R-Mode Baltic - Baseline and Priorities

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0.3	12/10/2018	60	Completion of the text	Various
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This report was created within the framework of the **R-Mode Baltic** project, which aims to develop and demonstrate a new maritime backup system for Position, Navigation and Time (PNT) purposes based on R-Mode technology. Within the project life time of three years the project consortium develops solutions for R-Mode transmitter and receiver prototypes, for independent time synchronisation of broadcasting stations and for a testbed concept and its deployment. The dissemination of R-Mode technology is supported by work in international standardisation bodies. The world's first operational testbed for a transnational R-Mode system will be completed by the project consortium in 2020.

The R-Mode Baltic project is co-financed by the European Regional Development Fund within the Interreg Baltic Sea Region Programme.

Executive Summary

The general target of this report is to define service requirements and perform an analysis in order to develop specifications for the new Ranging Mode (R-Mode) positioning system necessary when Global Navigation Satellite Systems (GNSS) are corrupted or unavailable. An R-Mode system independent of GNSS can minimise risks and improve safety of navigation. This report provides an analysis and evaluation of the current international legal documents treating about maritime radionavigation systems in the light of possible backup to GNSS and global perspectives to solve that problem.

Special attention has been paid to show the interoperability of the R-Mode service for use in international waters as well as the ability to exploit existing infrastructure of medium frequency (MF) radio beacons and/or Automatic Identification System (AIS) or Very high frequency Data Exchange System (VDES) base stations working within Very High Frequency (VHF) band. It is also indented to demonstrate that the R-Mode technology does not interfere or degrade legacy systems and signals currently in use. There is no intention to change any existing frequency distribution, available bandwidths or modulation schemes assigned to existing services defined by the International Telecommunication Union Radiocommunication Sector (ITU-R) or other regulatory bodies.

First two chapters deliver a review of regulatory documents in maritime navigation provided by International Maritime Organization (IMO), International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), ITU-R and European Maritime Radionavigation Forum (EMRF). The following section provides an overview of existing resolutions of navigation committees including Position, Navigation and Timing (PNT) development and e-Navigation strategy. Review of IALA documents shows the GNSS vulnerability and mitigation measures, like alternative means of navigation provided at various levels; fully redundant, backup and contingency. Then we have a description of differential GNSS (DGNSS) services in MF band and recommended provision of IALA radio beacons. This deals also with the possibility of integrated use of MF DGNSS and VHF AIS broadcasts within the scope of the IMO Performance Standard for Multisystem-Radionavigation Receivers. AIS operational features and the recommended system management are further elaborated in IALA and ITU-R documents. The VDES will be developed in the near future and can also be used as a signal of opportunity for R-Mode service. The importance of R-Mode as a source for robust and resilient PNT information is furthermore recognized in the current European Radio Navigation Plan which was published in 2018. The R-Mode service was there described as a possible backup for GNSS in both maritime and inland waterway areas.

Chapter 3 is devoted to Terrestrial Radionavigation Systems (TRS) and their ranging methods. Several well-known but historical TRS like Radio Direction Finding (RDF), DECCA, Long Range Navigation (Loran) and some still in use (e-Loran, Chayka) are described. The chapter concludes with a prediction as to the likely future mix of applied ranging methods and algorithms of phased out historical systems with the potential use of existing DGNSS and/or AIS land-based infrastructures to be re-used for R-Mode system.

Finally, location techniques are mentioned which are used in cellular networks. Every GSM (Global System for Mobile Communications) base station broadcasts its cell-ID to the terminals, so at all times the terminal is aware which base station is serving. In the simplest solution, the position of the mobile terminal is assumed to be the position of the base station currently serving the terminal. There are also described other methods and algorithms.

Chapter 4 presents an impact to R-Mode from other projects. The results of a review of other ongoing projects round the globe were summarised with regard to alternative positioning methods which satisfy different navigation requirements. The European INTERREG IVb North Sea Region Programme project ACCSEAS (2012-2015) developed the idea of R-Mode by supporting a feasibility study, which considered the addition of ranging information to marine MF radio beacons (DGNSS) and AIS base stations. The study stated that AIS R-Mode was feasible with the existing signal structure, but that DGNSS R-Mode would be greatly improved by actually modifying the signal, adding one or two continuous wave (CW) signals to the broadcast. In most of the maritime areas of the North Sea it appeared that 10 meter or better performance could be achieved via R-Mode[1].

Chapter 5 There are considerations on R-Mode general user applications and resulted requirements. Several factors are considered in determining the set of required parameters to be provided by a potential backup to GNSS as a component of the PNT system. These factors should include operational, technical, economical, radio frequency spectrum allocation or geographical limitations. Certain parameters like anti-jamming immunity, can also affect civil PNT service availability. Finally, basic requirements for a terrestrial GNSS backup system were extracted based on appropriate documents of IMO and IALA. Relevant parameters are presented in tables for the R-Mode system requirements.

Chapter 6 Contains the review of potential error sources influencing R-Mode system positioning and time. Methods of mitigation and suggested algorithms are listed for MF radio beacon as well as for VHF AIS base station ranging. Attention is also paid to propagation effects like signal delay and skywave interference.

Chapter 7 There are conclusions of the report, the most important are:

- International documents of IMO and IALA express the need of a GNSS backup system with an independent source of positioning and timing information.
- Solutions are in the radio frequency domain so-called Signals of Opportunity (SoOP).
- The terrestrial R-Mode system is proper and resorted solution referring to IALA, IMO, ITU-R documents. R-Mode technology qualifies as a backup that meets the resilient PNT requirement of the IMO e-Navigation strategy.
- It is recommended to use the existing terrestrial infrastructure of DGPS and/or AIS base stations to introduce the R-Mode Baltic service.
- The R-Mode system is able to meet ITU-R requirements.

The new R-Mode system will be of transnational relevance because derived requirements will serve as an input for the standardization of R-Mode on an international level. Once it is accepted by standardisation institutions it may have an impact on the changeover from existing maritime infrastructure towards R-Mode capable base stations world-wide.

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1) During day-time or if a combination of MF, VHF or eLORAN-signals are used.

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Abbreviations

AAPS	-	AIS Autonomous Positioning System
ACCSEAS	-	Accessibility for Shipping, Efficiency Advantages and Sustainability
ADC	-	Analog-Digital-Converter
AGPS	-	Assisted GPS
AIS	-	Automatic Identification System
ARPA	-	Automatic Radar Plotting Aid
ASM	-	Application Specific Messages
AtoN	-	Aids to Navigation
BAM	-	Bridge Alert Management
BDS	-	BEIDOU Satellite Navigation System – Chinese GNSS
BeiDou	-	Chinese satellite navigation system
BSH	-	Federal Maritime and Hydrographic Agency
BTS	-	Base Transceiver Station
CCRP	-	Consistent Common Reference Point
CCRS	-	Consistent Common Reference System
CID	-	Cell ID
CMDS	-	Common Maritime Data Structure
COG	-	Course over Ground
CPS	-	Cambridge Positioning Systems
DGNSS	-	Differential GNSS
DOP	-	Dilution of Precision - A measure of the receiver-satellite(s) geometry
ECDIS	-	Electronic Chart Display and Information System
EDAS	-	EGNOS Data Access Service
EGNOS	-	European Geostationary Navigation Overlay Service
eLORAN	-	Enhanced LORAN
EMRF	-	European Maritime Radionavigation Forum
eNB	-	Evolved Node-B (base station in the LTE system terminology)
ENC	-	Electronic Navigational Chart
E-OTD	-	Enhanced Observed Time Difference
EPFS	-	Electronic Position Fixing System
EU	-	European Union
GAGAN	-	GPS-aided Geo-augmented Navigation system –

		Indian SBAS
GAL	-	Galileo – European GNSS
GB	-	Great Britain
GBAS	-	Ground-Based Augmentation System
GLA	-	General Lighthouse Authority
GLONASS	-	Global Navigation Satellite System – GNSS provided by Russia
GMDSS	-	Global Maritime Distress and Safety System
GNSS	-	Global Navigation Satellite System
GPS	-	Global Positioning System –GNSS provided by USA
GSM	-	Global System for Mobile Communications
HDG	-	Heading
HDOP	-	Horizontal DOP
HNSE	-	Horizontal Navigation System Error
HPE	-	Horizontal Position Error
HPL	-	Horizontal Protection Level (as estimate of HPE)
HSC	-	High-Speed Craft
HW	-	Hardware
I	-	Integrity data
IALA	-	International Association of Marine Aids to Navigation and Lighthouse Authorities
ICAO	-	International Civil Aviation Organization
IMO	-	International Maritime Organization
INS	-	Integrated Navigation System
ION	-	Institute Of Navigation
IRNSS	-	Indian Regional Navigation Satellite System
ITU	-	International Telecommunication Union
ITU-R	-	ITU Radiocommunication Sector
LF	-	Low Frequency
LMU	-	Location Measurement Unit
LOP	-	Line of Position
LORAN	-	Long Range Navigation
LTE	-	Long Term Evolution
MF	-	Medium Frequency
MOG	-	Maritime Office in Gdynia
MSAS	-	MTSAT (Multi-functional Transport Satellite) – Japanese SBAS

MSC	-	IMO Maritime Safety Committee
NAV	-	Safety of Navigation Sub-Committee
NCSR	-	Navigation, Communication and Search and Rescue Sub-Committee
NMEA	-	National Marine Electronics Association
PDOP	-	Position DOP
PNT	-	Position, Navigation and Timing
PNT-DP	-	Position, Navigation and Timing Data Processing
PNT/I	-	Position, Navigation and Time Data including associated integrity data
PNT/S	-	Position, Navigation and Time Data including associated status data
PVT	-	Position, Velocity and Timing
PVT-DP	-	Position, Velocity and Timing Data Processing
Racon	-	Radar Beacon
RADAR	-	Radio Detection and Ranging
RAIM	-	Receiver Autonomous Integrity Monitoring
RDF	-	Radio Direction Finding
RF	-	Radio Frequency
ROTI	-	Rate of Turn Indicator
RTCM	-	Radio Technical Commission for Maritime Services
S	-	Status data
SAR	-	Search and Rescue
SBAS	-	Satellite Based Augmentation System
SDCM	-	System for Differential Corrections and Monitoring – Russian SBAS
SDME	-	Speed and Distance Measuring Equipment
SOG	-	Speed over Ground
SOLAS	-	Safety of Life at Sea
Sonar	-	Sound Navigation and Ranging
SoOP	-	Signals of OPportunity
STW	-	Speed through Water
SW	-	Software
TA	-	Timing Advance
TOA	-	Time of Arrival
TRS	-	Terrestrial Ranging Systems
UERE	-	User Estimated Range Error

UK - United Kingdom

UMTS - Universal Mobile Telecommunications System

USA - United States of America

UTC - Universal Coordinated Time

U-TDoA - Uplink Time Difference of Arrival

VDE - VHF Data Exchange

VDES - VDE System

VDL - VHF data link

VHF - Very High Frequency

VPE - Vertical Position Error

WAAS - Wide Area Augmentation System

WGS84 - World Geodetic System 1984

WSV - Federal Waterways and Shipping Administration

WWRNS - World-Wide Radionavigation Systems

QZSS - Quasi-Zenith Satellite System – Japanese regional system

1 Background

Global Navigation Satellite Systems (GNSS) (today GPS, Galileo, GLONASS and BeiDou) have become the primary source of positioning, navigation and timing (PNT) for maritime operations. Furthermore GNSS-based positioning is used by many systems on vessels, like AIS (Automatic Identification System), ECDIS (Electronic Chart Display and Information System), ARPA (Automatic Radar Plotting Aid), GMDSS (Global Maritime Distress and Safety System) and other navigation sensors. Safe navigation, the protection of the marine environment and the efficiency of access to ports are highly dependent on the availability, continuity, accuracy and integrity of GNSS based positioning.

Unfortunately, it is well known that low power satellite-based systems are vulnerable to jamming and natural interference, [1]. When GNSS is corrupted or unavailable, PNT information are seriously affected resulting in an increase in risks to the safety of navigation. Unavailable PNT data, even for short periods, results in numerous alerts raised by multiple systems on the bridge systems. Hazardously misleading information may occur in position errors that are large enough to have a severe impact on navigation safety but may be small enough to remain undetected and raise no alerts. These erroneous positions as well as their derivatives (e.g. Course Over Ground (COG), Speed Over Ground (SOG)) could even go unnoticed by the mariner and significantly increase the risk of grounding or collision.

Within the overall e-Navigation strategy the IMO has identified the user need on improved reliability, resilience and integrity of bridge equipment and navigation information as one of the five prioritized e-Navigation solutions, whereby the resilient provision of PNT data ranks 2nd in line of addressed issues, [2].

Regarding the need for redundancy in position fixing system, IMO has stated that "*there would be a need to provide an internationally agreed alternative system for complementing the existing satellite navigation, positioning and timing services to support e-navigation and recognized that potential backup systems could be made available and that it would be premature to identify any specific system before the users' requirements for e-navigation had been finalized*," [3].

A variety of technological solutions provide the potential to serve this backup requirement; for example, within the radio frequency (RF) domain "Signals of OPportunity" (SoOP) can deliver possible solutions. This term refers to the opportunistic use of RF signals, typically communications signals, which already exist in the geographical area of the user receiver. While these signals are not primarily intended for positioning, a SoOP navigation receiver attempts to exploit them as such. Specifically, if each SoOP can provide a (pseudo-)range to the receiver from a known location, a trilateration position solution is possible. Even if it is impossible to derive a complete position solution from the SoOP (e.g. due to insufficient, less than three signals being present), the available pseudorange information combined with measurements from existing positioning systems provide a position solution (e.g. combined with GNSS measurements limited by natural landscape (fjords) or "urban canyons").

The IMO opened up the usage of multiple position fixing systems by the inauguration of the Multisystem - Radionavigation Receiver Performance Standard (MSC.401(95)) [4] and the associated GUIDELINES FOR SHIPBORNE POSITION, NAVIGATION AND TIMING (PNT) DATA PROCESSING (MSC.1/circ.1575), [5].

