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| IALA Guideline |

DRAFT

on Implementation of R-Mode on MF and VHF frequencies

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# Introduction

## This Guideline provides the design, implementation and operational principles for R-Mode using MF and VHF frequencies. Scope of Document

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.

However, 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.

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.

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. The use of such ranging signals from existing DGNSS maritime radio infrastructure is known as “R-Mode” (ranging mode). Even if it is impossible to derive a complete position solution from R-Mode (e.g. due to insufficient, less than three signals being present), the available pseudorange information combined with measurements from existing positioning systems can provide a position solution.

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.

Based on various studies and implementation projects this guideline will focus on the R-Mode implementation using MF DGNSS radio beacon frequencies as well as VHF transmissions using the VHF terrestrial frequencies of VDES. Further a combination of such signals, is a possible approach and will be described in this guideline.

## Structure of document

# Performance requirements

## Definitions

System performance is characterised by a number of different aspects, including Accuracy, Integrity, Continuity,

Availability and Coverage, as:

**2.1.1. ABSOLUTE ACCURACY (GEODETIC OR GEOGRAPHIC ACCURACY)**

The accuracy of a position estimate with respect to the geographic or geodetic co‐ordinates of the Earth.

**2.1.2. INTEGRITY**

The ability to provide users with warnings within a specified time when the system should not be used for

navigation.

**2.1.3. CONTINUITY**

The probability that, assuming a fault‐free receiver, a user will be able to determine position with specified

accuracy and is able to monitor the integrity of the determined position over the (short) time interval applicable

for a particular operation within a limited part of the coverage area.

**2.1.4. AVAILABILITY**

The percentage of time that an aid, or system of aids, is performing a required function under stated conditions

(i.e. when it provides the required integrity for the given accuracy level). Non‐availability can be caused by

scheduled and/or unscheduled interruptions.

**2.1.5. COVERAGE**

The coverage provided by a radionavigation system is that surface area or space volume in which the signals are

adequate to permit the user to determine position to a specified level of performance.

## General R-Mode Requirements

Many operational, technical, economical, and radio frequency spectrum allocation related factors are considered in determining the set of required parameters for a potential backup to GNSS as a component of PNT system. . Most leading IMO and IALA documents show, 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 for terrestrial navigation. This resulted in the proliferation of multiple use of existing systems and is one of the strong advantages of R-Mode radionavigation service. R-Mode is intended to provide backup functionality to GNSS, either as a contingency system that allows safe completion of a manoeuvre or as a backup system that ensures continuation of the navigation application, but not necessarily with the full functionality of GNSS, [IALA R-129].

In contrast to GNSS, which has global coverage, the R-Mode system cannot achieve global coverage due to the limited range of the MF and VHF signals. To support the mariner world-wide it is important that navigation services are globally harmonization and in line with the e-Navigation. The highest risk for degradation of the GNSS signals due to intentional and unintentional interferences is expected to be in coastal waters. R-Mode, as a system, is designed for coverage in coastal waters and for port approach and restricted waters.

## 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 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), [x] and A.1046(27), [x] detail the requirements for future GNSS and 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.

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 x-y (see Appendix 1 of IALA Recommendation R-129, [X]). These requirements must be taken into consideration while designing components of the R-Mode system and service.

Table 1: Suggested minimum user requirements for general navigation – backup system, [6]. The red rectangle highlights the designated R-Mode service areas

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 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 |  | 99 | N/A² | Global | 60 |
| Coastal | 100 | 250 | 30 |  | 99 | N/A² | Regional | 15 |
| Port approach and restricted waters | 10 | 25 | 10 |  | 99 | 99,97 | Regional | 2 |
| Port | 1 | 2.5 | 10 |  | 99 | 99,97 | Local | 1 |
| Inland Waterways | 10 | 25 | 10 |  | 99 | 99,97 | Regional | 2 |

The R-Mode system and service should fulfil the above mentioned system and service level requirements for coastal waters, port approach and restricted waters.

In addition to Table 1 the R-Mode service should fulfil the following requirements:

* work partially or completely independent from GNSS,
* have unlimited user-capacity,
* provide a two-dimensional position fix (x,y),
* provide a position referenced to geographical system WGS84,
* the R-Mode System Time (RMST) has to be traceable to the Coordinated Universal Time (UTC),
* the R-Mode signals of a site should be synchronised better as 10 ns with the RMST,
* 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 within the defined time to alarm),
* provide in each minute all necessary dynamic information for a cold start of the receiver (e.g. clock error)

## R-Mode Levels of Operation

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. Table 2 and Table 3provide an overview on the various modes of R-Mode usage as well as different scenarios for timing and time synchronization.

Table 2: Suggested modes of operation

|  |  |  |  |
| --- | --- | --- | --- |
| Level of R-Mode usage | Method | Use case | Remarks |
| Low | Ranging with less than 33 R-Mode signals | Integrity for GNSS positioning | (MF, AIS/VDES or combined) |
| Medium | Positioning (Lat/Long) with 33 or more R-Mode signals | Combined GNSS/R-Mode Positioning | (MF, AIS/VDES or combined) |
| High | Positioning (Lat/Long) with 33 or more R-Mode signals | GNSS independent positioning | (MF, AIS/VDES or combined) |

Table 3: 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 |

## Timing, Synchronisation and Hold Over requirements

The R-Mode system requires an accurate timing of the R-Mode signal transmission. Any unobserved and not corrected transmitter site timing error will lead to an error in the range estimation at user side and therefore to an increase of positioning error. To keep the impact of uncompensated transmitter clock errors low two fundamentally different strategies for clock implementations at the R-Mode transmitter sites and its monitors exists. Middle paths are conceivable. Both in common is that they have to solve the issue of time synchronization with the RMST, provide accurate and stable timing signals to transmitter site equipment, provide hold over capabilities in times the synchronization is not possible and measure deviation of the transmitter site clock to the RMST. The first strategy has a focus on synchronization and the second follows the philosophy of stable oscillators and accurate measurements of time deviations. The requirements on the transmitter site and monitor timing solution depend on the chosen timing strategy.

