobile station.*
- ***Notices to mariners***. *Notices to mariners are a means to disseminate navigational safety information (as part of maritime safety information). SOLAS V, Regulation 9 (Hydrographic Services) notes that administrations should undertake to arrange the dissemination and update of all nautical information necessary for safe navigation (for example. predictive and real-time tides and currents). VDES could be used to provide this information, and changes to information, with respect to the waterway.*
- ***GNSS augmentation***. *SOLAS Chapter V, Regulation 19 notes that all ships, irrespective of size shall have a receiver for a global navigation satellite system or a terrestrial radio navigation system, or other means, suitable for use at all times throughout the intended voyage to establish and update the ship's position by automatic means. IMO Resolutions A.915(22) and A.953(23) provide the requirements for Maritime Radionavigation Systems. Distribution of GNSS augmentation corrections via VDES could allow GNSS users to get timing, integrity data and improved position accuracy.*

- ***Crowd sourced information***. *Information from users or ship systems may enhance and/or validate meteorological hydrological and hydrographic information that is made available to other vessels in the area and authorities. VDES could be used to facilitate crowd sourced information.*

6.3 Ranging Mode

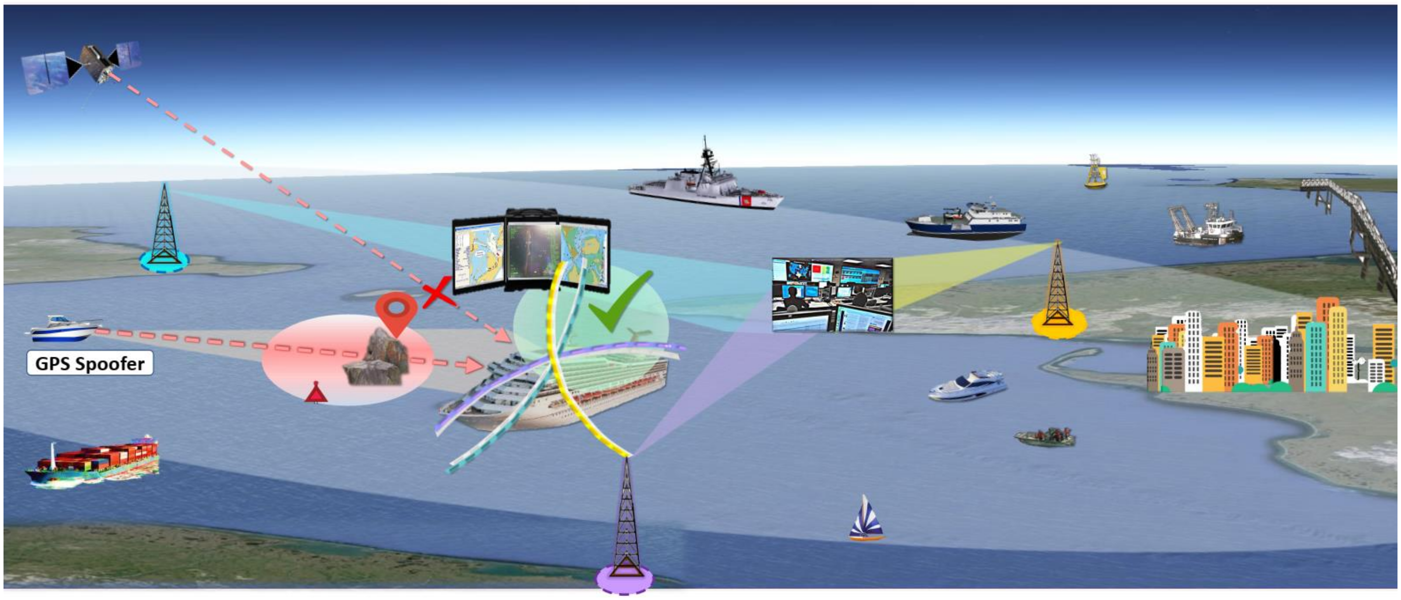


Figure 23. R-Mode use case.

6.3.1 R-Mode Description

R-Mode or Ranging Mode is the term used for ranging using signals of opportunity. The receiver measures the time of arrival of a signal, compares it to the time of transmission to get a travel time, and converts this to the range to the transmitter. If signals from multiple transmitters can be received, then a position can be estimated through multilateration.

In VDES, either the AIS, ASM or VDE-Ter channels could be used for R-Mode signals. From the ship's perspective, if they were operating in range of multiple base stations, they could use R-Mode as an alternative PNT source in case GNSS was denied or spoofed. If only a single base station was in range, it could still be used as a check on the GNSS position to verify that the position was not being spoofed.

Similarly, from the shore perspective, an R-Mode receiver could be used to estimate ranges from a ship's transmissions. This would enable the shore to validate the ship's reported position. If there were multiple base stations receiving the ship's transmissions, then an independent position could be estimated (this would require communications between the base stations).

6.3.2 Current State of R-Mode

The feasibility of AIS R-Mode was investigated in the ACCSEAS Project R-Mode Feasibility Study [25] in 2014. Since then there has been some further studies and tests on AIS R-Mode, primarily by the Chinese

[26-30]. As part of the R-Mode Baltic project[12] the participants, particularly DLR[13] have been examining R-Mode systems and performance. Most of the work to date has been on Medium Frequency (MF) R-Mode, but there has been some work on AIS and VDE-Ter R-Mode [31, 32] and some tests are planned as part of the R-mode Baltic project.

6.3.3 Primary Benefits of VDES to R-Mode

With the development of VDES there are additional channels with greater total bandwidth that could be used for R-Mode. Since the accuracy of the range estimate is a function of the bandwidth, more bandwidth equates to higher accuracy positions, thus VDE-Ter could provide higher accuracy than possible with AIS alone [31, 33]. R-Mode is probably not feasible with VDE-Sat, but this is not important as the critical need for Assured Positioning, Navigation and Timing (APNT) is closer to shore and in harbors, where VDE-Ter will be available.

