IALA

IALA GUIDELINE

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MEDIUM FREQUENCY R-MODE SIGNAL STRUCTURE AND NAVIGATION MESSAGE

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DOCUMENT REVISION

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1. INTRODUCTION

This Guideline provides specific information of the Medium Frequency (MF) R-Mode signal and the MF R-Mode navigation message.

1.1. SCOPE OF DOCUMENT

The members of IALA are developing with Ranging Mode (R-Mode) an alternative terrestrial navigation system [1] [2] [3], which enables positioning and timing in the R-Mode service area. It can be used together with the Global Navigation Satellite Systems (GNSS) and other sensors and services to increase availability, continuity and robustness of electronic navigation systems on vessels [4].

R-Mode follows a signal of opportunity approach to provide navigation signals from modified maritime radio infrastructure. These are:

- enhanced IALA radio beacons which provide a modified MF signal including the legacy service transmitting differential corrections for GNSS;
- Very high frequency Data Exchange System (VDES) base stations, which is described in the IALA Guideline 1158 [5]; and
- Very high frequency Data Exchange System (VDES) satellites.

Three R-Mode signals of the type MF or VDES have to be received to perform horizontal positioning on the surface of the earth.

MF R-Mode system can support navigation at sea with positioning accuracies (95 %) in the range of 10 m to 100 m depending on the availability, distance and geometry of the R-Mode transmitting stations. This was predicted in the ACCSEAS project for wide areas of the North Sea [6] with the available radio beacons in 2014 and in the R-Mode Baltic project for wide areas of the Baltic Sea [7]. It should be noted that there is a clear difference in daytime and night-time performance of MF R-Mode. At daytime the dominating ground propagation path provides for both areas at sea mainly positioning accuracies (95 %) between 10 m and 20 m. In the night a second propagation path for the R-Mode signal, the sky-wave, is effective. It causes fading especially for larger distances from the transmitting station [6]. Therefore, the MF R-Mode positioning performance drops in areas with larger distance to the transmitting stations. Measurements in the Baltic Sea area agree with the theoretical predictions for daytime and night-time [8]. Within the alternative PNT testbed in the Republic of Korea measurements indicate that the sky-wave induced fading can be reduced in the service area of a Differential R-Mode (DR-Mode) station [9]. With an accuracy of better than 100 m MF R-Mode provides navigational support as backup to GNSS especially for coastal areas [10]. The R-Mode system and service is currently in a phase of test and validation.

This Guideline focuses on the MF R-Mode signal structure and the navigation message which will be provided as a service of an R-Mode system of a certain region.

In areas between countries, R-Mode signal reception from different service providers is possible. Furthermore, VDES and MF R-Mode signals should be usable together to perform the best estimation in a navigation solution. Therefore, harmonisation between different R-Mode service implementations is needed.

The MF R-Mode navigation message defined in this Guideline enables:

- estimation of current date and time;
- transmission of station health status;
- transmission of MF transmitter antenna position;
- transmission of the signal component deviations and station clock delay;
- transmission of DR-Mode corrections and static data;

- combined use of R-Mode implementations with R-Mode System Time (RMST) delay and GNSS services because the provided R-Mode time information is traceable to the Coordinated Universal Time (UTC).

The maritime service providers implement the ITU-R M.823-3 [11] and the RTCM 10402.3 [12] standards respectively to transmit GNSS differential corrections from their IALA radio beacons [13]. This service shall not be impaired by the extension to R-Mode. Therefore, the design of the R-Mode navigation message should follow the RTCM 10402.3 standard keeping the header of RTCM 10402.3 and adding a new proposed message for R-Mode. In a practical implementation, GNSS corrections and the R-Mode navigation message can be sent sequentially one after the other. This will cause interruptions of the legacy transmission of GNSS corrections. The R-Mode service provider has to consider the ITU-R M.823-3 [11] that the minimum update rate for DGNSS messages is not violated.

1.2. STRUCTURE OF THE DOCUMENT

The Guideline consist of 3 main chapters and an annex beside the introduction.

Chapter 2 gives an overview about the MF R-Mode system and its optional component DR-Mode. It introduces the overall system architecture, the components of the system and the RMST as a reference frame for all R-Mode signal transmissions. For better understanding of the navigation message content the sources for MF R-Mode signal delay are explained.

Chapter 3 explains in detail the structure of the MF R-Mode signal and its timing. For typical radio beacon data rates, guidance is given for the selection of suitable frequencies for the signal extension.

Chapter 4 gives an overview about the MF R-Mode navigation message. It explains in detail the message structure, the content of the different words and the parameters.

The annex provides guidance for the MF R-Mode signal modulator specification.

2. MF R-MODE SYSTEM

2.1. R-MODE SYSTEM ARCHITECTURE

The R-Mode system follows a classical approach of a positioning and timing system by using radio signals. Synchronised transmitting stations broadcast the RMST with the help of specified signals. This enables the estimation of the signal travel time and from this the distance between the mobile receiver and the transmitting station, based on a known signal propagation speed. Positioning with R-Mode requires simultaneous reception of at least three R-Mode signals from different transmitting stations. The mobile receiver time is estimated together with the position.

Onsite, near-field and far-field monitors are used to monitor the proper work of the R-Mode transmitting stations and to measure signal delays. The time signature of the received signal is compared to the RMST realisation at the monitor site. Detected deviations can be used to tune the R-Mode signal modulator so that future transmissions meet better the signal specification or to generate the content of the navigation message which enables transmission of error corrections to the mobile user. To reduce the number of far-field monitor sites, locations in overlapping service areas of different transmitting stations are preferred.

The MF R-Mode signal propagation depends on the ground types it travels over which usually includes a land path component. The overland signal propagation speed is sensitive to the land electrical ground parameters. Changes in the ground parameters between the transmitting station and the mobile receiver caused by season or weather variations result in ranging and positioning errors. The impact can be reduced when the signal error is measured by a DR-Mode station and sent as differential MF R-Mode correction to the mobile receiver to correct its measurement. This principle is already well known from differential eLoran. Due to the spatial decorrelation of the propagation errors, when the signal travels to the differential station and the mobile user, the differential corrections are only valid for a certain area around the station. It is for eLoran about 30 km around the station [14]. For DR-Mode, which works with higher frequencies and shorter distances to the transmitting station, also several

10 km around the DR-Mode station are expected for the correction validity. The differential corrections compensate the change of land parameters, variation of sea salinity, temperature and ice coverage.

Figure 1 shows the general architecture of an R-Mode system. It contains a command, control and security centre beside the components introduced above. The R-Mode transmitting stations, the monitors, the RMST distribution and the command, control and security centre form the core of the R-Mode system. DR-Mode is an optional extension for one or several small-scale regions, where it can help to improve the R-Mode performance locally to reach a certain accuracy level around the DR-Mode reference station. Depending on the needs of the R-Mode service providers and the geographical preconditions some elements of the reference station and monitors may be combined at one site.