For the first time this new performance standard allows the combination of any recognised IMO World-Wide Radionavigation System (WWRNS) with terrestrial position fixing systems as well as wide area augmentation systems. The rising numbers of available ranging signals from any source benefit the determination of position accuracy and associated integrity.

This report deals with the integrated use of Medium Frequency Differential GNSS (MF DGNSS) broadcasts and Very High Frequency (VHF) Automatic Identification System (AIS) broadcasts within the scope of the IMO Performance Standard for Multisystem-Radionavigation Receivers (MSC.401)95)), [4].

An initial feasibility study on basic R-Mode performance was evaluated within the EU Interreg project ACCSEAS from 2012-2015, demonstrating the calculation of range information derived from SoOP in principle.

The importance of R-Mode as a source for robust and resilient PNT information is furthermore recognized in the current European Radio Navigation Plan (ERNP 2018), [21]. R-Mode is there described as a possible backup for GNSS in both maritime and inland waterway areas.

Taking into account all mentioned above argues the report delivers the preliminary definitions of R-Mode service requirements supported by analyse and propose solutions to create and build the new positioning system to be tested first in the Baltic Sea area.

2 Regulatory documents in maritime navigation

The following section provides an overview about existing requirements for a radio navigation system. For this purpose, existing resolutions, standards, recommendations and guidelines will be analysed.

2.1 IMO documents

This chapter contains a review of IMO documents concerning alternative to GNSS solutions and their requested parameters.

2.1.1 User requirements - Resolution A.915 (22)

The resolution formulated in 2001 the worldwide Maritime Policy and operational requirements for a Future GNSS depending on different phases of navigation and associated parameters. These requirements were specified quantitatively in several tables for proposed maritime applications using the parameters well defined in the Appendix 1of IMO Resolution A.915(22) [6]. This was a fundamental attempt of identification of system level parameters and service level parameters for vessels operating in ocean and harbour entrances, harbour approaches and coastal waters (see Table 2-1). Additional information can be found in the European Maritime Radionavigation Forum (EMRF) document “Applications and User Requirements”, [19].

Table 2-1: Table of the minimum maritime user requirements for general navigation, [6]

Phase of navigation	System level parameters				Service level parameters			
	Absolute Accuracy	Integrity			Avail-ability % per 30 days	Conti-nuity % over 3 hours	Coverage	Fix interval[2] (seconds)
	Horizontal (meters)	Alert limit (meters)	Time to alarm[2] (seconds)	Integrity risk (per 3 hours)				
Ocean	10	25	10	10^{-5}	99.8	N/A[1]	Global	1
Coastal	10	25	10	10^{-5}	99.8	N/A[1]	Global	1
Port approach and restricted waters	10	25	10	10^{-5}	99.8	99.97	Regional	1
Port	1	2.5	10	10^{-5}	99.8	99.97	Local	1
Inland waterways	10	25	10	10^{-5}	99.8	99.97	Regional	1

[1] Continuity is not relevant to ocean and coastal navigation.

[2] More stringent requirements may be necessary for ships operating above 30 knots.

2.1.2 Service requirements - Resolution A.1046 (27)

In 2011 the details of the requirements for Worldwide Radio Navigation Systems have been amended to include a requirement for ships to carry means of receiving transmissions from suitable radionavigation systems throughout their intended voyage considering vessels operating in ocean and harbour entrances, harbour approaches and coastal waters. These requirements are described quantitatively by: accuracy, integrity, availability, and continuity for positioning, [7].

2.1.3 Development of an e-Navigation strategy

Within the overall e-Navigation strategy the IMO has identified the user need on improved reliability, resilience and integrity of bridge equipment and navigation information as one of the five prioritized e-Navigation solutions, whereby the resilient provision of PNT data acts as Risk Control Option, see NAV-Committee reports: NAV54, WP.6, [2].

Further the IMO Strategy for e-Navigation contains a high level user need for data and system integrity that states:

"*e-Navigation systems should be resilient and take into account issues of data validity, plausibility and integrity for the system to be robust, reliable and dependable. Requirements for redundancy, particularly in relation to position fixing systems, should be considered.*"

2.1.4 NAV-Committee report: NAV53

Regarding the need for a backup position fixing system IMO has stated that "*there was a need to provide an internationally agreed alternative system for complementing the existing satellite navigation, positioning and timing services to support e-navigation and recognized that potential backup systems could be made available and that it was premature to identify any specific system before the users' requirements for e-navigation had been finalized*", [3].

2.1.5 Search and Rescue

Within the IMO the SAR Convention (International Convention on Maritime Search and Rescue 1979) was developed in the 1970-ties and was inaugurated in 1979 as basic regulatory framework for SAR requirements and actions, [8].

World-wide SAR operations and requirements are maintained in close cooperation between IMO and ICAO.

Within IMO the COMSAR/Circ.32 circular on HARMONIZATION OF GMDSS REQUIREMENTS FOR RADIO INSTALLATIONS ON BOARD SOLAS SHIPS [8] lists the available radio communication systems usable for global maritime distress calls and their coverage on a global scale. Basic prerequisite for emergency calls anywhere on the worlds' oceans is a reliable position report. Without a clear indication of the area and a sustainable position report on the distress origin time for rescue will increase significantly.

The technology used for position fixing within emergency communication systems has to provide robustness, reliability and availability. This project may show that the R-Mode technology complies or at least serves these requirements.

2.1.6 MSR and PNT guideline

IMO opened up a new path towards major improvements in accuracy, availability, continuity and integrity by the inauguration of the new Performance Standard for Multi-System Radionavigation Receivers (MSR) (MSC.401(95), [4] and the associated GUIDELINES FOR SHIPBORNE POSITION, NAVIGATION AND TIMING (PNT) DATA PROCESSING (MSC.1/circ.1575), [5].

As a direct follow-up on the identified gap of missing resilient PNT data, as pointed out by IMO's e-Navigation strategy reports, the new possibilities described in the above mentioned IMO publications can be used to introduce new integrity concepts as well as improvements on redundancy for GNSS by making use of terrestrial services like e-LORAN or yet to come future technologies like the R-Mode.

2.2 IALA documents

This chapter contains a review of IALA documents concerning alternative to GNSS solutions and their requested parameters.

2.2.1 Recommendation on GNSS Vulnerability and Mitigation Measures

IALA Recommendation R-129 [9] provides information on mitigation to GNSS vulnerability, including alternative systems. The recommendation introduces also a definition for alternative systems to GNSS as follows:

Alternative means of navigation may be provided at various levels; fully redundant, backup and contingency.

- A redundant system provides the same functionality as the primary system, allowing a seamless transition with no change in procedures.
- 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.

- A contingency system allows safe completion of a manoeuvre, but may not be adequate for long-term use.

2.2.2 Maritime Radionavigation Recommendation: R-115 DGNSS Services

The document recommends the use of proper radio frequency bands depending on geographical regions (1, 2 and 3) as defined by ITU-R documents. It is also stated that all national members consider the provision or enhancement of DGNSS services in the frequency band 283.5 to 315 kHz in Region 1 and 285 to 325 kHz in Regions 2 and 3 to improve the safety of navigation in confined coastal waterways and harbour approaches, [10]. The use of existing or redundant radio beacon stations for this purpose, where they are available, would have economic benefits. The last sentence opens the possibility to provide new R-Mode service to improve local safety.

2.2.3 DGNSS Service Provision: Recommendation R-150.

The text refers to the future of IALA DGNSS strategy as set out in Recommendation R-135 when considering the implementation of new services or the upgrade of existing services/infrastructure. National Administrations are asked to consider the potential for additional services that may be provided using the 300 kHz broadcast infrastructure in addition to DGNSS correction information. This may include the addition of a timing signal to provide GNSS independent positioning (R-Mode) or the provision of additional services to the mariner, such as described by Maritime Service Portfolios (MSP). In the case of discontinuation the DGNSS correction service, owners are asked to retain the 300 kHz infrastructure for future use, R-150 Edition 1.0 of Dec. 2016, [11].

2.2.4 AIS Service Recommendation

First IALA Recommendation A-123 on ‘The Provision of Shore Based Automatic Identification Systems (AIS)’ [12], encourages administrations to provide an AIS shore infrastructure in terms of navigation safety and protection of the environment. But very soon the AIS became a maritime, safety-related information service and first source of information during ship’s manoeuvres.

From the point of view of a competent authority the AIS provides an information service for shore-based VTS, traffic management schemes, ship reporting systems and other shore-based safety-related services. This service consists of information exchange between ships and shore and vice versa. Thus, operates the service exchange information between ships and maritime safety-related shore services, such as VTS.

Consequently, approaching the AIS use from a new safety related functional marine service like R-Mode service, will reuse existing infrastructure to enhance maritime safety in a way acceptable by IMO and IALA.

2.2.5 AIS Load Management

The Appendix 18 to IALA R-124 [12], presents AIS VHF data link (VDL) loading and the measures that should be considered by competent authorities to prevent or correct VDL overloading. Currently typical VDL in EU waters is on the level 5 to 10 % of AIS time frames, but the VDL tendency shows growth as there are many new class B or AIS Aids to Navigation (AtoN) applications. The first chapter looks at the definition and impacts of VDL loading, then the subsequent chapter discusses the prevention of VDL overloading, the third chapter refers to VDL load management and finally, the appendix concludes with mitigation methods for garbling.

The relation with R-Mode service and VDL level is mentioned here because additional R-Mode timing information can require more bits to be used in the message type #8.

2.2.6 Overview on VHF Data Exchange System (VDES)

IALA has issued a Guideline 1117 – on VDES to provide an introduction to VDES at an overview level. Guideline 1117 intends to assist in the understanding, development and promotion of VDES, [13].

VDES has a central role in the e-Navigation concept being the data link between ship and shore, as well as ship to ship. The main purposes of adding ASM (Application Specific Messages) and VDE (VHF Data Exchange) is to offload traffic from the AIS channels and to add new channels for data communications. AIS, ASM and VDE constitute VDES. The system shall be operational from 2021 (Figure 2-1).

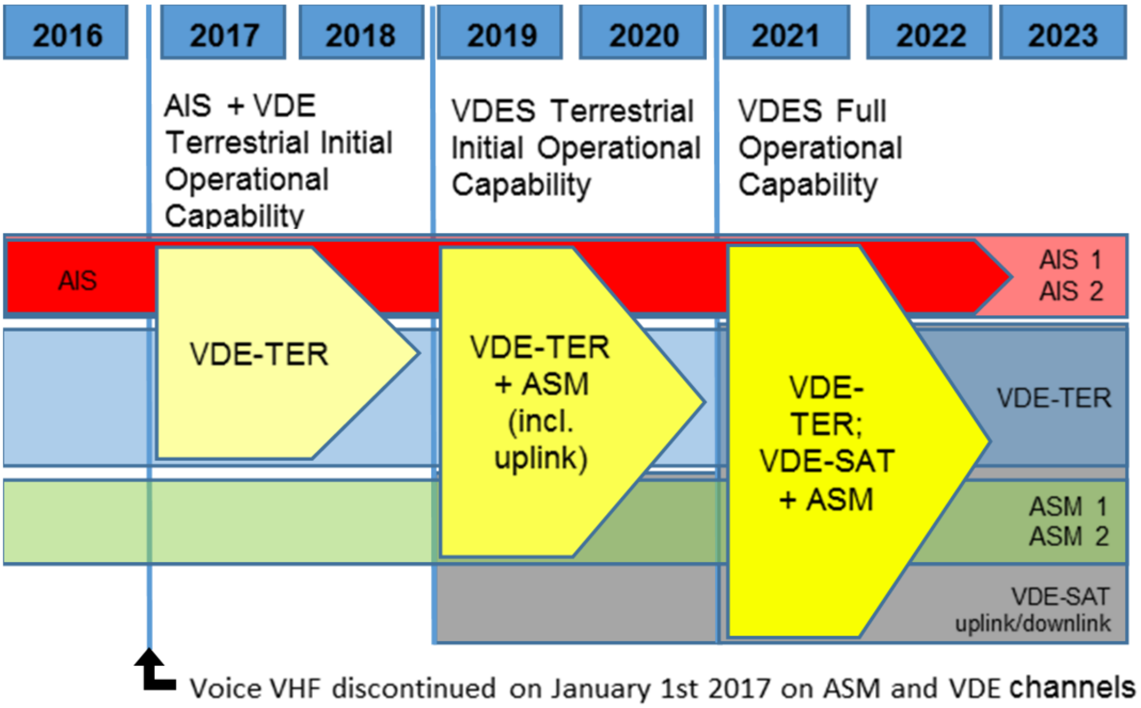

Figure 2-1: Implementation plan of VDES

2.2.7 Technical specification of VDES

The Guideline 1139- [14], has been prepared to provide technical information required in the development of VDES equipment, which integrates the functions of VDE, ASM and AIS in the VHF maritime mobile band (156.025 to 162.025 MHz).

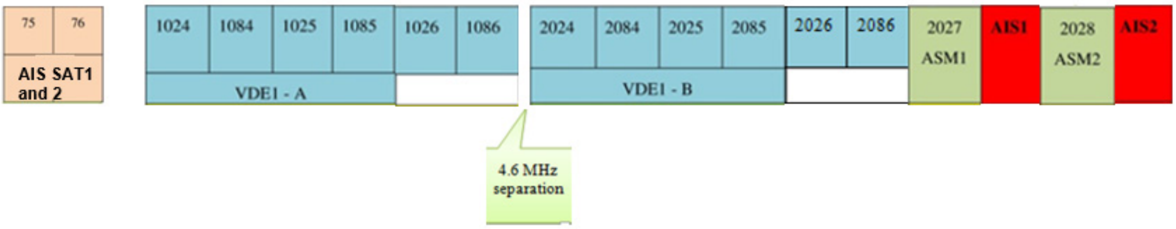

Figure 2-2: Channels for AIS, ASM and VDE

Guideline 1139 refers to ITU Recommendation ITU-R M.2092-0 [18], and is not intended to replace that document. The document provides additional details on VDES. It will be amended as required to reflect experience in implementing the technical solutions for VDES. IALA Guideline 1139 is a document under revision. Here, input will be included as appropriate and serves as a working document towards a revision of ITU-R M.2092.