6.4 SAR

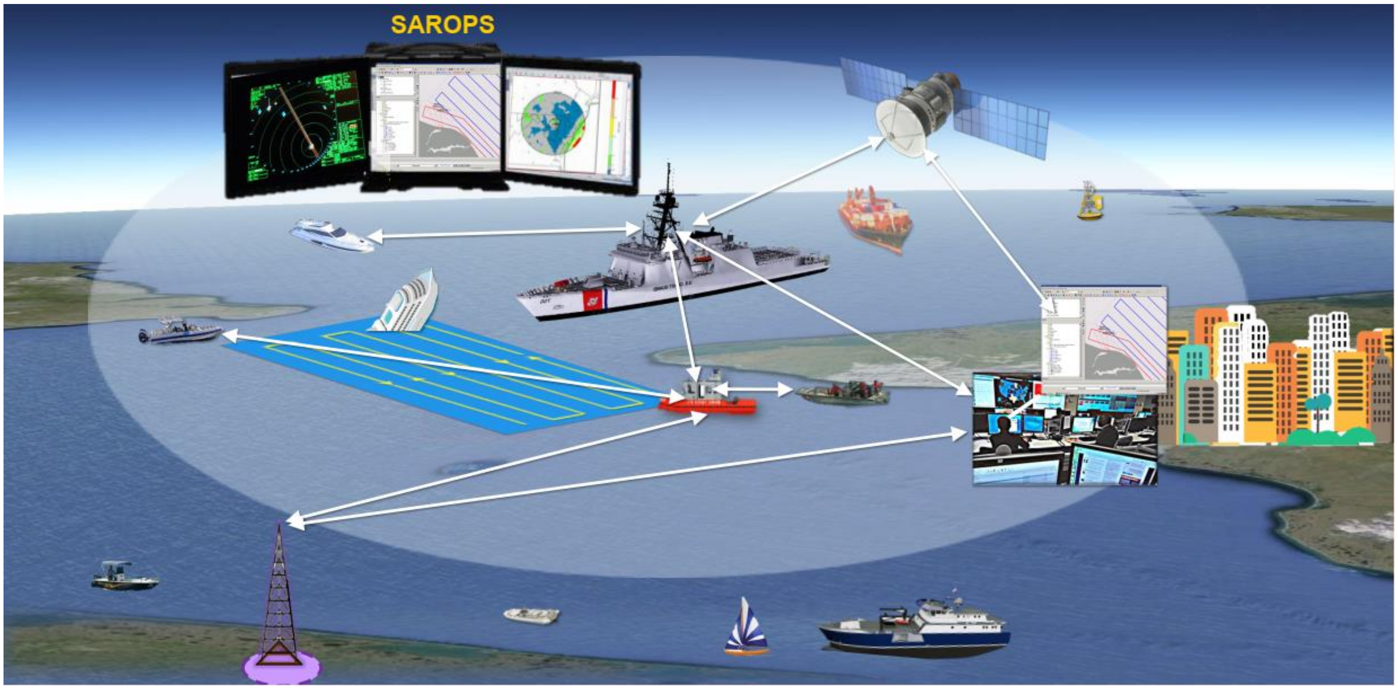


Figure 24. SAR use case.

6.4.1 SAR Description

SAR is one of the USCG's oldest missions. Minimizing the loss of life, injury, or property damage or loss by rendering aid to persons in distress and property in the maritime environment has always been a USCG priority. USCG SAR response involves multi-mission stations, cutters, aircraft and boats linked by communications networks. The National SAR Plan divides the U.S. area of SAR responsibility into internationally recognized inland and maritime SAR regions. The USCG is the Maritime SAR Coordinator.

[12] https://www.r-mode-baltic.eu/
[13] https://www.dlr.de/kn/en/desktopdefault.aspx/tabid-4308/6940_read-52591/

To meet this responsibility, the USCG maintains SAR facilities on the East, West and Gulf coasts, in Alaska, Hawaii, Guam, and Puerto Rico, as well as on the Great Lakes and inland U.S. waterways. The USCG is recognized worldwide as a leader in the field of search and rescue.[14]

To support the SAR mission, information needs to be exchanged between shore and ships and from ship to ship. This information includes distress reports, information about the distress, assigned search patterns, and results of searches.

6.4.2 Current State of SAR

The primary method of transmitting SAR patterns to operational assets is via voice (using VHF, Ultra High Frequency (UHF), or HF radios). The pattern information is then usually recorded by hand and then physically entered into the asset's navigation display system manually. The process is repeated to update or change follow-on tasking. This workflow is extremely inefficient and prone to data input errors resulting in assets searching incorrect areas and possibly missing search objects. Technology exists today that can automate the transmittal and input of SAR patterns with little to no user intervention to replace the outmoded current process. Existing AIS transmitters, receivers and display systems have the capability to transport and display SAR patterns and ASM standards exist to define a SAR pattern for AIS (encrypted and unencrypted). This was tested as part of an RDC project; however, is not currently implemented operationally. Scalable Integrated Navigation System version 2 (SINS 2), which is being fielded on USCG ships and boats, has the capability to receive and display the SAR patterns, and requires a shoreside information infrastructure to create, route, and transmit the messages [34].

6.4.3 Primary Benefits of VDES to SAR

The implementation of VDES would allow the USCG to improve the ability to transmit Environmental, Geographic Notice, SAR / Law Enforcement (LE) patterns, and Target of Interest (TOI) type messages to mariners and USCG underway assets [20].

The primary benefit of VDES is the increased bandwidth and expanded coverage (with VDE-Sat). The increased bandwidth would allow for more data to be transferred in digital form – whether ship-to-ship, or ship-to-shore. This would allow for more complex search patterns, and more detail on the search object and search results – including images. The use of VDES for SAR communications in general "would allow the rescue coordination center to poll ships in the vicinity to ask for their SAR capabilities in an automated manner. This service would make the coordination of SAR operations easier and faster."[1] The use of VDES for eMSI (see eMSI section) would also be beneficial for the SAR mission, to broadcast weather information and safety zones to the public.

A few scenarios have been proposed in IALA G.1117 [15] for the use of VDES:

- ***Distress Communications – Distress Relay.*** *Once a distress alert is initiated and the information has been forwarded to a Rescue Coordination Centre (RCC) through the established GMDSS process, the RCC forwards information of the incident to vessels in the area. The forwarding of information, using existing formats, could be provided by various communications means, including*

[14] (U. S. Coast Guard Office of Search and Rescue (CG-SAR) https://www.dco.uscg.mil/Our-Organization/Assistant-Commandant-for-Response-Policy-CG-5R/Office-of-Incident-Management-Preparedness-CG-5RI/US-Coast-Guard-Office-of-Search-and-Rescue-CG-SAR/)

VDES. The forwarding of data over a digital communications system such as VDES could facilitate the integration and display of information on external systems on-board (for example, Radar, ECDIS). Information could then be passed to the RCC and other vessels in the area including course to intercept, Estimated Time of Arrival (ETA) on-scene, on-scene conditions, sharing of a common operating picture, etc.

- ***SAR Operations – Initiate Search / Response.*** *SAR Mission Coordinator (SMC) develops response to SAR using resources, search plan, etc. Information to prosecute SAR operation is transmitted to the On Scene Commander (OSC) and SAR response units (SRU) (for example information on resources, plan, waypoints for search pattern, SRU responsibilities, etc.). This could be done using VDES, providing a common operating picture and information using standard templates and formats.*
- ***SAR Operations – Information Exchange.*** *During a SAR mission, the OSC and SRU provide regular updates on the search / response to the SMC. In addition, the OSC and SRU share information between each other to facilitate the response. The VDES could be used to exchange information on the SAR plan, SAR execution and other pertinent information to facilitate SAR operations. Information could be automatically integrated with, and portrayed on, external systems both ashore and on-board, including the RCC Geographic Information System (GIS), decision planning and support systems. Using information from other systems, such as vessel route, information provided could be tailored to be relevant for the vessel based on its route. In addition, the OSC and SRU could share information between each other to facilitate the response.*
- ***Tele-Medical.*** *A tele-medical happens when a person is injured or sick on-board a vessel or platform and there is a need to communicate with a doctor ashore for medical assistance and prognosis. The conversation with doctor could be by voice, with transfer of images / photos / indication from medical equipment on patient's condition. VDES could be used to transfer advice, images or other information. Where there are language difficulties, VDES could assist with machine to machine communications and/or language independent communication. Information exchange could be integrated with, and portrayed on, external systems on-board or ashore (medical facility).*
- ***MEDEVAC.*** *A Medical Evacuation (MEDEVAC) may be necessary to evacuate a severely injured or sick person. VDES may be used to exchange pertinent medical information from the ship to the SRU and destination medical facility. The SMC develops the response to prosecute the MEDEVAC and could use VDES to provide the plan to the ship and responding unit. Information on the status of the patient could be transferred during the MEDEVAC, both voice and* (data) *from medical equipment on the SRU.*