It is suggested that the unknown deviation (after applying provided clock correction from the navigation data) of the transmitter site clock to RMST does not exceed 10 ns (95 %) to fulfil the requirements on R-Mode defined in Table 1. This has to hold for times when synchronization of the transmitter site with the RMST source is possible but also when synchronization is not possible but the R-Mode service has to be available for limited or unlimited time which depends on the declaration of R-Mode as a backup or contingency system. The definitions of both system types are given in the IALA Recommendation R-129 [x].

The basic idea is that backup and contingency system shall enable continuation of ship operation in cases of loss or degradation of GNSS or its service. A reduced functionality compared to GNSS (e.g. less information, lower accuracy) is possible. The difference between the two systems is related to the time the system has to operate in the nominal range after unavailability of GNSS. The contingency system has to provide its service for at least a limited time to enable safe completion of a manoeuvre. How long this would take deviates from region to region. A value of 2 hours is suggested. This may have an impact on the requirements on the hold over capabilities of the transmitter site clock. The backup system has to operate in the nominal range all the time.

The focus of the first strategy mentioned above is on synchronization. The goal is to have a low deviation of the transmitter site clock to the RMST. The site clock deviates considerably less than 10 ns from RMST when synchronization is possible. In case the synchronization is lost the clock will make use of hold over capabilities. Here typically an integrated atomic oscillator (Rubidium or Caesium) is used to reduce the drift of the clock away from RMST. For a contingency system the maximum error of synchronization solution and time error caused by drift of the unsynchronized oscillator over the defined minimum system availability time has to sum up to 10 ns or less (95%). Clock corrections in the navigation data are not so important for this approach. If they are measured by a monitor station or will be estimated differently the 10 ns requirement holds for the site clock error after the corrections of the navigation data were applied.

For a backup system a stable solution for synchronization is necessary. The interruptions of synchronization of site clock to RMST has to be limited that over that time the hold over capabilities of the site clock can keep the clock error below 10 ns. The definition of the requirements for the local oscillator that provides hold over capabilities can be based on the synchronization accuracy, the expected duration of loss of synchronization and the requirement to stay below an error of 10 ns. As before, the capability to measure the time deviation from RMST can relax the requirements.

A slightly different approach is used in strategy two. A stable oscillator at the station site is in free running mode. The synchronization channel is used to measure the time deviation and drift of the site clock (with integrated oscillator) with respect to the RMST. The deviation will be given as clock error correction in the navigation data to the user. The implementation of this strategy has to keep the uncorrected time error below 10 ns.

In the following suggested technicalt requirements for synchronization and hold over for a contingency system with 2 hours minimum availability after loss of synchronization.

* Requirements on timing performance with respect to RMST when the time device is nominally synchronized:
  + Synchronization error < 5 ns at all times
  + MTIE < 10 ns at all times
  + MTIE < 1 ns at 5 s time intervals
* In this case the R-Mode transmitter must continuously provide useable ranging signals for at least two hours. For this, a sufficiently stable local oscillator is needed, thus the free-running clock shall have the following general statistics:
  + Short term ( 60 s) TDEV shall be < 0.1 ns
  + Medium term ( 2 h) TDEV shall be < 1 ns
* When losing synchronization and the timing device switches to a hold-over state, the device shall have the following characteristics with respect to the RMST:
  + Short term ( 60 s) MTIE shall be < 1 ns
  + Medium term ( 2 h) MTIE shall be < 10 ns

# System Architecture

The overarching architecture as adopted by IMO for e-Navigation is developed from IALA Guideline 1113 on “DESIGN AND IMPLEMENTATION PRINCIPLES FOR HARMONISED SYSTEM ARCHITECTURES OF SHORE‐BASED INFRASTRUCTURE”, [x]

Figure 2 shows how R-Mode fits in the overall e-Navigation system architecture. R-Mode will be implemented as a new shore site service which could provide data and ranging information to the ship side. The R-Mode system with its services to provide synchronised ranging signals is part of the overall PNT supporting e-Navigation architecture.