2.2.8 IALA World Wide Radio Navigation Plan

The IALA World Wide Radio Navigation Plan in edition 2, [15], aims to build on individual national and regional plans and identify the radio navigation components which will be a key to the successful implementation of e-Navigation. There are listed potential components of WWRNS providing requested availability robust position-fixing, navigation and timing services as shown in Figure 2-3.

In addition, there is chapter 3.9 dealing with the potential extension of existing systems and R-Mode on MF beacons and AIS stations - the two maritime systems with widespread distributed infrastructure. The proposed functionality of the R-Mode system is the provision of timing information from shore to the ship. The shipboard radio receiver can then calculate a distance (range) to the transmitter. Using several such calculations from a number of different transmissions, the shipboard equipment is able to calculate the ship position. Coverage, geometry and interference questions would need to be investigated. The provision of R-Mode services via MF or VHF transmissions (see Figure 2-3) would require the availability of an accurate non-GNSS timing source at the transmitter. This could be provided by high stability clocks at each station. However, this would be expensive and it is more likely that this would be sourced from a low frequency radio time clock or eLORAN.

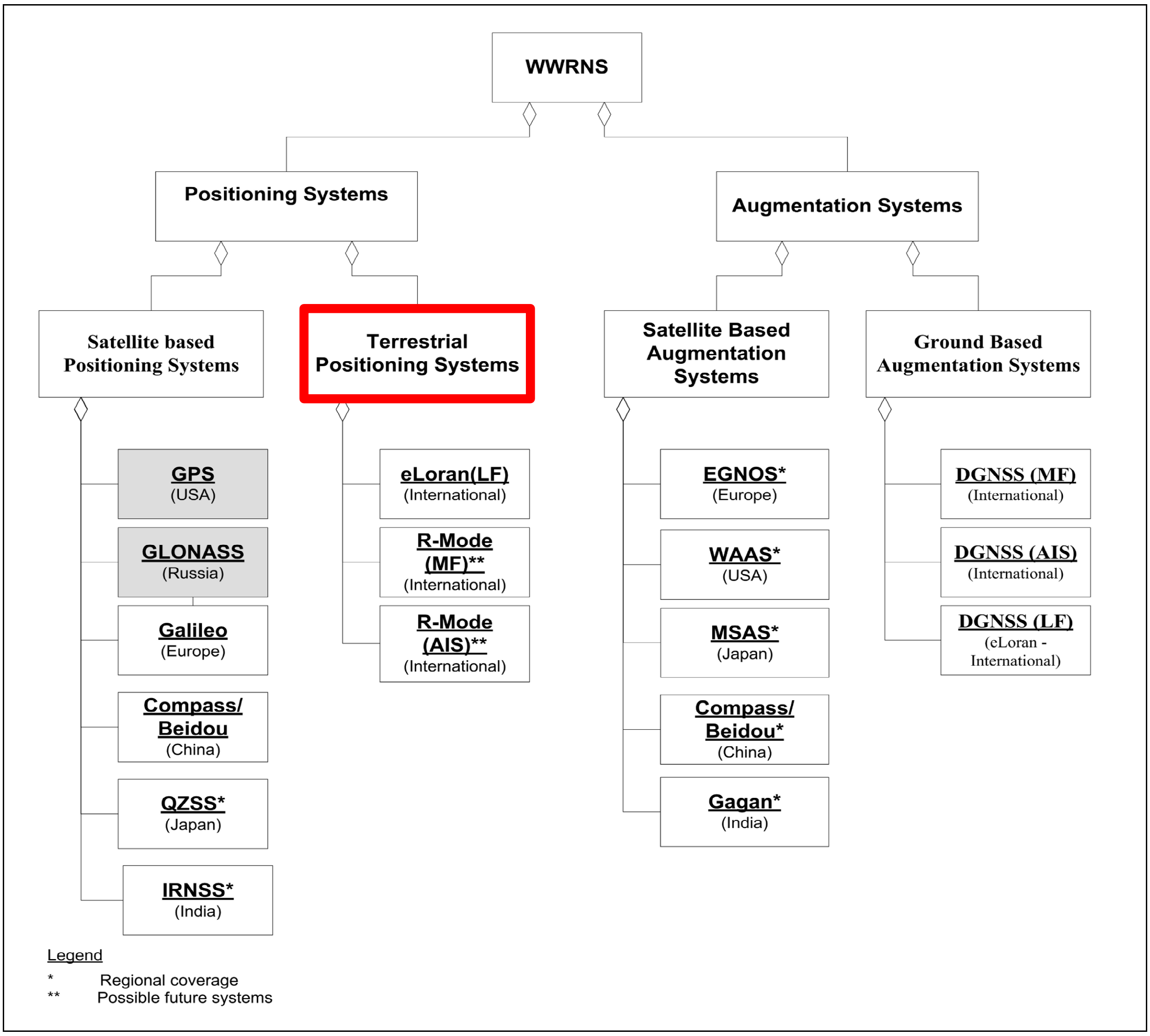

Figure 2-3: IALA terrestrial candidates to provide robust PNT, [15].

2.2.9 Requirements for a Backup Navigation System

Where the risk assessment concludes that a backup system (i.e. a system ensuring continued operation, but not necessarily with the full functionality of the primary system) is necessary, suggested minimum maritime user requirements (derived from IMO Resolution A.915(22)) for such a system are listed at Appendix 1 of IALA R-129, [9] (see Table 2-2).

Table 2-2 Suggested minimum user requirements for general navigation - backup system, [6]

	System level parameters				Service level parameters			
Maritime region	Absolute Accuracy	Integrity			Avail-ability % per 30 days	Continuity % over 15 minutes[3]	Coverage	Fix interval [s]
	Horizontal [m]	Alert limit [m]	Time to Alarm[2] [s]	Integrity Risk (per 3 hours)				
Ocean	1000	2500	60	10^{-4}	99	N/A[2]	Global	60
Coastal	100	250	30	10^{-4}	99	N/A[2]	Regional	15
Port approach and restricted waters	10	25	10	10^{-4}	99	99,97	Regional	2
Port	1	2.5	10	10^{-4}	99	99,97	Local	1
Inland Waterways	10	25	10	10^{-4}	99	99,97	Regional	2

Notes:

1. This table derived from IMO Resolution A.915(22).
2. Continuity is not relevant to ocean and coastal navigation.
3. IMO Resolution A.1046(27) amended the Continuity Time Interval to 15 minutes, rather than 3 hours as originally required in IMO Resolution A.915(22).
4. Although these are suggested minimum requirements, a Risk Assessment will include many variables that may alter the minimum requirements. Refer to IALA Guideline on the Provision of Aids to Navigations for Different Classes of Vessels, including High Speed Craft, Dec. 2003 for the variables of different waterways, ship and environments.

Suggested IALA requirements derived from IMO resolutions have been limited to basic user requirements. No detailed specification on any operational requirements for service providers, with respect to system structure and architecture has been provided.

2.3 ITU-R documents

This chapter reviews existing ITU-R documents with respect to radio regulations which could have potential impact on the provision of R-Mode signals.

2.3.1 Technical characteristics of DGNSS differential transmissions

The Recommendation M.823-3 for differential transmissions for DGNSS contains the technical characteristics to which such transmissions should be conform for corrections to the GPS and/or GLONASS. The recommendation also describes the various types of differential correction messages used for those systems and respective message formats (binary codes). In addition, it contains details of message transmission schedules. Furthermore, this recommendation specifies frequency band regulations (e.g. bandwidth, spurious emissions, protection ratio, etc.). This recommendation applies to the R-Mode signal as well as new messages can be created to support R-Mode functionality, [16].

2.3.2 AIS Technical characteristics

This Recommendation M.1371- ver.5* - [17], provides the full set of technical characteristics of an AIS using time division multiple access technique in the VHF maritime mobile band. There is a wide description of all system logical and technical solutions including methods of time synchronization (UTC), time division, types of messages and reporting intervals. Although this system was intended to be used primarily for ship surveillance and safety of navigation purposes in ship to ship use, ship reporting and vessel traffic services (VTS) applications, it may also be used for other maritime safety related communications, provided that the primary functions are not impaired.

Thus ITU-R recommendation anticipated also other services like R-Mode by saying "*the system should be capable of transmitting additional safety information on request*".

2.3.3 Technical characteristics for data exchange system in the VHF maritime mobile band

ITU-R Recommendation M.2092, [18], provides the technical characteristics of the VDES which integrates the functions of VDE, ASM and AIS in the VHF maritime mobile band (156.025 to 162.025 MHz).

The system consists of a terrestrial component, mobile and base stations, and a satellite element. Opposed to the AIS satellites only containing an AIS receiver, the VDES satellites will carry both transmitter and receiver making the system operational worldwide.

In the World Radio Conference (WRC) 15 the frequencies for terrestrial VDE and ASM was assigned, whilst the proposed satellite frequencies were not assigned. The satellite frequencies, ref Table 2-3 below, will be subjected for new discussions in WRC 19.

Table 2-3: Channels for VHF data exchange systems applications

RR Appendix 18 channel number		Transmitting frequencies (MHz)	
		Ship stations (ship-to-shore) (long range AIS) Ship stations (ship-to-satellite)	Coast stations Ship stations (ship-to-ship) Satellite-to-ship
AIS 1		161.975	161.975
AIS 2		162.025	162.025
75 (long range AIS)		156.775 (ships are Tx only)	N/A
76 (long range AIS)		156.825 (ships are Tx only)	N/A
2027 (ASM 1)		161.950 (2027)	161.950 (2027)
2028 (ASM 2)		162.000 (2028)	162.000 (2028)
24/84/25/85 (VDE 1)	24/84/25/85/26/86 (Ship-to-satellite, satellite-to-ship)	100/150 kHz channel (24/84/25/85, lower legs (VDE1-A) merged) Ship-to-shore (24/84/25/85/26/86) Ship-to-satellite	100/150 kHz channel (24/84/25/85, upper legs (VDE1-B) merged) Ship-to-ship, Shore-to-ship (24/84/25/85/26/86) Satellite-to-ship
24	24	157.200 (1024)	161.800 (2024)
84	84	157.225 (1084)	161.825 (2084)
25	25	157.250 (1025)	161.850 (2025)
85	85	157.275 (1085)	161.875 (2085)
	26	157.300 (1026)	161.900 (2026)
	86	157.325 (1086)	161.925 (2086)

2.4 European Radio Navigation Plan 2018

The importance of R-Mode as a source for robust and resilient PNT information is furthermore recognized in the current European Radio Navigation Plan, Draft Version, [21].

General precautions

Efforts must now focus on how Europe and the various sectors covered in this plan can optimise their PNT infrastructure in terms of finding the right system mix whilst considering the overall costs, the need to offset risk and the need to deliver continued high performance of PNT services to user communities. Contingency plans must be devised for such cases, resorting to redundancy, fault tolerance, recovery procedures, and/or independent backup PNT solutions. Importantly, the additional technical means required to deliver adequate redundancy are often sector specific, and not necessarily radio-based.

Backup for GNSS

Studies are ongoing to test the feasibility of a backup PNT system for GNSS using trilateration techniques based on signals from existing IALA beacon stations, AIS base stations (both for the maritime and inland community) and LORAN-C transmitters, or a subset of these.

2.5 Other standards and documents

2.5.1 Radio Technical Commission for Maritime Services (RTCM)

RTCM

The internationally accepted data transmission standards for DGNSS are defined by Radio Technical Commission for Maritime Services (RTCM), particularly by its Special Committee SC-104. RTCM SC-104 is a standard that defines the data structure for differential correction information for a variety of differential correction applications. It was developed by the RTCM and has become an industry standard for communication of correction information. The current recommended standard document for DGNSS is RTCM SC-104 Version 2.3, [22] which contains information for GPS and GLONASS code corrections. For GNSS phase corrections (e.g. for Real Time Kinematic applications), a version 3.x series is available.

For R-Mode the RTCM Version 2 standard is of specific interest. R-Mode may affect the provision of site specific data (site calibration, time shifts, corrections, etc.)

RSIM

RSIM (RTCM Recommended Standard for Differential GPS and GLONASS Maritime Reference Stations and Integrity Monitors) is a document which delineates the performance, functional interface and environmental parameters for Differential GNSS reference stations and integrity monitors, [23]. The intent of this document is to facilitate both the manufacture and the purchase of service provider equipment in order to make the use of DGNSS more economical and deployable through standardization. It will encourage consistency from one service provider to the next and thereby facilitate the use of DGNSS. In the context of the development of R-Mode via MF radio beacons this standard ensures the proper communication between the various onsite installations, like GNSS receiver equipment (reference and monitor receivers), transmitter and the R-Mode modulator.

2.5.2 IEC/NMEA standards for on-board data exchange

In general data exchange on-board a vessel is specified by international accepted system standards. In the EU and most parts of the world the International Electrotechnical Commission (IEC), in the USA the National Marine Electronics Association (NMEA), develop and maintain these standards, listed as IEC-61162 / NMEA 0183 series, in cooperation.

Currently different technical data transmission techniques are defined within the IEC-61162 series, [24].

- IEC61162-1 serial interfacing up to 4800bps and EC61162-2 serial interfacing up to 38400bps: Based on a 2-wire differential bus topology. Each device connects to the bus as preconfigured talker or listener. There is only one talker on the bus, or interface circuit, and there may be multiple listeners, depending on the driving capability of the talker.

Multiple interface circuits may be provided to accommodate vessels with more than one talker, but each circuit has only one talker and is independent and wired separately. Note that a single device that sends and receives data may participate as a talker in one circuit and as a listener in another.

- IEC61162-3 CAN-Bus technology:

  Fully CAN compliant data transmissions, each device can act as talker and listener on a single bus connecting multiple devices. Special messages are defined to code the transmitted information.