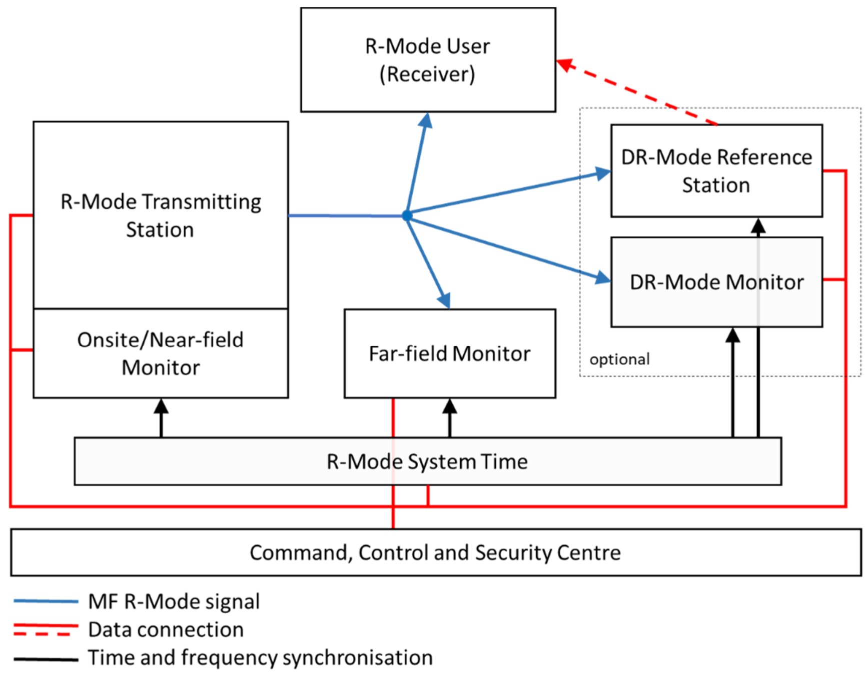

Figure 1 Logical R-Mode architecture

R-Mode Transmitting Station

The R-Mode transmitting stations provide the R-Mode service with the transmission of synchronised R-Mode signals and navigation information using the data channel of the radio beacons. Data from the legacy service DGNSS can also be transmitted.

The transmitting stations have their own realisation of the RMST which is regularly synchronised with the central source of RMST (see section 2.2 for more details). The local realisation of RMST is used to align the R-Mode signals to the RMST.

The transmitting stations get regularly information about the broadcast signal from onsite/near-field and far-field monitors. This information contains availability, quality and timing of the broadcast R-Mode signal. The information is used to optimise the R-Mode signal generation and to generate the R-Mode navigation message with health and error information which are provided to the mobile user via the radio-beacon data channel.

The optional DR-Mode reference station and DR-Mode monitor provide measured R-Mode signal deviation to the expected values in an area of interest like harbours. It will be used to generate the DR-Mode navigation submessage.

The command, control and security centre monitors the station operation and can influence the signal transmission and the content of the R-Mode navigation message (e.g. health status, maintenance information).

Onsite/Near-field Monitor

The onsite or near-field monitor catches the signal in the moment of R-Mode signal transmission or shortly after signal transmission. This can be done by picking up the signal from the transmitter antenna ATU or with a receiver antenna in the near field of the R-Mode transmitter antenna. The monitor can be implemented onsite the transmitting station or at another site preferable near the transmitting station (near-field monitor). The time delay of the received signal is measured with respect to the time reference of the monitor which is synchronised to RMST. Recognised delays are reported to the control centre and the transmitting station. An integration of the onsite/near-field monitor into the transmitting station is recommended.

Far-field Monitor

The far-field monitor acts as a mobile receiver with static, known position and time. It checks the availability of the signal, the proper timing and the content of the R-Mode navigation message. The time delay of the received signal is measured with respect to the time reference of the monitor which is synchronised to RMST. Recognised delays, errors in the navigation message and unavailability of the signal are reported to the control centre and the transmitting station.

R-Mode System Time (RMST)

The RMST is the realisation of UTC which is used as time reference in the entire R-Mode system (i.e. transmitting stations, monitors and reference stations, users) in a region operated by one or more R-Mode service providers. It will be synchronised by proper means with the different elements of the system (Figure 1). Further information is given in section 2.2.

Command, Control and Security Centre

The command, control and security centre fulfils all tasks related to monitoring of the R-Mode system components (Figure 1) except monitoring of the R-Mode user. It enables modification of the system configuration and can influence the R-Mode service. Furthermore, it hosts security related services for the R-Mode system.

R-Mode User (Receiver)

The R-Mode user is typically an R-Mode capable receiver onboard a ship. It receives the signals of at least three R-Mode transmitting stations to perform positioning and timing. The performance here depends on the distance to the transmitting stations, the transmitting station power, the composition of ground path between the transmitting station and the receiver, the condition of the atmosphere and the transmitting station and receiver geometry. The mobile user receives the navigation messages over the radio beacon data channel. Alternatively, differential corrections can be received over an independent communication channel (red dashed line in Figure 1).

The receiver has to apply the error corrections and differential corrections, if the latter is available, given in the navigation message to achieve the intended performance level of the R-Mode service provider.

The R-Mode receiver provides position and time information to the mariner, to bridge systems or other application.

DR-Mode Reference Station

The DR-Mode reference station is an additional monitor station which is not mandatory for the R-Mode system operation. The DR-Mode reference station receives the R-Mode signals and compares its time signature with its own realisation of the RMST considering the content of the navigation message and the expected signal phases which depends on the signal propagation speed over sea and land between the receiver and the transmitting station. The use of correction maps will be required as it is also used by the mobile receiver (see subchapter 4.11).

Timing deviations of the received signal compared to the expected signal are used to generate additional R-Mode corrections which mainly contains uncompensated transmitter errors and the impact of weather, sky-wave and season.

The DR-Mode reference station generates its health status information based on the input from the DR-Mode monitor.

The DR-Mode reference station provides heath and correction information as part of the R-Mode navigation message over the radio beacon or alternately by another, so far not defined, communication channel.

DR-Mode Monitor

The DR-Mode monitor station is located in the DR-Mode service area of typically a few 10 km around the DR-Mode reference station. The DR-Mode monitor confirms the proper operation of the DR-Mode reference station. It receives the R-Mode signal and gets DR-Mode corrections. It also applies all available corrections on the timing of the received signals including:

- R-Mode service values in the R-Mode navigation submessage 1 to 4;
- DR-Mode corrections in the R-Mode navigation submessage 5 and 6;
- correction maps for the R-Mode stations in that region (see subchapter 4.11).

The resulting R-Mode range and position error is compared to the defined performance level of the DR-Mode service provider. The DR-Mode health information is generated based on the result of that test and provided to the command and control centre and the DR-Mode reference station.