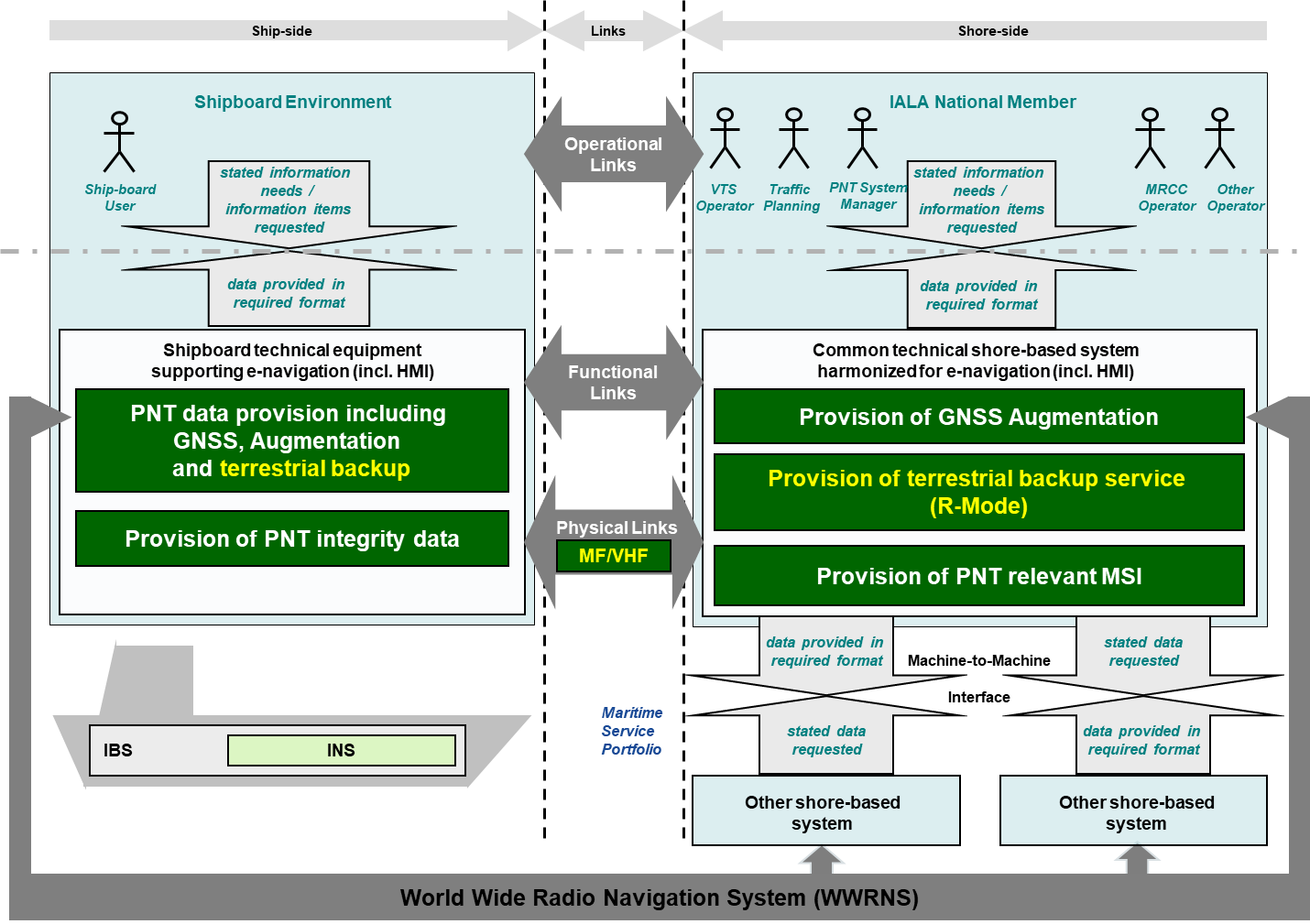


Figure 1: R-Mode embedded in the overarching IMO e-Navigation architecture

## Logical R-Mode System architecture

The R-Mode system consists in general of the following components (**Fehler! Verweisquelle konnte nicht gefunden werden.**):



Figure 2 Logical R-Mode architecture

1. R-Mode transmitter station

A station that provides R-Mode service. It is intended to use existing maritime radio beacon installations and VHF (AIS/VDES) shore sites. The functions include:

* Synchronize with R-Mode reference time
* Hold over synchronized time
* Generate MF/VHF R-Mode signal (include ranging and data messages)
* Transmit MF/VHF R-Mode signal
* Receive information from R-Mode monitor

1. R-Mode monitor

Station that monitors broadcasted signals of R-Mode transmitters. The functions include:

* Monitor availability of MF/VHF R-Mode signal
* Monitor integrity of R-Mode navigation messages
* Estimate the health status of the R-Mode transmitters

1. R-Mode reference time:

Time distribution infrastructure that provides in a region the R-Mode reference time which is used for R-Mode service provision. The functions include:

* Synchronize to UTC or keep the time scale traceable to UTC
* regularly publish its offset and uncertainty

1. Command and control, Security center

Central infrastructure of a region that is used to control and command the complete network. It provides a security services for the R-Mode system and service. The functions include:

* Configure R-Mode base stations inside the region
* Collect and share information
* Monitor status of R-Mode system
* Alarm and control of R-mode base stations in the region

1. R-Mode user

User of R-Mode service. The functions include:

* Receive MF/VHF R-Mode Signal
* Ranging
* Positioning

## Physical R-Mode Architecture

Figure 4 provides a common physical R-mode architecture identifying physical elements which are required for both, R-Mode using MF transmissions as well as R-Mode using VHF transmissions.

The physical R-mode architecture of a region is composed of R-mode base station & monitoring station pairs, user stations, RMST system and command and control, Security center. The R-mode base station generates and transmits MF / VHF R-mode signal, and the user station receives the signal and calculates the position information. At the same time, the R-Mode monitoring station also receive the MF / VHF R-mode signal from the corresponding base station. It evaluates the health status of the base station by the analysis of the received signals, transmits the dynamic messages to the corresponding base station in real time, and also transmits monitoring results to the command and control, security center through network. The R-Mode monitoring station broadcasts correlation data for the users in the work area.The command and control, security center manages all base stations, monitoring stations and RMST system in the region, and evaluates the operation status and security of the R-mode system. RMST system provides synchronized time for base stations, monitoring stations and command and control, security center.