- IEC61162-4xx Ethernet based data transmissions:

  Data transmission based on IEEE Ethernet standard as known for local area high-speed computer networks. Special maritime data structures are defined, suitable for use in standardized TCP/UDP IEEE protocols. These maritime Ethernet standards allow multiple talkers and listeners as well as non-standardized equipment on the same network. Precautions are defined as requirements for data rates, gateway and routing functions. The network structure allows redundant connections.

2.5.3 European Maritime Radionavigation Forum (EMRF)

The EMRF gathers together different bodies from maritime administrations to ship owners' organisations to focus on the co-ordination of European maritime interests in the field of radionavigation systems for development within Europe. One of its main aims is to promote the maritime requirements for the safety assessment and certification of future satellite systems, their augmentation systems and backup, and to develop material to achieve recognition and operational approval of those systems as part of the IMO WWRNS. For R-Mode the EMRF can be seen as platform to promote the international recognition of the system for the maritime domain and seek support from EU policy makers. First information on R-Mode was already presented at an EMRF meeting in Warsaw in 2016, [20]. Thus R-Mode is already recognized by EMRF as a potential backup system.

- Applications and User Requirements

  The EMRF has worked on a document which is concerned with the identification of a comprehensive set of maritime applications and the specification of harmonised navigation and positioning requirements associated with those applications, [19]. The identified applications covering the following functions: navigation, operations, traffic management, port operations, casualty analysis, offshore exploration and exploitation, fisheries and military. The requirements for these applications have been specified quantitatively as far as possible using the parameters: accuracy, integrity, coverage, availability, continuity and fix rate. The given tables are nearly identical to those listed in IMO Resolution A.915(22), [6].

3 Terrestrial radionavigation systems

Within the overall context of radionavigation also developments concerning present and historical terrestrial systems should be taken into consideration.

This chapter delivers an overview of historical and existing Terrestrial Radionavigation Systems (TRS). Most of them civil controlled were phased out in result of competition with freely available GPS or GLONASS services, like the most popular OMEGA and DECCA.

The chapter concludes with the predictions as to the likely future mix of applied methods and algorithms of phased out historical radionavigation systems with the potential use of existing MF radio beacon and/or AIS land-based infrastructure to be re-used for R-Mode service.

3.1 TRS classification

The main target of terrestrial radio navigation is position fixing. However, some of them can also transfer the time. Referring to transmitters with known positions on the land and a ship's receiver to be determined, specific navigation systems provide information on directions, angles, distances, pseudo ranges and combinations of these types of data. Considering these quantities as measurements, the term line of position (LOP) becomes fundamental. Depending on the LOPs involved, various kinds of terrestrial systems can be sorted as shown in Figure 3-1.

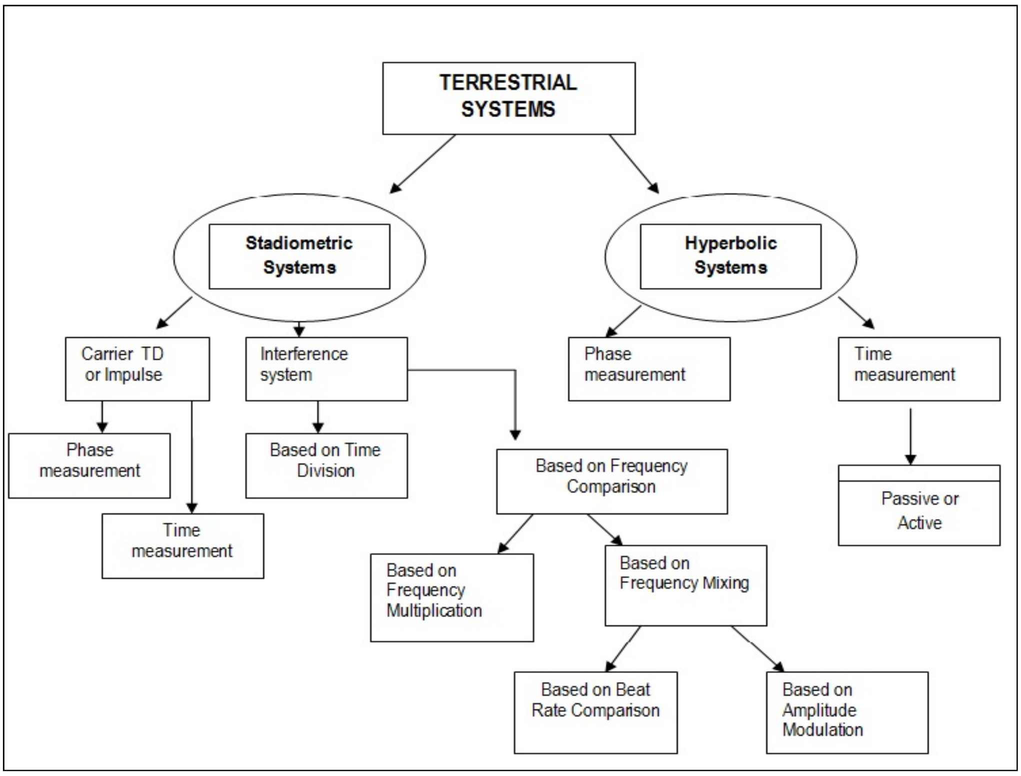

Figure 3-1: Diagram of TRS depending on LOP type and signal processing, [26].

Apart from the geometric aspects of the LOPs, elementary properties of the electromagnetic wave propagation as described in the literature [25] are mandatory for an understanding of the transmission and reception of radio signals. The propagation of radio waves is definitely a nontrivial matter because of so many relevant parameters: the frequency band of the signal, the time of the day, the radio emission type and the incidental angle (subject to physical impacts), air pressure, the sun spots and many others.

Some of TRS have been recognized to be representative and listed in the Table 3-1 showing their basic characteristics. There might be two approaches: focusing on potential coverage and system capacity or on position accuracy and possible maritime applications, [26].

Table 3-1: Selected Terrestrial Radionavigation Systems, [26]

No	System name	Type of measurement	Range	Frequency	Position Error
LONG RANGE					
1	OMEGA	Pulse, FTD	global	10-14 kHz	1-2 NM
2	LORAN A LORAN C eLORAN	Pulse, phase Hyperbolic ASF	500-700 NM 1000 NM	100 kHz	0.05-0.25 NM 8-20 m 20m <error
3	Chayka	Pulse, phase	1000-2500 km	100 kHz	100–500 m
MID RANGE					
4	Decca Navigator Decca Survey	Hyperbolic phase	200-450 km	70-130 kHz	25-250 m 2 m
5	TACAN	Bearing and distance	370 km	960–1215 MHz	600 m
6	Syledis	Hyperbolic Stadiometric Pseudostadiometric	50-80 km 100-220 km	420-450MHz	3-5 m 8-10 m
7	Hi-Fix, SeaFix, HyperFix	Hyperbolic phase	200 km	1.6-3 MHz	1.5-2 m at 50 km
8	HiFix 6	Hyperbolic stadiometric	160 km	1.6-5 MHz	2 m
SHORT RANGE					
9	RDF	Direction Bearing Triangulation	75 km 150 km	VHF MF	0.3-0.4 NM
10	AD-2	Hyperbolic phase	10-20 km 100 km	1.6-3 MHz	1-3 m 5-8 m

3.2 Active TRS

Thanks to TRS experience up to date it has been proved that methods and associated algorithms can still be applicable. Very important system distinction is the way in which the incoming signals were analysed upon reception, as they differ. Either the receiver determines the time differences only or they compare signal phases. However, both types detect in reality time intervals and time shift of one signal with respect to another. An attempt has been made to determine for certain systems the probable value of the resultant of possible random errors. The range of a system depends primarily on the SNR (signal to noise ratio), the frequency adopted (attenuation with distance and surface interaction) and final error of position. In practice, the range can obviously be limited by the ambient noise (random errors) or interference (ionospheric or/and multipath effect).

Some of TRS, like modern VHF RDF or enhanced eLORAN are in use up to date and are often foreseen as potential candidate for backup to GNSS.

3.2.1 Radio Direction Finding (RDF)

RDF may be regarded as a fundamental method for radio positioning. As described, the basic idea is the determination of the direction to a known transmitting station. The resulted LOP is a straight line on a chart. Applying this idea to two different and known transmitting stations, the position can be determined as the intersection point of the two LOPs. Obviously, also the baseline between the two transmitting stations is well known. Direction finding method (bearing) was the earliest use of radio waves for navigational purposes and even today, it continues to perform a useful function for radio-emitting object identification. This method is also used for ship localisation by two or more shore RDF stations installed for VTS purposes, [27].

3.2.2 LORAN

LORAN is the pulse hyperbolic navigation system developed in the 1940 (LORAN-A), then modernized and today most commonly referred to as LORAN-C or “standard” LORAN. It is still in use in some parts of the world. Standard LORAN provides position, navigation, and timing solutions from “chains” of stations to users with operating receivers in paired-station mode. The LORAN-C service provides accurate, all-weather PNT services independent of and being complementary to Global Navigation Satellite Systems. LORAN-C transmitters vary in radiated power from less than 200 kW (kilowatts) to over 2 MW (megawatts). Thus is giving its coverage of more than 1000 NM.

LORAN is not as precise as GPS, but it is with 0.3 NM accuracy better over a much larger area than any other ground-based alternative. Most modern LORAN-C stations provide improved accuracy, integrity, continuity, and availability performance therefore several countries have identified LORAN as the best backup to be used for marine transportation, [28].

3.2.3 eLORAN

eLORAN – enhanced LORAN, is a modernized and improved version of standard LORAN.

It provides a high-power PNT service for use by all modes of transport and in other applications. LORAN signals are all transmitted on a 100 kHz carrier within a 20 kHz double-side band having vertical polarization and using TDMA multi-access method. System defines a hyperbola-shaped LOP. Like LORAN-C it employs ground-wave propagation, which enables long range independently of altitude. With modern user equipment and transmitter ranges of 1,000–1,700 km over land and 1,700–2,400 km over sea are possible.

eLORAN comprises advancement in receiver design and transmission characteristics, which increase the accuracy and usefulness of the traditional LORAN. The key difference between the eLORAN transmitted signal and the traditional LORAN-C signal is the addition of a data channel. The data channel can transfer real time ASF (Additional Secondary Factor) corrections, warnings, and signal integrity information to the user's receivers. With reported position accuracy as good as 8 m in the coastal zone, the system becomes competitive with unenhanced GPS. At present eLORAN has recapitalized infrastructure, upgraded firmware and modernized technology. That includes major improvements to transmitters, timing and frequency equipment, antennas and control functionality. The data channel can take several forms. Administrations are researching versions of a LORAN data channel. At the moment, no standardized international data channel method has been selected, [29], [30].

3.2.4 Chayka

Chayka this is the name of Russian terrestrial radio navigation system, similar in functionality to LORAN-C. It operates in similar frequency band around 100 kHz and uses the same techniques of comparing both the envelope and the signal phase to determine LOPs and calculate geographical position. Both systems differ primarily in details, so they can be synchronized to cooperate in common chains. Both LORAN and Chayka chains may include 1 Master and 2-5 Slave stations.

3.3 R-Mode technology synopsis

- Methodology of time difference converted into range difference, supported by phase measurement is still valuable. By applying algorithms of trilateration and triangulation it is possible to calculate the receiver position in relation to fixed shore-based radio transmitters.
- The broad knowledge and experience with pulse radio signals propagation effects like: multipath phenomena, frequency band and ground conductivity, ambient radio noise, interference, should help to mitigate the systematic and random errors.
- Dependence of receiver position accuracy on reference radio base positions, their geometry and receiver’s distance from transmitting locations were investigated.
- Methods of resolving position ambiguity has been proved.
- Autocorrelation techniques and phase locking methods have been applied.
- Reference stations can be organized in networks.
- Main station in the network can also serve for timing.

3.4 Cellular networks

There are several important topics which need to be considered when using GSM networks for positioning.

3.4.1 GSM

Cell-ID – is a very simple location technique used in cellular networks. Every base station broadcasts its cell-ID to the terminals, so at all times the terminal is aware which base station is serving it and knows its Cell-ID. In this method, the position of the mobile terminal is assumed to be the position of the base station currently serving the terminal. The exact position of the terminal within the cell cannot be determined in the method, though. To improve the accuracy of the method, the so-called Timing Advance (TA) can be utilized in the GSM network. TA is a mechanism where the terminal starts its transmission with an advance corresponding to the distance between itself and the serving base station. The value of TA is calculated by base station and broadcast to terminals. Consequently, the terminal, knowing its TA, can estimate the distance from the base station as a function of delay.

Advantage – very simple in implementation, does not require any dedicated network infrastructure or terminal upgrades

Disadvantage – low accuracy

Assisted-GPS – In this method both base station and terminals need to be equipped with GPS receivers. The information about visible satellites and other assistance data is provided to the terminals by the base station, which significantly reduces the terminals' acquisition time and helps to reduce power consumption, because the terminals do not need to actually look for the satellites themselves (they are assisted by the base station in that respect). Since the base station knows its true position and knows its position calculated by the GPS, a suitable correction can be calculated and provided to all the terminals.

Advantage – high accuracy

Disadvantage – method performance drops significantly in indoor environment, base stations and terminals require hardware upgrade (must be equipped with GPS receivers), [31].

Enhanced Observed Time Difference (E-OTD) – This method is based on hyperbolic lateration. Each base station broadcasts an ad-hoc message to its cells. This message is received by the terminal that compares the relative times of arrival to estimate its distance from each visible BTS. Then terminal calculates its position via trilateration. E-OTD requires the mobile stations to be upgraded to properly manage the ad-hoc messages. E-OTD solution is supplied by CPS, Ericsson and BT Cellnet.

Advantage – accuracy is better than in Cell-ID method

Disadvantage – requires a software modification in the mobile stations

Uplink Time Difference of Arrival (U-TDoA) – This method is also based on hyperbolic lateration, but is applied in the uplink. The pilot signals emitted from a terminal are observed by the network. U-TDoA determines location based on the time it takes a signal to travel from a mobile phone to each of the sensitive receivers called Location Measurement Units (LMUs). By using the timing information from multiple LMUs, U-TDoA calculates the mobile phone's location.