6.5 STEDS (SAR/LE Search Patterns, BFT, TOI)

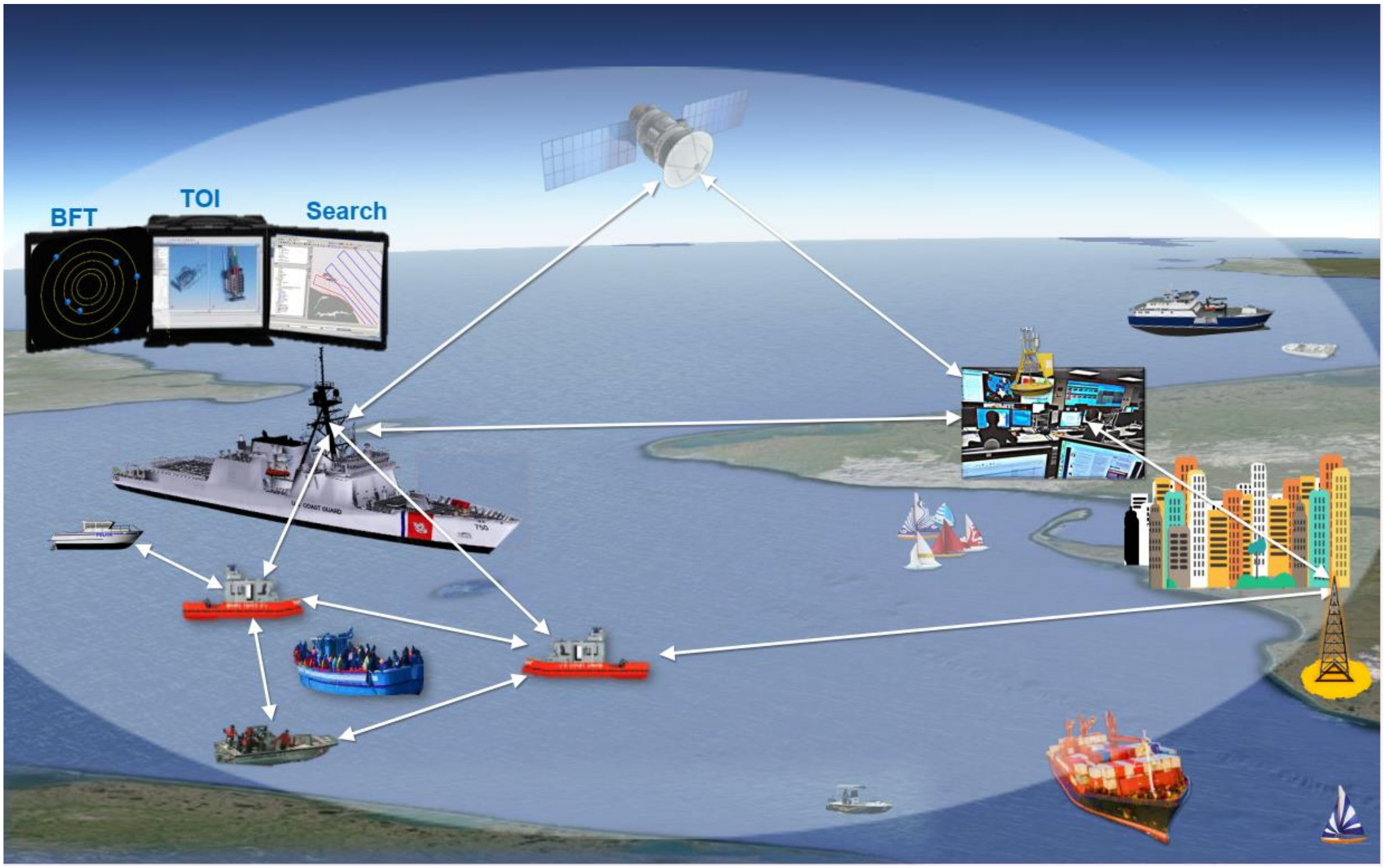


Figure 25. STEDS use case.

6.5.1 STEDS Description

STEDS is the USCG's specification for transmitting Law Enforcement (LE) data between shore and mobile units (air and sea). This includes a specification of encrypted ASMs [35] that details the message formats for use with AIS. There are message types defined for transmitting mobile unit's position (Blue Force Tracking or BFT), TOI, and Search Patterns among others. These message types are encrypted using Advanced Encryption Standard (AES) encryption before transmission and are sent using AIS messages 6, 8, or 26.

6.5.2 Current State of STEDS

The USCG has developed the message specifications and the software to display the messages. The primary new system is SINS 2, which is being installed on all small boats and cutters. The legacy Vega system supports some of the messaging and the new SEAWATCH system will support the messaging at some point. The STEDS BFT, TOI, and SAR message types were successfully tested on two RDC projects [34, 36] using custom software to create the messages to be transmitted over AIS and then displayed on the cutter and boat displays. BFT is the only message type routinely used in operations with the position reports being automatically generated by the small boats using either the L-3 AIS Class A or SINS 2. Under the old system, the encryption was handled by the L-3 Class A AIS, but this is being transitioned to the SINS 2. The USCG is also currently working on shifting the messages from AIS message 8 to AIS message 26. On the shore side, the BFT messages are displayed on WATCHKEEPER and CGONEVIEW and the unencrypted tracks are saved at the USCG Operations Systems Center.

6.5.3 Primary Benefits of VDES to STEDS

The primary limitation of using AIS for STEDS is the limited data capacity. Messages must be small (maximum of ~1,000 bits) and can only take up a small percentage of the messages in each frame (maybe 5% or less in order to preserve the bandwidth for safety of navigation). Thus the main benefit offered by VDES is expanded data capacity to allow for more information to be transmitted. This could be more messages or more bandwidth intensive messages such as more detailed graphic overlays, pictures, or other S-100 based information. The second main benefit of VDES is with the satellite component (VDE-Sat) there will be increased coverage range for the transmission of data from shore to ship, and improved reception of data from ship (AIS messages via satellite AIS currently are only received <10% of the time in the Atlantic and <30% of the time in the Pacific based on USACE testing).

7 RELEVANT STANDARDS

The implementation of VDES was expected to be nearing full operational capability (FOC) in 2021 (see Figure 26); this expected timeline has lagged about 2 years. A listing of relevant International standards is in the subsections below. The timelines for some of the standards have also slipped from the original plan.