2.2. R-MODE SYSTEM TIME (RMST)

The RMST is a realisation of UTC. Furthermore, it is 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 an R-Mode station network, monitoring facilities, DR-Mode reference station and monitor, and control segment are synchronised to the RMST. Any deviation of local clocks and signal timing are referred to RMST within the R-Mode network and reported as deviation to RMST within the R-Mode navigation message.

Compared to a GNSS, the R-Mode systems follow a decentralised approach. Therefore, adjacent R-Mode systems operated by different service providers can differ in their RMST. Besides a time offset, the stability of the RMST can 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 system 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 RMST offset to UTC by its navigation data.

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

- realisations of Coordinated Universal Time, UTC(*k*), as realised by a national metrological institute. Combinations of several UTC(k) spanning different administrations need to be communicated and applied by the timing devices;
- 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. System time offsets between different GNSS time scale need to be considered when they are combined;
- R-Modes own central timing scale. It is strongly suggested to keep the time scale traceable to UTC and regularly publish its offset and uncertainty.

Figure 2 shows three different approaches to realise the traceability of the RMST to UTC. Here, *xx* and *xxx* are typically small numbers. In reality, more complicated schemes than given in Figure 2 are used.

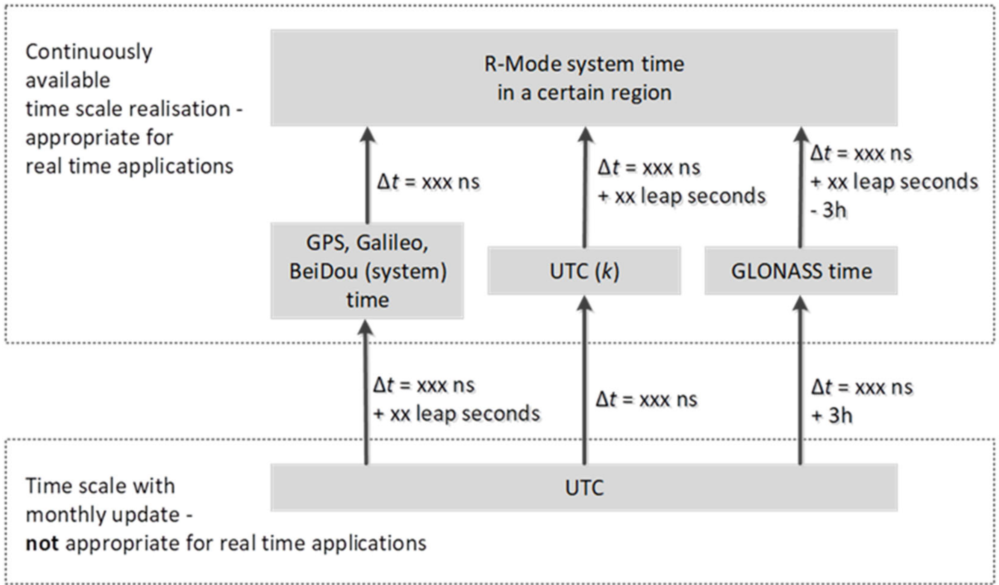

Figure 2 Different ways to realise the traceability of RMST to UTC

It is important to understand that 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 to each implementation of R-Mode (MF, 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 the primary time source is interrupted for a long period.
- The user should be notified if the RMST lost traceability to UTC or if any R-Mode station lost its local realisation of RMST.
- Depending on the R-Mode system requirements, the time deviation of RMST to UTC should be known within reasonable accuracy.
- R-Mode system should have sufficient hold-over capacity and/or self-synchronisation capabilities to keep the RMST within 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.

2.3. SOURCES FOR MF R-MODE SIGNAL DELAYS

MF R-Mode is a system based on the distribution of timely synchronised signals using specified MF broadcasts. Due to technical limitations, delays occur during time transfer between different clocks and signal distortions in active and passive components of the transmitter chain as well as on the propagation path to the receiver. The task of the service provider is to measure the delays and signal distortions and send this information to the R-Mode user with the help of the R-Mode navigation message. The user will use this information to correct its own measurements before performing positioning and timing.

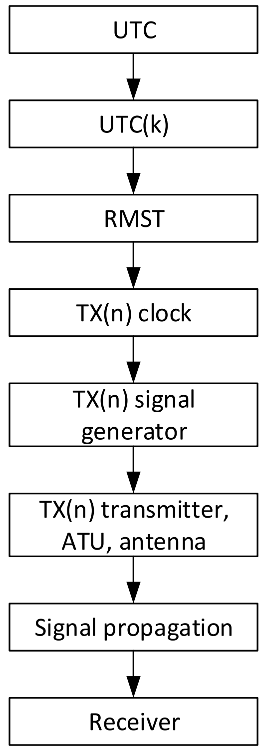

Figure 3 Steps which take the time information from UTC to the receiver

Figure 3 gives an overview of the different steps the time information takes to reach the R-Mode receiver. Starting from UTC which is realised as UTC(k) by a national metrological institute or another organisation. The RMST can be directly connected to a UTC(k) e.g. with the help of optical fibre cables or its own realisation of UTC with a known offset to a UTC(k). In any case, the R-Mode service provider should be aware of the deviation of RMST to UTC. The deviation of RMST should be in the order of a few ns. The offset between RMST and UTC is part of the navigation message (Conversion RMST to UTC). It should be identical for all transmitting stations of a service provider.

The RMST is distributed by proper means to the different transmitting stations and monitoring sites of the R-Mode system. The RMST synchronised local clocks ("TX(n) clock" in Figure 3) provide frequency and time to all components of the transmitting station, e.g. signal generator. The local clock can have an offset of several ns to the RMST and vary over the time. This "clock offset" of the transmitting station is part of its navigation message. It deviates from station to station. Uncorrected clock offsets of one station will directly go into the range error on the receiver site.

The signal generator ("TX(n) signal generator" in Figure 3) uses as an input the data stream of R-Mode navigation information and GNSS code corrections as well as time and frequency from the local clock. Most often additional parameters for the predistortion of the signal are given. These parameters should compensate the impact of active and passive components (including cables, “TX(n) transmitter, ATU, antenna” in Figure 3) of the transmitting stations. In case that predistortion cannot ensure proper transmission of the R-Mode signal as specified in Chapter 3, any measured signal distortion can be reported to the user using the parameters “Delay lower CW” and “Delay higher CW”.

The data set of “conversion RMST to UTC”, “clock offset” and “delay lower/higher CW” provides all information to trace the R-Mode transmitted signal features back to UTC.

As another block in Figure 3, “Signal propagation” summarises all effects that have an impact on the signal in the time between broadcast and reception. These are

- self-interference of the ground-wave, which is used in R-Mode for the ranging, with a signal reflection in the ionosphere mainly during night-time and
- a ground dependent delay (compared to propagation over sea water), which can vary over the time due to direct or indirect weather impact.

These two effects can be measured by an DR-Mode Reference station and result in correction parameters for all transmitting stations in view. These corrections are valid in the vicinity of the area monitor. They are provided as information of the DR-Mode message. The information transmitted contains only the deviations from a correction map. Far-field monitor and mobile receiver have to apply the same correction map to the measurements.