Advantage – does not require any special chip, hardware or software in the mobile stations; good accuracy

Disadvantage – requires physical access to the cellular network's base stations. It is only available to the owner of the network.

Time of Arrival (TOA) – This method estimates the distance of a terminal with respect to a set of LMUs, evaluating the differences between the arrival times of the access bursts sent by the mobile device. The network calculates the final position via trilateration. This technology requires the installation of an LMU at each BTS.

Advantage – high accuracy

Disadvantage – requires the installation of an LMU at each BTS and it is therefore expensive (approximately ten times the price of an E-OTD system), [32], [33].

3.4.2 UMTS

Cell-based methods - The general principle is the same as in the Cell-ID method described above, i.e. the terminal position is assumed to be the position of the serving base station (Node-B). In order to increase the accuracy, the actual distance between the terminal and Node-B should be taken into account. To do so, the RTT (round trip time) parameter available in the UMTS network can be utilized. Alternatively, the AOA (angle of arrival) technique can be employed in the base station.

Advantages/disadvantages: the same as for the Cell-ID method

Observed time difference of arrival with idle period downlink (OTDoA-IPDL) – This method is equivalent to the GSM's E-OTD algorithm described above. The terminal receives signals from three base stations and calculates its position via trilateration. However, due to the specific characteristics of the UMTS system, the downlink transmission needs to be periodically interrupted (hence the "idle period downlink" in the method's name). This is necessary to mitigate the so-called *hearability problem* that may degrade timing measurements.

Advantages/disadvantages: the same as for the E-OTD

3.4.3 LTE

Assisted-GNSS – In this method both base station and terminals need to be equipped with GNSS receivers. To overcome the line-of-sight and low signal level drawbacks of GNSS the cellular network assists the GNSS receiver by providing assistance data for the visible satellites (similar to the Assisted-GPS solution). Assistance data typically includes the Almanac and/or Ephemeris data which is normally received via the satellite navigation message. This assistance data improves the performance for start-up and acquisition times – TTFF (Time to First Fix), sensitivity, and power consumption. In an Assisted GNSS system, the contents of the navigation message are supplied to the receiver by the cellular network. This enables the receiver to know which satellites are in view and what their most likely Doppler shift is. This information allows the search region to be restricted and the TTFF can be reduced down to a few seconds as opposed to an autonomous cold start TTFF of many minutes.

Advantage – high accuracy

Disadvantage – method performance drops significantly in indoor environment, base stations and terminals require hardware upgrade (must be equipped with GNSS receivers).

Observed Time Difference of Arrival (OTDOA) – This method uses the measured time difference of arrival of downlink signals received from multiple eNBs to locate the user device in relation to neighboring eNBs. In dense urban and indoor environments OTDOA can be used to supplement AGPS/AGNSS. A precondition is that the user device can detect position reference signals (PRS) from three or more eNBs. Current solutions are based on both Inter-Band and Intra-Band eNB measurements. With future network deployments of LTE Advanced Carrier Aggregation (LTE-A CA), OTDOA can be further extended to measurements of LTE-A Component Carriers (CC's).

Advantage – accuracy is better than in Cell-ID method, better than A-GNSS method in indoor areas

Disadvantage – requires a software modification in the mobile stations.

Enhanced Cell ID– In this method the position of the device is estimated using the knowledge of the geographical coordinates of its serving base station, in terms of LTE the eNB. The knowledge of the serving cell can be obtained executing a tracking area update or by paging. The position accuracy is in that case linked to the cell size, as the location server is only aware that the device is served by this base station. Enhanced Cell ID has been defined with LTE, mainly for devices where no GNSS receiver has been integrated. On top of using the knowledge of the geographical coordinates of the serving base station, the position of the device is estimated more accurately by performing measurements on radio signals. Position is localized to a finer level compared to CID, using additional radio-related measurements, [47].

Uplink time difference-of-arrival (UTDOA) – this method works in the same way as in the GMS system (described above). As a key benefit, it offers minimal impact on air interface resources.

4 Impacts from other projects – status of R-Mode

4.1 ACCSEAS

The European INTERREG IVb North Sea Region Programme project Accessibility for Shipping, Efficiency Advantages and Sustainability (ACCSEAS) (2012-2015) developed the idea of R-Mode by supporting a feasibility study, which considered the addition of ranging information to marine radio beacon DGNSS and AIS base stations.

The ACCSEAS feasibility study was split into the following parts:

- Part 1 and 2 examined the R-Mode potential of the MF DGNSS signal [41, 48]; the recommended approach was to add CW signals to the broadcast and to develop the pseudorange from the carrier phase.
- Part 3 and 4 examined the R-Mode potential of the AIS signal [49, 50]; the recommended approach was to estimate the pseudorange from timing bit transitions and requires no modification to the signal structure.
- Part 5 examined the combination of MF transmission together with AIS and the combination with eLoran which at that provided time operated from 5 stations around the North Sea area, [34].

The performance assessments for each of the three signal types outlined above were considered in the feasibility study and the lower bounds of the expected positioning accuracy were calculated based on conservative assessments.

As the position is calculated through trilateration from terrestrial transmitters, the resulting performance is a function of the received signal power, the observation time of the receiver (nominally assumed to be 5 seconds) and the geometry of the known transmitter locations. For each signal considered the sources of error were considered where possible. However, errors such as unknown offsets in the synchronization of transmitters (this is relevant to all three signals) and propagation delays that would increase the observed range estimates (this is known to impact both MF and eLORAN signals since they propagate as ground waves) were omitted.

The ACCSESS project concluded in 2015. The project information remains available on the project website (www.accseas.eu) with the project deliverable reports available on the IALA website within the e-Navigation test bed area.

4.2 MF-R-Mode in Germany

In 2013 the German Federal Waterways and Shipping Administration contracted for a feasibility study of R-Mode using MF differential GNSS (DGNSS) and VHF AIS signals as well as those signals in combination and in combination with eLORAN. This study was part of the ACCSEAS project. The study stated that AIS R-Mode is feasible with the existing signal structure (beyond synchronizing the broadcasts and, perhaps, adding a fixed ranging message), but that DGNSS R-Mode would be greatly improved by actually modifying the signal, adding one or two continuous wave (CW) signals to the broadcast (i.e. not be a pure SoOP, but a hybrid version). In most of the shipping lanes of the North Sea it appeared that 10 m or better performance could be achieved via R-Mode. Rather than define desired performance up front, the approach of the ACCSEAS project was to try to identify what level of performance was possible and identify what limited the system performance.

To continue that work, prototypes of an MF-DGNSS R-Mode modulator and receiver were developed. The modulator was installed at a transmission site in Ijmuiden (Netherlands) and the receiver deployed to the south along the Dutch coast for initial on-air testing of the R-Mode concept. While positioning is not possible with only one R-Mode transmitter, the combination of a synchronized transmitter and receiver pair allowed for useful testing of the R-Mode concept. Specifically, having both the transmitter and receiver clocks synchronized to a common time source allows the receiver to estimate a true range (rather than a pseudorange). Hence, the stability of the range with environmental variations (e.g. weather, day/night skywave effects, etc.) could be studied. To further study propagation and skywave effects, the R-Mode modulator was relocated to a more powerful transmitter at Heligoland in the North Sea and the receiver moved to a location near the Kiel Canal (east of the transmitter). A second receiver was installed to the west of the transmitter to enable simultaneous comparison of two different propagation paths. A third receiver site, nearly along the signal propagation path to the Kiel Canal, was added. In 2017 the WSV has established a second R-Mode transmitting site in Zeven and contracted for a 2-channel R-Mode receiver which enables first positioning measurements. A report concerning the test bed setup, the measured ranges and the concept of the new receiver concept was presented at ION 2017, [34]

4.3 R-Mode in the Netherlands

Ranging mode has been demonstrated on an MF beacon in the Netherlands. This was performed during the ACCSEAS project (see above) on a test R-Mode site in Ijmuiden. After the project the Netherlands supported the analyse of R-Mode signals over larger base lines with an R-Mode receiver installation at Terschelling. This receiver site is still in operation.

In addition, the Netherland is interested in a common North Sea testbed with partners from the UK and Germany. Main goal is the test of combined solutions (MF, AIS/VDES and eLoran) as well as the research of ASF corrections for R-Mode.

4.4 MF-R-Mode in UK

The General Lighthouse Authority (GLA) has performed an R-Mode interference study in 2017. This study focused on the analysis, how a large number of R-Mode signals would impact legacy DGNSS radio beacon users. As part of the prototype modulator development, very limited experiments were performed to assess the impact of the new signals on legacy DGNSS receivers. Specifically, during all of the on-air testing, a commercial DGNSS receiver was able to accurately demodulate and decode the on-air transmissions from the single prototype R-Mode transmitter; however, the impact of multiple signals was not examined. Thus, a study was initiated by the GLA to analyse how legacy equipment would respond to multiple R-Mode signals at different frequencies, both in-band and out-of-band. Results of this study were reported at ION 2017, [34].

4.5 MF-R-Mode in Canada

The Canadian Coast Guard plans to establish an MF R-Mode testbed in 2018 in the vicinity in Canadian waters. This testbed will consist of one MF R-Mode site and an improved receiver concept which will allow for a multi-site reception. The test will enable to test the MF

R-Mode signal transmitted with high power levels and over large distances (500 km). Furthermore, the tests enable to analyse propagation over thick ice/snow areas as well as the impact of larger frequency separation of the CW signals in a 1000 Hz channel. First results are expected in 2019.

4.6 AIS/VDES R-Mode China (AAPS)

China presented at IALA eNAV18 a presentation of an AIS R-Mode testbed in China, [35]. This testbed was developed with a 3 years (2012-2015) project called the AIS Autonomous Positioning System (AAPS). The AIS R-Mode testbed presentation provides promising results in the order of 10 m within the trial area.

4.7 AIS/VDES R-Mode Korea

Mr. Shim Woo-Seong from Chung-Nam National University, Daejeon, Korea has performed a PhD dissertation concerning the performance analysis of AIS based ranging method for asynchronous R-Mode. As a result, he estimated that such an AIS-TWR concept could provide accuracy in the range of, 36-150 m, 2 drms if the signal processing delay is fixed, [36].

5 R-Mode general requirements

Many factors are considered in determining the set of required parameters to be provided by potential backup to GNSS as a component of PNT system. These factors include operational, technical, economical, radio frequency spectrum allocation, international parameters but also homeland security and/or national defence needs. Most leading IMO and IALA documents show (chapter 2), that important technical parameters include: system accuracy, integrity, coverage, continuity, availability, reliability and radio frequency spectrum usage. Certain parameters, such as anti-jamming immunity, will also affect civil PNT service availability. The expected investment in the shore-based service provider equipment and user onboard equipment must also be considered.

In most cases, the systems that are in place today were developed to meet different user requirements but can easily be reused. This resulted in the proliferation of multiple use of existing systems and is one of the strong advantages of R-Mode radionavigation service.

The R-Mode project works on a proof of concept. In the long term, if it works as described, it is intended as a backup system, or in between a contingency and backup system, to GNSS. GNSS systems have a global coverage. A global coverage is not possible with R-Mode due to the selected carriers (AIS and MF). But a global harmonization in line with the e-Navigation concept is important. The highest risk for degradation of the signal due to intentional and unintentional jamming is expected to be in coastal waters. R-Mode, as a system, is designed for coverage in coastal waters.

5.1 Applications

The Baltic Sea region comprise a variety of regions were support from a terrestrial based absolute positioning is desirable to enable integrity information for GNSS based positioning or as alternative to GNSS based positioning. Lowest requirements are for a voyage in open waters.

A large number of maritime applications have been identified, covering the following functions:

- navigation
- operations
- traffic management
- port operations
- casualty analysis
- offshore exploration and exploitation
- fisheries
- search and rescue
- pilotage
- support of e-Naviagtion (resilient navigation)
- military

5.2 R- Mode system expected performance

5.2.1 R-Mode user requirements for onboard positioning performance

Since 1974 the UN/ IMO SOLAS (Safety of Life at Sea) Convention and its amendments enforce the carriage requirements on minimum equipment needed for safe voyage at sea.

Currently any vessel operated under SOLAS is required to carry at least one electronic position fixing system (EPFS). The minimum performance of this system is described in IMO minimum Performance Standards. These standards are available for single GNSS like GPS, Galileo, GLONASS and BeiDou as well as for combined GPS/GLONASS.

IMO Resolutions A.915(22), [6] and A.1046(27), [7] detail the requirements for WWRNSs considering vessels operating in ocean and harbour entrances, harbour approaches and coastal waters. These requirements are typically described by: accuracy, integrity, availability, and continuity for positioning, as it is shown in the Table 2-1.

A stand-alone fully operational R-Mode receiver would need to comply with the above stated values at any time within R-Mode reception area. The R-Mode system will be a regional offered service unlike the GNSS.

Depending on the different levels of R-Mode realization, as described in chapter 5.3, the R-Mode capability varies from simple augmentation service to fully operational, GNSS independent, EPFS.

If the R-Mode Baltic project demonstrates the usability of the R-Mode technology according to the requirements in general, two ways of R-Mode inauguration are to be considered.

- First approach would be the development of an R-Mode Performance Standard within IMO, just as those already in force for GNSS. This implies an R-Mode development as stand-alone EPFS.
- Second approach would be an open approach making use of the latest developments on the Multi-System Radionavigation Receiver (MSR). An integration of R-Mode capability into the MSR as a terrestrial component does not rely on fully stand-alone R-Mode capability and enables the exploitation of any kind of R-Mode signals at least for integrity calculations.

IMO opened up a new path towards major improvements in accuracy, availability, continuity and integrity by the inauguration of the new Performance Standard for Multi-System Radionavigation Receivers (MSR) (MSC.401(95)) and the associated GUIDELINES FOR SHIPBORNE POSITION, NAVIGATION AND TIMING (PNT) DATA PROCESSING (MSC.1/circ.1575), [5].