Figure 3 Physical system architecture

1. R-Mode transmitter station

It consists of timing device and R-Mode MF transmitter / VHF transceiver.

The timing device is a precise clock, which can be optional disciplined by GNSS. It can regularly synchronize with RMST, and hold over the synchronized time in the interval of synchronizations, and also in the case when the time synchronization between timing device and RMST is disrupted. Different synchronization methods might be used. VHF transceiver might receive signals from adjacent base station, and synchronize time with it to achieve precise time synchronization between adjacent R-Mode base stations. Timing device provides R-mode MF transmitter / VHF transmitter with:

* Pulse Per Second (1PPS)
* 10 MHz sinusoidal signal

The R-Mode MF transmitter generates and transmits MF signals, while the R-Mode VHF transceiver generates and transmits VHF signals, and receives VHF signals from other base stations. It is recommended to use the longitude and latitude of survey and RMST time provided by time device. When the above position and time information is not available, GNSS is optional to provide position and UTC time information.

1. R-Mode monitor

The R-Mode monitoring station in fig.3 is used for the far field monitoring. It is responsible for the integrity of R-Mode signal for long-distance transmission.

The R-Mode monitoring station should fulfil the following requirements

* Receive the MF / VHF R-mode signal from the corresponding base station.
* Analyze the received signals.
* Transmit the dynamic messages to the corresponding base stations.
* Transmit monitoring results to the command and control, security center through network.
* Broadcasts correlation data for the users in the work area

1. R-Mode reference time system:

It provides following information for timing device in R-Mode base station, monitoring station and command and control, security center:

* Pulse Per Second (1PPS)
* Data of RMST (year, month, day, hour, minute, second)
* Data of RMST offset and uncertainty
* Offset to UTC

1. Command and control, Security center

The center can receive the data information of R-mode base stations, monitoring stations and RMST system through the network, manage and share these received information. It can also send command to R-mode base stations, monitoring stations and RMST system for control.

1. R-Mode user

Receive signals from at least three R-mode base stations to calculate position information.

## Components of a MF Radio Beacon Transmitting site

The following sketch includes general components of a MF R-Mode transmitting site:



Figure 4 General R-Mode Components

## Components of A VHF transceiving site



Figure 6 VHF Transceiving Site Components

The components of VHF transceiving site is as shown in Figure 6, including RF circuit, VHF modulator/ demodulator, timing device, the matching monitoring station and optional GNSS receiver.

When the VHF transceiving site works in transmitting mode, it can transmit the R-Mode ranging signals and navigation messages. When it works in receiving mode, it can synchronize with other R-Mode stations by receiving and processing their R-Mode radio signals.

1. RF circuit

In transmitting mode, the RF circuit converts the modulated R-mode digital IF signal into analog VHF signal and transmits it through the antenna.

In receiving mode, the RF circuit converts the received VHF signal into digital IF signal, which can be used for demodulation or synchronization by R-Mode radio signal in the VHF modulator/demodulator.

1. VHF modulator/demodulator

In transmitting mode, the VHF modulator generates the R-Mode ranging signals, packages the navigation messages, and carries out the carrier modulation to get the R-Mode digital IF signal.

In receiving mode, the VHF demodulator can get the navigation message from other R-Mode stations, and the optical correlator can get the corresponding pseudo-ranges. The navigation messages and the corresponding pseudo-ranges can be used to synchronize the local R-Mode station with the others.

1. Timing device

The timing device provides 10MHz reference clock with high stable frequency, synchronous 1PPS and optional RMST time information.

In the optional R-Mode radio signal synchronization mode, it can adjust the RMST time information and 1PPS phase according to the time correction information from the VHF modulator/demodulator.

1. R-Mode Monitor

The R-Mode monitor can provide dynamic messages (e.g. clock offset, status data etc.) to the VHF modulator /demodulator.

1. GNSS Receiver

The GNSS receiver can be optional if the timing device can provide stable and accurate RMRT time information and synchronous 1PPS independently.

## Monitoring



Figure 7Monitoring Site Components

### Monitoring System (VHF)

The R-Mode monitoring system includes three parts: on site monitoring, far field monitoring and network monitoring. The on site monitoring function is integrated in the R-Mode transmitter station and is responsible for the status of the transmitter station equipment. The far field monitoring is shown as the R-Mode monitoring station in fig.3 and is responsible for the integrity of R-Mode signal for long-distance transmission. The network monitoring function is integrated in the Command and Control, Security Center and is responsible for the management of normal operation of R-Mode system.

### On Site Monitoring

The on site monitoring function is integrated in the R-Mode transmitter station. It monitors the status of the R-Mode transmitter station equipment, like GNSS receiver, rubidium clock, etc.

* RCF (on site configuration)



The format of the latitude and longitude of antenna is a signed integer number, the unit is 1/100000 minute (precision 1/60 m) or 1/1000000 minute (precision 1/6 cm).

The unit of transmit and receive delay is ns.

When the R-Mode configuration is not supported, it can be null.

### Far field monitoring (FFM)

The far field monitoring is shown as the R-Mode monitoring station. It monitors the integrity of R-Mode signal for long-distance transmission and the synchronization status of the R-Mode transmitter station.