Figure 3 shows a generic scheme. A specific implementation may deviate in details for the different R-Mode systems. Expected delays and distortions in active and passive receiver components are not subject of this guideline.

3. MF R-MODE SIGNAL

The MF R-Mode signal should be designed to enable ranging while not affecting the legacy DGNSS service. Research on the MF R-Mode signal structure has been conducted through the ACCSEAS project [6], and a proposal has been made to add continuous wave (CW) tone signals on both sides based on centre frequency of the minimum shift keying (MSK) signal, taking into consideration the technical feasibility, implementation cost and difficulty. All performed tests in the various projects and measurement campaigns use this transmission method.

The ITU-R recommendation M823-3 [11] defines the radio-beacon frequency to be a multiple of 500 Hz for region 1 to 3. Furthermore, ITU-R M823-3 [11] provides information about the useable bandwidth of one transmitting station for region 1 with the “maximum permitted occupied bandwidth should be 230 Hz” in the frequency band 283.5 kHz to 315 kHz. The R-Mode service provider has to consider ITU-R M823-3 when they plan to broadcast MF R-Mode.

3.1. SIGNAL SPECTRUM

The MF R-Mode signal consists of an MSK signal combined with two CW signals. The MSK signal is intended for the existing DGNSS service, while the two CW signals are for ranging purposes. Therefore, the spectrum of the MF R-Mode signal is a combination of the MSK signal spectrum with the addition of two CW signals. The frequency of the added CW signals varies depending on the RTCM data rate of the MSK. Figure 4 shows a typical MSK signal (at a data rate of 100 Bit/s) with the added ±225 Hz CW signals. Figure 5 and Figure 6 represent signal spectra measured at the transmitting station and show ±250 Hz and ±450 Hz CW signals at the data rate of 200 bps.

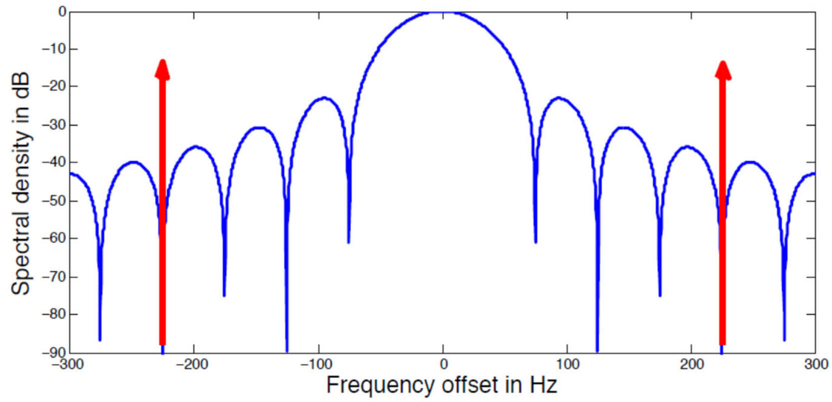

Figure 4 MF R-Mode signal spectrum: MSK spectrum in blue (data rate 100 bps) and CWs in red (±225 Hz)

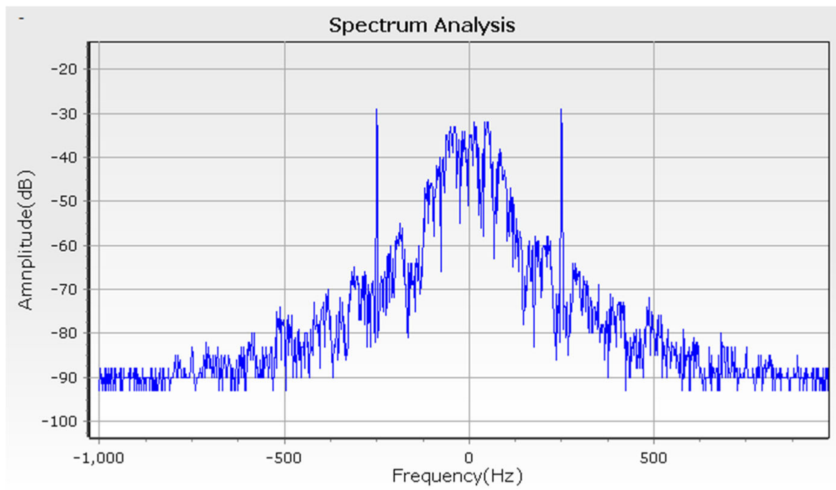

Figure 5 MF R-Mode signal spectrum on transmitting station (data rate 200 bps, CWs at ±250 Hz)

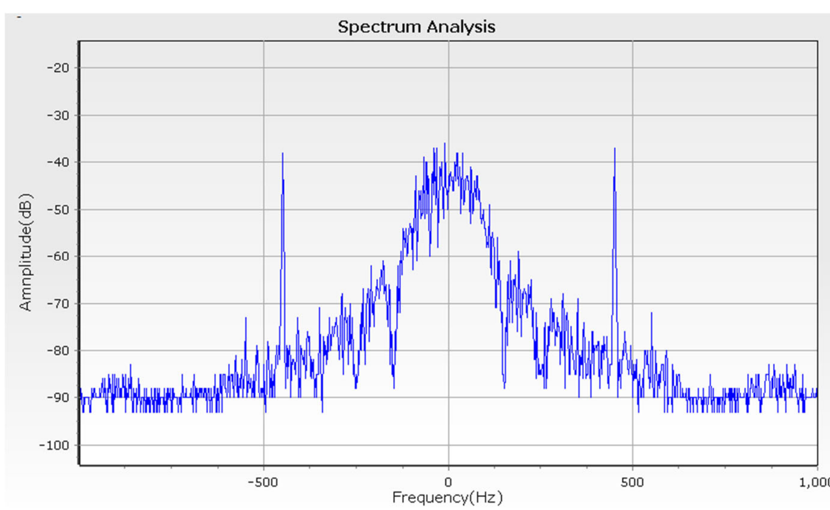

Figure 6 MF R-Mode signal spectrum on transmitting station (data rate 200 bps, CWs at ±450 Hz)

3.2. CW FREQUENCY CONSIDERATIONS

The CW signals should be positioned within the null intervals of the MSK frequency spectrum to ensure signal acquisition by the receiver. However, the null intervals of the MSK frequency spectrum vary depending on the RTCM data rate of the DGNSS service. Therefore, careful consideration is necessary when selecting the frequencies for the CW signals.

Figure 7 shows the MSK frequency spectrum according to MSK data rate. The allowable frequencies for CW signals are as follows:

- for a 100 bps rate, it is ±(75 + 50*n) Hz with n = 0, 1, 2, 3, ... to both sides of the MSK carrier frequency;
- for a 200 bps rate, it is ±(150 + 100*n) Hz with n = 0, 1, 2, 3, ... to both sides of the MSK carrier frequency.