Table 5-1 shows the performance parameters given by IMOs' PNT-DP Guideline (MSC.1/circ.1575 Table C-1), mainly based on the availability of multiple navigations signals received by one MSR.

Table 5-1: Performance parameters given by IMOs' PNT-DP Guideline, [5]

PNT Output Data	Operational Accuracy Level				Level of Confidence[8] [%]
	A	B	C	D	
Horizontal Position [m]	100.0[9]	10.0[9,10]	1.0[10]	0.1[10]	95
SOG [kn]	0.5	0.4	0.3	0.2[11]	95
COG [°]	3.0	1.0	0.5	0.1	95
Time[12]	1.0 s	0.1 s	0.0001 s	50.0 ns[13]	95
Heading [°]	1.5[14]	1.0[14,15]	0.5[14]	0.2[14]	95
ROT [°/s]	1.0	0.5[16]	0.3	0.1	95
STW [kn]	0.5	0.4	0.3	0.2[11]	95
CTW [°]	3.0	1.0	0.5	0.1	95
Vertical Position [m]	10.0	5.0	1.0[10]	0.5	95
Depth [m]	5.0	1.0	0.5	0.2	95
Pitch [°]	1.5	1.0	0.5	0.2	95
Roll [°]	1.5	1.0[15]	0.5	0.2	95

Today all satellite-based systems correlate to the same errors caused by physically identical parameters. The availability of terrestrial systems like the R-Mode enables uncorrelated augmentation and even independent position calculation to support target performance comparison and calculated protection levels at least for the given Operational Accuracy Levels A and B.

In nominal operational state, using multiple signals from uncorrelated sources, enables extensive position integrity checking and provides highly reliable information to the mariner serving the safety of voyage.

In case of missing or corrupted signals, clear indication of the operational state shall be available and due to the independent multiple signal sources at least a subset of information is available for the mariner– A GNSS backup appears within reach by the prove of concept for the R-Mode technology.

Minimum requirements for a terrestrial GNSS backup system were extracted from IMO and IALA publications. As a result, "suggested minimum user requirements for general navigation (backup system) are shown in Table 5-2 - (see Appendix 1 of IALA Recommendation R-129, [9]). These requirements must be taken into consideration while designing components of the R-Mode system.

Table 5-2: Suggested minimum user requirements for general navigation – backup system, [6].

	System level parameters				Service level parameters			
Maritime region	Absolute Accuracy	Integrity			Avail-ability % per 30 days	Continuity % over 15 minutes	Coverage	Fix interval [s]
	Horizontal [m]	Alert limit [m]	Time to Alarm [s]	Integrity Risk (per 3 hours)				
Ocean	1000	2500	60	10^{-4}	99	N/A[2]	Global	60
Coastal	100	250	30	10^{-4}	99	N/A[2]	Regional	15
Port approach and restricted waters	10	25	10	10^{-4}	99	99,97	Regional	2
Port	1	2.5	10	10^{-4}	99	99,97	Local	1
Inland Waterways	10	25	10	10^{-4}	99	99,97	Regional	2

Additionally, by basic design the R-Mode system shall:

- work independently from GNSS, based on existing but modified infrastructure,
- have unlimited user-capacity,
- provide a two-dimensional position fix (x,y),
- provide a position referenced to geographical system WGS84,
- provide position ambiguity resolution at high confidence level,
- be based on Coordinated Universal Time (UTC) with an error of less than 10 ns per station,
- be designed to support self-test ability (e.g. clock), remote monitoring and integrity warning-reporting to the user,
- not disturb or degrade any legacy services (e.g. additional R-Mode messages should not prevent transmission of legacy service integrity information that the user can always be informed about a system unavailability in the defined time to alarm),
- provide in each minute all necessary information for a cold start of the receiver (e.g. station coordinates, clock error) and
- MF and VHF R-Mode transmitters shall be usable for positioning in a mixed signal mode.

5.2.2 System requirements with regard to MF base stations (Beacons)

Based on the ACCESS project, certain parameters and functionalities of the MF beacon stations have been developed. These are:

- The system is designed to work within the 500 Hz channels spacing in Europe (USA 1 kHz channel spacing)
- The system is designed to work with up to 200 bps Minimum Shift Keying (MSK)
- Additional CW carriers can be required to be broadcast along with standard MSK signal
- Precise and stable clock – the source for both the carrier phase and the time of bit transmission
- Any additional CW and resulted spectrum change should comply with ITU-R regulations as investigated in the study [37].
- Possible R-Mode implementation on MF beacon is shown in Figure 5-1, [37].

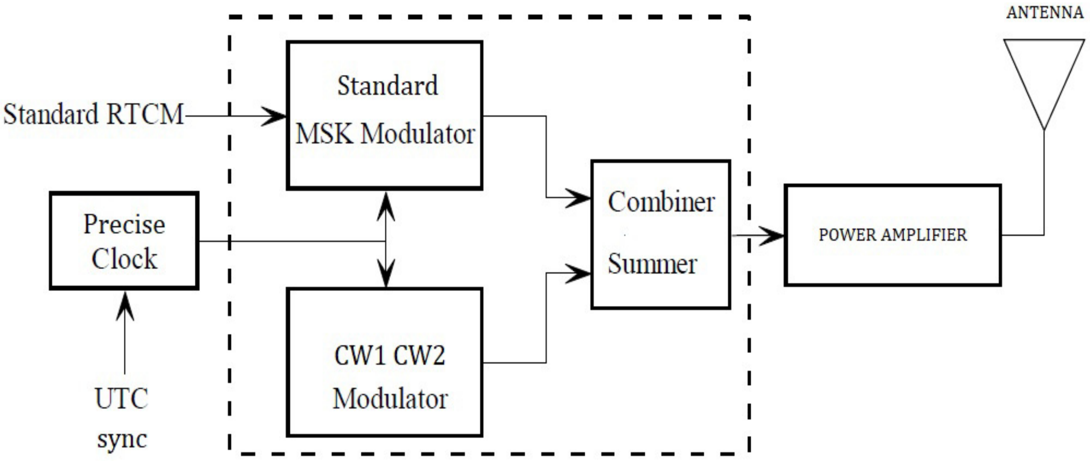

Figure 5-1: Block diagram of possible solution for MF beacon, [37]

Typical output power of DGPS stations in Europe is 100-200 W. Broadcast of additional CW's beside MSK signal will require a higher output power to maintain the nominal coverage of the station. This has to be in line with regulatory restrictions for each station.

5.2.3 System requirements with regard to AIS

- AIS use the two channels of 161.975 and 162.025 MHz with and bandwidth of 25 kHz. Only these are allowed for signal transmissions. An exception exists when switching to VDES.
- The exchange of safety-relevant information has priority. This limits the possibilities to add additional AIS messages which increase the channel load in a certain region.
- Precise and stable clock – the source for both the carrier phase and the time of bit transmission

5.2.4 R-Mode station coordinates

Reference frame

To reach the goal of an international network of R-Mode transmitting station that enables seamless positioning in Europe waters and beyond the coordinates of stations transmitting antennas has to be provided in the same reference frame. The World Geodetic System 1984 (WGS84) is today wildly used in the maritime world because it is the reference frame used in the United States Global Positioning System. It deviates about few cm from International Terrestrial Reference Frame (ITRF), a realization of the International Terrestrial Reference System (ITRS), which is based on a network of worldwide stations.

It is recommended to survey and provide coordinates in WGS84.

Coordinate accuracy

Due to the movement of the tectonic plates the coordinates of the R-Mode transmitting antennas changes depending on the site with a rate of up to a few cm per year. This makes regular survey of current position depending on the level of accuracy requirement necessary because the error of antenna position is one component of total error of distance estimation from user to the R-Mode station.

The date of coordinate survey should be made available together with station coordinates in WGS84.

5.2.5 R-Mode station time

The time accuracy at R-Mode stations is fundamental for accurate distance estimation between a user receiver and an R-Mode transmitter station. An error of 10 ns equates to 3 m distance estimation error. To enable a potential R-Mode accuracy of better than 10 m the synchronisation error should not exceed a 10 ns deviation to UTC (or the R-Mode time reference frame).

There are different options for the type of station clock and the way of time synchronisation with UTC. Each provides a different level of accuracy and independence from GNSS. At the end each maritime administration has to consider which solution fulfils their requirements. A cost-benefit analysis is needed for this purpose.

5.3 Various levels of R-Mode implementation

The R-Mode technology may be implemented in various service levels. Starting from a low level integration, serving single range information which may be used for integrity calculations, only. Up to a full GNSS independent stand-alone positioning system. Precise time distribution and time synchronization of the individual R-Mode beacons has a significant impact on the accuracy of R-Mode. On a user level R-Mode may only be used to bridge short GNSS outages (< a couple of hours) enabling a safe termination of a started manoeuvre, or it may be based on a complete GNSS independent time synchronization without any limitations.

Today no formal requirements exist that could be referred to for the implementation of R-Mode as a GNSS backup. It is obvious that the R-Mode installation costs will mainly depend on the implementation of an intersystem time synchronisation network for the R-Mode transmitters. Within the R-Mode Baltic project a cost benefit analysis will be performed. This analysis will allow estimation of costs for different levels of R-Mode implementation for the system provider as well as for the user site. Table 5-3 and Table 5-4 provide an overview on the various modes of R-Mode usage as well as different scenarios for timing and time synchronization.

Table 5-3: Suggested modes of operation

Level of R-Mode usage	Method	Use case	Remarks
Low	Ranging with less than 4* R-Mode signals	Integrity for GNSS positioning	(MF, AIS/VDES or combined)
Medium	Positioning (Lat/Long) with 4* or more R-Mode signals	Combined GNSS/R-Mode Positioning	(MF, AIS/VDES or combined)
High	Positioning (Lat/Long) with 4* or more R-Mode signals	GNSS independent positioning	(MF, AIS/VDES or combined)

*) The number of stations could be reduced by one if priory information is available.

Table 5-4: Suggested levels of R-Mode usage

Level of R-Mode implementation	Method	Gap-Time during GNSS outage	Use case
Very Low	GNSS time synchronization	No	Bridge outages at user site (e.g. local interference)
Low	Use of protected GNSS-Antenna Use of Galileo PRS	Depends on reason of outage	Bridge outages at user site (e.g. local interference). R-Mode TX site may withstand local jamming spoofing
Medium	GNSS time synchronization with Rb-clock GNSS time synchronization with CS-clock	< 3-6 h < 12-24 h	End manoeuvre in case of full GNSS outage
High	Use of R-Mode specific time synchronization corrected time differences of an asynchronous R-Mode system	24/7	Independent system in case of full GNSS outage

6 Sources of possible errors

6.1 Positioning domain

6.1.1 Positioning error sources

The major sources of errors that directly affect positioning algorithms' accuracy are as follows [1]:

Clock errors – mainly caused by offsets and drifts which lead to instability and inaccuracy of the clock mechanisms operation. These types of error are practically unavoidable, and they potentially influence any positioning method based on time measurements. This error might have different impact depending on whether it affects the reference station or the receiver site.

NLOS conditions – in cases where no line of sight between terminal and base station exist, the signal reflection becomes the dominant propagation mechanism. This may result in substantial delays of the reflected paths and as - a consequence - might generate significant range errors. NLOS (Non-Line of Sight) conditions is also an important error source for AoA (Angle-of-Arrival) methods (the reflected signal might arrive from virtually any direction).

Multipath propagation – multiple „replicas" of the transmitted signal arrive at the receiver at different instants of time and at different angles (due to obstacles at the propagation path), so the amplitude and phase of the resulting signal might be distorted. This factor might adversely affect any positioning method based on phase measurements.

Ionospheric and tropospheric refraction – refraction in the Earth's atmosphere causes small deviations of the speed of the signals from the speed of light. This type of error is relatively hard to predict because the ionization level changes over time. Atmospheric refraction mostly affects satellite positioning systems.

Bad geometry of stations – if stations involved in the positioning process are arranged along a straight line or are placed very close to one another, etc., it might lead to range and angle errors. Such situation is usually referred to as "bad geometry" because in this case the signals arrive at the terminal at very shallow angles, which makes the positioning algorithm much more difficult and prone to errors. (Ideally this angle should be as close to 90° as possible).

Incorrect station coordinates – in positioning algorithms involving lateration, the true position of the station should be known. Any errors in this position's determination obviously affect the positioning accuracy. This error is particularly critical for satellite positioning because the actual position of the satellite usually slightly differs from the calculated position due to non-spherical shape of Earth, external gravitation, solar winds and other factors which might be problematic to take into account. In case of terrestrial-based stations, this error could be minimised by performing precise measurements (e.g. geodetic surveying) of these stations' positions.

Medium access type – this type of error can affect positioning methods in many systems, including the cellular systems. Some of the medium access scenarios utilised in such systems (e.g. FDMA in GSM or low-throughput TDMA in AIS system) were not originally invented for the position determination and when used for that purpose, they might lead to significant inaccuracies. E.g. in the AIS, the symbols are rather long which makes the correlation process more difficult and prone to errors. On the other hand, in spread spectrum-based systems (e.g. GPS) the signals (chips) are very short, which is a much more desired scenario.

6.1.2 Potential methods to mitigate errors in positioning algorithms

Below, a list of potential methods to minimize errors that might affect positioning accuracy is presented. Please note, this is merely a theoretical discussion and it should not be considered a final recommendation for the R-Mode project.

Clock errors – To mitigate this error on the reference station side, a rubidium oscillator (at least) should be utilised. Additionally, the positioning algorithms might be supported by the reference signal from the GNSS system, but this option should only be employed if the correctness of this reference signal can be reliably verified.

In case of the terminals, three solutions could be considered: (a) rubidium oscillator (very expensive option!), (b) using independent positioning method, e.g. TDOA-based (might complicate the entire solution); (c) using TOA (Time-of-Arrival) method with clock corrections' calculation (requires additional reference station – so at least 4 station in total are necessary).

NLOS conditions – To consider this type of error, one should first decide whether the NLOS scenario (propagation behind horizon) is relevant and actually needs to be considered. If yes, then an appropriate method to mitigate this type of error is a proper modelling of the NLOS conditions. To do so, a measurement campaign might be required.