The main functions of monitoring station are:

* Monitoring the time difference of the station chain. It must have the function of recording the monitoring results.
* The monitoring results must be transmitted to the control center in the form of required to assist the synchronization of control system.
* The monitoring station achieves the system calibration with the control center and the shore-based station, and determines the standard value of the system.
* The monitoring station provides reference data and verification data for the propagation correction of the system for the users in the work area.

Configuration principles of monitoring station are:

* The monitoring station should be set up in areas with good receiving conditions.
* The monitoring station should be set up at a representative location, and the time difference of the monitoring station should be closely related to the main working area of the system.
* The monitoring station can achieve data transmission with the shore-based station by the communication methods specified by the system.

Monitoring accuracy requirements: (TBD)

### Network monitoring

The network monitoring function is integrated in the Command and Control, Security Center. It monitors the normal operation of R-Mode system.

* RCK (Transmitter Station -> Center):

The R-Mode transmitter station reports the synchronization status of rubidium clock, the R-Mode transmitter station type, and the GNSS status to the center.



# Technical Implementation of R-Mode

## MF R-Mode

### Brief description of existing DGNSS radio beacon service

Differential GNSS (DGNSS) is a means of improving the accuracy of GNSS and providing integrity monitoring to the user. DGNSS involves having reference stations, at precisely known locations that provide real‐time corrections and integrity information for GNSS signals. The radio beacon DGNSS generates and broadcast code-based corrections with a focus on the maritime domain, by using transmissions in the radio beacon band (285 – 325 kHz / 283.5 – 315 kHz LF/MF). At present DGNSS provides augmentation for GPS and GLONASS. Further details on the DGNSS radio beacon service are given in IALA guideline G-1112 on performance and monitoring of DGNSS services in the frequency band 283.5 – 325 kHz [X]. A list of worldwide implemented DGNSS sites is also hosted at IALA [x]

The purpose of a DGNSS service can be described by two general functionalities realised by two complementary   
services:

* the GNSS augmentation service is responsible for the generation of GNSS correction and integrity data
* the MF transmission service generates and broadcasts MF signals in the radio beacon band, which are   
  used as carrier of DGNSS messages.

The generalised functional architecture of a system providing a DGNSS Service is shown in Figure 1 and reflects both the functionalities and assigned services. The figure illustrates how a radio beacon DGNSS site could be implemented based on the DGNSS augmentation and the MF transmission service. The implementation for the DGNSS augmentation service can be performed following the classical approach with local reference and monitoring receivers or the network approach based on virtual reference stations. The realisation of the MF transmission is following a straightforward design which is typically identical for both methods.

For the purpose of R-Mode implementation on an existing DGNSS service the transmission service (containing the modulator, amplifier and medium wave antenna) are of utmost interest.



Figure X Implementation of a DGNSS service in the radiobeacon band

Besides the generation and transmission of DGNSS corrections the DGNSS service further provides integrity monitoring. This is typically divided in an onsite integrity monitoring (see figure x) and a far field monitoring to validate the performance of the service.

R-Mode, providing ranging signals on the existing radio beacon DGNSS sites, will be mainly integrated in the transmission service by adding continuous wave signals (CW) into the existing MSK spectrum. This requires typically only modifications in the existing MSK modulator. It is essential that the addition of R-Mode does not interfere with the legacy DGNSS service using MSK modulation. An “R-Mode Noise Investigation Study “, [x] concludes that the additional CW signals will not introduce interference which cause an increased bit error on the legacy DGNSS signal.

### The MF DGNSS/R-Mode Signal

Marine radiobeacon transmissions are configured to provide signals over large geographical areas and are well distributed around the northern hemisphere and parts of the southern hemisphere. The ACCSEAS feasibility study considered a number of possible methods of adding a ranging signal to the existing marine beacon system. The different options considered are outlined in the ACCSEAS feasibility study [x, y], from which the approach of adding two CW signals in the MSK spectrum was selected as the optimum solution. The MF DGNSS system transmits its information via a binary modulation 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 milliseconds) 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 [3] examined the potential performance of estimators of time of arrival (TOA) from these two parameters. It was argued 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 given as

in which T is the observation period, 𝜔c is the MF carrier frequency, and SNR is the received signal to noise ratio. Converting to meters and taking a square root for standard deviation is given as:

Figure 5 shows the potential performance (measured in secondsseconds of standard deviation) as a function of signal to noise ratio (SNR) (in dB based upon predicted signal levels and typical North Sea noise values in dBμV).

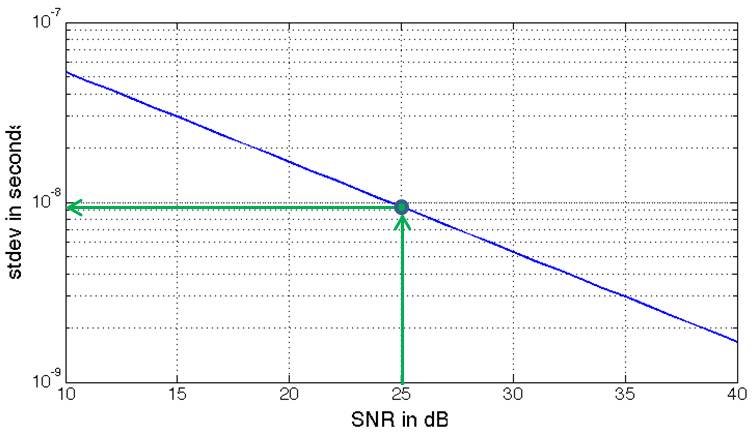


Figure 5: The modified CRB for estimating the time from the phase. For the same typical 25 dB SNR, the standard deviation is ~9 nanoseconds which equates to ~2.7 meters