As the distance from the centre frequency increases, the signal acquisition by the receiver becomes easier for CW signals. Therefore, the CW frequencies 225 Hz beside the MSK carrier frequency are most suitable within the 500 Hz bandwidth (typical channel spacing) of 100 bps transmitting stations. The R-Mode service provider has to consider ITU-R M823-3 with its limitation of the bandwidth of 230 Hz [11] in region 1.

For 200 bps the minimum suitable frequencies are 250 Hz bedside the MSK carrier frequency and the most suitable is 450 Hz beside the MSK carrier frequency. But this would in practice exceeds the allocated 500 Hz bandwidth of most transmitting stations. Therefore, if RTCM messages are transmitted at the data rate of 200 bps, a bandwidth of 1 kHz is recommended for MF R-Mode transmitting stations.

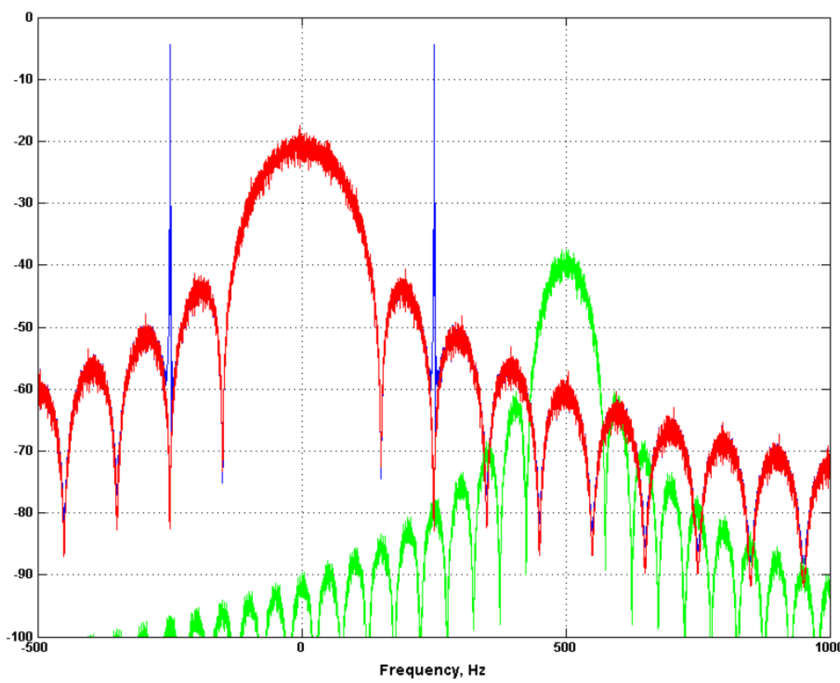

Figure 7 MSK spectrum in red (200 bps), CW signals in blue, adjacent channel MSK in green (100 bps) [6]

3.3. PROPERTIES OF THE R-MODE SIGNAL

3.3.1. R-MODE SIGNAL TIMING

The MF R-Mode signal consists of three signal components, the legacy MSK signals and two CW signals. For accurate ranging, the phase of these three signal components is precisely synchronised with RMST. Additionally, the bit transition timing of the MSK signal is synchronised as shown in the Figure 8.

Signal specification:

- The CW signal components have a deflection of 0 and a rising edge (phase 0 of sine) at integer RMST seconds (Figure 8).
- The MSK signal component has a bit transition at integer RMST seconds (Figure 8). Each change of RMST hours coincides with the transmission of the bit transition between two RTCM 10402.3 words.

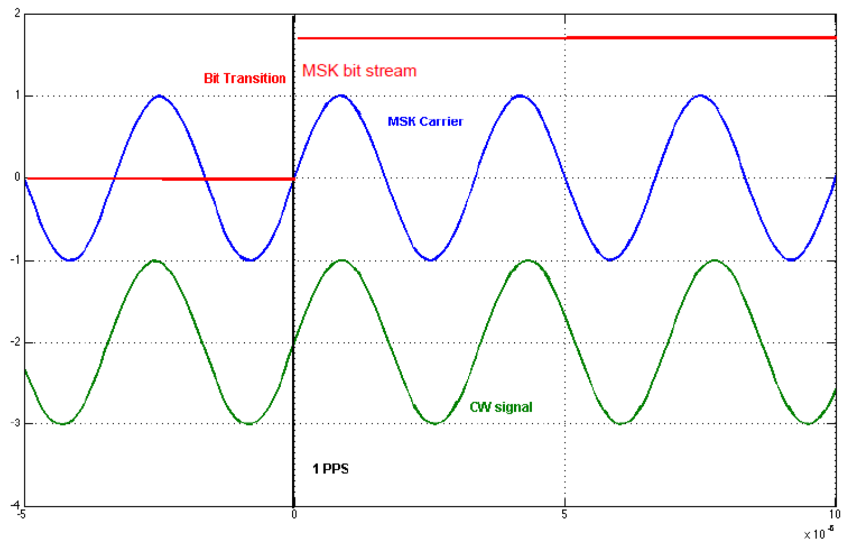

Figure 8 Example of time relations between MSK bit transition, 1PPS (synchronised with RMST), MSK and CW signal components [15]

3.3.2. AMPLITUDES

Validation measurements in test beds in Asia and Europe suggest an amplitude ratio between MSK and CW signal components of 1:1 to 3:1.

3.4. SOLVING MF R-MODE SIGNAL AMBIGUITIES

Due to the low bandwidth of 500 Hz or 1000 Hz for the transmission of the MF R-Mode signals, two signal ambiguities must be considered. The CWs have a wavelength of about 1 km. By measuring the phase of the CW the time for signal propagation within the last signal period is measured. The number of complete CW signal periods can be estimated from the beat signal of both CWs which has, depending on the transmission rate, a typical wavelength of 333 km to 667 km. By estimating the phase of the beat signal, a rough estimate for the signal propagation time within the period of the beat signal can be conducted which solves the ambiguities of the CWs.

The beat signal has a frequency between 450 Hz and 900 Hz. This results in an ambiguity which can be solved by using the entire time information of the first bit of the received R-Mode message taking into account the RTCM frame offset, the modified Z-count and the hour of the week, which are all part of the R-Mode message header shown in chapter 4.

4. R-MODE NAVIGATION MESSAGE

The R-Mode receiver needs information about the provided R-Mode service and the transmitting station to perform positioning and timing. It is foreseen to use the data channel of the DGNSS radio beacons. For the purpose of R-Mode a dynamic RTCM 10402.3 [12] message with the proposed ID 55 was defined. The proposed message consists of a header with all important status information that has to be provided very frequently (approximately 1 / 5 s) and further static and dynamic navigation data in submessages which can be transmitted with lower frequency. The maximum length of message 55 is 240 bits.

Two submessages provide dynamic and static DR-Mode data and User Defined Range Error (UDRE). This is a special version of the navigation message because different error components are summarised in one correction parameter per CW.

4.1. R-MODE NAVIGATION INFORMATION

For R-Mode based ranging, positioning and timing different R-Mode navigation data are necessary. They have to be provided with different minimum update rates. Table 1 gives an overview.

