IALA

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VDES R-MODE

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DOCUMENT REVISION

Revisions to this document are to be noted in the table prior to the issue of a revised document.

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December 2020	First issue	Council 72
July 2022	Edition 1.1 Editorial corrections.	
December 2024	Edition 2.0 Editorial changes to change from G1139 to ITU-R M.2092-1 Added VDE-ASM R-Mode	Transition Council 3

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1. INTRODUCTION AND SCOPE

The scope of this Guideline sets out guidance for authorities to setup VDES R-Mode and developers to design a VDES R-Mode receiver or transmitter.

The Guideline builds up on the stakeholder [3] and system requirements [4] and introduces the VDES R-Mode architecture. It defines the needed PHY and MAC layer essentials based on the VDES Specifications ITU-R M.2092-1 [6]. Further, the document provides support on how VDES R-Mode is setup in the VDES framework, the additional navigation data and outlines potential performance expectations under different conditions and environments.

1.1. IDENTIFICATION

This Guideline describes the system requirements and goals for a VDES R-Mode System to be developed by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA). The document is intended to be used as the basis for design, development, verification, and acceptance of the system.

1.2. INTENDED USE OF THE VDES R-MODE SYSTEM

IALA members intend to establish the VDES R-Mode System as a contingency Positioning, Navigation and Timing (PNT) system for maritime shipping. The operational concept is that, when there is a disruption to Global Navigation Satellite System (GNSS) services on-board a ship, the VDES R-Mode system (possibly together with other terrestrial PNT systems such as MF R-Mode and eLoran) provides ranging measurements to an on-board navigation system so that the impact of the GNSS service outage on the ship's ability to navigate safely is minimised.

Additional information on the intended use of the system can be found in reference [3].

1.3. SYSTEM OVERVIEW

The VDES R-Mode System will send accurately timed VHF transmissions from a network of land-based and, possibly, offshore Base Stations (BSs). A shipborne VDES R-Mode Sensor (VRMS) will measure the timing (and other) parameters of the received signals and output the signal observables to an external PNT processor, such as the Multi-system Shipborne Radionavigation Receiver (MSR) described in reference (IMO-*MSC.401(95)*). The PNT processor will then use the observables to determine the user's position, speed over ground and other navigation parameters.

VDES R-Mode should, as far as possible, use pre-existing shore side infrastructure, including shore stations and Monitoring and Control Centres (MCC'), and pre-existing AIS/VDES shipborne installations. Monitoring and control data is likely to be carried between the Base Stations, Far-field Monitoring Stations (FMS') and one or more Monitoring and Control Stations (MCS') via pre-existing Wide Area Networks.

VDES R-Mode will be synchronised to an external Time Source traceable to a common time scale in order to facilitate interoperability with other PNT systems.

2. SYSTEM ARCHITECTURE

The R-Mode system with its service to provide synchronised ranging signals is part of the overall PNT supporting e-Navigation architecture as shown in Figure 1.

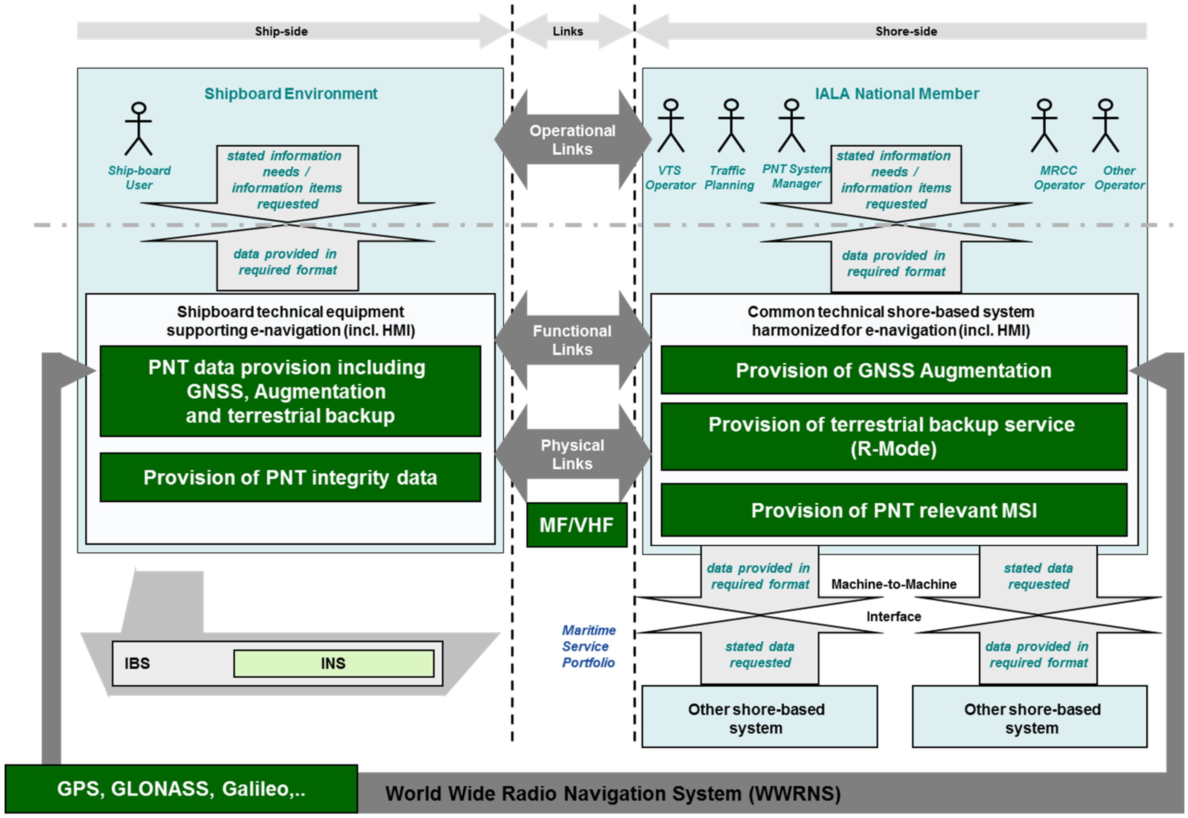

Figure 1 R-Mode embedded in the overarching IMO e-Navigation architecture

2.1. ARCHITECTURE OVERVIEW

The R-Mode system consists in general of the following components (shown in Figure 2 and Figure 3):

- R-Mode transmitter station: A station that provides R-Mode service. It is intended to use existing VDES base stations.
- R-Mode monitor: Station that monitors broadcasted signals of R-Mode transmitter.
- R-Mode system time (RMST: Time distribution infrastructure that provides in a region the RMST which is used for R-Mode service provision.
- Command and control, Security centre Central infrastructure of a region that is used to control and command the complete network. It provides a security service for the R-Mode system and service.
- R-Mode user: User of R-Mode service.

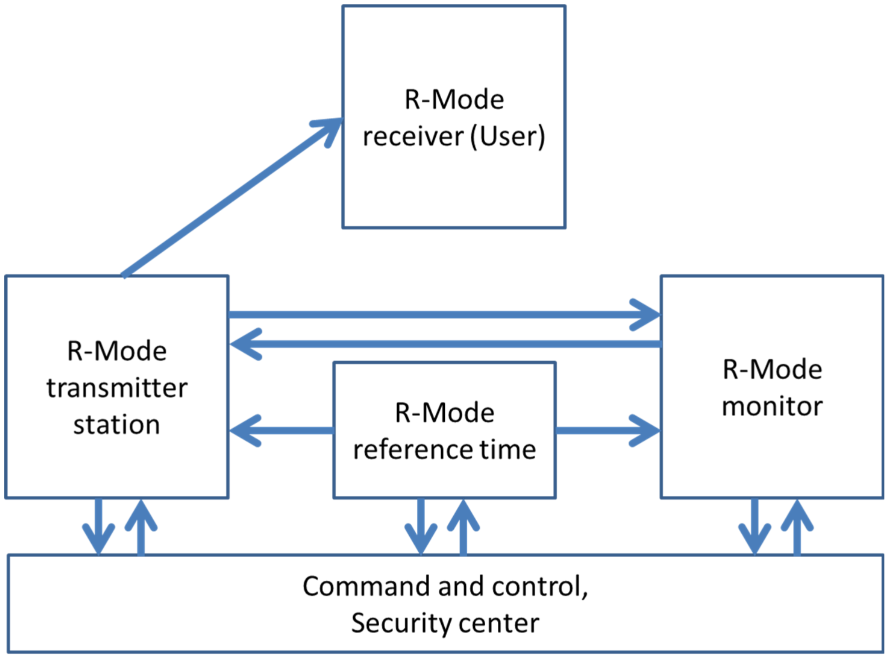

Figure 2 Logical R-Mode architecture

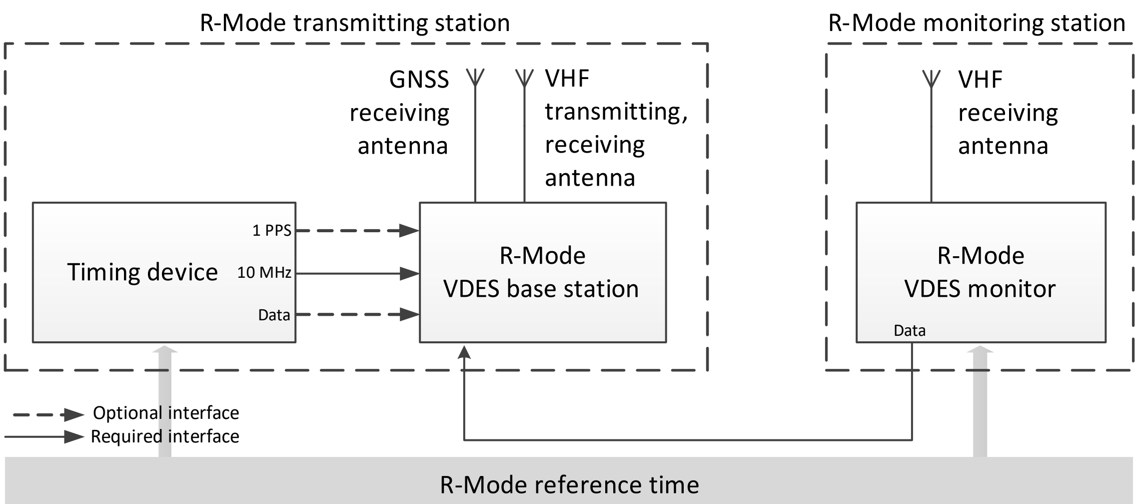

Figure 3 Synchronization of R-Mode transmitter and monitor with RMST

2.2. R-MODE SYSTEM FUNCTIONAL ARCHITECTURE

The IDEF0 modelling approach is used here to outline a functional architecture for VDES R-Mode. For an introduction to IDEF0 please see Annex A A.4. The architectural diagrams shown here are consistent with the External System Diagrams for the VDES R-Mode System contained in the Stakeholder Requirements Document [6].

Section 2.2.1 presents the architecture for a VDES R-Mode System using GNSS in conjunction with high-stability local oscillators for base station synchronization, thus representing a *contingency system*[1] with a holdover time dependent on the (in)stability of the local oscillator. The architecture uses outputs from the base station's internal GNSS receiver to calibrate the local oscillator and estimate parameters of a clock error model, which can then be used during a (short-term) GNSS service outage to discipline the VDES R-Mode base station's clock.

Section 2.2.2 presents an alternative system architecture using a timing device external to the VDES base station unit. Assuming this device operates independently of GNSS, this architecture represents a *backup system*[2].

Figure 4 and Figure 7 in the following sections show the top-level functional breakdown, data flows and key system elements for the two system architectures, respectively. Of particular relevance to this specification is the Transmit VHF Signal Function, which is expanded in Figure 5 and Figure 8, and further in Figure 6 and Figure 9, respectively. Descriptions of the data flows and key system elements shown in the diagrams are provided (in alphabetical order) in Table 1 in Section 2.2.3.

1 IALA defines in [5] a *contingency* Positioning, Navigation and Timing system as one that allows safe completion of a manoeuvre but may not be adequate for long-term use.

2 A *backup* system ensures continuation of the navigation application, but not necessarily with the full functionality of the primary system and may necessitate some change in procedures by the user.