Multipath propagation – to minimize this type of error, a channel delay profile should be obtained for all relevant propagation environments (open sea LOS open sea NLOS, coastal, etc.). To do so, a measurement campaign might be required.

Ionospheric or tropospheric refraction – this type of error is particularly important for the MF-based systems. To minimize it, the properly modelled skywave propagation should be taken into account.

Bad geometry of stations – there are two options to consider: (a) to provide redundant reference stations, (b) the station's position should be selected in a way to ensure a good geometry. Regardless whether we choose (a) or (b), "exclusion zones" should be determined to indicate areas where station geometry might be bad and which consequently should be avoided.

Incorrect station coordinates – there are two options: (a) using a data base with stations' positions (if available), (b) measurement of the exact position of the station. In case of (b), the measurement should be as accurate as possible, preferably using geodetic surveying methods.

Medium access type – in case of TDMA (AIS) – correlation techniques will normally be employed to support symbol edge detection. To ensure an optimum performance of this method, binary sequences used in the system should be properly designed (obviously those sequences must not cause interference with the legacy systems). In case of MF-based systems – phase measurements will normally be employed. Again, the signal used in the system should be properly designed in order to optimize this method, [32].

6.1.3 Other methods to minimize positioning errors

TDOA (Time Difference of Arrival) – the main benefit of this method is a fact that the reference station's clocks do not need to be synchronised with the mobile terminal's clocks.

Since the propagation time of the signal is measured differentially, time synchronisation at the reference station side (only) is sufficient. This is caused by very precise clocks (e.g. rubidium) that are usually utilised in the reference stations and are usually NOT utilised in the terminals (due to high costs). Such precise clocks obviously allow to reduce the clock errors (offset and drift), and consequently - to significantly improve the accuracy of the position estimation. It should be noted that a signal propagation time measurement error of 1 µs translates into a position estimation error of around 300 m. Additionally, the fact that in the TDOA method, the difference of the propagation times is determined (rather than the propagation time itself) means that the negative influence of some phenomena occurring in the radio channel can be minimised (e.g. refraction, NLOS or multipath effects). An important benefit the method is also the fact that the exact moment of the reference signal transmission does not need to be known while calculating the terminal's position by the reference station.

Kalman filtering – it is an algorithm that uses a series of measurements (e.g. designated position, distance to measurement stations and vessel speed) observed over time, containing some inaccuracies (caused by different position error sources) and produces estimates of unknown variables (vessel position) that tend to be more accurate than those based on a single measurement alone. The algorithm works in a two-step process: prediction and estimation and it is recursive. It can run in real time, using only the present input measurements and the previously calculated state and its uncertainty matrix. No additional past information is required.

Correlation – Generally, correlation is a method to determine how two sequences are “similar” to each other. Two types of correlation can be distinguished: autocorrelation and cross-correlation. An autocorrelation defines a correlation between an N-element sequence c_i and a shifted version of the same sequence. A cross-correlation is a correlation of two sequences c_i and c_j comprised of N elements shifted with respect to one another.

The numerical value of auto- and cross-correlation can be in the range between -1 and +1. The value of +1 means that both sequences match perfectly. 0 means that there is no relation whatsoever between the sequences. -1 means that one sequence is an inverse version of the other (and vice versa).

Autocorrelation is an important measure to ensure synchronization between the transmitter and receiver. An N-element sequence has good correlation properties if its autocorrelation value is equal to 1 for the multiples of its length (i.e. for 0, N, 2N, …)[2] and is approximately equal to–(1/N) elsewhere. The receiver needs to detect a beginning of this sequence using the above property.

A small cross-correlation value is required for a proper separation of various channels in the received signal. Two sequences with a cross-correlation equal to zero are said to be orthogonal.

Some examples of sequences with good correlation properties include: Gold, Walsh and Barker sequences as well as m-sequences. Utilization of sequences having very good correlation properties may result in correlation peaks even below the receiver's sensitivity and consequently it might improve the range. A properly designed system can also allow to reliably determine the timing of a peak's occurrence if this peak is high and distinct. And obviously a reliable time measurement translates into reliable range measurement. To sum

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[2]) these are so-called “correlation peaks”

up: selection of a proper correlation sequence will result in correlation peaks that are distinguishable with respect to their power and their time, which will substantially improve the quality and accuracy of the positioning algorithm.

Receiver Signal Strength (RSS) measurement – the method based on RSS measurement is very simple but on some occasions it might efficiently assist the "primary" propagation method (e.g. TDOA). For example if two potential positions are considered as a main algorithm's output, the RSS method might help instantly discard one of them (the one that is obviously erroneous), [39], [40].

6.2 R-Mode signal generation

6.2.1 MF ranging (Estimating TOA)

The ACCSEAS Milestone 2 report presented methods to employ the MF DGNSS broadcasts in R-Mode, [41]. This section reviews the results presented in that report.

The MF DGNSS system transmits its information via a binary modulation, a method known as Minimum Shift Keying (MSK). Assuming that the MSK transmission is controlled by a precise time/frequency source, both the times of the bit transitions (potentially once every 10 ms) and the underlying phase of the transmitted signal (a sinusoid at approximately 300 kHz) could be exploited to estimate the time of arrival (TOA) for ranging applications. The report [41] examined the potential performance of estimators of TOA from these two parameters.

The report further showed that with the existing signal strengths and beacons locations, the time of bit transition is too imprecise for effective ranging. However, assuming that the lane ambiguity could be resolved, the carrier phase could yield sufficient accuracy. Further, while this level of performance is conceptually possible with the direct MF transmission, it would be significantly easier if in-band CW signals accompanied the MF and its phase was estimated. As an added benefit, producing beat frequencies from multiple CW signals could help resolve the ambiguity. For phase estimation the Cramér-Rao lower bound on accuracy is

$$\sigma_t^2 \geq \frac{1}{2\,\omega_c{}^2 T\, SNR} \quad \text{seconds}$$

in which T is the observation period, ω_c is the MF carrier frequency and SNR is the received signal to noise ratio.

6.2.2 AIS ranging

In the ACCSEAS report, "Feasibility Study of R-Mode using AIS Transmissions" [50], three approaches for using AIS as a signal of opportunity was assessed. The recommended approach was to use a standard AIS message 8. In the process with establishing the requirements for R-Mode AIS message 26 has been suggested instead of message 8.

The message 26 allows for predictability of when the next time tagged message will be transmitted. It supports both ITDMA and SOTDMA allowing the receiver to know forehand when the next message 26 will be transmitted. In addition, using a different access scheme than RATDMA (message 8 uses RATDMA unless it is put in an FATDMA slot); will lower the risk of other AIS transmitters inadvertently sending at the same time. This will increase the chances of message 26 being received by the mobile station.

The base stations shall transmit a signal (message) for the mobile units to use for ranging, from which the mobile units can calculate a position. This raises the question of which time in an AIS transmission to use. There are several candidates (see Figure 6-1);

- Time tagging the training sequence, which starts just short of T1.
- Getting the time of the start flag (HDLC flag) at T2 is another option.
- Using the end flag is a third option.
- Start of the slot.

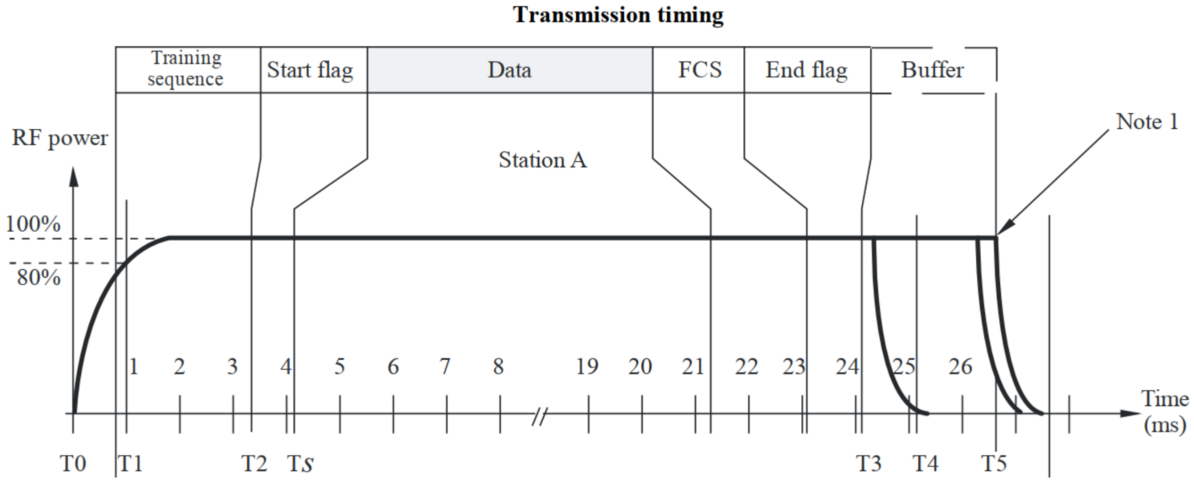

Figure 6-1: ITU-R M.1371-5 showing RF power as a function of time, [17].

Time at Training sequence

The benefit of time tagging the training sequence is that it is the absolute start of the modulated radio transmission. The problem is that the training sequence is not transmitted at peak power, opening for the possibility that the first bits of the training sequence are not received. It is possible to do the math and calculate where it is based on the training sequence bits received, as the baud rate is constant.

Time at start flag

The start flag is always transmitted at peak power, and it is a well-defined field in HDLC data packet. If the start flag is not received, there will be no AIS message received at all.

Time at end flag

This flag is with regard to construct and function very similar to the start flag, where the only difference is that it comes at the end of the AIS message payload and not at the beginning. As the baud rate is constant, it would not make much difference to tag the end flag or the start flag.

Time at slot start

The time at the slot start is well defined, and should be easy to time stamp. The problem is that the start of the transmission can have small variations (allowed in ITU-R M.1371) making time of slot start less accurate.

6.3 Potential R-Mode errors sources (MF and AIS/VDES)

There are several important topics which need to be considered when using MF and VHF ranging:

6.3.1 Ambiguity resolution (MF)

Ranging using carrier phase requires the resolution of cycle ambiguity, the fact that the phase repeats every wavelength of the signal (this is approximately 1 km for MF DGNSS signals). Additional CW allows for several ambiguity resolution approaches: (1) initializing the receiver at a fixed location and "counting" cycles as the platform moves or (2) using time synchronized, multiple frequency signals and solving for a position that simultaneously satisfies all of the ambiguity equations with integer solutions. This was accomplished in the Omega system by using different frequencies from spatially separated transmitters.

6.3.2 Propagation delay (MF)

Another topic is that the propagation of an MF transmission is delayed according to the characteristics of the ground over which it is travelling. These additional secondary factors (ASFs) must be taken into account for positioning applications. While computer modelling tools can "predict" ASFs using databases of ground conductivity and topography, the quality of the prediction is typically insufficient for the desired positioning accuracy [43], [44]. The tools also do not describe the time varying nature of the ASFs. The current solution to ASFs involves surveying the area of interest to account for spatial effects based upon topography and ground conductivity and establishing monitor sites (with appropriate communications links) to provide temporal corrections to account for the time variation in the delay.

6.3.3 Skywave interference (MF)

MF transmissions can suffer from multipath interference due to signal reflections at the ionosphere. This is referred to as skywave interference. This effect is most pronounced at night. While pulsed signals (such as Loran) can mitigate this effect, continuous transmission (as in MF) will always suffer from it.

6.3.4 Ducting effect (AIS/VDES)

At VHF frequencies, the signal is primarily a Line Of Sight (LOS) propagation path. It is fairly common, under certain weather conditions, for there to be ducting effects, which allow these signals to be received at distances well beyond the LOS.

6.3.5 Interference in the VHF band (AIS/VDES)

The primary source of interference is man-made noise, [50]:

- Ambient atmospheric noise is modelled as Gaussian with a flat power spectral density. The average noise power level due to black body radiation is

  $$kT_0b$$

  where $k = 1.38 \times 10^{-23}$ W/Hz/K is Boltzmann's constant, $T_0 = 288$ K is the absolute temperature and b is the receiver's noise equivalent bandwidth measured in Hz.

- Man-made sources account for additional noise above this level. A common model for the average noise power from these sources, above the noise floor and measured in dB, is

  $$F_{am} = c - 27.7\, log_{10} f \;\; dB$$

in which f is the frequency in MHz and c is a constant depending upon the locality (76.8, 72.5, and 67.2 dB for business, residential, and rural environments, respectively). For the VHF band of interest (near 160 MHz), the average man-made noise is 15.75, 11.4, or 6.1 dB above the noise floor, respectively.

- For example, a 25 kHz AIS channel observed in a residential environment would see an average noise level of
$$(-160\ + 11.4)\ dBW = -148.6\ dBW = -118.6\ dBm$$

This corresponds with the use of -117 dBm as a minimum received signal level as this would correspond to approximately 0 dB SNR.

6.3.6 Jamming and spoofing (MF and AIS/VDES)

Since the AIS and MF DGNS are not encrypted, the signals of both services can easily be generated with off-the-shelf components (spoofing). Furthermore, it is possible with sufficient transmission power to interfere with the signal of the services in such a way that reception is no longer possible (jamming). Due to the large wavelength, the transmission of spoofing and jamming signals in the MF band requires very large transmission antennas or transmission powers. With the smaller wavelength in the VHF band, the required transmitting equipment becomes considerably smaller and can consist of widely available components. Therefore, AIS signals are more susceptible to externally generated signals.