Table 1 R-Mode static and dynamic navigation data

Information	Part of R-Mode message	Minimum update rate
Identification of transmitting station and indication of transmission time	Header	Each transmission
Transmitting station status	Header	1 / 5 s
Signal health status and navigation data validity	Header	1 / 5 s
Transmitting station clock correction and delays of signal components	Submessage 1	1 / 1 min
Static navigation data of R-Mode transmitting station	Submessage 2	1 / 1 min
Relation of the R-Mode System Time (RMST*) to Universal Coordinated Time (UTC)	Submessage 3	1 / 5 min
Offset of free running local clock to RMST	Submessage 4	1 / 1 min
Differential R-Mode corrections**	Submessage 5	1 / 1 min***
Static navigation data of Differential R-Mode station**	Submessage 6	1 / 5 min
Downtime and maintenance notification	Header	1 / 1 min

** RMST is used as time reference for any signal generation and as reference for given clock deviations*

*** Optional message in case of transmitting correction data and the UDREs*

**** Higher update rate is required to mitigate the sky-wave effect during night-time*

The update rates were defined based on the following assumption: The R-Mode message has to be integrated into the DGNSS data stream. Due to the length of certain DGNSS messages, the next possible transmission of an R-Mode navigation message has to wait one or a few seconds. To make sure that the R-Mode receiver gets at least one R-Mode status information within 10 s, the transmission of R-Mode status is desirable each 5 s.

In case of a cold start the receiver should get all necessary information to perform R-Mode based positioning within one minute. Interoperability with other navigation systems should be possible after five minutes.

4.2. R-MODE TIME AND SIGNAL TIMING

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 and 22nd of August 1999 UTC (GPS week number rollover). Every R-Mode related navigation message refers to the RMST. The local clock of the transmitting station is synchronised with RMST. Known timing deviations will be provided in the R-Mode navigation message. The R-Mode signal will be generated and transmitted based on the local implementation of RMST (local clock).

The time of transmission of an R-Mode message is given by three parameters. The week of RMST, the hour of the RMST week and the modified Z-count [12] which gives the time within the hour in 0.6 second steps. The time refers to the leading bit edge of the first bit of R-Mode message preamble.

The MSK signal component, the legacy differential GNSS correction data stream which is extended by the R-Mode navigation message, is the third usable signal component of R-Mode. The signal component is defined such that each change of RMST hours coincides with the transmission of the bit transition between two RTCM 10402.3 words. This means that each RMST hour starts with the transmission of a 30-bit word. Independent from the radio beacon data rate each 3 s the word transition coincides with the second change in RMST which is typically aligned to Galileo and GPS system time within an accuracy of few 10 ns.

The additional two aided carriers (the two CW) are transmitted as sine waves with phase 0.0 and at full seconds. They are transmitted with the same frequency offset to both sites of the MSK carrier frequency in minima of the MSK-signal spectrum. Lower and higher CW refer to the CW with lower and higher frequency.

Deviations of the MSK or CW signal components from definition above are given as delays of the transmitted signal in the navigation data.

4.3. R-MODE MESSAGE

Messages that follow the RTCM 10402.3 definition have the fundamental structure of two header words and up to 31 data words. Each word has a length of 24 bit for data followed by 6 parity bits [12].

The transmission of R-Mode information shall not disturb legacy DGNSS receivers. Therefore, the two header words must not be changed. Already available information will be used for R-Mode purposes. The further use of the current header has also the benefit that DGNSS receivers will further receive DGNSS station health information.

A single message number is needed for R-Mode. The message ID 55 is proposed for this purpose.

The proposed R-Mode message 55 has a dynamic length depending on the data it contains. It always starts with an R-Mode specific header word that follows the two header words of the RTCM 10402.3 standard. Within the R-Mode specific header word is an indicator for an R-Mode submessage. Each R-Mode header can follow one of seven possible R-Mode submessages. If the submessage ID is set to 0 no submessage will follow the header. Each submessage has a defined length in data words.

The R-Mode header holds all information from Table 1 which requires a high update rate. Therefore, the status message which should be transmitted approximately every 5 s can be replaced by a message 55 with additional navigation data in a submessage.

The maximum length of the currently defined R-Mode message (with submessage) is eight words (240 bits) including the three header words. This implies a transmission time of up to 2.4 s for 100 bit/s radio-beacon transmission bit rate or in other words the DGNSS correction data stream will be interrupted for up to 2.4 s.

4.4. RTCM 10402.3 HEADER

The following definition is given in the RTCM 10402.3 standard for the two header words (Figure 9) [12].

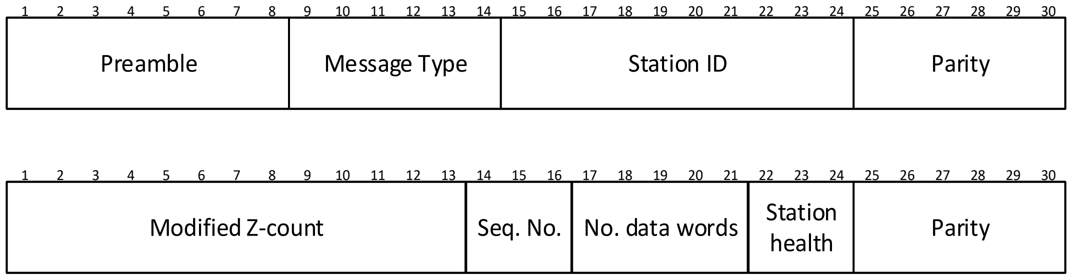

Figure 9 First and second word of RTCM 10402.3 messages

For R-Mode the following parameters are important.

Message type: For R-Mode message number 55 is proposed.

Station ID: It is proposed to use the radio beacon station IDs also as an identifier for the MF R-Mode station.

Modified Z-count: Relates message transmission to RMST. See section 4.3 for more information. The modified Z-count provides the transmission time of the first bit of the R-Mode message (bit 1 of the preamble) within one hour calculated by the integer division by 0.6 seconds.

No. data words: The number of data words will be adjusted to the R-Mode submessage. It can have values from 3 to 8 for the message defined below.

4.5. R-MODE HEADER

The R-Mode header is the third word of the proposed message 55. It follows the RTCM 10402.3 header. It contains the overall status information of the R-Mode service provided by that station and five specific status indicators for parts of the system and service. Further parameters refer the beginning of message transmission to the week of RMST and inform about planned service unavailability. The last parameter is the identifier for the submessage which will follow the header (Table 2 and Figure 11).