2.2.1. SYSTEM ARCHITECTURE USING GNSS FOR SYNCHRONIZATION

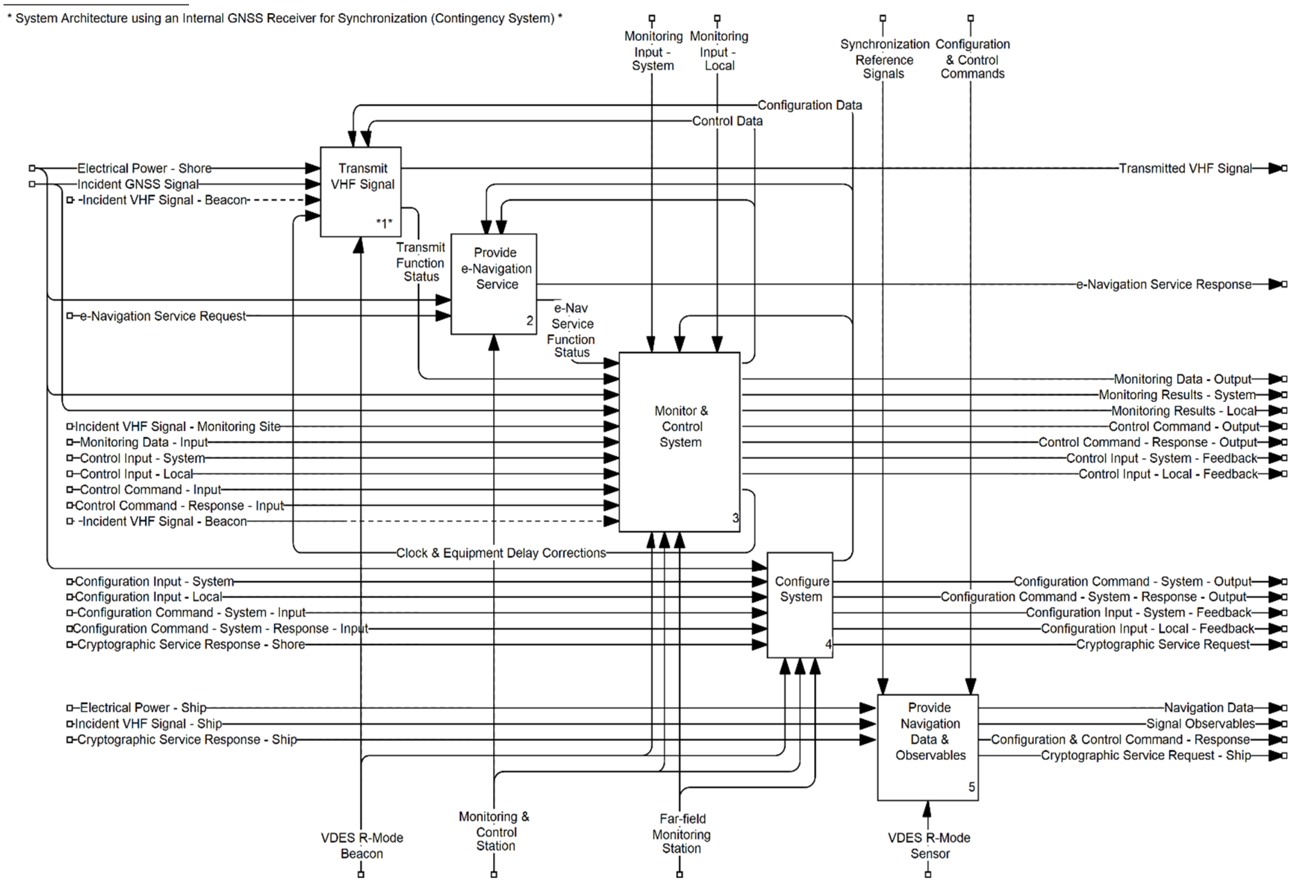

Figure 4 Top-level functional breakdown for a VDES R-Mode System using GNSS for synchronization (contingency system configuration)

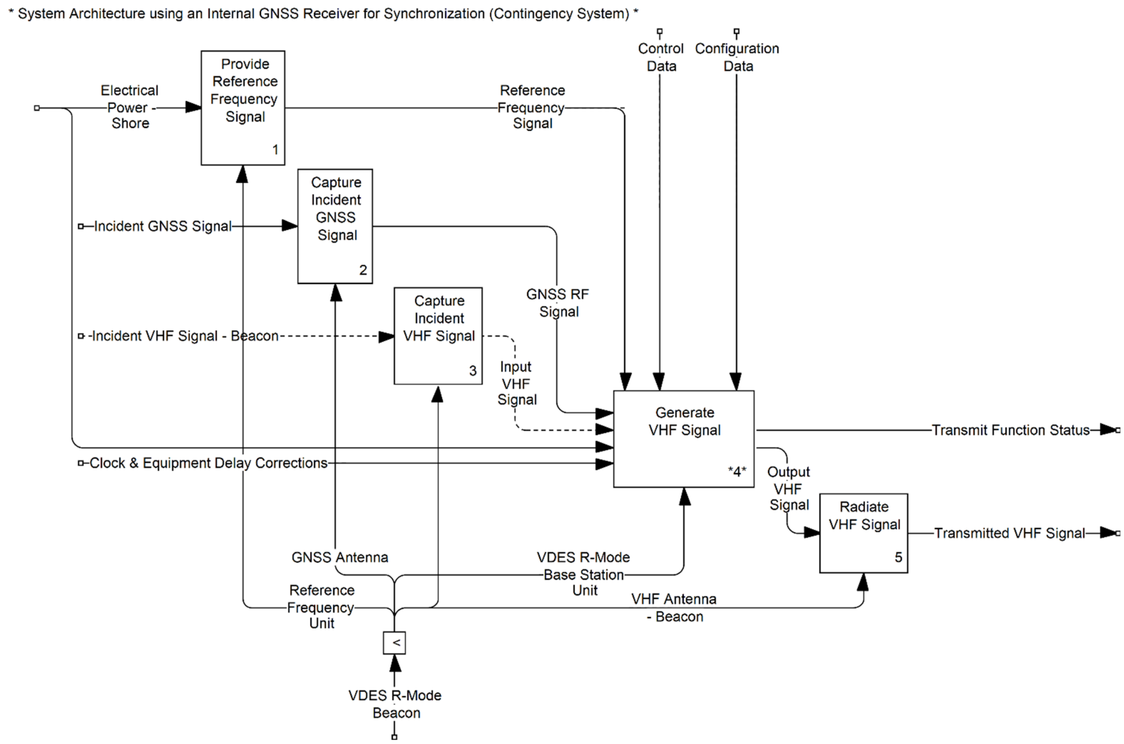

Figure 5 Transmit VHF Signal Function (contingency system configuration)

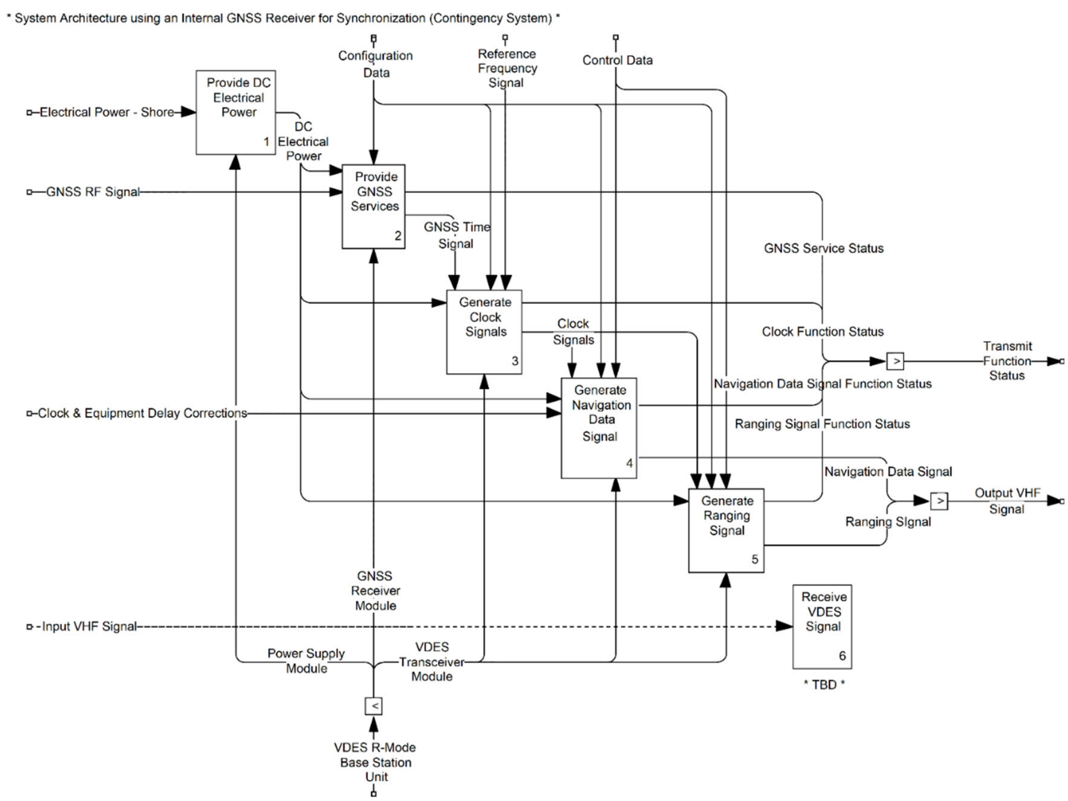

Figure 6 Generate VHF Signal Function (contingency system configuration)

2.2.2. System Architecture Using a Non-GNSS Source for Synchronization

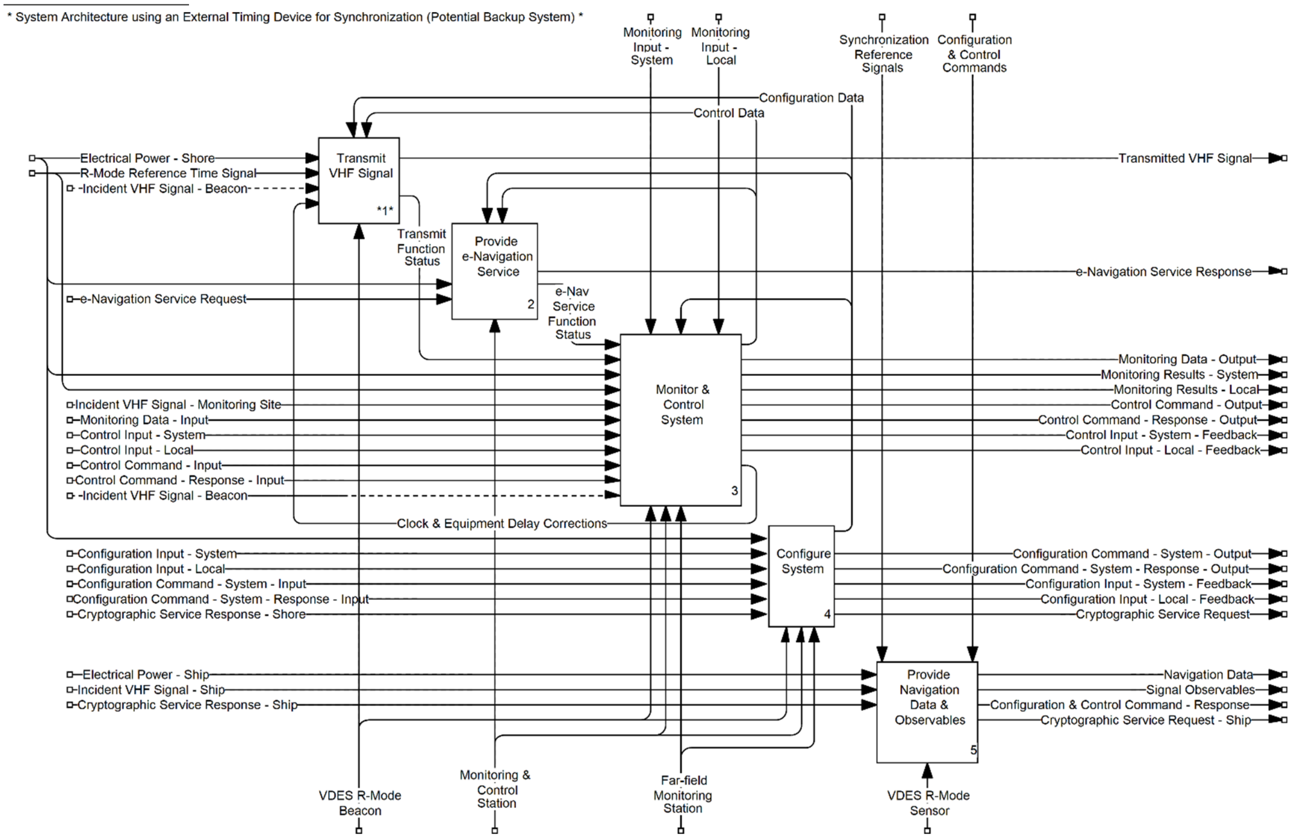

Figure 7 Top-level functional breakdown for a VDES R-Mode System using a non-GNSS source for synchronization (backup system configuration)

* System Architecture using an External Timing Device for Synchronization (Potential Backup System) *

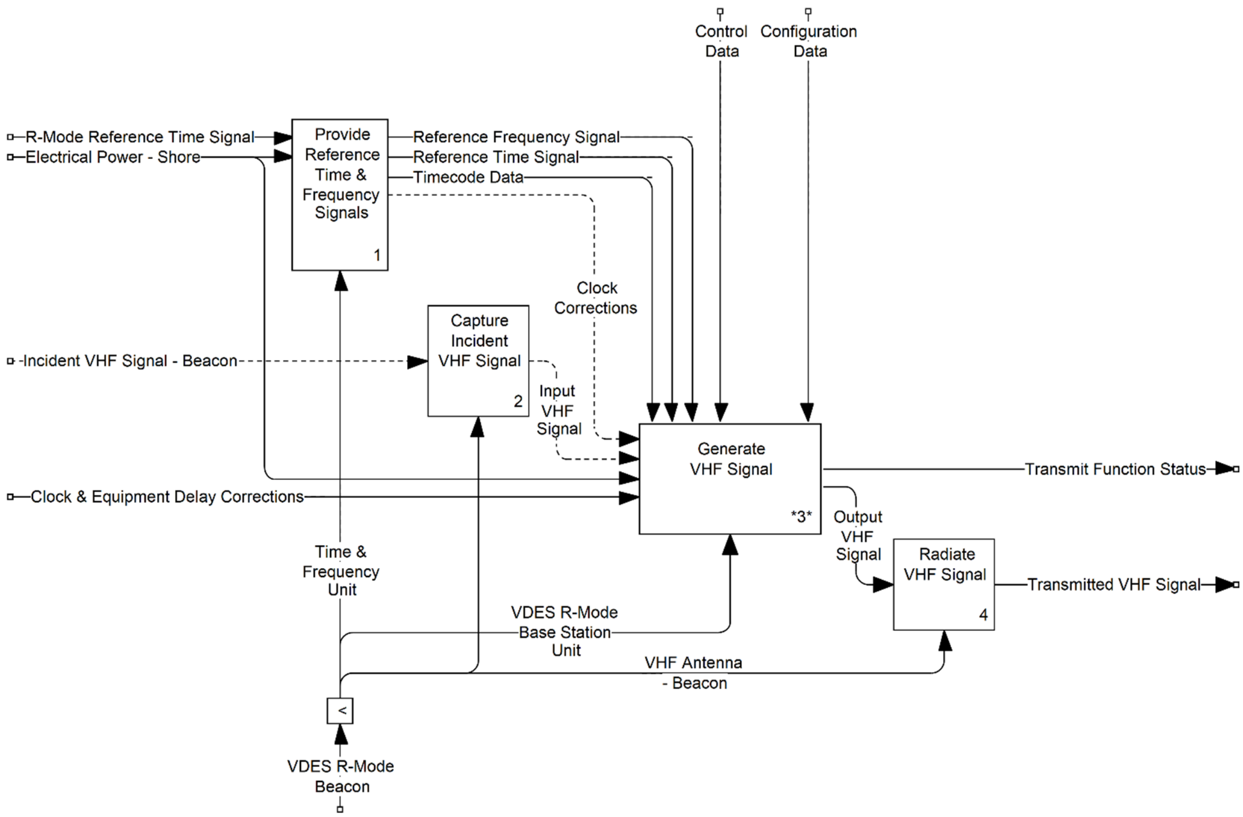

Figure 8 Transmit VHF Signal Function (backup system configuration)