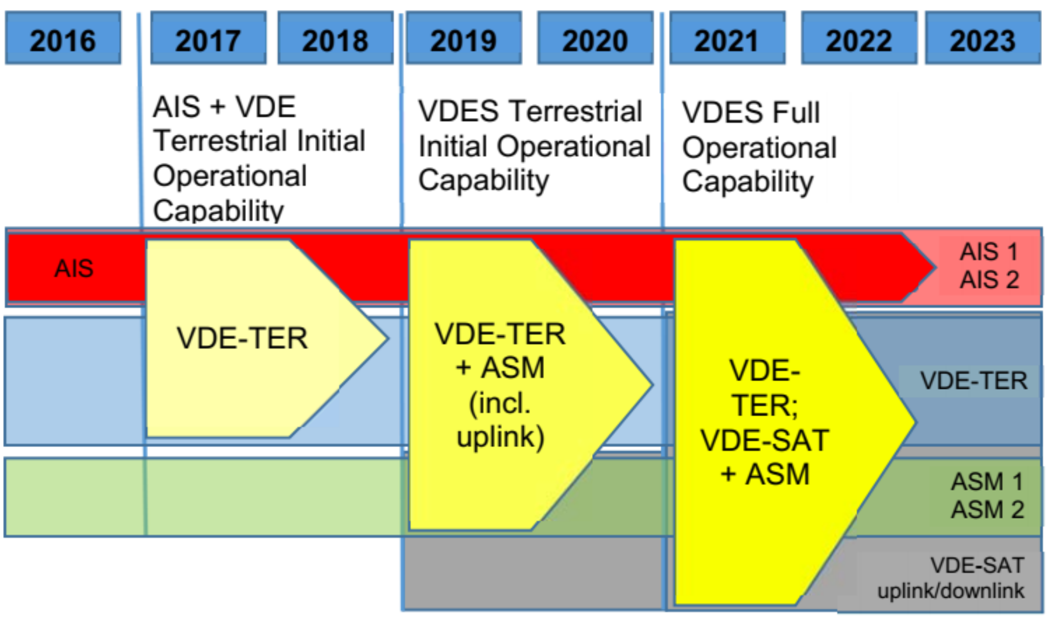


Figure 26. VDES implementation schedule (from IALA G.1117).

7.1 ITU-R M.2092-0 - Technical Characteristics for a VHF Data Exchange System in the VHF Maritime Mobile Band

The ITU Recommendation M.2092-0 [8] was published in 2015 and was due to be updated in 2019. Due to the timelines involved in the approval cycles and disagreements amongst some countries, exacerbated by COVID19 delays on meetings, this has been delayed until at least 2021, and more likely 2022. There are updated drafts in circulation with numerous changes including the inclusion of the VDE-Sat downlink channels, which were approved at last year's WRC19. The latest draft revision by the Correspondence Group of ITU-R M.2092-0 was just sent to ITU in early November 2020. This draft revision was coordinated and harmonized by all participants, including Canada, so the standard appears to be on track now for final approval by 2022.

7.2 IEC PAS 63343 ED1 - Maritime Navigation and Radiocommunication Equipment and Systems – VHF Data Exchange System – Requirements and Methods of Testing for Stations Including ASM Functionality

The IEC Working Group (WG) 15 is working on the test standard for equipment; and, hopes to have a publicly available standard (PAS) before 2021 (the draft [37] is currently in circulation). This is just a preliminary standard, but one manufacturers can use to start building equipment to, prior to the International Standard (IS) being completed and published in 2022. At this time, this standard just covers the ASM component of VDES. It also includes the ASM Presentation Interface (PI) sentence descriptions.

7.3 IALA G.1139 - The Technical Specification of VDES

IALA Guideline 1139 [13] has the same information as in the ITU R.2092; however, the IALA ENAV WG is more engineer-centric and can move more swiftly without the mandated approval cycle timelines of ITU. Thus, the Guideline 1139 is, and will remain for the near future, the most up-to-date information on the VDES standards.

7.4 IALA G.1117 - VHF Data Exchange System (VDES) Overview

IALA Guideline 1117 [15] provides an introduction to VDES at an overview level without the technical details. It includes a large section on potential uses of VDES along with a mapping of these uses to the relevant Maritime Service Portfolios (MSPs).

7.5 ITU-R M.2371 - Selection of the Channel Plan for a VHF Data Exchange System

ITU Recommendation M.2371 [38] discusses pros-and-cons of various channel allocation schemes that had been proposed. The currently approved channel scheme is not the exact same as any of the ones proposed, but this report provides some background on the issues involved in selecting the channels. Additional discussion on channel allocations can also be found in [39].

7.6 ITU-R M.2435 - Technical Studies on the Satellite Component of the VHF Data Exchange System

ITU Recommendation M.2435 [40] is a report from ITU to the WRC in support of the request for the satellite VDES frequencies. "This report provides a summary of why a VDES satellite component is required, identifies the spectrum requirements and provides a technical description of the satellite component of VDES and the results of the appropriate sharing and compatibility studies."

7.7 ITU-R M.1371 - Technical Characteristics for an Automatic Identification System using Time Division Multiple Access in the VHF Maritime Mobile Frequency Band

ITU Recommendation M.1371 [12] describes the technical characteristics for the AIS portion of VDES. It is currently in the 5th edition (2014); though work is underway on the 6th edition.

7.8 IEC 62288 - Maritime Navigation and Radiocommunication Equipment and Systems - Presentation of navigation-related information on shipborne navigational displays - General requirements, methods of testing and required test results

A Committee Draft (CD) of Edition 3 of IEC Standard 62288 [41] is currently in circulation. This standard is for the presentation of navigation-related information on shipboard navigational displays. The standard specified general requirements, methods of testing and required test results. Edition 3 contains new requirements for AIS, ASM and Digital Selective Calling (DSC) presentation.

7.9 IEC 61162-1 - Maritime Navigation and Radiocommunication Equipment and Systems - Digital Interfaces: Part 1: Single talker and multiple listeners / NMEA 0183 NMEA 0183 - Standard for Interfacing Marine Electronic Devices

These two standards [42, 43] contain the same information; the sentences used for maritime communications systems such as AIS and VDES to communicate with presentation interfaces. New sentences to support the ASM channels have been drafted and are being incorporated into the standards (see IEC PAS 63343). Sentences to support VDE-Ter and VDE-Sat still need to be drafted. These standards updates will most likely not be finalized until 2021.

8 EQUIPMENT

The authors researched and identified all companies currently known to have developed or may have plans to develop VDES equipment. This research included reaching out to all prospective companies identified; some have responded, and some have not. The results of this market research are contained in Table 6. Details on the four known products are contained in Appendix A. In general, the proposed costs for the new equipment appears to be comparable (maybe 30% increase) to that of existing AIS equipment that it would replace: $5,000 for a mobile unit and $15,000 for a base station.

Table 6. VDES equipment market research.

Company	Current AIS Products	VDES Product Planned?	Responded	Estimated Availability
CML	No	VDES 1000 mobile/base	Yes	now
SAAB	Base station, Class A	R60 VDES base station R6 VDES mobile	Yes	Base - Oct 2020 Mobile - Q1 2021
Kongsberg	Base station, Class A	VDES 300 mobile station VDES 610 Base station	Yes	Oct-Dec 2020
Gradiant	No	VDES transceiver	Yes	now
JRC	Class A	Yes, but no details	No	Unknown
L3	Class A, Aid to Navigation (AtoN)	Unknown	No	
Shine Micro	AtoN	Unknown	No	
CNS	Base station	Unknown	No	
Furuno	Class A	No	Yes	

9 VDES TESTING

9.1 Previous VDES Tests

Over the past decade there have been several tests of VDES concepts which have helped to further the standards development. These tests are listed in Table 7.

Table 7. Summary of previous VDES tests.