Table 2 Content of the third R-Mode message word

Parameter	Number of bits	Range
Transmitting station health	2	0 = fully operational 1 = limited use 2 = not usable 3 = *not used*
Monitoring status	1	0 = R-Mode transmitting station is monitored 1 = R-Mode transmitting station is unmonitored
Status R-Mode signal	2	0 = Signal usable for ranging 1 = Signal out of service 2 = Signal is under test 3 = *not used*
RTCM frame offset	2	0 – 3 words
Status clock	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 = Deviation of local clock to RMST unknown
Status navigation data	1	0 = Navigation data valid 1 = Navigation data not usable
Hour of week	8	0 – 167 hours
Submessage ID	3	0 = no additional information 1 = RMST week, signal delays and offset (3 words) 2 = Static navigation data (3 words) 3 = RMST to UTC conversion (5 words) 4 = Free running clock offset (2 words) 5 = Differential R-Mode corrections (2 words) 6 = Static navigation data for Differential R-Mode station (3 words) 7 = *not used*
Planned service interruption	3	See description below
Parity	6	

Station health: This is the fundamental indicator for usability of the R-Mode service which is transmitted by the station.

- Fully operational: Station is monitored and signals are within defined performance limits considering the provided navigation data.
- Limited use: Some status indicators show service limitation (for example, monitoring station or DR-Mode station is not working). The user has to decide if the limitations given by the specific indicators in the message are acceptable for the planned application.
- Not usable: The R-Mode service is not usable.

Monitoring status: When set as monitored the R-Mode service of the station is continuously monitored. Any identified deviation will either be corrected in future transmissions or result in adjustments to the R-Mode navigation information.

Status R-Mode signal: The signal is indicated as usable to perform ranging if the signal fulfils the definition given in section 4.2. Known deviations are given in the navigation data. If these conditions are not met the signal is indicated as not usable. Signal under test is transmitted when the signal is usable but working without performance commitment.

RTCM frame offset: The RTCM frame [12] offset is the number of preceding words in the evenly spaced time interval, which is defined by the modified Z-count, with respect to the start of the transmission of the current message (see example in Figure 10). The RTCM frame offset is always an integer value.

The offset can be calculated using the following method. The modified Z-count provides the transmission time of the first bit of the R-Mode message (one RTCM frame) within one hour calculated by the integer division by 0.6 seconds. Depending on the data rate of the transmitting station, there can be a residual portion of the division, which corresponds to the transmission time of up to one word at a transmission rate of 100 bps and up to 3 words at a transmission rate of 200 bps. The rest of the integer division given in the number of words for the transmission rate of the transmitter is the RTCM frame offset.

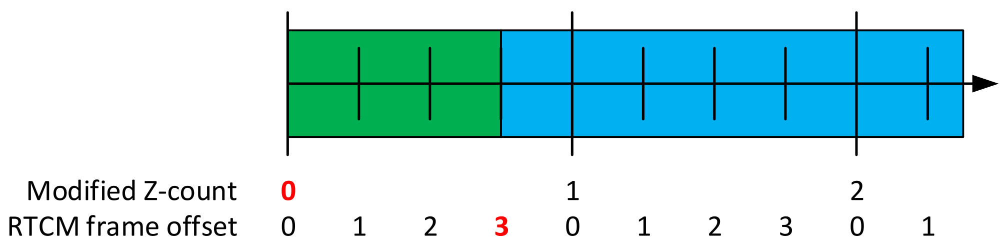

Figure 10 Example for a transmission rate of 200 bps to illustrate the concept of the RTCM frame offset. The blue indicated RTCM frame starts with three preceding words in the time interval of the modified Z-count with the value 0. The header for the blue RTCM frame shows a modified Z-count of 0 and a RTCM frame offset of 3

Status clock: Status of the local clock synchronisation to RMST.

Status navigation data: Status of transmitted R-Mode navigation data in submessage 1 to 7.

Hour of week: Gives the hour of the RMST week in which the transmission of the message started. It is the same hour for GPS and Galileo system time. See section 4.3 for more information.

Submessage ID: Defines a submessage (ID from 1 to 7) that follows the R-Mode header word.

Planned service interruption: A planned R-Mode service interruption can be specified as given in Table 3.

Table 3 Parameter values for planned service interruption

Value *n*	Explanation
0	R-Mode service interrupted / not available / do not use The interruption is ongoing or will begin in less than 10 minutes.
1 – 5	Planned service interruption starts in time *T* with $10 * 2^{n-1}$ min <= $T < 10 * 2^n$ min Intervals: (10, 20), (20, 40), (40, 80), (80, 160), (160, 320) min
6	Interruption planned in more than 320 min
7	No service interruption planned

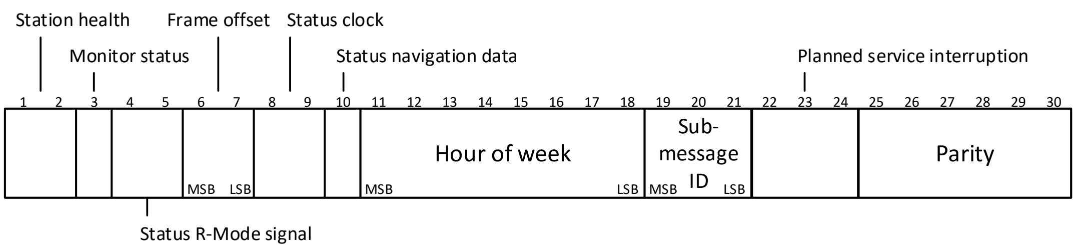

Figure 11 Third R-Mode message word

4.6. SUBMESSAGE 1: RMST WEEK, SIGNAL DELAYS AND OFFSET

This submessage has three groups of parameters (Table 4 and Figure 12).

Timing: It provides the RMST week number of the transmitted message. The entire time information is given by the modified Z-count (second word), RTCM frame offset (third word), hour of week (third word) and week number (R-Mode submessage 1).

Clock offset: Typically, the local clock of the transmitting station which is used to align the transmitted R-Mode signal with RMST deviates by several ns from RMST. The transmitting station clock should have certain stability so that the clock offset can be described by a single clock offset parameter each minute. To inform the R-Mode service user about the timing quality of the transmitted signal a transmitting station clock offset uncertainty is provided. These two parameters are used in case the transmitting station clock is in synchronisation mode.

Signal delays: The three signal components may face delays and phase shifts during transmission that cannot be compensated by other means. To inform the user about the timing of the transmitted signal components the delay of each component and a phase value for the MSK signal component are provided.

Table 4 Content of R-Mode submessage 1: RMST week, signal delays and offset

Parameter	Number of bits	Scale factor and units	Range
Week number	12	1 week	0 – 4095 weeks
Clock offset	9*	1/3 ns	± 85.0 ns
Clock uncertainty	5	-	See description below
Delay lower CW	14*	1/3 ns	± 2730.33 ns
Delay higher CW	14*	1/3 ns	± 2730.33 ns
Delay MSK	14*	1/3 ns	± 2730.33 ns
Phase MSK	2	0.5 π rad	0 rad - 1.5 π rad
Reserved	*2*		*For future use*
Parity	18		

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the most significant bit.

Week number: Number of RMST week for the transmission of the message.

Clock offset: Current offset of local clock at the transmitting station to RMST.