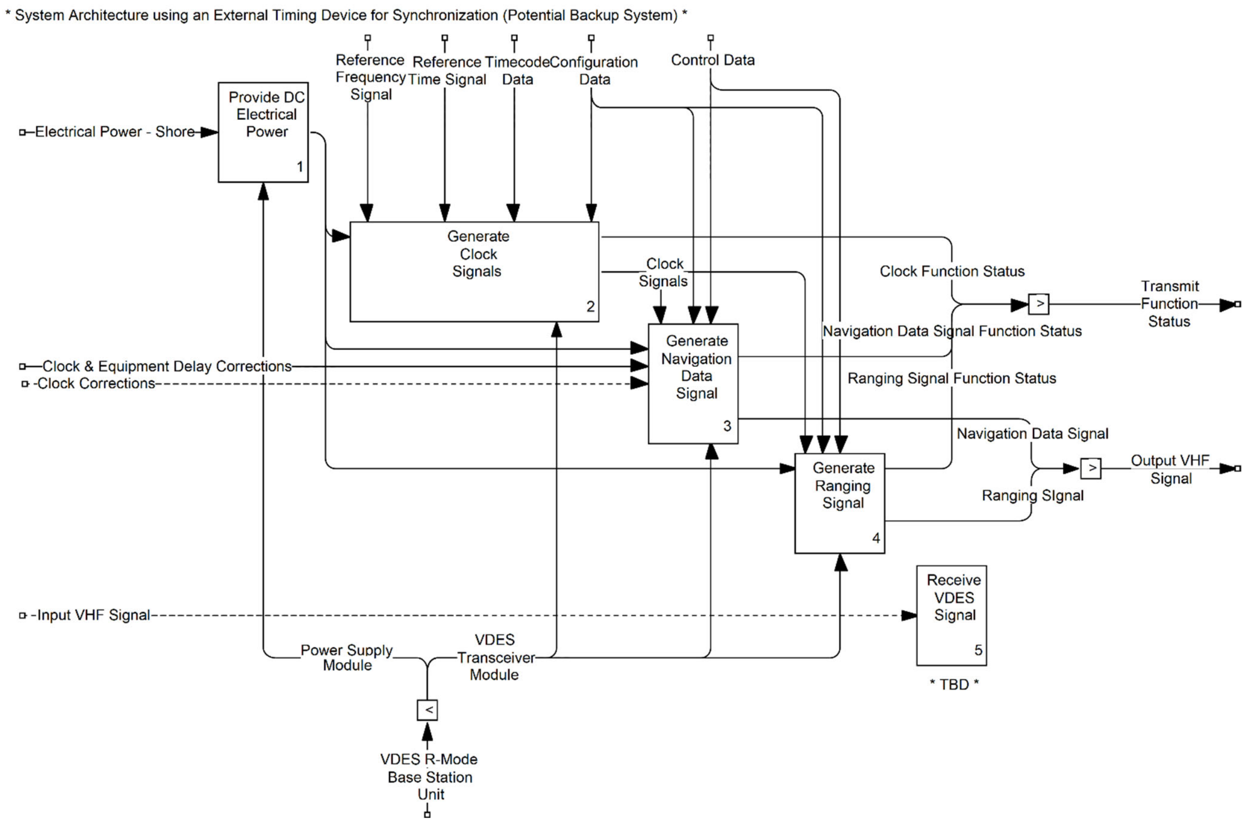

Figure 9 Generate VHF Signal Function (backup system configuration)

2.2.3. DATA FLOW AND SYSTEM ELEMENT DESCRIPTIONS

Table 1 Data flows and key system elements in a VDES R-Mode System

Data Flow / System Element	Description
Clock & Equipment Delay Corrections	(Near) real-time signal timing corrections produced by the Monitor & Control System Function in order to compensate for changes in the signal time of transmission due to changing environmental parameters
Clock Corrections	Parameters of a clock error model produced by the Time & Frequency Unit
Clock Function Status	Status of the Generate Clock Signals Function
Clock Signals	Internal clock signals used within VDES R-Mode Base Station Unit
Configuration & Control Command – Response	Response to a Configuration & Control Command received from a Multi-system Shipborne Radionavigation Unit
Configuration & Control Commands	Configuration & Control Commands received from a Multi-system Shipborne Radionavigation Unit
Configuration Command – System – Input	Configuration commands sent from the Monitoring & Control Station via a Wide Area Network to other shore side system elements
Configuration Command – System – Output	Remote configuration command to be sent to a shore side system element via a Wide Area Network

Data Flow / System Element	Description
Configuration Command – System – Response – Input	Response from a shore side system element to configuration commands sent from the Monitoring & Control Station via a Wide Area Network
Configuration Command – System – Response – Output	Response to a configuration command sent via a Wide Area Network
Configuration Data	Configuration data for the Transmit VHF Signal Function, Provide e-Navigation Service Function and Monitor & Control System Function
Configuration Input – Local	Enables an operator - system administrator to configure a shore side system element via a local human-machine interface
Configuration Input – Local – Feedback	Feedback to an operator - system administrator on whether a configuration operation requested via a local human-machine interface has been successfully completed
Configuration Input – System	Enables an operator - system administrator to configure the shore side system elements using commands sent via a Wide Area Network
Configuration Input – System – Feedback	Feedback to an operator - system administrator on whether a previously requested remote configuration operation has been successfully completed
Control Command – Input	Control commands sent from the Monitoring & Control Station via a Wide Area Network to other shore side system elements
Control Command – Output	Control Commands to be sent from a Monitoring and Control Station via a Wide Area Network to other shore side system elements
Control Command – Response – Input	Response from a shore side system element to a control command sent from the Monitoring & Control Station via a Wide Area Network
Control Command – Response – Output	Response to a control command received via a Wide Area Network
Control Data	Control data for the Transmit VHF Signal Function and Provide e-Navigation Service Function
Control Input – Local	Enables an operator to control the operation of a shoreside system element via a local human-machine interface
Control Input – Local – Feedback	Feedback provided to an operator via a local human-machine interface on whether a previously requested control operation has been successfully completed
Control Input – System	Enables an operator to control the operation of the shoreside system elements from a Monitoring & Control Centre
Control Input – System – Feedback	Feedback to an operator located in a Monitoring & Control Centre on whether a previously requested control operation has been successfully completed
Cryptographic Service Request	Request for cryptographic material (such as private/public keys and certificates) required for signing the Transmitted RF Signal and verifying the authenticity of the received R-Mode VHF signal, to be sent via a Wide Area Network to a cryptographic server
Cryptographic Service Request – Ship	Requests for cryptographic material (such as public keys and certificates) required for the authentication of the R-Mode VHF signal received at the ship, to be sent to a Multi-system Shipborne Radionavigation Unit
Cryptographic Service Response – Ship	Response from a Multi-system Shipborne Radionavigation Unit to a cryptographic service request sent by the VDES R-Mode Sensor

Data Flow / System Element	Description
Cryptographic Service Response – Shore	Response from a cryptographic server to a cryptographic service request sent by a shore side system element via a Wide Area Network
Electrical Power – Ship	Electrical power from a Multi-system Shipborne Radionavigation Unit
Electrical Power – Shore	Electrical power from the facilities in which the shoreside system elements are installed
Far-field Monitoring Station	Participates in the following system functions: Monitor & Control System and Configure System
GNSS Antenna	Provides a GNSS RF signal to the GNSS Receiver Module within the VDES Base Station Unit
GNSS RF Signal	GNSS signal captured by the GNSS Antenna at the VDES R-Mode Beacon
GNSS Receiver Module	Provides reference time signals (such as 1 PPS and UTC datum) to the Generate Clock Signals Function performed by the VDES R-Mode Base Station Unit
GNSS Service Status	Status of the Provide GNSS Services Function
GNSS Time Signal	Reference time signals (such as 1 PPS and UTC datum) used within VDES R-Mode Base Station Unit
Incident GNSS Signal	GNSS signal incident on the GNSS Antenna, used for synchronization of the VDES Base Station Unit
Incident VHF Signal – Beacon	VHF signal incident on VHF Antenna - Beacon
Incident VHF Signal – Monitoring Site	VHF signal incident on the Far-field Monitoring Station
Incident VHF Signal – Ship	VHF signal incident on VHF Antenna - Ship
Input VHF Signal	Signal captured by VHF Antenna - Beacon
Monitoring & Control Station	Is installed in a Monitoring & Control Centre and performs or participates in the following system functions: Provide e-Navigation Service; Monitor & Control System; and Configure System
Monitoring Data – Input	Monitoring data from the shoreside system elements received via a Wide Area Network
Monitoring Data – Output	Monitoring Data generated by the shoreside system elements to be sent via a Wide Area Network to a Monitoring and Control Station (MCS) located in a Monitoring and Control Centre Several redundant MCS' may be used, installed at different locations
Monitoring Input – Local	Enables an operator to perform monitoring functions on a shoreside system element via a local human-machine interface
Monitoring Input – System	Enables an operator to perform system monitoring functions (such as selecting monitoring results to be displayed and acknowledging alarms) from a Monitoring & Control Centre
Monitoring Results – Local	Real-time monitoring results for a shoreside system element displayed to an operator co-located with that element
Monitoring Results – System	Real-time system monitoring results displayed to an operator located in a Monitoring and Control Centre
Navigation Data	R-Mode Navigation Data to be output to a Multi-system Shipborne Radionavigation Unit

Data Flow / System Element	Description
Navigation Data Signal	VHF signal carrying the R-Mode Navigation Data
Navigation Data Signal Function Status	Status of the Generate Navigation Data Signal Function
Output VHF Signal	RF signal feeding VHF Antenna – Beacon
Power Supply Module	Provides DC electric power to modules within VDES R-Mode Base Station Unit
R-Mode Reference Time Signal	Time transfer signal used to distribute the R-Mode Reference Time to VDES Beacons
Ranging Signal	VHF signal carrying the R-Mode ranging sequence
Ranging Signal Function Status	Status of the Generate Ranging Signal Function
Reference Frequency Signal	e.g. a 10 MHz sine-wave signal
Reference Frequency Unit	Frequency standard (such as a Rubidium oscillator) providing a stable reference frequency signal to the VDES Base Station Unit
Reference Time Signal	e.g. a 1 PPS signal
Signal Observables	R-Mode signal observables to be output to a Multi-system Shipborne Radionavigation Unit
Synchronization Reference Signals	Reference signals input from a Multi-system Shipborne Radionavigation Unit (MSRU) allowing the VDES R-Mode Sensor to synchronize its clock to the MSRU clock
Time & Frequency Unit	Provides reference frequency and time signals to the VDES Base Station Unit; optionally may provide parameters of a clock error model
Timecode Data	Information required to disambiguate the Reference Time Signal
Transmit Function Status	Status of the Transmit VHF Signal Function
Transmitted VHF Signal	Transmitted VHF Signal having a Navigation Data and a ranging signal component
VDES R-Mode Base Station Unit	Includes the following components: VDES Transceiver Module; GNSS Receiver Module; and Power Supply Module, and performs the Transmit VHF Signal Function
VDES R-Mode Beacon	Includes the following components: Reference Frequency Unit; GNSS Antenna; VHF Antenna - Beacon; and VDES Base Station Unit, and performs or participates in the following system functions: Transmit VHF Signal; Monitor & Control System; and Configure System
VDES R-Mode Sensor	Performs the Provide Navigation Data and Observables Function
VDES Transceiver Module	Provides a VDES transmit/receive capability
VHF Antenna – Beacon	Antenna used for transmitting the R-Mode Navigation Data and ranging signals
e-Nav Service Function Status	Status of the Provide e-Navigation Service Function
e-Navigation Service Request	e-Navigation Service Requests sent from an e-Navigation Service Client via a Wide Area Network
e-Navigation Service Response	Response to an e-Navigation Service Request from an e-Navigation Service Client received via a Wide Area Network

3. PHYSICAL LAYER

3.1. VDE-TER R-MODE

VDES R-Mode is based on the specification of the VDE-TER specification in ITU-R M.2092-1. The physical layer of the R-Mode application requires a ranging sequence and additional navigation data to determine the distance between VDES R-Mode base stations, transmitters, and receiver. The ranging sequence is predefined and adapted by the network depending on the expected coverage areas. VDE-TER schedules the resources based on a TDMA scheme between VDES base stations that are coordinated by the network provider(s). The VDES R-Mode base stations shall transmit their ranging sequence every second based on the configuration of link-ID 37. The additional navigation data shall be communicated every minute via the link-ID 11 within the network and via one VDES R-Mode base station.

3.1.1. RANGING SEQUENCES

The ranging sequence is a concatenation of two known sequences to customize the required performance based on the given scenarios. The scenarios considered are:

1. Shorter distances with high SNR between shore station and vessels ($\gamma > 0.5$).
2. Longer distances with lower SNR between shore station and vessels ($\gamma < 0.5$).

Figure 10 describes how both sequences are concatenated as part of the data message of a VDE-TER slot based on the γ factor.