Test	Date	Notes	References
VDES Channel Sounding Campaign	2014 - 2017	Early work on investigating VDES channels.	[44-46]
Australian Maritime Safety Authority Brisbane VDES trials	2015	VDES field trial performed in Brisbane Jun – Sep 2015. The trial focused on the performance of the new VDE channel in open and urban environments as well as the impact of interference from other VDES channels.	[47, 48]
Singapore Trials	2014 – 2017	The SESAME Straits project (http://straits-stms.com/index.html) Used Kongsberg base station and ship unit.	[49, 50]
Data Exchange using VHF channels has been tested in the Baltic Sea	2017	VDES tested in Baltic. Part of EfficienSea2 (http://cirm.org/news/?p=119) https://academy.iala-aism.org/technical/e-nav-testbeds/sesame-straits-project/ https://www.iala-aism.org/e-bulletin/sesame-straits-project/ https://www.kongsberg.com/maritime/about-us/news-and-media/news-archive/2017/successful-final-demonstration-of-sesame-straits-e-navigation-project-in/	[51]
Norway Testing of Satellite	2018	"Field trials of the VHF data exchange system (VDES) satellite downlink component" https://ieeexplore.ieee.org/document/8742514	[52]
JERICHO VDE – VDE	2017 - 2018	Assessing the potential of future maritime applications in the context of VDE. The principal aim of the feasibility study is the identification and specification of new viable VDES services, combining space and non-space assets. (https://www.itl.waw.pl/en/national-projects-and-research-programs/eu-structural-funds/projekt-vde-fututre-jericho-vde)	[53]
Canadian Coast Guard	2014 – 2020	Options and Impacts for VDE and AIS Systems: A Wireless Communications Study, see "Canadian Coast Guard VDES Trials" https://www.cmlmicro.com/canadian_coastguard_vdes_trials/	[16, 39]
Australian Trials	2019	Kongsberg equipment used in Sydney CML 1000 used: https://www.cmlmicro.com/worlds-first-vdes-bases-station-installed/	[50]
Arctic Test	2019	Satellite test of using VDES for Satellite-based Augmentation System (SBAS) data	[50, 54]
Spain – POLARYS Project	2019	Developed VDE transceiver (Gradiant) http://www.proyecto-polarys.com/en/news/	[10]
Korea SMART Navigation Project	2015 – 2020	http://www.smart-navigation.org/eng/html/SMART-Navigation_New/summary.php http://www.smart-navigation.org/eng/html/Research_New/wp06.php http://nfas.autonomous-ship.org/events/ow2018/16_Lee.pdf	none

9.2 RDC Planned Tests

As part of RDC Project 8703, RDC plans to conduct two field tests between 2021 and 2023. The first field test will be an assessment of the use of the ASM channels for messaging in place of the AIS channels. The test will focus on USCG STEDS messages, especially, BFT. The field test will consist of VDES mobile units installed on several USCG maritime assets and two base stations (installed at RDC and Fisher's Island, NY). The primary goal is to prototype and validate the concept of USCG STEDS messaging on the ASM channels and to identify any issues that need to be resolved for a potential USCG-wide implementation. The resulting product will be a Transition Plan for the USCG to shift messaging from the AIS channels to the ASM channels. Data will be collected during the test in order to quantify transmission range and message reception success rate of the ASM channel compared to the AIS channel as part of the overall concept assessment.

The second field test will expand upon the first, to include the use of the VDE-Ter channel(s). A VDES base station will be installed at a location where it will not interfere with AIS reception on a Rescue 21 tower and mobile units installed on a variety of commercial and USCG vessels. The goal of this test is to assess the ability of VDES to meet USCG communications needs, both for internal (USCG to USCG) and for external (USCG to maritime public) communications. Systems will be set up on ships and on shore to create messages to transmit as described in the Use Cases. Data will be collected to quantify items such as transmission range and message reception rate. The test will also investigate system operations to identify any issues that would need to be resolved for a potential USCG-wide implementation. This includes details such as use of the Terrestrial Bulletin Board (TBB) and channel sharing between own usage at a base station and coordination with adjacent base stations. This test may also be conducted in partnership with Canada, in order to evaluate channel sharing and coordination issues across borders, and USACE for inland use. Additionally, equipment from several commercial venders will be tested in order to assess the state of the market and interoperability of equipment from multiple venders. The resulting products will be a Transition Plan which will include the results of an operational needs assessment, as well as a VDES Field Test Summary that will document the tests and the results.

10 CONCLUSIONS

VDES is the future of International maritime communications. It is an information technology infrastructure that will enable safety, security, productivity, and efficiency improvements. This Technology Roadmap has presented the current state of VDES and the benefits to be achieved by implementing VDES. The most important specific technical benefits are:

- Increased capacity for data communications with VDE-Ter (up to 32 times the capacity of AIS).
- Increased coverage area provided by VDE-Sat, including the Arctic.
- Ability to layer in cyber-security.
- Provides a backup PNT for GNSS-denied environment and the ability to de-spoof AIS.

This improved technical capability (i.e. physical infrastructure) requires an extensive effort and coordination by multiple agencies to develop the procedures and processes to gather, share, and deliver the information mariners need. Likewise, the USCG would need to develop the capabilities to fully utilize VDES to enhance USCG tactical operations through STEDS. This process will most likely be evolutionary and based on a gradual transition towards a service-oriented information exchange infrastructure. The USCG along with its maritime agency partners will need to develop goals and coordinate efforts to develop a framework to support information services to feed VDES.

The physical system can be installed as a replacement for the current AIS system as part of incremental technology improvements. VDES standards and equipment are maturing rapidly and commercial equipment should be ready when the standards are finalized in 2022. Prototype equipment is available now for testing purposes. The planned RDC tests of VDES will provide a quantitative assessment of some aspects of the physical system and will identify issues that need to be resolved for potential VDES implementation USCG-wide.

Although a few challenges have been identified for the physical system, most have solutions and are resolvable. The biggest challenge for implementation is in developing the information architecture that will be required to provide the information that the system will use to achieve the full potential of VDES. The designed NAIS capability, did not include the ability to disseminate information via AIS ASMs, even though AIS was designed to perform this function. To date, the USCG has not been able to integrate the use of AIS channels for transmission of information to the mariner, beyond BFT and virtual AtoN. VDES is entirely designed to be a two-way communication system for maritime users. It is imperative therefore, that the USCG and its maritime agency partners develop the information technology infrastructure to enable communications over VDES, as envisioned by the example Use Cases provided in this report, for both internal and external maritime communications.

11 REFERENCES

[1] F. Lázaro, R. Raulefs, W. Wang, F. Clazzer, and S. Plass, "VHF Data Exchange System (VDES): an Enabling Technology for Maritime Communications," *CEAS Space Journal,* July 2018.

[2] "Development of an E-Navigation Strategy," IMO Maritime Safety Committee, Input Paper submitted by Japan, Marshall Islands, the Netherlands, Norway, Singapore, the UK, and the US MSC 81/23/10, 19 December 2005.

[3] J. E. Hagen, "eNavigation, Communications, and Human Element," World Maritime University, August, PowerPoint presentation, unpublished.

[4] I. Gonin and G. W. Johnson, "RDC Review/Status of IMO MSI Systems," USCG Research and Development Center, New London, CT, Final Report R&DC UDI # 1731, October 2017.

[5] "What new Maritime Technology did the 2019 World Radio Conference bring us?," RTCM paper 2020-GENDIST-0002, 2020.

[6] "Use of Appendix 18 to the Radio Regulations for the Maritime Mobile Service," International Telecommunications Union, Geneva, Report ITU-R M.2231-1, November 2014.

[7] "Radio Regulations," International Telecommunications Union, Radiocommunication Assembly (ITU-R), Geneva, Report2016 2016.

[8] "Technical Characteristics for a VHF Data Exchange System in the VHF Maritime Mobile Band," International Telecommunications Union, Radiocommunication Sector, Recommendation ITU-R M.2092-0, October 2015.