The curve shown in Figure 5 suggest the level of performance assuming a 5-second averaging window on the estimator. There are several important points to remember for MF R-Mode ranging:

* 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). CW allows for several ambiguity resolution approaches: (1) initializing the receiver at a knownknown 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.
* A second point is that the propagation of an MF transmission is delayed according to the characteristics of the ground over which it is traveling. 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 [see table x]; 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.
* Finally, MF transmissions can suffer from multipath interference due to signal reflections off of the ionosphere; this is referred to as sky wave 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.

As given above, all studies on MF R-Mode suggests the use of two CW signals, positioned ±225Hz to prevent overlap of CW signals between neighboring (in terms of frequency) channels. Figure x shows a typical MSK-signal (on a data rate of 100 Bit/s) with the added continuous wave signals. All performed tests in the various projects and measurement campaigns use this transmission method.



Figure X: MSK spectrum in blue (date rate 100 bit/s) and continuous wave signals in red (± 225Hz).

* Technical Background (Theory of MF-R-Mode)
  + How to add ranging to DGNSS broadcast
  + The DGNSS/R-Mode ignalignal
  + MF R-Mode ranging and positioningpositioning
* MF-R-Mode System implementation
  + System components and functional description
  + Site considerations
    - Amplifier
    - ATU
    - Transmitter Antenna
  + Interaction of system components (clock, transmitter and monitor)
  + How to retrofit a MF radio beacon site into a R-Mode/DGNSS site
  + Measurements and calibrations
* MF R-Mode Service
  + The Ranging signal
    - Defined signal transmission: At full second rising zero crossing CW signal components at the transmitter antenna; for MSK signal bit transition
    - We should highlight that the signal has three components which requires transmitters capable to amplify such signals without causing intermodulations.
    - We should add information where to put CW for 200 Bits/s
    - Relative Signal level MSK/CW
  + The Data Channel
    - DGNSS (G1112)
    - R-Mode navigation message

### Navigation message

The R-Mode receiver need some basic information about the system and the transmitter site to perform positioning and timing. It is foreseen to use the data channel of the DGNSS radio beacon service. Therefore, the R-Mode static and dynamic navigation data has to be coded into RTCM2 messages. Possible messages are 55 and 56.

* Update rate of navigation information? Has to be specified.

**Transmitter health status**

Use the stations health flag (3 bits) of the second word in the header of an RTCM2 message

111 - full operational  
xx0 - not synchronized with RMST (R-Mode System Time)  
x0x - R-Mode signal: Service has limited use  
0xx - R-Mode navigation data: Service has limited use

**CONTINUOUS R-MODE SYSTEM TIME**

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

The transmission time of an R-Mode message can be specified by the Z-count, the hour of the week and the week number since start of RMST.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **unit** | **Bits** | **scale** | **range min** | **range max** | **Notice** |
| **Week number** | week | 12 | 1 | 0 | 4095 | about 78 years; RMST start epoch is defined as 13 seconds before midnight between 21st August and 22nd August 1999 UTC (GPS week number rollover of 1999) |
| **Hour of week** | hour | 8 | 1 | 0 | 255 | current hour of the week (beginning of preamble) |

**TRACEABLE RMST TO UTC**

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



**CLOCK AND DELAY CORRECTIONS**

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

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **unit** | **Bits** | **scale** | **range min** | **range max** | **Notice** |
| **Clock offset (CO)** | ns | 9 | 1/3 | -85.33 | 85.0 | Offset of local clock to RMST (0.1m = 3\*10^8 m/s \* 1/3 ns) |
| **Clock uncertainty (CU)** | ns | 5 | exponential | 0 | 1008.74 | Uncertainty u=k^n-1 and k=1.25 in ns (series: 0, 0.25, 0.56, 0.95, …, 1008.74) u = 0 means out of range |
| **Delay CW (low)** | ns | 14 | 1/3 | 0 | 5461 | delay of lower CW |
| **Delay CW (high)** | ns | 14 | 1/3 | 0 | 5461 | delay of higher CW |
| **Delay MSK** | ns | 14 | 1/3 | 0 | 5461 | delay of MSK component (limited to one period) |
| **Phase of MSK signal** | π rad | 2 | 0.5 | 0 | 2 | phase of the MSK signal component at the beginning of message (preamble); possible values are 0, 1/2 π, π, 3/2 π |

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

**Coordinates of transmitter antenna / frequency offset CW**

* Coordinates of MF transmitter antenna given in WGS 84
* Provide information about used MSK minima for CW transmission

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **unit** | **Bits** | **scale** | **range min** | **range max** | **Notice** |
| **Antenna latitude** | ° | 28 | 8.98E-07 | -90 | 151.14 | Latitude antenna (resolution 360 ° / (6,378,137 m \* 2 \* π) \* 0.1 m) |
| **Antenna longitude** | ° | 29 | 8.98E-07 | -180 | 302.28 | Longitude antenna |
| **Frequency offset CW** | minimum | 3 | 1 | 1 | 8 | Identifies the minima n used for CW in MSK spectrum (±frequency offset of CW to carrier Δf = x \* (1/data rate) with x = 0.75, 1.25, 2.25, 3.25, 4.25) |