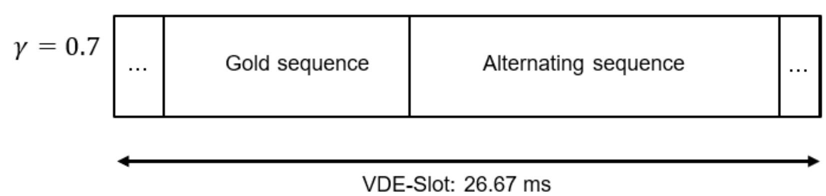

Figure 10 Example of sequence concatenation

Both sequences are concatenated, and factor γ defines the portion of the whole sequence used by parts of the Gold code sequence. The remainder is filled up by symbols of the alternating sequence.

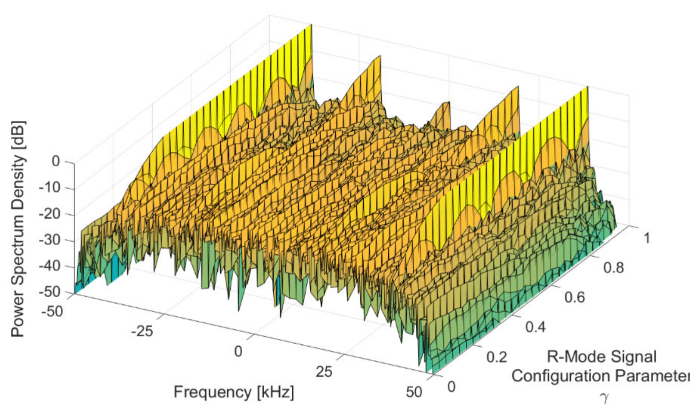

Figure 11 Power spectral density expressed over the 100 kHz of the combined sequences depending on the γ factor

The ranging sequences are defined in the following. The first sequence is based on the pi/4-QPSK modulation alphabet and alternates its constellation points. Figure 12 shows the principle on how the sequence is generated with an arbitrary length. The alternating sequence starts with 01.

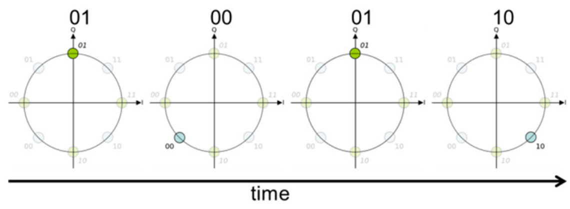

Figure 12   Generating alternating sequence (CC3.0 (Wikipedia))

The second part of the ranging sequence is a Gold code. Here the length of 1877 symbols are defined:

C_I	**1,1,1,1,0,0,1,0,0,0,0,1,0,1,0,0,1,1,0,0,0,0,0,0,0,1,0,0,1,1,1,0,1,0,1,0,0,1,1,0,1,0,0,1,1,1,1,0,0,1,1,0,0,0,1,0, 0,0,1,1,0,1,1,0,1,1,0,0,1,0,1,0,1,0,0,0,0,1,1,0,0,0,1,1,1,1,1,1,1,0,1,1,1,0,1,0,0,0,0,0,0,1,0,0,0,0,0,1,1,1,1,0, 1,1,1,1,1,0,1,0,1,1,0,1,1,1,0,1,1,0,0,0,1,0,1,1,1,1,1,0,0,0,0,1,0,1,1,0,1,1,1,1,0,0,0,1,0,1,1,0,0,1,1,1,0,1,0,1, 0,0,0,0,1,0,0,0,0,0,1,0,0,1,1,1,0,0,0,1,0,0,0,1,0,1,0,1,0,0,0,1,0,1,0,0,0,0,1,1,0,0,1,1,0,0,1,0,0,0,1,0,0,0,0,1, 1,1,0,1,0,0,1,0,0,0,1,0,1,1,1,0,1,1,1,0,1,0,1,1,0,0,0,1,1,1,0,1,1,0,0,1,0,0,0,0,1,1,1,0,1,1,1,1,0,1,1,0,1,1,0,1, 1,1,0,1,1,1,1,0,1,0,1,0,1,1,1,1,0,1,0,1,1,1,1,0,0,1,1,0,1,0,1,0,1,0,0,1,1,1,0,1,0,0,0,1,1,0,0,1,0,1,1,0,0,0,1,1, 0,0,1,1,1,0,0,1,1,0,0,1,1,1,1,0,1,1,0,0,1,0,0,0,1,0,0,0,1,1,0,0,1,0,1,1,0,1,1,1,1,0,0,0,1,0,1,0,1,0,1,1,0,0,1,0, 0,1,1,1,0,0,0,0,1,0,0,1,0,0,0,0,0,1,0,1,1,1,0,0,1,0,1,1,0,1,0,1,0,0,1,1,0,1,1,0,0,0,1,0,0,0,0,0,1,0,1,1,1,0,1,1, 1,0,0,1,1,1,1,1,1,0,1,0,0,1,1,1,1,1,0,1,1,1,1,1,1,0,1,1,0,1,0,0,0,0,1,0,0,0,1,1,1,1,0,1,1,1,0,0,1,1,1,0,1,1,0,1, 1,1,0,1,1,0,1,0,0,0,1,0,0,1,0,1,0,1,1,1,1,0,0,1,0,0,0,0,0,1,1,1,0,0,0,0,1,1,1,1,1,1,0,1,0,0,0,0,1,0,1,0,1,1,0,0, 1,0,1,1,1,0,0,0,1,0,1,0,1,0,0,1,1,0,0,1,1,0,1,1,1,1,0,0,0,0,0,1,0,0,0,0,0,1,0,0,1,0,0,1,1,1,1,0,1,1,0,1,1,0,1,1, 0,1,0,1,0,1,1,0,0,1,1,0,0,0,0,1,0,1,0,1,1,1,1,1,1,0,1,1,1,1,0,1,1,1,0,0,1,0,1,0,0,0,0,1,1,1,0,1,1,0,0,1,1,1,0,1, 1,1,1,1,0,0,1,0,0,0,0,0,0,1,1,0,0,0,0,1,0,0,0,0,0,1,1,0,1,1,0,1,0,0,1,0,0,0,1,0,1,0,1,1,1,1,0,0,0,1,0,0,0,1,1,1, 0,1,0,1,0,1,0,1,0,1,1,0,0,0,1,1,0,1,1,1,1,0,0,1,0,1,0,0,1,1,1,1,1,1,0,0,0,0,0,0,0,1,0,1,0,0,1,1,1,0,1,0,1,1,0,1, 1,0,0,1,0,1,0,0,1,0,1,0,1,0,1,1,0,0,0,0,1,1,1,1,1,0,0,1,0,1,0,0,1,0,0,0,0,1,0,1,0,1,1,1,1,1,0,0,1,1,0,0,0,1,0,0, 1,1,1,0,0,0,0,0,1,0,0,0,1,0,1,0,1,0,1,1,0,1,1,1,0,1,0,1,0,0,0,1,0,0,1,0,0,1,0,0,1,1,0,0,1,0,1,1,0,0,1,0,1,0,1,0, 1,0,1,0,1,0,1,1,1,1,1,1,0,0,0,1,0,1,1,1,0,0,1,0,0,0,0,0,0,1,0,1,1,0,1,1,0,1,1,1,0,1,0,0,1,0,0,1,1,1,1,0,1,0,1,0, 1,0,0,0,1,0,1,0,1,1,0,0,1,0,1,0,0,0,1,0,0,1,1,0,0,1,1,1,0,0,1,0,0,1,1,0,1,0,0,0,1,0,1,0,0,1,1,0,1,1,0,1,0,1,0,1, 1,0,0,0,0,0,0,0,0,1,1,0,0,1,0,1,0,0,1,0,1,0,1,0,1,1,0,1,0,1,0,0,0,1,0,0,1,1,0,0,0,0,1,0,1,0,0,0,1,0,1,0,0,1,1,1, 1,0,0,0,1,0,1,0,0,0,1,0,0,0,1,1,1,0,1,0,1,0,1,1,1,0,0,0,1,0,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,1,0,1,0,1, 1,0,1,0,1,1,0,0,0,0,1,0,1,1,0,1,1,0,1,0,0,0,0,0,1,1,0,1,1,0,1,1,1,1,1,1,1,1,1,1,0,1,0,0,1,0,1,1,0,0,1,0,0,0,1, 1,1,0,0,1,1,1,0,1,0,0,0,0,0,0,1,1,1,0,0,0,0,1,0,1,0,1,0,1,0,1,0,0,0,0,0,0,0,0,0,0,1,0,1,0,0,0,0,1,1,1,1,1,1,0,1, 1,0,0,0,1,0,1,1,0,1,1,0,1,0,0,0,1,1,1,1,0,1,0,0,1,1,1,0,0,1,0,0,1,1,1,0,0,0,0,1,1,0,0,1,1,1,0,0,0,0,1,1,1,1,1,0, 1,0,1,1,0,0,0,0,1,1,0,1,0,0,1,0,1,1,1,0,1,0,0,1,0,0,0,1,0,1,0,0,1,1,1,0,1,1,1,1,0,0,0,0,1,1,1,0,1,1,0,0,1,1,1,0, 1,0,1,1,0,0,1,1,1,0,1,1,0,1,1,0,1,1,0,0,1,1,0,1,1,0,1,1,1,1,0,0,1,1,0,0,1,1,1,1,0,0,0,1,0,1,1,1,0,0,0,1,0,1,0,0, 0,0,1,0,1,1,1,1,0,1,0,1,1,1,1,0,0,0,0,1,0,1,1,1,1,0,1,0,0,0,0,0,1,1,0,1,0,0,0,1,0,0,1,0,1,1,1,1,0,0,0,1,1,1,1,1, 1,1,0,0,0,0,1,1,1,0,0,0,1,1,1,0,1,1,0,0,1,1,1,1,1,1,1,0,1,0,0,1,1,0,1,0,1,0,1,0,1,0,0,0,0,1,0,1,0,0,1,1,1,1,0,1, 0,0,0,0,1,0,1,1,1,1,0,1,0,1,0,1,0,0,1,0,1,1,1,0,1,0,1,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,1,0,1,1,0,0,0,0,0,1,1,1,1,0, 0,0,0,0,0,0,1,1,1,1,0,1,1,1,0,0,0,0,0,1,0,1,1,1,1,1,1,0,0,0,0,1,0,1,1,0,1,1,1,0,0,1,1,1,0,1,0,1,0,1,1,0,0,1, 1,0,0,0,0,1,1,0,1,0,0,1,1,0,1,1,0,1,0,0,1,0,0,1,0,0,0,1,1,1,1,1,1,0,1,0,1,1,0,0,1,0,1,1,0,1,0,1,1,0,1,1,1,1,0,0, 0,1,1,1,1,0,0,1,1,1,1,0,0,0,1,1,1,0,0,1,0,1,0,1,1,1,1,1,1,0,0,0,0,0,1,1,1,0,0,1,1,0,0,1,1,0,0,1,0,0,0,1,1,0,1,0, 0,1,1,1,0,1,0,0,0,1,0,0,1,0,0,1,0,0,0,0,1,0,0,1,1,1,1,1,1,0,1,1,0,0,1,0,1,0,1,0,0,0,1,0,1,0,0,1,0,0,0,1,0,1,1,0, 0,0,0,0,0,0,1,0,1,0,1,1,1,1,0,0,0,0,1,1,1,0,1,0,1,1,0,1,0,1,1,0,1,1,1,1,0,0,0,1,1,1,1,0,0,0,0,0,0,0,1,1,0,0,1,1, 0,1,1,1,0,0,1,0,0,1,1,0,0,1,1,0,0,0,1,0,0,0,0,1,0,0,0,0,1**
C_Q	**0,1,1,0,0,1,1,1,1,0,1,1,1,1,0,1,1,0,1,0,0,1,1,0,0,0,1,0,0,1,1,1,0,0,1,1,0,0,1,1,1,1,0,0,1,0,0,0,1,1,0,0,1,0,1,1, 1,0,0,1,1,1,1,1,1,0,0,1,1,1,0,0,1,1,0,1,1,1,0,0,1,0,0,1,1,0,1,0,1,1,0,1,0,0,0,0,0,1,0,1,1,1,1,0,0,1,1,1,0,1,1,1, 1,0,0,1,1,1,0,0,0,1,0,0,0,1,0,0,1,1,0,1,0,0,0,1,0,1,0,0,1,0,0,0,0,0,1,1,1,0,0,1,0,1,0,0,0,0,0,0,1,1,1,0,0,0,1,1,**