[9] M. Luglio, C. Roseti, and F. Zampognara, "VDES Performance Evaluation for Future e-Navigation Services," presented at the 15th International Joint Conference on e-Business and Telecommunications (ICETE 2018), Porto, Portugal, 2018.

[10] (2019, Nov). *The Digitalisation of Maritime Communications (1st ed.)*.

[11] N. Molina, F. Cabrera, V. Arana, and M. Tichavska, "An Overview About the Physical Layer of the VHF Data Exchange System (VDES)," presented at the Computer Aided Systems Theory – EUROCAST 2019, Las Palmas de Gran Canaria, Spain, 2019.

[12] "Technical Characteristics for an Automatic Identification System using Time Division Multiple Access in the VHF Maritime Mobile Frequency Band," International Telecommunications Union, Radiocommunication Sector, Recommendation ITU-R M.1371-5, February 2014.

[13] "The Technical Specification of VDES," International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), Guideline G.1139, June 2019.

[14] I. H. Organization, "S-100 – Universal Hydrographic Data Model," International Hydrographic Organization (IHO), Monaco, Publication S-100, December 2018.

[15] "VHF Data Exchange System (VDES) Overview," International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), Saint Germain en Laye, France, Guideline G.1117, Dec 2017.

[16] "Canadian Coast Guard (CCG) Report on VDE-TER and AIS colocation testing," Canadian Coast Guard, unpublished.

[17] J. van Gils, "Service Description: Harmonised Data Exchange with Inter-VTS Exchange Format (IVEF)," ACCSEAS, Project Report Issue 1, 18 May 2015.

[18] "Guidance on the Use of AIS Application-Specific Messages," IMO, Maritime Safety Committee, London SN.1/Circ. 289, 2 June 2010.

[19] G. W. Johnson, I. Gonin, L. Alexander, and B. Tetreault, "USCG AIS Transmit Capability Functional Requirements Study," USCG Research & Development Center, Groton, CT, Pre Phase I Final Report CG-D-01-09, July 2008.

[20] S. Fields, L. Luft, S. Lester, I. Gonin, J. Fletcher, G. Johnson, *et al.*, "Western Rivers Joint Capability Technical Demonstration," USCG Research and Development Center, New London, CT, Final Report RDC UDI#1553, June 2017.

[21] I. M. Gonin and G. W. Johnson, "Alaska AIS Transmit Prototype Test, Evaluation, and Transition Summary Report," USCG Research and Development Center, New London, CT, Final Report CG-D-04-19, October 2018.

[22] G. W. Johnson, B. J. Tetreault, and I. M. Gonin, "Development of an AIS Transmit Architecture to support the dissemination of electronic Marine Safety Information (eMSI)," presented at the European Navigation Conference (ENC2014), Rotterdam, Netherlands, 2014.

[23] G. W. Johnson and B. Tetreault, "Identification of Standards Needed to Support Robust and Reliable AIS Transmit Operations," presented at the European Navigation Conference (ENC2016), Helsinki, Finland, 2016.

[24] G. W. Johnson, K. Dykstra, G. Dhungana, and B. Tetreault, "Sharing Ships' Weather Data via AIS," presented at the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019), Miami, FL, 2019.

[25] G. W. Johnson and P. F. Swaszek, "Feasibility Study of R-Mode Combining MF DGNSS, AIS, and eLoran Transmissions," German Federal Waterways and Shipping Administration, Final Report 25 September 2014.

[26] Y. Jiang, Q. Hu, and D. Yang, "Analysis of Positioning Error for Two-Dimensional Location System," *Mathematical Problems in Engineering*, vol. 2013, 11 October 2013.

[27] Q. Hu, Y. Jiang, J. Zhang, X. Sun, and S. Zhang, "Development of an Automatic Identification System Autonomous Positioning System," *Sensors*, vol. 15, pp. 28574-28591, 11 November 2015.

[28] K. Zheng, Q. Hu, and J. Zhang, "Positioning Error Analysis of Ranging-Mode Using AIS Signals in China," *Journal of Sensors*, vol. 2016, 2016.

[29] X. Wang, S. Zhang, and X. Sun, "The Additional Secondary Phase Correction System for AIS Signals," *Sensors*, vol. 17, 31 March 2017.

[30] Y. Jiang, J. Wu, and S. Zhang, "An Improved Positioning Method for Two Base Stations in AIS," *Sensors*, vol. 18, 27 March 2018.

[31] M. Wirsing, A. Dammann, and R. Raulefs, "Investigating R-Mode Signals for the VDE System," presented at the Oceans 2019 MTS/IEEE, Seattle, WA, 2019.

[32] M. Wirsing, A. Dammann, and R. Raulefs, "Designing a Ranging Signal for use with VDE R-Mode," presented at the 2020 IEEE/ION Position, Location and Navigation Symposium (PLANS), 2020.

[33] J. Safar, A. Grant, P. Williams, and N. Ward, "Performance Bounds for VDES R-mode," *Journal of Navigation*, 2019.

[34] S. Lester, S. Fields, G. Johnson, and T. Berube, "Automatic Transport of Search & Rescue (SAR) Patterns to CG Assets," USCG Research and Development Center, Final Report RDC UDC #1551, September 2017.

[35] "Encrypted Automatic Identifiation System (EAIS) Interface Design Description (IDD) v.5.5.4," United States Coast Guard, Portsmouth, VA, EAIS IDD v.5.5.4, 23 April 2020.

[36] G. Johnson, "Configuration and Installation Guide for the Intelligent Gateway " Alion Science and Technology, New London, CT, Deliverable 5 under Project "Vectoring Over The Horizon Cutter Boat (CB-OTH) For Non-Compliant Vessel (NCV) Intercept", 14 December 2017.

[37] "Maritime Navigation and Radiocommunication Equipment and Systems – VHF Data Exchange System – Requirements and Methods of Testing for Stations Including ASM Functionality," International Electrotechnical Commission (IEC), United Kingdom, Draft Publically Available Specification (DPAS) IEC PAS 63343 ED1, 2 October 2020.

[38] "Selection of the Channel Plan for a VHF Data Exchange System," International Telecommunications Union, Geneva, Report ITU-R M.2371-0, July 2015.

[39] H. LeBlanc, "Canadian Coast Guard Options and Impacts for VDE and AIS Systems: A Wireless Communications Study," Roche Ltd Consulting Group21 July 2014.

[40] "Technical Studies on the Satellite Component of the VHF Data Exchange System," International Telecommunications Union (ITU), Geneva, Switzerland, Report ITU-R M.2435-0, November 2018.

[41] "Maritime Navigation and Radiocommunication Equipment and Systems - Presentation of Navigation-Related Information on Shipborne Navigational Displays - General Requirements, Methods of Testing and Required Test Results," International Electrotechnical Commission (IEC), United Kingdom, Committee Draft IEC 62288 ED3, 29 May 2020.

[42] "NMEA 0183: Standard for Interfacing Marine Electronic Devices, Version 4.1," National Marine Electronics Association, Severna Park, MD, Standard NMEA 0183 Version 4.1, June 2012.

[43] "Maritime Navigation and Radiocommunication Equipment and Systems - Digital Interfaces: Part 1: Single talker and multiple listeners," International Electrotechnical Commission, Standard IEC 61162-1, 31 August 2016.

[44] J. Safar, "VDES Channel Sounding Campaign: Trial Report," GLA Research & Radionavigation Directorate, Harwich, UK RPT-09-JSa-14, 4 March 2014.