**Navigation data validity and signal health status**

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Bits** | **Notice** |
| **Status station monitoring** | 1 | 0 - R-Mode transmitter monitored 1 - R-Mode transmitter unmonitored |
| **Status R-Mode signal MSK component** | 2 | 0 - Signal usable 1 - Signal out of service 2 - Signal will be out of service 3 - Signal currently in test |
| **Status R-Mode CW signal component with lower frequency** | 2 | 0 - Signal usable 1 - Signal out of service 2 - Signal will be out of service 3 - Signal currently in test |
| **Status R-Mode CW signal component with higher frequency** | 2 | 0 - Signal usable 1 - Signal out of service 2 - Signal will be out of service 3 - Signal currently in test |
| **Status clock synchronisation** | 2 | 0 - Local clock is synchronised to RMST and synchronisation link is available 1 - Local clock is synchronised to RMST and synchronisation link is not available (use hold over capabilities of station) 2 - Free running clock (separate message for offset to RMST) 3 - Local clock is not synchronized to RMST |
| **Navigation Data validity status** | 1 | 0 - Navigation data valid 1 - Working without guarantee |

**Offset of free running local clock**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **unit** | **Bits** | **scale** | **range min** | **range max** | **Notice** |
| **Reference time** | min | 14 | 1 | 0 | 16383 | Time of R-Mode week (second 0 of given minute) the clock offset is given |
| **Clock offset** | ns | 16 | 1/3 | -10922.67 | 10922.33 | Offset of local clock to RMST (0.1m = 3\*10^8 m/s \* 1/3 ns) |
| **First derivative of clock offset** | ns/h | 8 | 1 | -128 | 127 |  |

**Downtime / maintenance notification**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **unit** | **Bits** | **scale** | **range min** | **range max** | **Notice** |
| **Planned service interruption** | min | 4 | exponential | 1 | 4096 | n = 0 - R-Mode service interrupted / not available / do not use y = 2^(n-1) for 0 < n < 14 - planned service interruption in y min (rounded off) (series is 1, 2, 4, …, 4096 min) n = 14 - Interruption planned in more than 8192 min (about 137 h) n = 15 - No service interruption planned |

**Authentication of transmitter of navigation messages**

Options?

## VDES R-Mode

* Technical Background
  + Brief summary of existing VDES R-Mode guideline (IALA G-1158)
* VDES-R-Mode System implementation
  + System components and functional description
  + Site considerations
    - Colocation/antenna separation
    - Filtering
    - Slot management
  + Interaction of system components (clock, transmitter and monitor)
  + How to retrofit an AIS base station into a VDES R-Mod site
  + Measurements and calibrations
* VDES R-Mode Service
  + Brief summary of existing VDES R-Mode guideline (IALA G-1158)

# Timing ands synchronisation

## R-Mode System Time (RMST)

The RMST is as a realisation of UTC the time reference of an R-Mode system which provides R-Mode signals through a limited network of R-Mode stations in a region. Each component of the system consisting of R-Mode station network, monitoring facilities and control segment are synchronized to the RMST. Any deviation of local clocks or deviation of the timing of the signals in the network are reported with respect to the RMST.

Compared to a GNSS the R-Mode systems follow a decentralised approach. Therefore, adjacent R-Mode systems which are operated by different service providers may differ in their RMST. Beside a time offset also the stability of the RMST may differ dependent on the used approach for the realisation of UTC, synchronisation and hold-over capabilities in the R-Mode system.

The RMST is traceable to UTC. This is a precondition that the signals of different adjacent R-Mode systems or in general of an R-Mode system and another positioning or navigation systems like GPS can be used for the generation of reliable positioning and timing data without the necessity to estimate the intersystem time offset. Each R-Mode system provides an estimate of the current and predicted offset of the RMST to UTC by its navigation data.

Usually, the RMST is tied to another timing source by appropriate means of synchronisation. Possible RMST sources are:

1. Realisations of Coordinated Universal Time, UTC(*k*), as realised by national metrological institutes. Combinations of several UTC(k) spanning different administrations need to be communicated and applied by the timing devices.
2. Constellation time of one or more GNSS (e.g. Galileo, GPS, GLONASS, BeiDou, etc.). In this case RMST will be the same as the GNSS time. Combinations of different GNSS need to take system offsets into account.
3. R-Mode own central timing scale. It is strongly suggested to keep the time scale traceable to UTC and regularly publish its offset and uncertainty.

Figure 6 emphasis the possible dependency of the RMST from other realisations of UTC.



Figure 6 Traceability of RMST to UTC

Important to know, UTC is calculated in post processing over one-month data batches of worldwide distributed atomic clocks. It is made available with monthly update rate. Therefore, UTC is not appropriate for real time applications. The UTC realisations of metrological institutes (UTC(k)) and of the GNSS systems differ usually by some leap seconds (GPS, Galileo, BeiDou) and some nanoseconds which varies over longer periods. These realisations are continuously available and therefore appropriate for real time applications. A similar difference of some leap seconds and some nanoseconds can be assumed when the RMST is derived from the GNSS system time, UTC(k) or another timing source.

The RMST is a continuous time scale like GPS and other GNSS. The handling of leap seconds is typically prone for errors especially in times when the number will be changed. Therefore, the R-Mode system should use a continuous time scale which can be converted to UTC at any time. To be in line with the number of leap seconds of GPS and Galileo the RMST start epoch is defined as 13 seconds before midnight between 21st August and 22nd August 1999 UTC. A change in the number of leap seconds has to be published by the R-Mode navigation data.