	1,0,1,0,1,1,1,0,1,0,0,0,0,0,1,0,0,1,0,0,0,1,1,1,0,0,1,1,0,1,1,1,1,1,1,0,0,1,1,0,0,1,0,1,0,1,0,0,1,0,0,0,0,1,1,1, 1,0,0,0,0,1,1,1,0,1,0,0,1,0,1,1,0,1,1,1,0,0,1,0,1,0,0,0,0,1,0,0,0,0,0,0,0,1,1,0,1,0,0,0,0,1,1,0,0,0,0,0,1,0,0,0, 1,0,1,1,0,1,1,1,1,1,1,1,1,0,1,0,1,1,1,1,1,0,1,1,1,1,1,1,1,0,0,1,1,0,0,0,1,0,0,0,1,1,1,0,0,1,1,0,0,1,1,0,1,1,0, 1,0,1,0,1,1,1,1,1,1,1,1,0,1,0,0,1,0,1,0,1,1,0,1,1,1,0,1,1,0,1,0,1,1,1,0,1,1,1,0,0,0,1,0,1,1,0,0,0,0,1,0,1,0,1,1, 1,1,0,1,1,0,1,0,0,0,1,1,0,1,0,1,0,0,0,0,1,0,1,0,0,0,0,1,1,1,0,0,1,0,0,1,0,0,0,0,1,0,1,1,0,1,1,0,0,0,1,0,0,0,1,0, 1,1,1,1,0,1,1,0,0,0,0,0,0,1,0,0,1,1,1,1,0,1,0,1,1,0,1,1,1,1,0,1,0,1,1,0,1,1,0,1,0,0,0,1,0,0,1,1,0,0,0,0,1,1,1, 1,0,0,0,0,0,1,1,0,1,1,1,1,1,0,0,1,1,1,0,0,0,1,1,1,0,0,1,1,1,1,0,1,0,1,0,1,0,0,1,1,0,1,1,0,1,0,1,0,0,0,0,0,1,0,1, 0,0,1,0,0,0,1,0,1,1,1,1,0,0,1,1,1,1,1,1,1,1,0,1,1,0,0,1,1,0,0,0,1,0,1,0,1,1,1,0,0,0,1,1,0,1,0,0,1,0,0,0,0,0,1,0, 1,1,0,0,0,0,1,1,0,0,0,0,1,0,0,0,1,1,1,1,1,0,1,0,1,1,1,0,1,0,1,1,0,1,1,0,0,0,0,0,1,1,1,1,0,1,1,0,0,1,1,1,0,0,0, 1,0,0,1,1,0,1,1,1,0,0,1,0,0,1,1,1,0,1,1,1,0,0,1,1,1,1,1,1,0,1,1,1,0,0,0,1,0,0,0,1,1,0,1,0,1,0,1,1,1,1,0,1,1,1,0, 1,1,0,0,0,0,1,1,0,0,0,0,0,1,0,1,1,1,0,1,0,0,1,1,0,0,1,0,0,1,1,0,0,1,0,1,1,0,0,1,0,0,0,0,0,1,0,1,1,1,0,0,0,1,1,1, 1,1,0,0,1,1,1,0,1,1,1,1,1,1,0,1,1,0,1,0,1,0,1,0,0,0,1,1,0,0,0,1,1,1,1,0,1,1,0,0,0,0,0,1,1,0,0,1,0,1,0,1,0,0,0,1, 1,0,0,0,0,1,1,0,1,1,0,1,1,1,1,1,0,0,1,0,0,0,1,0,1,1,0,0,1,0,0,0,0,1,1,1,1,1,0,1,0,1,0,1,0,0,0,1,1,0,0,0,0,0,0,0, 0,0,0,0,1,1,0,1,1,0,0,1,0,1,0,0,0,0,1,0,1,0,0,0,1,1,0,1,1,0,0,1,1,0,1,0,0,1,0,1,1,0,1,0,0,0,0,1,0,0,0,1,1,0,0, 0,0,1,0,0,0,0,0,0,1,0,1,1,1,0,0,0,1,0,0,0,0,0,0,0,0,1,1,0,1,1,1,1,0,0,1,1,1,0,0,0,1,1,0,0,0,0,0,1,1,1,0,0,1,1, 1,1,1,0,0,1,1,0,1,1,1,1,0,0,0,0,1,0,1,1,1,1,0,0,1,0,1,1,0,0,1,0,0,0,0,1,0,1,1,0,1,0,1,1,0,0,1,0,0,0,0,0,1,1,0,1, 0,0,0,1,0,0,0,0,0,1,1,1,1,0,0,1,0,0,0,0,1,1,1,0,1,1,0,1,0,0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,0,0,0,1,0,1,0,0,0,0,0,0, 1,1,1,1,1,0,1,0,0,1,1,1,1,0,0,0,1,1,1,1,1,0,1,0,1,0,0,0,1,1,1,0,0,1,0,1,0,1,0,1,0,0,0,0,1,1,0,0,0,0,0,0,0,1,0,0, 0,1,1,0,0,1,0,0,1,1,0,1,0,1,0,0,1,0,0,1,0,1,1,1,1,1,0,0,0,0,1,1,0,1,0,1,1,0,0,1,0,0,1,1,0,1,0,1,0,1,0,1,0,1,1,1, 1,1,1,0,0,0,1,0,1,1,0,0,0,0,1,0,0,1,0,1,1,1,1,0,0,1,0,0,1,1,0,1,1,0,1,1,0,1,0,0,0,0,1,1,0,1,0,1,1,0,0,1,0,1,0,0, 1,1,0,1,0,1,0,1,0,1,1,1,1,0,0,0,1,0,0,0,0,0,0,0,1,1,1,0,0,1,0,0,1,1,1,1,0,1,0,0,1,0,1,0,1,1,1,1,0,0,1,1,0,0,0, 1,1,1,0,0,1,1,0,0,0,0,1,0,0,1,1,0,1,1,0,1,0,0,0,1,1,1,0,1,0,1,0,1,0,1,0,0,1,1,0,1,0,0,0,1,1,0,1,1,0,0,0,1,1,0,1, 1,0,1,1,0,1,0,1,1,1,0,0,1,0,1,1,0,1,0,0,1,1,1,0,1,1,1,1,0,1,1,0,0,1,0,0,0,1,1,1,1,0,1,1,0,1,1,0,1,0,1,1,1,0,1,0, 1,0,0,1,0,1,1,0,0,0,1,0,0,1,0,0,0,1,1,0,0,1,1,0,1,0,0,0,0,0,1,1,1,1,1,1,0,0,1,1,0,0,0,1,1,1,0,0,1,0,1,0,1,0,0,0, 1,0,0,1,0,0,1,0,0,1,0,0,0,0,0,0,1,0,1,1,0,1,0,0,1,1,0,0,1,0,1,0,0,0,1,0,0,0,0,1,1,1,1,1,0,1,0,1,1,0,0,0,0,0,1,1,1, 1,0,0,1,1,0,1,0,1,0,1,1,0,1,1,0,1,0,0,1,0,0,1,0,1,0,1,0,1,1,1,0,1,1,1,1,1,1,1,0,1,1,1,1,1,0,0,0,0,0,1,1,1,1,0,0, 1,1,1,0,0,0,0,0,1,1,0,0,1,1,0,1,0,0,1,0,0,0,1,1,1,0,0,0,0,1,1,0,0,0,0,0,1,0,0,1,1,1,0,1,0,0,0,0,0,0,1,0,0,1,1,0, 0,0,1,0,0,0,1,1,1,0,0,0,0,1,1,0,0,0,1,1,0,0,1,1,1,0,0,1,1,1,0,1,1,0,0,1,1,1,0,0,1,1,1,1,0,0,0,0,0,1,0,0,1,1,0,0, 1,1,0,1,0,0,1,0,1,1,1,0,0,0,1,1,1,0,0,1,0,0,1,1,0,1,0,1,0,0,0,1,0,1,1,1,1,1,1,1,0,1,0,0,0,0,1,1,1,0,1,1,0,0,0,0, 0,1,0,1,1,0,0,0,0,0,0,1,0,1,0,1,1,0,0,1,1,1,1,1,0,1,1,1,0,0,0,0,1,0,0,1,0,1,1,1,1,0,0,0,0,1,0,1,1,0,1,0,1,0,0,1, 0,0,0,1,0,1,1,1,1,1,0,0,1,1,1,1,0,1,0,0,1,0,0,0,0,1,1,0,0

Both sequences are shortened by a weighting and then concatenated. The length of the alternating sequence is multiplied with a weighting factor $\gamma(short) = 0.7$ for short distances (higher SNR) and $\gamma(large) = 0.3$ for larger distances (lower SNR). The length of the Gold code is multiplied with a weighting factor $1 - \gamma(short) = 0.3$ for short distances and $1 - \gamma(large) = 0.7$ for large distances.

3.1.2. NAVIGATION DATA

The navigation data contains all the data used to calculate the range between the VDES R-Mode base station and the receiver. The navigation data is transmitted every minute by a regular VDE-TER message. The navigation data of multiple R-Mode base stations can be combined in one VDE message and should indicate which base station the navigation data addresses with the network. This shall be covered by the network provider of the base stations.

3.2. ASM-TER R-MODE

The general slot format of ASM-TER is shown in Table 1. Each slot consists of six parts: Ramp up, Training sequence, Link ID, Data, Ramp down and Guard. The ramp-up time for power change from -50 dBc to -1.5 dBc is approximately417 microseconds (us), to provide spectral shaping and reduce interference, and the modulation is not specified for the ramp up. The training sequence is described in detail in the next paragraph. The Link ID based on π/4 QPSK modulation follows the training sequence to define the channel configurations. The Data payload with its Cyclic Redundancy Check (CRC) is interleaved encoded scrambled and bit mapped. The ramp down time from full power to −50 dBc should be no more than 417 us. The rest Guard time is for delay and jitter.

Table 1 ASM-TER General Slot Format

Ramp up	Training Sequence	Link ID	Data	Ramp Down	Guard
0.41 ms	27 symbols (1 1111100110101 0000011001010)	16 symbols	Data with CRC	0.41 ms	0.83 ms

The training sequence of ASM-TER is a 27-symbols sequence with π/4 QPSK modulation. The last 26 symbols are barker13 code (1 1 1 1 1 0 0 1 1 0 1 0 1) and inverted barker13 code (0 0 0 0 0 1 1 0 0 1 0 1 0) with ideal autocorrelation, which can be used to detect the weak target signal submerged in noise. The ideal autocorrelation of the double Barker 13 code can be used for ranging. In the training sequence, the symbol "1" maps to π/4 QPSK symbol "3" (1 1), and the symbol "0" maps to π/4 QPSK symbol "0" (0 0).

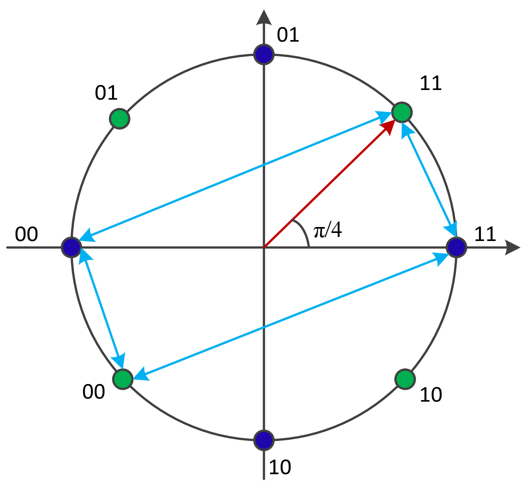

Figure 13 Bit Mapping for π/4 QPSK and Phase Alternating of the Training Sequence

Figure 1 shows the bit mapping for π/4 QPSK used in ASM-TER, and the phase alternating of the training sequence. There are 4 possible phase variations of ± π/4 and ±3π/4 when the symbol changes. Since there are only "11" and "00" in the training sequence, without "01" and "10", it has only four kinds of phase alternating as shown in Figure 2. The first the symbol "1" of the training sequence maps to π/4 QPSK symbol "3" (1 1), is mapped to the constellation defined by the point (1+j)/√2; the next symbol "1" is mapped to the constellation defined by point 1+0j (shown in blue in Figure 2); the next symbol "1" is mapped to the constellation defined by point (-1-j)/√2 (shown in green in Figure 2) and so on.

According to the structure of the training sequence shown in Table 1, if the first symbol of the link configuration ID is 0, as received sequence shown in Figure 2, the correlation value is the maximum when the local reproduced 26 symbols exactly match the received signal. Because ms is 26 and ns is 0, where ms is the number of matched symbols and ns is the number of mismatched symbols. The correlation value is the minimum when the locally re-produced 26 symbols are 1 symbol time Ts earlier or later than the received signal, for ms is 13 and ns is 13, as shown in Figure 2. Therefore, the navigation data can be transmitted via ASM-TER with the link-ID 48 to make the first symbol 0, and the link configuration parameters are the same as link-ID 1.

Received:	1	1	1	1	1	1	0	0	1	1	0	1	0	1	0	0	0	0	0	1	1	0	0	1	0	1	0	0	
Local 1 symbol Earlier:	1	1	1	1	1	0	0	1	1	0	1	0	1	0	0	0	0	0	1	1	0	0	1	0	1	0			ms=13; ns=13
Local Prompt:		1	1	1	1	1	0	0	1	1	0	1	0	1	0	0	0	0	0	1	1	0	0	1	0	1	0		ms=26; ns=0
Local 1 symbol Later:			1	1	1	1	1	0	0	1	1	0	1	0	1	0	0	0	0	0	1	1	0	0	1	0	1	0	ms=13; ns=13

Figure 14 Number of matched symbols ms and number of mismatched symbols ns

3.3. CLOCK REQUIREMENTS

For a positioning system, which provides time information in the ranging signals, synchronisation and calibration are essential for the performance of the R-Mode service. Therefore, each ranging signal generator, the VDES base station for VDES R-Mode, has to be synchronised to the RMST in this region. The time information will be given by a 1 PPS and 10 MHz signal. Additionally, information to disambiguate the PPS pulses and about the clock error will be given over a data channel from the timing source, if not supplied internally. Further information about the clock requirements can be found in Section A.3.

For the generation of accurate ranging signals, it is important that all internal oscillators of the VDES base station are synchronised with the external 10 MHz signal.

4. LINK LAYER

The link layer of VDE-TER enables VDES R-Mode together with precise timing at the transmitter. The VDES R-Mode base station broadcasts the ranging sequence via the Ranging Channel once per second at a known and defined time instance with link-ID 37.

4.1. R-MODE INTEGRATION WITH VDE-TERRESTRIAL LINK LAYER

In the link layer the ranging sequence shall be transmitted by the Ranging Channel and utilizes the shore-to-ship short message (#93). The navigation data shall be communicated by a shore originated broadcast message.

4.2. R-MODE INTEGRATION WITH ASM-TERRESTRIAL LINK LAYER

There are two transmission modes of the ASM-TER R-Mode ranging signals can be used, synchronous mode and asynchronous mode. The synchronous transmission of ranging signals will reduce the error of the receiver clock jitter and the error of time different of arrival (TDOA) caused by ship motion. However, the complexity of synchronous transmission is higher, and the ranging performance of the weaker signal would be affected.