[45] J. Šafář, M. Bransby, A. Grant, and N. Ward, "The VHF Data Exchange System, A New Communications System for Maritime," presented at the 30th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2017), Portland, Oregon, 2017.

[46] A. Macikunas, "Deliverable D1.17. Project Summary Report – VDES Channel Model Refinement," EfficienSEA216 Nov 2017.

[47] "Australian Maritime Safety Authority Brisbane VDES trials: VDES Field Trial Report," Stone Three Venture Technology, IMIS Global Limited, and Australian Maritime Systems, Somerset West, South Africa, VDES Field Trial Report SDR002-D003-1.0, September 2015.

[48] "Australian Maritime Safety Authority Brisbane VDES trials: VDES Lab Trial Report," Stone Three Venture Technology, IMIS Global Limited, and Australian Maritime Systems, Somerset West, South Africa, VDES Lab Trial Report SDR002-D00401.0, June 2015.

[49] "If it Works in Singapore it Works Anywhere," SESAME Straits project, 25 Jan, unpublished.

[50] C. G. Eliassen, "VDES Market Perspective and Status," Kongsberg, unpublished.

[51] (2017, 1 Oct). *Data Exchange Using VHF Channels Has Been Tested in the Baltic Sea*. Available: https://efficiensea2.org/data-exchange-using-vhf-channels-has-been-tested-in-the-baltic/

[52] "Norsat-2: AIS + VDES," Norwegian Space Center, Feb, unpublished.

[53] (2017, 1 Oct). *Jericho VDE - Assessing The Potential Of Future Maritime Applications In The Context of VDE (VHF Data Exchange System)*. Available: https://business.esa.int/projects/jericho-vde

[54] S. E. Christiansen, "AMNAS Project: Challenges and Opportunities for Satellite Commuications and Navigation Augmentation Systems in Maritime VHF Bands," ESA, Noordwijk, Executive Summary Report ESTEC Contract Number 4000119199/16/NL/FE, 5 March 2019.

APPENDIX A. VDES EQUIPMENT

A.1 SAAB

A.1.1 R60 Base Station

Meet the new R60 VDES Base Station.

AIS/ASM/VDE Base Station with Software Defined Radio.

The R60 VDES Base Station from Saab TransponderTech is a VDES compliant base station, including AIS and ASM functionality. It is also prepared for the new VDE channels, pending international approval.

The R60 VDES Base Station is the successor to the market-leading R40 AIS Base Station, which assures for high quality and stable performance.

Thanks to its market leading Software Defined Radio (SDR) design, it is built to be future proof and support coming changes to international standards and requirements.

The R60 is compliant with the RED Directive and applicable international standards such as VDES-standard, AIS Base Station Standard IEC 62320-1, Aton Standard IEC 62320-2 and AIS Repeater Standard 62320-3.

The R60 VDES Base Station is the main component of a Physical AIS Shore Station as defined by IALA. Its main purpose is to receive data from and transmit data to AIS/VDES equipped vessels travelling within the coverage area of the Base Station. The R60 can either be installed on a stand-alone basis or integrated into a network, such as the market leading Saab MARITIMECONTROL platform.

Ensuring a high degree of reliability and availability has been the key design goal during the development of the R60, resulting in an MTBF better than 100,000 hours. Furthermore, the R60 includes several Ethernet ports to allow for full network connection redundancy and remote power cycling of the base station.

The R60 also has a built in NTP-server option to support local time synchronisation for LAN connected equipment.

Furthermore, it supports extensive possibilities for VDL analysis via FSR/VSI-message information, giving details such as Received Signal Strength, Time of Arrival and Signal to Noise Ratio. The R60 also supports channel management via both AIS and DSC.

To allow for simple monitoring and configuration a colour display with touch interface is available on the front. For more advanced configuration, monitoring and remote updates, there is a built in WEB server.

FEATURES OVERVIEW

- Fully Compliant to all AIS Base Station Requirements (IEC 62320-1)
- Aids to navigation (AtoN) functionality (IEC 62320-2)
- Built in Repeater (IEC 62320-3)
- Reception and transmission of all applicable AIS and ASM messages
- Simultaneously supports AIS 1, AIS 2, ASM 1, ASM 2 * and Secure AIS (option)
- Software Defined Radio (SDR)
- Sensitivity better than -115 dBm
- Multiple Ethernet and serial ports, supporting redundancy and adaptation for Cyber Security
- Dedicated Ethernet service port for independent remote power control
- Built in advanced WEB-server
- Supports SNMP status monitoring
- Support for VDL Signal Information Message (VSI)
- Support for Frame summary of AIS reception (FSR)
- Internal memory for storage of data
- Built in Base Station Controller (BSC)
- MTBF > 100,000 hours
- Hot Standby Support
- NTP-server functionality (option)
- Optional support for Secure AIS, which offers encrypted communication

* As defined in VDES standard ITU-R M.2092-0 (2015), Annex 2. / IALA G.1139 (dec-2017)

TECHNICAL SPECIFICATIONS

PHYSICAL DATA	
Type	19" Rack-mount. Unit height: 2U
Dimensions	
Height	89 millimetres (3.51")
Width	483 millimetres (19.02")
Depth	357 millimetres (14.06")
Weight	6 kilograms (13 Lbs)
DISPLAY	
Colour display	4.3" WQVGA with touch interface
INPUT POWER	
Power input requirements	12-24 VDC, AC 100-240 volts @ 50/60 Hz
Recommended fuse size	20 A (T20A 50VDC) 5x20 mm, 3 A (T3A 250V) 5x20 mm
GNSS INTERNAL RECEIVER	
Number of channels	> 50 channels
Supported systems	GPS, BeiDou, Galileo, GLONASS
Sensitivity	Better than –162 dBm
Frequency	L1 (1575 MHz)
Update rate	1 Hz
VHF TRANSCEIVER	
Frequency	155 – 163 MHz
Channel Bandwidth	25 kHz, future VDE options 50 kHz, 100 kHz
Channel Selection	Channel numbers as in ITU-R M. 1084-4
Output power	AIS: LOW (1W) and HIGH (12.5W) ASM: from 1W to 12.5W
Receiver sensitivity	Better than -118 dBm (AIS) and -115 dBm (ASM) at 20% PER
Bit rate (Tx/Rx)	9.6 kbps (AIS), 19.2 kbps (ASM), 307.2 kbps (VDE option max bit rate)
ELECTRICAL INTERFACES	
Data Ports	RS-232/422 V11. Bit-rate up to 115 200 bps
TCP/IP Ports	3 x Ethernet (UDP, UDP Multicast, TCP). The VDES Base Station supports up to ten simultaneous connections via the Ethernet interface.
GNSS-Antenna	TNC-Female, with 5V @ 40mA power supply to GNSS antenna pre-amplifier
VHF-Antenna	N-Female, separate RX and TX antenna ports (option)
1PPS and IRIG-B 003	Via the 9-pin D-sub (male)
Digital Input and Output Port	Via the 9-pin D-sub (male)
AC-power	IEC 320 connector
DC-power	AMP CPC Type III+
Serial data	9-pin D-sub (male)
STANDARDS	
Compliance to standards	Radio Equipment Directive (RED) 2014/53/EU VDES-standard ITU-R M.2092-0 AIS Base Station Standard IEC 62320-1 Aton Standard IEC 62320-2 AIS Repeater Standard 62320-3
ENVIRONMENTAL DATA	
Temperature	-20°C to +55°C (Operational), -55°C to +85°C (Storage)
Humidity	0-95%
MTBF	MTBF is >> TBD hours and availability figure is TBD %
COOLING	
Fanless design	No cooling required within the operational temperature range