Requirements on the R-Mode system with respect to RMST

* RMST should be traceable to UTC; deviations and uncertainties has to be published in the navigation data.
* RMST should refer in each implementation of R-Mode (MF, VDES, AIS/ASM/VDES) on a specific time during signal transmission (e.g. zero crossing of a signal component, bit transition or beginning of a slot).
* RMST should be stable and traceable to UTC even if the mean for synchronisation with primary time source is interrupted for a longer time.
* The user should be notified if the RMST lost traceability to UTC or any R-Mode station lost its local realisation of RMST.
* Depending on the requirements on the R-Mode system the deviation of RMST to UTC should be known within reasonable accuracy.
* R-Mode system should have sufficient hold-over capacity or/and self-synchronisation capabilities to keep the RMST and fulfil the regional requirement of a backup or contingency system.

Numerically, RMST is expressed with sub-nanosecond resolution and with respect to the R-Mode epoch, which shall be suitably defined for each R-Mode implementation.

## Synchronization of R-Mode system components

All R-Mode system components use the RMST as reference time. Any local clock is therefore synchronised to RMST within a defined accuracy level which depends on the supported applications in that region. Typical time synchronisation methods are:

1. Wired time transfer based on optical fiber networks, such as White Rabbit/PTP[[1]](#footnote-2).
2. Common view methods with GNSS.
3. Use signals and data channel of R-Mode to distribute RMST in the network of R-Mode transmitters.
4. GNSS receiver time solutions, representing GNSS system time[[2]](#footnote-3). To increase robustness of time synchronization, special services like Galileo PRS and/or OS-NMA could be used.

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

## Hold-over capabilities of local clocks

The connection between the source of RMST and the local clock of an R-Mode system components, e.g. transmitter site, can be disrupted. To keep the deviation of the local time to the RMST within defined limits the local clocks have to have hold-over capabilities. The allowed deviations depend on the requirements on the R-Mode system in those regions and is dependent on the supported maritime applications.

## Processing of time information in the station

A well synchronised network of R-Mode transmitters is the precondition of the R-Mode system. At any point in time, each transmitted ranging signal has to have a well-known time delay with respect to a time reference here referred to as RMST, which will locally be provided by a timing device (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Therefore, each R-Mode VDES base station has to use

* Pulse Per Second (1PPS) and
* 10 MHz sinusoidal signal
* Data channel

of the external timing device as a time-base for all internal clocks which are used for the ranging signal generation. Coherence between the signals at the electrical reference plane is mandatory; the 1PPS carries the traceable timing used for disambiguation of the cycles of the 10 MHz signal. The datum of the 1PPS is communicated to the VDES base station as part of a data channel using an appropriated serial interface. Beside R-Mode VDES base stations also R-Mode monitoring stations are synchronized to RMST (**Fehler! Verweisquelle konnte nicht gefunden werden.**). The data channel and 1PPS from timing device can already be integrated into the R-Mode VDES base station



Figure 7. Synchronization of R-Mode transmitter and monitor with R-Mode reference time (1 PPS and data link from timing device has an optional external interface – could also be integrated in the VDES base station.)

# Operational Aspects

## Basic R-Mode considerations

* Service area
* Key Performance Indicators (KPI)
* Service level
  + Accuracy
  + Integrity
  + contingency / backup
* Service requirements (application / navigation phases)
  + Accuracy
  + availability
  + continuity
  + Integrity
* Expected Service Coverage and accuracy
* Define time scale the RMST refers to (GPS, Galileo, Beidou, UTC(k)...)

## Performance Verification

* Measure performance with the help of KPI
* (learn from G1112; how to)
* Monitoring
  + Synchronization of transmitters and monitors with the RMST
  + Signals available

## Operation and Maintenance

* (learn from G1112; how to) - consider the aspect that the stations are more a network then current radiobeacons
* Service Provider Aspects in an R-Mode Network
  + Develop an overall approach for a certain region (e.g. Baltic Sea, North Sea)
    - sites
    - maintenance
    - command and control centre
  + Exchange of Information
    - define (S-2xx) for R-Mode
  + Memorandum of understanding (MOU)
  + Keep track of time differences of R-Mode stations

## Publication of Information

* basic information about the R-Mode service (service level statement)
* provide information about the current and historical R-Mode service performance (use KPI)
* List of transmitters and health status
* (learn from G1112; how to)

# ACRONYMS & Definitions

## Acronyms

## Definitions

The definition of terms used in this Guideline can be found in the International Dictionary of Marine Aids to

Navigation (IALA Dictionary) at (<http://www.iala‐aism.org/wiki/dictionary>).

# REFERENCES

1. IALA ….

***Other Topics raised during meeting on 11th October***

G.B.:

* Maybe a special bullet could be included, in order to guide IALA DGNSS MF Beacon service providers detailed steps to implement R-Mode on IALA DGNSS MF Beacon sites
* Another bullet that could be included is about the impact on user receiver and antenas that were used only to receive DGNSS IALA MF Beacon…Thank you.

1. Theory of MF R-Mode
2. Theory of VDES R-Mode

1. IEEE-1588 [↑](#footnote-ref-2)
2. The use of PT receiver solutions to access GNSS system time is in general discouraged. [↑](#footnote-ref-3)