4.2.1. SYNCHRONOUS TRANSMISSION

The ASM-TER R-Mode ranging signal transmission from the VDES base station can be carried out in the way shown in Figure 3. The transmission modes of all base stations are divided into three types: A, B and C:

- Type A base stations continuously transmit two slots on ASM1, and then stop one slot.
- Type B base station transmits one slot on ASM2 first, and after a slot interval, transmits one slot on ASM1.
- Type C base stations stop for one slot, and then continuously transmit two slots on ASM2.

The base station management system first defines the base station as A1, B1, C1; A2, B2, C2. At the beginning of the transmission period (for example 6 seconds), transmit ASM ranging signals in order of A1 B1 C1; B1 C1 A2, C1 A2 B2, A2 B2 C2.....

Therefore, if the transmission period is 6 seconds, it allows 225 base stations to transmit the signals once in the period. The base station capacity of ASM-TER R-mode network can be up to 225. If the transmission period is extended, the capacity of the base station can be increased correspondingly, but the location update rate of the user receiver will be decreased accordingly.

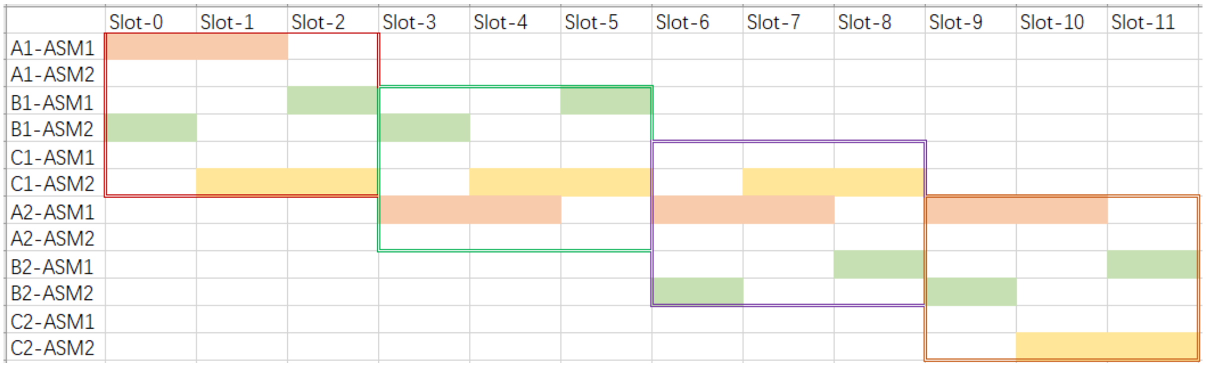

Figure 15 ASM ranging signal synchronous transmission slot diagram

4.2.2. Asynchronous Transmission

The asynchronous transmission rule of the base station ranging signal is shown in Figure 5. The base station management system firstly numbers the base stations according to the position as No1, 2, 3, 4, 5, 6, etc. At the beginning of the transmission period (for example 6 seconds), the ranging signal is transmitted on the same channel (ASM1 or ASM2) in sequence in the order of numbers.

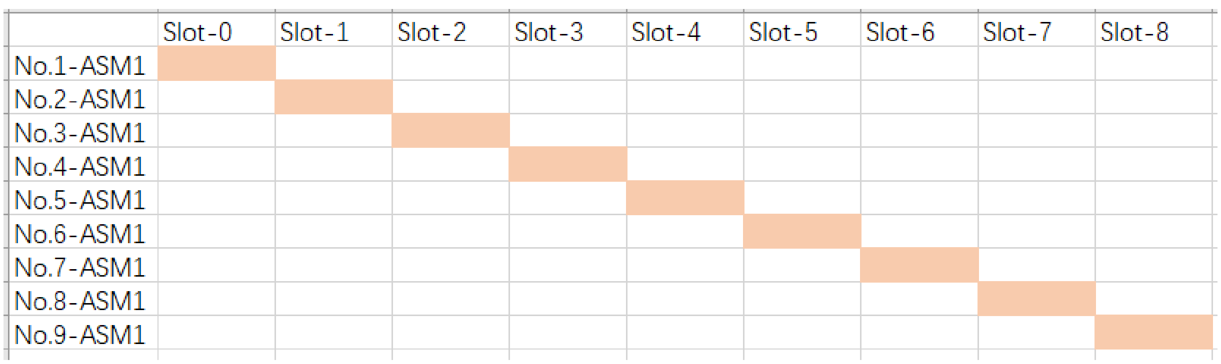

Figure 16 ASM ranging signal asynchronous transmission slot map

Similarly, if each transmission period is 6 seconds, the base station capacity of the ASM-TER R-Mode network is 225.

5. APPLICATION LAYER

5.1. VDE-TER R-MODE NAVIGATION DATA

The VDES R-Mode receiver requires additional information, termed navigation data, to determine the distance to the base station utilizing the received ranging sequence.

The navigation data is transmitted via VDE-TER from a VDES base station with the link-ID 11 every minute. It accommodates information to allow a cold start and determines a position latest after 16 minutes. Up to 16 VDES

R-Mode base stations have a unique ID within the local VDES R-Mode network. Each ID of a VDES R-Mode base station is linked to clock and delay correction data and the coordinates of the phase centre of the VDES R-Mode base station.

As shown in Table 2, the navigation data comprises of the R-Mode System Time (RMST) and conversion data to UTC, and clock information of four VDES R-Mode base stations. Therefore, the relevant clock information of up to 16 VDES R-Mode base stations is received latest every 4 minutes. The coordinates of the phase centre of specific VDES R-Mode base station. Therefore, the coordinates of all relevant VDES R-Mode base stations in the network are broadcast with an update rate of 16 minutes maximum.

If the VDES R-Mode network has less than 16 VDES R-Mode base stations, the system provider may repeat the clock and delay correction information more frequently.

Table 2 Ordering and number of bits of the navigation data

Bit order in the message	Purpose		Bits per stations	Total bits of network
1	RMST	1	32	32
2	RMST to UTC conversion	1	99	99
3	Clock and delay corrections + ID	4	26+4	120
4	Validity and signal health status in the network	1	3	3
5	Coordinates of phase centre of transmitter antenna + ID	1	71+4	75
6	γ factor of concatenated ranging sequences	1	2	2
	Total bits		241	331
	Spare bits for future use			101
	Total bits (link-ID 11)			**432**

5.1.1. CONTINUOUS R-MODE SYSTEM TIME

The R-Mode system uses a continuous time scale which can be converted to UTC at any time. To be in line with the number of leap seconds of GPS and Galileo the RMST start epoch is defined as 13 seconds before midnight between 21st August and 22nd August 1999 UTC.

The R-Mode system accommodates the RMST which is represented by 32 bits.

Table 3 RMST by week number (1-4096) and time of week (0-604799s)

Parameter	Definition	Bits	Scale factor	Unit
WN	Week number	12	1	Week
TOW	Time of week	20	1	s

TOW and WN refers to the beginning slot 0 of current VDES frame (60 s length).

5.1.2. TRACEABLE RMST TO UTC

The RMST is established by the VDES R-Mode service provider which is usually the national maritime service provider. Neighbouring regions or countries may have deviating RMST. The RMST shall be traceable to UTC to enable positioning by VDES R-Mode from different regions and with other navigation systems, such as GNSS and MF R-Mode. Otherwise, the system time offset would have to be estimated at the user site.

Table 4 RMST UTC conversion

Parameter	Definition	Bits	Scale factor	Unit
	Constant term of polynomial	32*	2^{-30}	s
	1st order term of polynomial	24*	2^{-50}	
	Leap second count before leap second adjustment	8*	1	s
	UTC data reference time of week	8	3600	s
	UTC data reference week number	8	1	Week
	Week number of leap second adjustment	8	1	Week
	Day number at the when a leap second adjustment becomes effective	3**	1	Day
	Leap second count after leap second adjustment	8*	1	s

*Parameters are two complements, with the sign bit (+/-) occupying the Most Significant Bit (MSB).

** The value range of DN is from 1 (=Sunday) to 7 (Saturday)

Depending on the realisation traceability can be reached as shown in Figure 17 below.

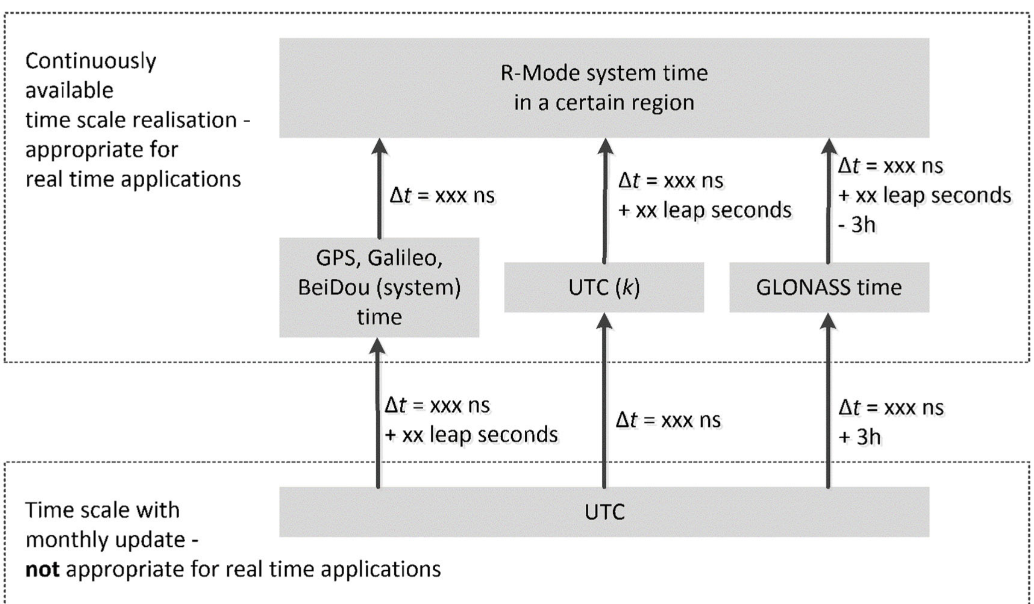

Figure 17 Traceability of RMST to UTC

5.1.3. Clock and Delay Corrections

The clock of the base station provides offset of transmission of VDE ranging message, and other delays as offset to the RMST. The clock error is given by an offset (CO) and its uncertainty (CU) as 1σ confidence level. The parameters CO and CU are defined in Table 5.

Table 5 Parameter to describe clock effect of transmitted signal (26 bits)

Parameter	Definition	Bits	Scale factor	Unit
CO	Clock offset	21	10^{-10}	s
CU	Clock uncertainty	5		

The 5 bits of CU offer 32 levels *n* of uncertainty, using u = k^n-1 and k=1.25. It describes uncertainties ranging from 0 to about 1008 ns. The value 0 defines out of range or overflow.

5.1.4. Navigation Data Validity and Signal Health Status

The network provider or each base station shall provide the validity status of provided navigation data and the signal health status. The parameters are defined in Table 6.

Table 6 Parameter navigation data validity and signal health status (3 bits)

Parameter	Definition	Bits	Scale factor	Unit
DVS	Navigation Data validity status 0 - Navigation data valid 1 - Working without guarantee	1	N/A	dimensionless
HS	Signal Health Status 0 - Signal OK 1 - Signal out of service 2 - Signal will be out of service 3 - Signal currently in test	2	N/A	dimensionless

5.1.5. Coordinates of transmitter antenna

The coordinates of the transmitter antenna are given in WGS84 as latitude, longitude, and altitude. To reach better than decimetre accuracy, a scaling factor of $7*10^{-7}$ is used for latitude and longitude.

In addition, four bits are set for which of the 16 base stations of the covered area the coordinates are transmitted. The ID of the VDES R-Mode base station is set by the network operator and shall remain constant within a supported VDES R-Mode area.

Table 7 Antenna position in WGS84 (75 bits)

Parameter	Definition	Bits	Scale factor	Unit
LO	longitude	29*	$7*10^{-7}$	°
LA	latitude	28*	$7*10^{-7}$	°
AL	Altitude**	13	1	m
ID	Base station identifier (set by network provider)	4		

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the Most Significant Bit (MSB).

** Please the calculation of the altitude below.

The altitude h_a can have values from -200 m to 7991 m. It is given by the equation below.

$$h_a = AL - 200 \quad (m)$$

5.1.6. γ FACTOR OF RANGING SEQUENCE

The γ factor determines how the sequences are concatenated and is set by the following bit sequence. This sequence is unique for the base station with the given coordinates.

Table 8 The chosen γ factor for concatenating ranging sequence is communicated for the indicated base station.

Parameter	Definition	Bits
γ	1	00
	0.7	01
	0.3	10
	0	11

5.2. ASM-TER R-MODE NAVIGATION DATA

The navigation data is transmitted via ASM-TER from a VDES base station with the link-ID 48 every 6 seconds. Scheduled broadcast ASM message #10 can be used to transmit ASM-TER R-Mode navigation message. Its training sequence can be used to obtain ranging values. The navigation message is as shown in Table 3. It comprises of the source station information, UTC time, and differential correction parameter.