saab.com/maritime

SAAB

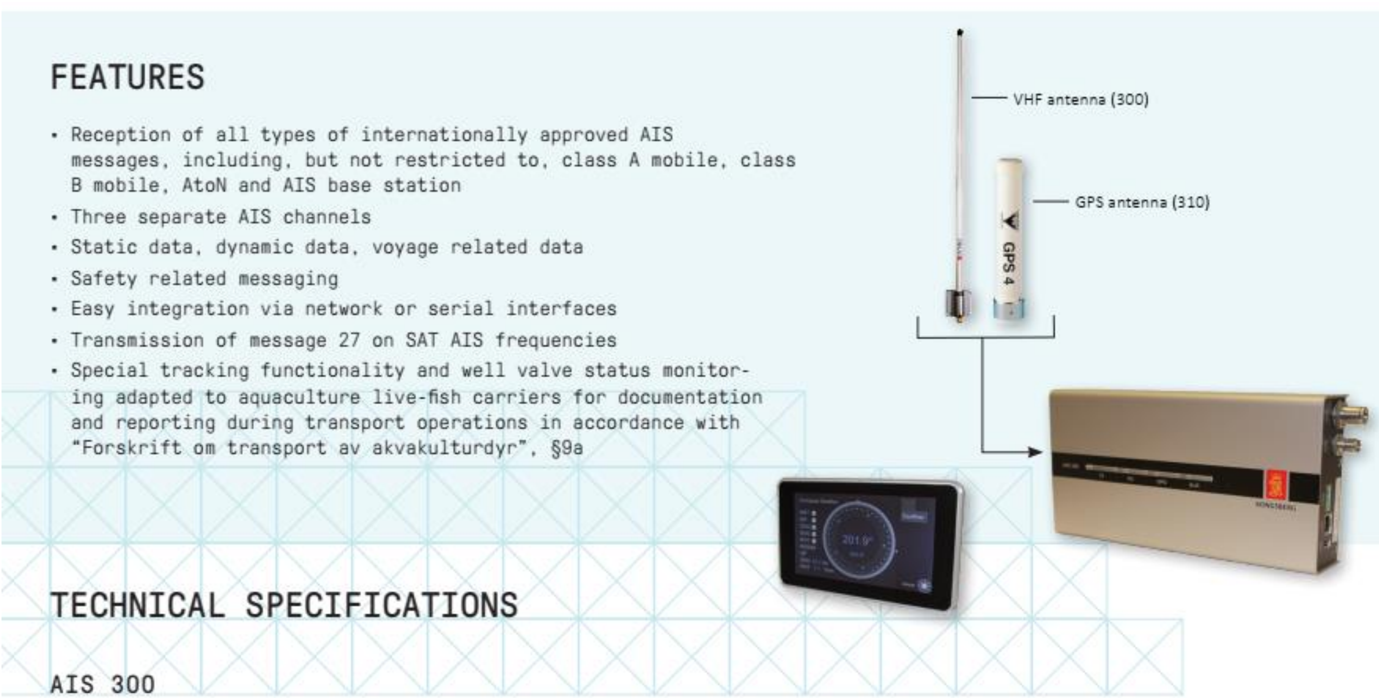
A.2 Kongsberg

Kongsberg plans to upgrade it's BS610 base station and AIS 300 mobile to VDES units; however, no product specification sheets exist at this time.

A.2.1 BS610 Base Station

The AIS BS610 is a product in the new generation AIS Base Station range from Kongsberg Seatex. It has a sensitivity better than -115 dBm and 1U 19" rack mountable smooth design. The AIS BS610 is designed and tested in accordance with all relevant international standards including IEC 62320-1 and ITU M-1371.

A.2.2 AIS 300 Mobile



A.3 CML

A.3.1 VDES 1000 Base/Mobile

CML Microcircuits
COMMUNICATION SEMICONDUCTORS

VDES1000
Complete Marine VDES Solution

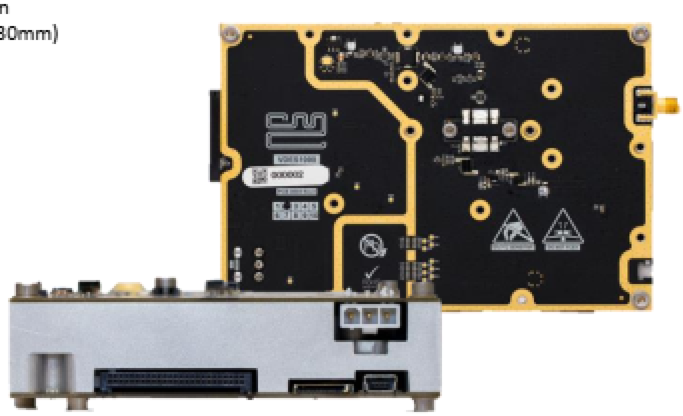
	VHF Data Exchange System (VDES) - Solution	
D/VDES1000/3 April 2019	DATASHEET	Advance Information

Features

- Software Defined Radio (SDR) solution
- Fully compliant AIS Class A
- Fully compliant VDES
- Upgradeable and future proof
- OEM module available
- ODM reference design available against license and royalty
- Output power: 12.5W rms
- RF range covered: 156.025 – 162.025 MHz
- Hardware interfaces:
  - 6 x isolated RS422
  - 1 x NC Relay output
  - Ethernet, 1000 base-T
- Single supply: 24V
- Small volume solution (165mm x 100mm x 30mm)

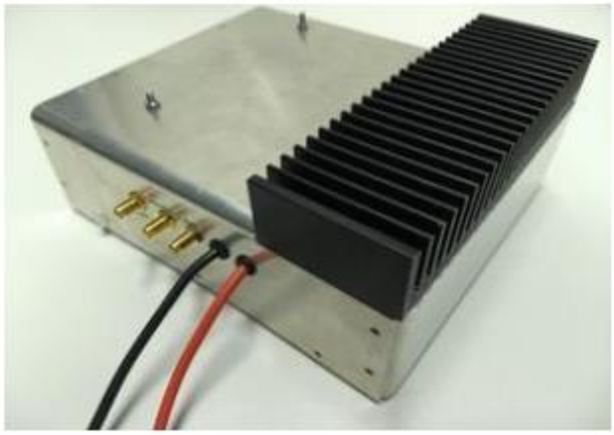
Applications

- Ship station (mobile) installation
- Coastal station (base station) installation
- AIS Class A transceiver
- ASM transceiver
- VDE transceiver
- Complete VDES transceiver (AIS class A + ASM + VDE)



A.4 Gradiant

A.4.1 VDES Transceiver



VDES Transceiver

Technical data sheet

The VDES Transceiver by Gradiant is based on a SDR platform and supports VDE, ASM, AIS and AIS-S components

Technical features

Supported standards	VDE-TER, ASM, AIS, AIS-S
Frequency Band	156,025 MHz – 162,025 MHz
Tx Power	20 W
Power supply	13 - 40 V; 15 A
Size	18x15x6 cm (without sink)
	18x15x8 cm (with sink)
Weight	1.8 kg
Interface	Ethernet
	VDE/ASM: JSON packages over TCP/IP
	AIS/AIS-S: NMEA sentences over UDP/IP
Other:	GPS receiver integrated
	SigFox transmitter integrated (Nemeus)

(This page intentionally left blank.)