6.4 Radiowave propagation

6.4.1 MF

A marine radio beacon transmits omni-directionally. Its signal reaches the receiver by two main paths: groundwave and skywave. The groundwave-propagated component travels over the surface of the Earth. The skywave-propagated one is refracted by the ionosphere and is more prevalent at night. As a groundwave signal propagates, its field strength is progressively attenuated. The rate of this attenuation depends on the frequency of the signal and the type of ground it travels across. The ITU provide a series of propagation curves within ITU P.368-9 [45] which can be used to predict the expected signal strength given the type of ground and its electrical conductivity. The conductivity of the ground for the propagation path being considered can be identified via the ITU World Atlas of Ground Conductivities, from which it's possible to identify the different conductivities affecting the propagation path. Where a propagation path crosses ground of more than one conductivity type, the ITU recommend the use of Millington's method to calculate the total path attenuation. A detailed description how to calculate coverage prediction using the Millington method is given in [46]. To enable the calculation of the coverage the following information is required from a MF radio beacon site:

- ERIP: Effective radiated power with respect to 1 kW
- Knowledge of transmitted power and specific antenna effectivity of the MF transmitting antenna
- Knowledge of field strength at given distance to the transmitter and given propagation path (e.g. sea level)

A full coverage prediction will also consider the following aspects:

- Skywave (self-fading)

- Interference (co-channel and neighbouring-channels)
- Atmospheric noise (based on ITU-R model)

6.4.2 VHF

Transmission in the AIS system is based on VHF. AIS mobile stations (on board vessels), AIS AtoNs, AIS Base Stations and other AIS devices are transmitting on two standardised AIS channels; Channel A (161.975 MHz) and Channel B (162.025 MHz). Two power levels are used on the vessels; low (1 W) and high (12.5 W).

The range, distance between transmitting unit and receiving unit, is mainly depending on antenna height and the antenna installation. Use of combiners will introduce a loss and hence reduce the range. It is important to install the antenna as high as possible.

Theoretical range can be estimated based on the following formula, which is a line of sight estimation:

$$D\,(km) = \sqrt{12,75xH\,(m)}$$

D = Distance (range) in kilometres. H = antenna height in metres.

Note that both the transmitter and receiver side (see figure) need to be considered. This is an estimation of line of sight, and is very conservative for VHF range calculations.

To give a better estimate of VHF range under normal metrological conditions 10-20 % should be added to the line of sight distance. Special metrological conditions may affect the radio range considerably. Programs are available to make sophisticated calculations based on more parameters.

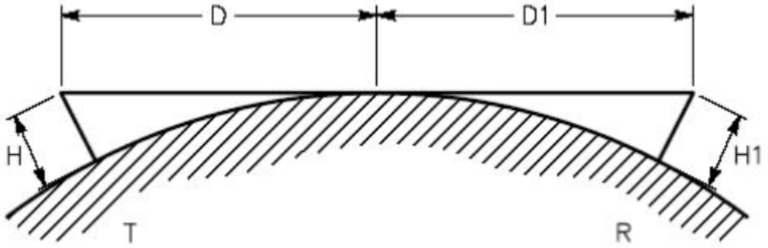

Figure 6-2 VHF LOS calculation

6.5 Combined R-Mode signal reception

The position solution (actually position and clock offset) from radionavigation TOA observables does not, in general, have a closed form solution, [38]. The usual approach is to assume some approximate position and iteratively solve a linearized version of the problem. For terrestrial systems (such as Loran) this is typically a weighted least squares solution with error weights dependent upon the accuracy of the individual TOA measurements. Assuming n transmitters, at azimuth angles φ_k with respect to the assumed position, the linearized equations are

$$\begin{bmatrix} \sin\varphi_1 & \cos\varphi_1 & 1 \\ \sin\varphi_2 & \cos\varphi_2 & 1 \\ \vdots & \vdots & \vdots \\ \sin\varphi_n & \cos\varphi_n & 1 \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \\ c\delta t \end{bmatrix} = c \begin{bmatrix} \delta TOA_1 \\ \delta TOA_2 \\ \vdots \\ \delta TOA_n \end{bmatrix}$$

in which δx,δy, and δt are the differentials in the x and y position and clock offset solutions, respectively (relative to the assumed solution), c is the speed of light, and each δTOA_k is the differential in the TOA measurement. It is common to write this in set of equations in matrix form as

$$\boldsymbol{A\delta} = \boldsymbol{z}$$

defining the direction cosines matrix ($\boldsymbol{A}$), the vector of differential TOAs (**δ**) and the position/clock differential vector (**z**). The HDOP if defined by first computing

$$\boldsymbol{H} = (\boldsymbol{A}^T\boldsymbol{A})^{-1}$$

and then

$$HDOP = \sqrt{H_{1,1} + H_{2,2}}$$

Assuming independent TOA measurements, the covariance matrix of z is

$$\mathbf{R} = \begin{bmatrix} \sigma_1^2 & 0 & \cdots & 0 \\ 0 & \sigma_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_n^2 \end{bmatrix}$$

(i.e. white noise with variances σ_k^2 on the k^{th} TOA measurement), the weighted least squares solution using weight matrix $\mathbf{R}^{-1}$ is

$$\boldsymbol{\delta} = (\boldsymbol{A}^T\boldsymbol{R}^{-1}\boldsymbol{A})\boldsymbol{A}^T\boldsymbol{R}^{-1}\,\boldsymbol{z}$$

which has error covariance (a 3-by-3 result)

$$\boldsymbol{G} = (\boldsymbol{A}^T\boldsymbol{R}^{-1}\boldsymbol{A})^{-1}$$

The weighted HDOP (skipping the variance of the clock offset solution, $G_{3,3}$) is found as

$$\sigma_{position} = \sqrt{G_{1,1} + G_{2,2}}$$

Hence, to measure performance at a particular location, we need to know which signals are available, the geometry to the signals and what their accuracies are.

Assuming that all observable signals are synchronized at transmission, there is no need to limit the measurements to being from one type of source. We can combine measurements from multiple sources as long as we have estimates of their individual accuracies (in the same units) and angles to the transmitters. Specifically, angles φ_k, differential measurements δTOA_k, and variances σ_k^2 could come from MF DGNSS for $k = 1,2,\ldots n_1$, from AIS for $k = n_1+1,\ldots n_2$, and e.g. from eLoran for $k = n_2+1,\ldots n$.

Note that the addition of new measurements from additional transmitters cannot increase the HDOP or weighted HDOP. At worst (and this occurs if the new transmitter's location is at the same azimuth as a current transmitter), the HDOP and weighted HDOP stay the same, [42].

Figure 6-3 contains a block diagram of such a combined signal, “all-in-view” R-Mode receiver. Is essentially combines the separate MF, AIS, and eLoran receivers with a common “position calculation” block implementing the algorithm just described. For simplicity the diagram shows three distinct antennas although MF-DGNSS and eLoran could potentially share an antenna due to their closeness in frequency.

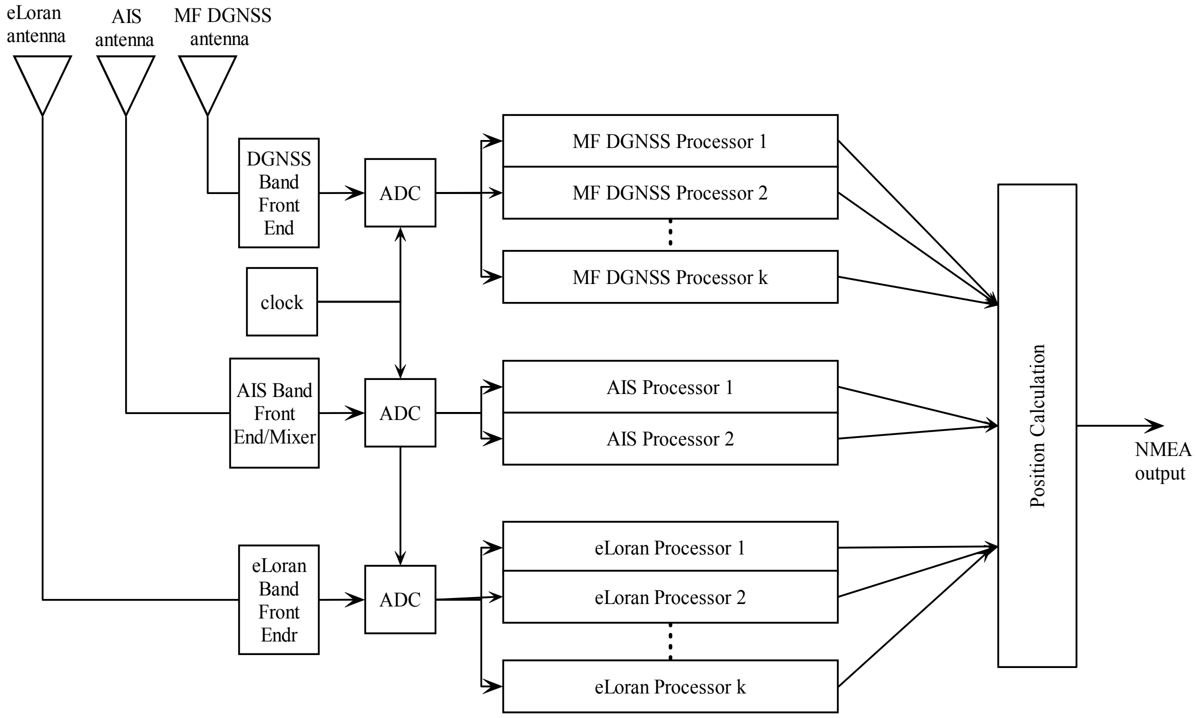

Figure 6-3: MF+AIS+eLoran “All-in-View” R-Mode receiver, [38].

7 Conclusions

As these documents deals with an extensive amount of information provided from multiple sources, such as international standardisation organisations, intergovernmental and non-governmental organisations as well as world-wide operating expert groups, it is envisaged to provide short but comprehensive conclusions dealing with the essential information derived from this document.

- International documents of IMO and IALA, express the need of a backup system to GNSS. A variety of technological solutions serving this backup requirement are within scope - In the radio frequency (RF) domain so-called “Signals of OPportunity” (SoOP) form a promising approach since their availability is already given.

- Referring to IALA documents a promising solution is available - The terrestrial R-Mode Service. R-Mode technology qualifies as a backup to GNSS that meets the resilient PNT requirement of the IMO e-Navigation strategy and fits well into the SoOP concept.

- It is recommended by IALA to use the existing terrestrial infrastructure of DGPS and/or AIS base stations to introduce the R-Mode service.

- The R-Mode system meets ITU-R requirements if used as embedded service within the IALA radio beacon broadcasts or embedded into the AIS/VDES transmissions. Both implementations don’t require any change of current bandwidths.

- e-Navigation architecture takes into account terrestrial backup systems that are an independent source of positioning and timing information.

- Methodology of time difference converted into range difference, supported by phase measurement is still valuable. By applying algorithms of trilateration and triangulation it is possible to calculate the receiver’s position in relation to fixed shore based radio transmitters.

In the framework of the R-Mode Baltic project research and development activities of R-Mode technology and system will be performed which are in line with the user requirements which were identified within this report. In the Appendix these were mapped to the different project tasks.

Appendix

The project R-Mode Baltic will develop R-Mode as a backup system to GNSS. It shall provide positioning and timing in times with reduced GNSS performance so that begun maritime manoeuvres could be finished with electronic navigation support. The passage of areas with narrow shipping lanes (port and port approach, traffic separation scheme, path through ice-covered waters) which requires such support can take several hours. Therefore, it is assumed that R-Mode should be available for at least 2 h after GNSS has failed within the R-Mode accuracy requirement.

The accuracy of the R-Mode based position depends on different parameters:

- the time accuracy of the transmitted R-Mode signal, which depends on accuracy of local transmitter clock,
- the geometry of transmitter stations used for positioning which could be MF and / or AIS/VDES,
- the accuracy of ranging or ranging difference which depends on the signal strength has a strong dependency of the distance.

With respect of an assumed transmitter clock error of 3 m (in the ranging domain) the MF or AIS/VDES based ranging should have an accuracy of about 5 m within the transmitting station service area to enable the support of port approaches, navigation in restricted waters and inland waterways which requires a 2D positioning accuracy of 10 m (see Table 5-2). Furthermore, the system should fulfil the requirements for coastal navigation, which are less demanding.

Based on this assumption and the findings of this document the following requirements will be used within the context of the project for the R-Mode system to be developed.

Requirements on time accuracy and time synchronisation

- Time accuracy of local clock of each R-Mode transmitter site should be at least 10 ns to UTC reference without notifying the user.
- In case of higher clock deviation the user should be informed about the current clock error of R-Mode transmitter that he can correct his measurements to be better than 10 ns.
- Each R-Mode station should keep the 10 ns clock accuracy limit for at least 2 h.
- Higher clock errors or unmonitored clocks should be the cause of a warning to the user.
- An R-Mode time frame, in which all R-Mode stations operate, could be an alternative to UTC.

Requirements on R-Mode maritime radio beacons

- The requirements are given in the subchapters 5.2.1 and 5.2.2.
- The system should support port approaches, navigation in coastal region, restricted waters and on inland waterways.

Requirements on R-Mode AIS base stations

- The requirements are given in the subchapters 5.2.1 and 5.2.3.
- The system should support port approaches, navigation in restricted waters and on inland waterways.

Requirements on R-Mode testbed

- The testbed should include areas with different requirements formulated for a backup system in subchapters 5.2.1.
- These areas should be in range of a sufficient number of AIS/VDES base stations and / or radio beacons to support single MF and AIS/VDES as well as combined R-Mode positioning.

Requirements on R-Mode receiver

- The requirements are given in the subchapters 5.2.1.
- Each calculated R-Mode position information should be provided by the R-Mode receiver for the time of UTC second change. Raw data should be provided interpolated or extrapolated on UTC second change.

Requirements on R-Mode standardisation

- The implementation of R-Mode on maritime radio beacon or AIS/VDES base station signals affect existing standards for the communication channel as well as guidelines and recommendations for station setup and operation. These documents have to be identified and the necessity for changes announced.
- R-Mode developments have to be standardised for expansion of R-Mode network.

Requirements on cost-benefit analysis

- The analysis shall cover current available technologies for local clocks and time synchronisation and give their achievable accuracies. Furthermore, it should indicate the degree of independence from GNSS and the assumed costs per R-Mode station (see Table 5-4).
- The cost-benefit analysis should consider different levels of navigations support (see Table 5-3).

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