Table 9 ASM-TER R-Mode navigation message format

Parameter	Length(bit)	Comment
Message ID	4	Identifier for Message 10; always 10
Source ID	32	MMSI number of source station
Reserved	4	Set to 0
Shore station longitude	28	Longitude in 1/10 000 min
Shore station latitude	27	Latitude in 1/10 000 min
Shore station height	12	0-4094 m
UTC year	14	1-9999
UTC month	4	1-12
UTC day	5	1-31
UTC hour	5	0-23
UTC minute	6	0-59
UTC second	6	0-59
Synchronization States	2	0.GNSS valid； 1.GNSS short-term invalid； 2. GNSS long-term invalid， synchronized with reference station； 3. GNSS long-term invalid and is not synchronized with the reference station。
Slot number /Communication status	TBD	TBD
Differential correction parameter	TBD	Set to 0
Reserved	TBD	Set to 0
Total	352	

6. DEFINITIONS

The definitions of terms used in this IALA document can be found in the International Dictionary of Marine Aids to Navigation (IALA Dictionary) and were checked as correct at the time of going to print. In addition, the terms below are defined. Where conflict arises, the IALA Dictionary should be considered as the authoritative source of definitions used in IALA documents. In addition, for this document specifically:

Accuracy	The degree of conformance between the estimated value of a parameter at a given time and its true value at that time.
Availability	The percentage of time that a system (or a system element) is performing a required function under stated conditions. Non-availability can be caused by scheduled or unscheduled interruptions.
Continuity Risk	The probability that a system (or a system element) remains available over a specified Continuity Time Interval, assuming it was available at the beginning of the interval.
Continuity Risk	Continuity Risk is calculated as one minus the Continuity requirement; for example, the Continuity requirement of 99.97% per 15 minutes is equivalent to a Continuity Risk of 3e-4 per 15 minutes.
Continuity Time Interval	The time-period required to complete an operation during which continuous availability of a system (or a system component) is required.

DRMS Accuracy	The Root Mean Square value of the Horizontal Position Error.
Global Navigation Satellite System(s)	Any combination of one or more of the following systems that provide autonomous geo-spatial positioning with global coverage. GNSS includes, GPS, GLONASS, Galileo, Beidou and other Regional Navigation Satellite System (RNSS) such as Indian Regional Navigation Satellite System (IRNSS) and Quasi-zenith Satellite System (QZSS).
Hazardously Misleading Information	The occurrence of a position fix with Horizontal Position Error larger than the Horizontal Alert Limit without an alarm being raised within the Time to Alarm.
Horizontal Alert Limit	The maximum tolerable Horizontal Position Error for a given application/phase of voyage. Typically, this is set as 2.5 times the corresponding R95 Accuracy requirement for the application.
Horizontal Position Error	The distance between the true position of a sensor at a given time and the projection of the estimated position onto the local tangent plane containing the true position at that time.
May	May expresses permissive guidance.
Multisystem Shipborne Radionavigation Unit	Multisystem Shipborne Radionavigation Unit means a multisystem shipborne radionavigation receiver/transceiver.
Passive Ranging Service	Passive Ranging Service means the provision of VDES R-Mode navigation data and passive ranging observables.
Positioning Availability	The percentage of all positioning epochs in any given period for which an external PNT processor has a position fix and can guarantee its integrity. Non-availability can be caused by a range of factors such as: Loss of navigation data; insufficient number of visible ranging signals; receiver fault; inability to perform integrity monitoring (due to insufficient number of visible ranging signals or poor HDOP); fixes which are determined by the integrity monitor to represent a risk; and fixes for which the determined level of integrity is not sufficient to meet the requirements.
Positioning Continuity	The probability that a user will be able to determine position with specified accuracy and is able to monitor the Integrity of the determined position over a specified Continuity Time Interval applicable for a particular operation. It is assumed that, at the beginning of the operation, the user equipment is fault-free, and the system is available. Events which cause loss of Continuity are the same ones which cause loss of Positioning Availability with the exception of events which can be forecast, such as poor HDOP or announced down-time of some aspect of the system.
Positioning Integrity	The ability of a system to provide timely warnings to users when the system should not be used for navigation. It is usually specified in terms of an Integrity Risk, a Horizontal Alert Limit and a Time to Alarm.
Positioning Integrity Risk	The probability of the user being presented with Hazardously Misleading Information at any time during a stated operation window.
R95 Accuracy	R95 Accuracy means the Horizontal Position Error not exceeded with a probability of 95%.
Radio Station	The single facility where one or more transmitters, receivers, or transceivers, including the accessory equipment is established for two-way communication via radio waves.

Service Area	The geographical area designated by the VDES R-Mode system provider within which the system is expected to meet all requirements applicable to the Navigation Data Output Function and Passive Ranging Observables Function as specified in this document.
Service Availability	The percentage of time a given service meets all requirements applicable to that service stated herein.
Shall	Shall expresses a characteristic which is to be present in the item which is the subject of the specification, i.e. 'shall' expresses a binding requirement.
Should	Should expresses a target or goal to be pursued, but not necessarily achieved.
Station	Station means a facility in which equipment is housed and used to support safe navigation.
Time of Arrival	Time of Arrival is the absolute time instant when a radio signal emanating from a transmitter reaches a remote receiver.
Time of Transmission	Time of Transmission is the absolute time instant when a radio signal emanates from a transmitter
Transmission Time	Transmission Time is the measurement of the time taken by a wave to travel a distance through a medium. Measured between Time of Transmission and Time of Arrival.
User	User means a machine (such as the Multi-system Shipborne Radionavigation Receiver or similar) that makes use of the navigation data and observables produced by the VDES R-Mode System to determine position, speed over ground, coarse over ground and time.
User Range Accuracy	User Range Accuracy means an estimate of the one-sigma range error to a Base Station due to the intrinsic Base Station and reference Time Source errors.
VDES R-Mode Base Station	VDES R-Mode Base Station means a Radio Station installed at a fixed, known location, capable of being used by a VDES R-Mode Sensor as a reference object for ranging or pseudoranging.
VDES R-Mode Sensor	VDES R-Mode Sensor means a Radio Station, typically installed on a ship, capable of using VDES to obtain range or pseudorange measurements to VDES R-Mode Base Stations.
Will	Will expresses a declaration of intent on the part of IALA. 'Will' does not express a binding requirement. 'Will' may also be used to express simple futurity.

7. ABBREVIATIONS

1PPS	One Pulse Per Second
ARAIM	Advanced Receiver Autonomous Integrity Monitoring
CRC	Cyclic Redundancy Check
CTI	Continuity Time Interval
EIRP	Effective Isotropic Radiated Power
FMS	Far-field Monitoring Station
GNSS	Global Navigation Satellite System(s)
HAL	Horizontal Alert Limit

HMI	Hazardously Misleading Information
HPE	Horizontal Position Error
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IR	Integrity Risk
MCC	Monitoring and Control Centre
MCS	Monitoring and Control Station
MRAIM	Maritime RAIM
MSR	Multisystem Shipborne Radionavigation Receiver
MSRU	Multisystem Shipborne Radionavigation Unit
PKI	Public Key Infrastructure
PNT	Positioning, Navigation and Timing
RF	Radio Frequency
RMS	Root Mean Square
RMST	R-Mode System Time
SA	Service Area
SINR	Signal-to-Noise-and-Interference Ratio
TBC	To Be Confirmed
TBD	To Be Defined / Determined
TOA	Time of Arrival
TOT	Time of Transmission
TTA	Time to Alarm
URA	User Range Accuracy
VDES	VHF Data Exchange System
VRM	VDES R-Mode
VRMS	VDES R-Mode Sensor
WAN	Wide Area Network

8. REFERENCES

The following documents are referred to in this document:

[1] IMO-MSC.401(95), 'IMO Resolution MSC.401(95)', Performance Standards for Multi-system Shipborne Radionavigation Receivers.

[2] RMB-B&P-1v0, 'R-Mode Baltic - Baseline and Priorities', Issue 1.0, March 2019.

[3] IALA. 2019, 'Stakeholder Requirements for R-Mode', Input document no. ENAV24-6.1.17.3, ENAV24.

[4] 'System Requirements for VDES R-Mode', 18/06/2019, v0.2

[5] IALA. Recommendation R-129 GNSS Vulnerability and Mitigation Measures

[6] ITU-R M.2092-1 (2/2022) – The Technical Specification of VDES

[7] ISO/IEC/IEEE 31320-1:2012 Information technology — Modeling Languages — PART 1: Syntax and Semantics for IDEF0

ANNEX A INFORMATIVE CONTENT – FOR DEEPER UNDERSTANDING

A.1. REPORTS OF TRIALS (INFORMATIVE)

Figure A 1 A1 shows theoretical bounds describing the performance for different gamma combining both sequences. The performance curves for low SNR show a better performance of the Gold codes. For a ranging performance of better than 100 m the combined version improves by 4dB, and for ranging performances better than 10 m the pure alternating sequence is best. However, the further performance gains are marginal.

The search for an optimized gamma using an AWGN channel results in the best ranging performances shown in Figure A2.

Figure A3 compares both sequences in measurements on the Ammersee. The applied transmit power was 30 dBm using a 100 kHz VDE waveform with both different codes individually. Measurements using a 100 kHz signal comparing the ranging performances of the Gold codes and the alternating sequence with a $\gamma = 0$ (Gold code in red) and $\gamma = 1$ (alternating sequence in blue).

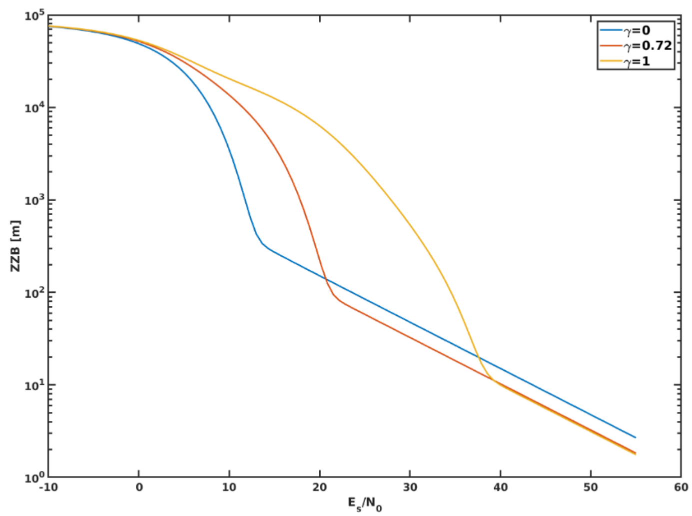

Figure A 1 Theoretical (Ziv-Zakai bound) for combined sequences versus Gold and alternating sequence. The proposed weighting factor $\boldsymbol{\gamma = 0.72}$

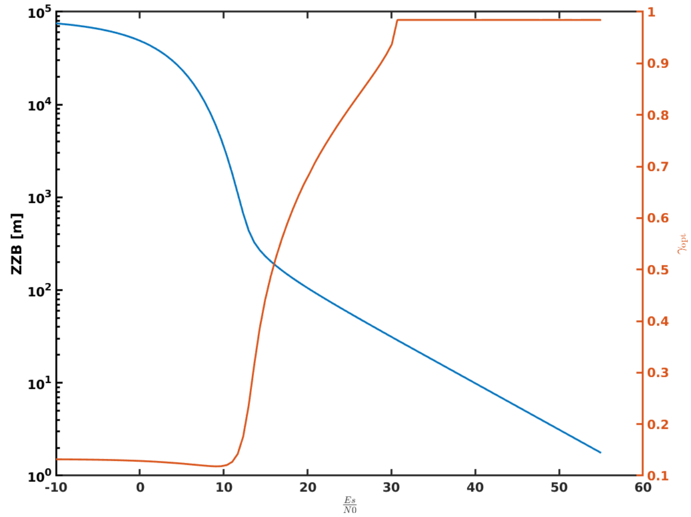

Figure A 2 Showing the ranging performance for the optimal weighting factor $\boldsymbol{\gamma}$

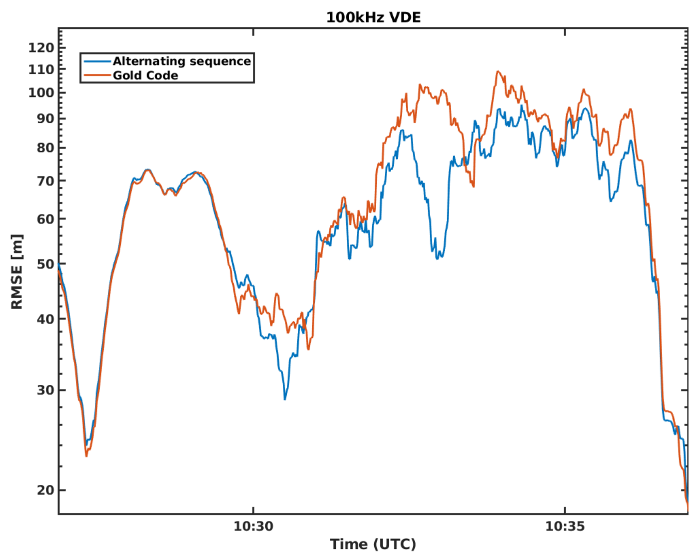

Figure A 3 Measurement of results

A.2. TIME SOURCE FOR R-MODE VDES BASE STATIONS

A well synchronized network of R-Mode transmitters is the precondition of the R-Mode system. At any point in time, each transmitted ranging signal has to have a well-known time delay with respect to a time reference here referred to as R-Mode system time (RMST), which will locally be provided by a timing device(S). Therefore, each R-Mode VDES base station must use:

- Pulse Per Second (1PPS) and
- 10 MHz sinusoidal signal

of the external timing device as a time-base for all internal clocks which are used for the ranging signal generation. Coherence between the signals at the electrical reference plane is mandatory; the 1PPS carries the traceable timing used for disambiguation of the cycles of the 10 MHz signal.

The datum of the 1PPS is communicated to the VDES base station as part of a data channel using an appropriated serial interface. Beside R-Mode VDES base stations also R-Mode monitoring stations are synchronized to RMST (S).

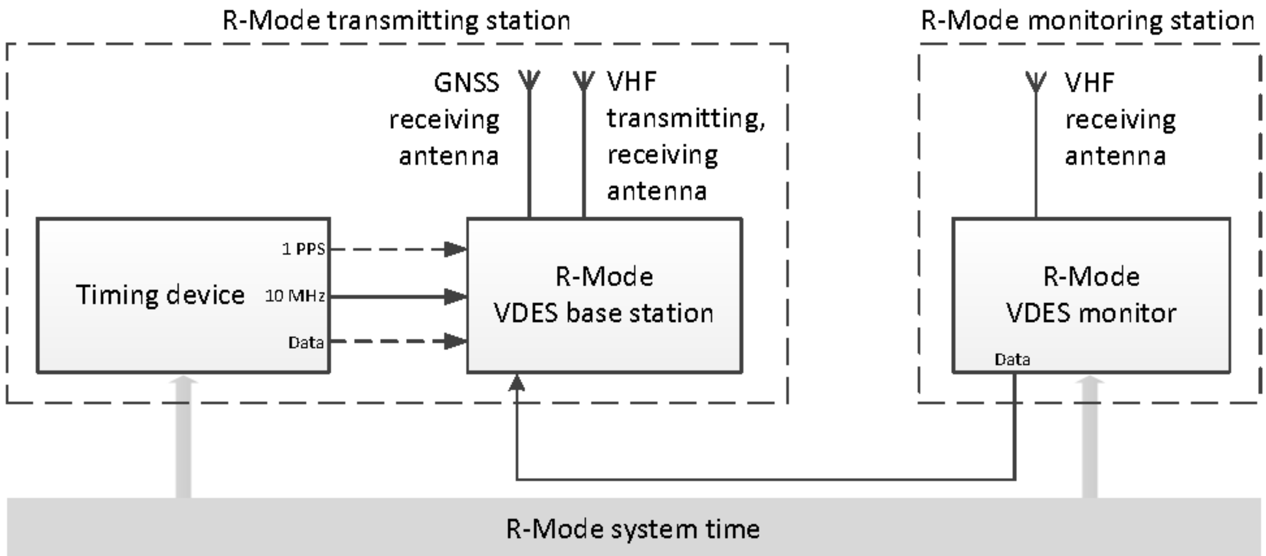

Figure A 4 Synchronization of R-Mode transmitter and monitor with RMST

Figure A4 illustrates synchronization of R-Mode transmitter and monitor with RMST (1 PPS and data link from timing device has an optional external interface – could also be integrated in the VDES base station).

The local timing device, which is connected to the R-Mode VDES base station, has to be regularly synchronized with RMST. To keep a high performance of the R-Mode system in times, when synchronization is not possible, each timing device has to provide hold over capabilities.

The following requirements are based on the assumption that the R-Mode VDES base station time device has to provide signals with less than 10 ns error with respect to the RMST. This error may only be exceeded if the synchronization with RMST was not possible for at least two hours [2].

In the following the Maximum Time Interval Error (MTIE) and Time Stability (TDEV) are used as measures for the time device performance.

The given numbers below are minimum requirements. It might be necessary for certain regions or maritime applications that higher requirements on the time device will be defined.

A.2.1. R-MODE SYSTEM TIME

For each area of service RMST has to be defined/specified. It is suggested to tie RMST to other well established and accessible references of time.

RMST may be based on:

1 Realizations of Coordinated Universal Time, UTC(*k*), as realized by national metrological institutes [3]. Combinations of several UTC(k) spanning different administrations need to be communicated and applied by the timing devices.

2 Constellation time of one or more GNSS (e.g., Galileo, GPS, GLONASS, BeiDou, etc.). In this case RMST will be the same as the GNSS time. Combinations of different GNSS need to take system offsets into account.

3 This approach faces the problem that UTC, which would be best choice as RMST, is not defined continuously.

3 Central timing scale. It is strongly suggested to keep the time scale traceable to UTC and regularly publish its offset and uncertainty.

Numerically, RMST shall be expressed with nanosecond resolution and with respect to the R-Mode epoch, which shall be suitably defined. Handling of leap seconds is in general discouraged; a leap second offset should be published, if necessary, for the application.

A.2.2. TIME SYNCHRONIZATION

All R-Mode transmitter sites, which are usable for R-Mode based positioning within the region of service, must be synchronized to RMST with the required time accuracy level. Typical time synchronization methods would be:

1 Wired time transfer could be based on optical fibre networks, such as White Rabbit/PTP[4] protocol.

2 Derive timing information from GNSS to discipline a local clock.

3 Use signals and data channel of VDES R-Mode to distribute RMST in the network.

4 GNSS receiver time solutions, representing GNSS system time[5]. To increase robustness of time synchronization, special services like Galileo PRS and/or OS-NMA could be used.

Any synchronization technique is required to be regularly calibrated with appropriated calibration methods. Calibration results need to be propagated to the R-Mode system in order to be applicate.

Requirements on timing performance with respect to RMST when the time device is nominally synchronized as follows:

- MTIE < 10 ns at all times.
- MTIE < 1 ns at 5 s time intervals.

A.2.3. TIME HOLD OVER

The time synchronization between the timing device and RMST might be disrupted. In this case, the R-Mode transmitter must continuously provide useable ranging signals for at least two hours. For this, a sufficiently stable local oscillator is needed, thus the free-running clock shall have the following general statistics:

- Short term 60 s TDEV shall be < 0.1 ns
- Medium term 2 h TDEV shall be < 1 ns

When losing synchronization and the timing device switches to a hold-over state, the device shall have the following characteristics with respect to the RMST:

- Short term 60 s MTIE shall be < 1 ns
- Medium term 2 h MTIE shall be < 10 ns

A.2.4. TIMING UNCERTAINTY AND CLOCK ERROR MODEL

Development of ranging errors can partly be described by a clock error model, which in turn can be used to minimize range errors and allow timing uncertainty propagation into the R-Mode positioning solution uncertainty. Timing uncertainties are a combination of calibration errors, modelling errors and local oscillator instabilities in hold over

4 IEEE-1588

5 The use of PT receiver solutions to access GNSS system time is in general discouraged.

mode. It is recommended to describe the clock error with three parameters: (1) phase error, (2) frequency error and (3) frequency drift error referenced to the estimation epoch. Every error estimate is accompanied with its estimation uncertainty. The phase error and its uncertainty shall also accumulate the result from the current calibration. Likewise, the instability of the above parameter set of the free running oscillator shall be described in terms of an Allan Deviation.

The ranging user shall either[6] infrequently (hours) receive a parameter set (synchronization status + epoch + model + uncertainty + Allan), or frequently (<minutes) receive phase error and uncertainty estimates calculated by the timing device. With infrequent model transmissions, other mechanisms need to be used to communicate the parameter set.

A.2.5. SPECIFICATION OF DATA CHANNEL PROTOCOL

The time device should continuously report every second over the data interface:

- Connection status to the source of RMST (connected or not).
- Synchronization status (within defined accuracy level or outside).
- Disambiguating time code of RMST.
- Time difference to RMST.
- Estimated error of time difference.

A.3. CLOCK AND DELAY CORRECTION

A.3.1. ASSUMPTIONS

The VDES error budget for the slot transmission time is 100 µs. Start of transmission of the fixed correlation sequence must be derived by the receiver. Nominal time of start of slot/frame is estimated from the frame number within the minute of frame transmission. Start of transmission is erroneous by an amount of time due to static calibration offsets, clock offsets and dynamic delays of the transceiver chain caused by aging or environmental sensitivity. The R-Mode timing device, a monitoring input and/or, possibly, other means may provide information about this time offset and the accompanying estimation uncertainty.

A special case arises when synchronization of the local oscillator clock is lost, and the free running clock's instability causes unpredictable development of the start of frame timing. The clock used for signal timing is required to have its frequency stability specified or measured; expressed in terms of an Allan Variance describing the statistics of the specific clock (or type) over relevant time intervals. The variance shall be used to estimate the station timing uncertainty during the time the synchronization to RMST is lost. This function is internal to the timing device, which shall frequently relay the state of its synchronization and timing uncertainty of synchronization and hold over to the application layer of R-Mode.

A.3.2. TIME RESOLUTION

R-Mode is sensitive to mutual time errors of about 10 ns. The timing error estimate and its uncertainty should at least have a resolution one order better than the timing requirement. A choice of 1 ns resolution would be practical.

6 Other, more optimal combinations of communicating clock error statistics are of course possible

A.3.3. UPDATE RATE

We consider Rubidium atomic oscillators as the frequency standards with the lowest performance level required for R-Mode. Typically, the best frequency stability can be expected to be around some minutes of integration time, in the order of 1e-12 ADEV. The used synchronization method would normally require other, often longer, integration times (e.g., 10 … 60 minutes for GPS C/A receivers), restricting the rate of phase and/or frequency changes to the clock or a synthesizer.

The update rate shall be such that the offset estimate communicated to the user is of significance. It is reasonable to require that R-Mode synchronization of the clock to be done with fractional frequency uncertainties of maximal 1e-11, which corresponds to about 10 ps time error per second. Thus, an update rate of 60 s would suit Rubidium stability and 1 ns time resolution. Local oscillators with higher stability will allow the update rate to be decreased. Figure A5 shows the time Allan deviations over different averaging time spans.

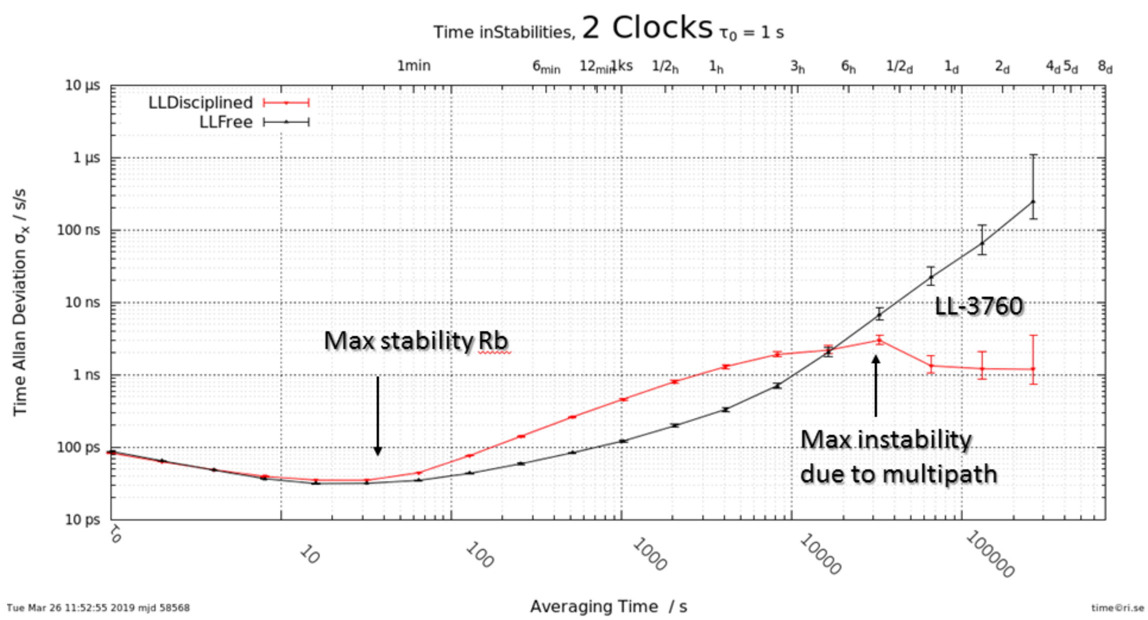

Figure A 5 Time Allan Deviation over different averaging time spans

A.3.4. OFFSET AND UNCERTAINTY DYNAMICS

The offset that needs to be relayed is bounded by the allowable slot timing error of ± 100 µs. With 0.1 ns resolution 21 bits would offer ±105 µs. Table A1 defines the time offset distribution.

Uncertainty of the timing error is in principle bounded to the same dynamics as the offset. However, uncertainties much larger than the timing requirements of R-Mode are not meaningful, because users that assess the uncertainty would reject range measurement above a certain level of uncertainty. It is recommended to introduce an exponential scale expressing the uncertainty in uneven steps but with the same resolution as the time offset. The oscillator depicted above has a free running statistical time deviation of 1 µs over an integration time of several days. 5 bits offer 32 levels *n* of uncertainty, using $u = k^n-1$ and k=1.25, describes uncertainties ranging from 0 to about 1008 ns. Which is coded in Table A 2 Uncertainty of the clock, and 0 defines out of range or overflow.

Table A 1 R-Mode time offset distribution

Offset	21 bits	int21_t	$\Delta t = n/10^{10}$ [ns]
Uncertainty	5 bits	uint5_t	$u=k^n-1$ and k=1.25
Update rate	60 s		

Table A 2 Uncertainty of the clock

Level of uncertainty: n	Uncertainty in [ns]: u	
0	0	Out of Range (OOR)
1	0.25	
2	0.56	
3	0.95	
…		
30	806.79	
31	1008.74	

A.4. MODELLING CONVENTIONS

A.4.1. IDEF0

IDEF0 is part of the ICAM Definition for Function Modelling (where ICAM stands for Integrated Computer Aided Manufacturing) family of modelling languages, used to produce a structured representation of the functions, activities or processes within a system or subject area.

IDEF0 defines two basic semantical elements: functions and flows (of resources, energy or information).

A *function* is a transformation that turns inputs into outputs, represented by a box annotated with a verb-noun phrase and a number which provides context within the model.

A *flow* is represented by an arrow or an arc labelled by a noun phrase. The label represents the items being passed to/from the function to which the flow is attached.

Inputs enter the function box from the left, *controls* that guide the transformation of inputs into outputs enter from the top, *mechanisms* (physical resources that perform the function) enter from the bottom and *outputs* leave from the right, as illustrated in the diagram below.

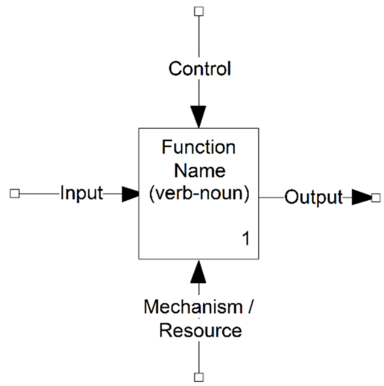

Figure A 6 IDEFO-1 IDEFO Box format

For clarity, the number of functions in an IDEF0 diagram should not exceed five or six. An IDEF0 diagram thus usually represents a particular *viewpoint* from which the system is observed rather than the system in its entirety.

For more information on IDEF0, see for example the *IEEE 31320-1-2012* standard.