Clock uncertainty: The clock offset uncertainty is given as 1σ confidence level. It offers 32 levels n of uncertainty u which are given by

$$u = (k^n - 1)\ \text{ns} \quad \text{for} \quad 0 < n < 31 \quad \text{with } k = 1.25\,. \qquad \text{Eq. 1}$$

It describes uncertainties ranging from 0.25 ns to about 806.8 ns. The values of n = 0 and n = 31 have a special meaning (Table 5).

Table 5 Parameter values for station clock offset uncertainty

Value n	Explanation
0	Clock offset uncertainty is unknown
1 – 30	Clock offset uncertainty is below u u = 0.25 ns, 0.56 ns, 0.95 ns, …, 806.8 ns
31	Clock offset uncertainty is larger than 806.8 ns

Delay lower CW: Delay of lower CW signal component.

Delay higher CW: Delay of higher CW signal component.

Delay MSK: Delay of MSK signal component. The delay is limited to about one period of the carrier frequency.

Phase MSK: This parameter provides the phase of the MSK signal component at the leading edge of the first bit in the preamble (first word). Possible values are 0, 1/2 π rad, π rad, and 3/2 π rad.

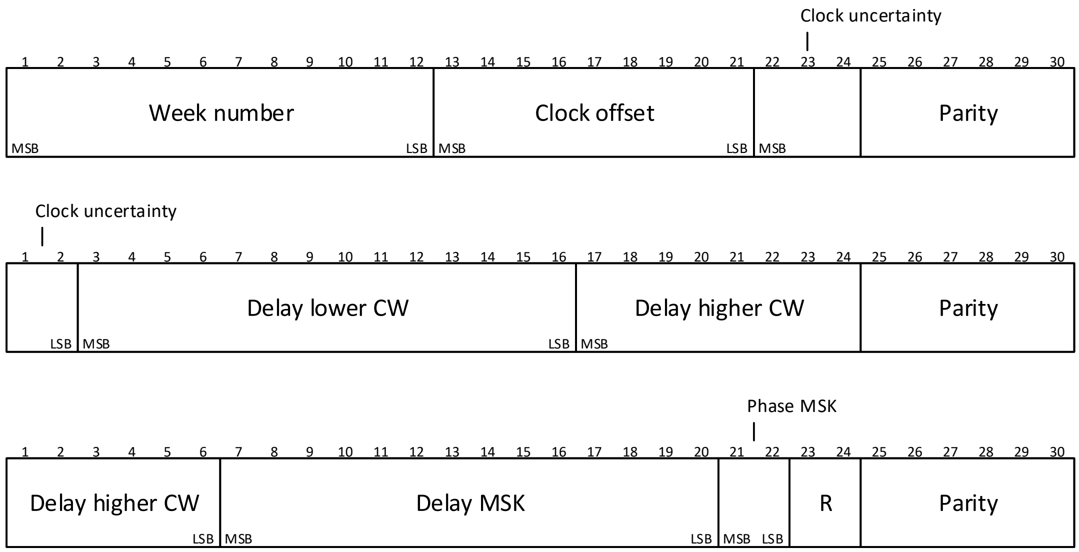

Figure 12 R-Mode submessage 1: RMST week, signal delays and offset

4.7. SUBMESSAGE 2: STATIC NAVIGATION DATA

The R-Mode submessage 2 provides all static parameters of the R-Mode transmitting station. These are latitude and longitude of the MF R-Mode transmitter antenna phase centre given in WGS-84 reference frame. Furthermore, the broadcast bit rate of the MSK modulated data stream and the frequency of the two CWs are provided (Table 6 and Figure 13).

Table 6 Content of R-Mode submessage 2: Static navigation data

Parameter	Number of bits	Scale factor and units	Range
Latitude	28*	$90 / (2^{27}-1)$ °	± 90 °
Longitude	29*	$180 / (2^{28}-1)$ °	± 180 °
Broadcast bit rate	1	-	0 = 100 bits/sec 1 = 200 bits/sec
CW frequency offset	3	-	See description below
Reserved	*11*		*For future use*
Parity	18		

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the most significant bit. "+" values indicate North Latitude or East Longitude.

CW frequency offset: The R-Mode signal consists of the MSK component and two CW components (Chapter 3). The two CWs are symmetrically located in the radio-beacon channel of the station in two minima of the MSK signal spectrum. The parameter "CW frequency offset" n identifies the minima counted from the MSK carrier frequency. The frequency offset Δf from CW to the MSK carrier frequency is computed according to the following equation:

$$\Delta f \,/\, f_{\text{bit}} = (3 + 2n)/4 \quad \text{with } n = 0, 1, 2, \ldots, 7 \,. \qquad \text{Eq. 2}$$

Here f_{bit} is the broadcast bit rate.

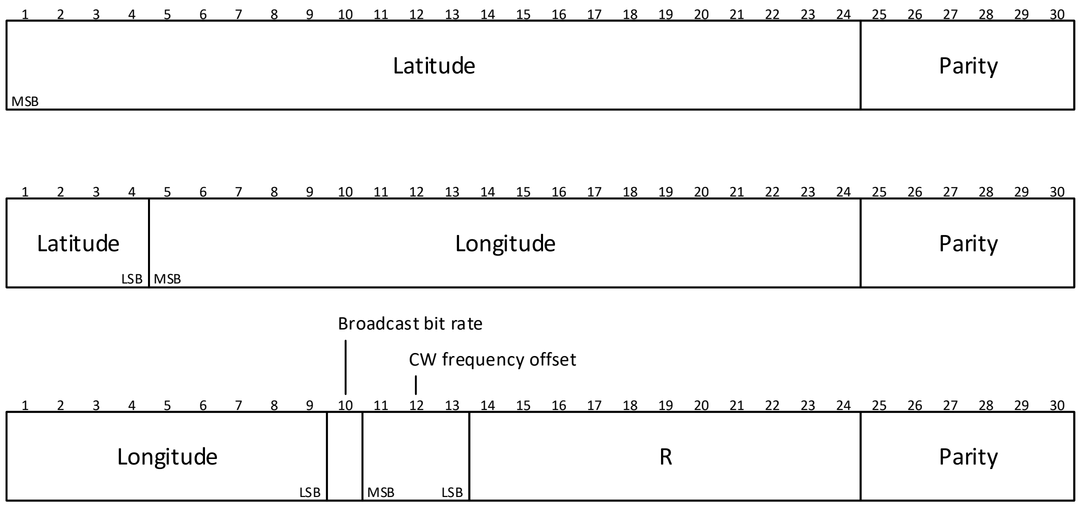

Figure 13   R-Mode submessage 2: Static navigation data

4.8. SUBMESSAGE 3: RMST TO UTC CONVERSION

The RMST is established by the R-Mode service provider which is usually the national maritime service provider. Neighbouring regions or countries may have different RMST. The RMST shall be traceable to UTC to enable positioning by 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's location.

Table 7   Content of R-Mode submessage 3: RMST to UTC conversion

Parameter	Number of bits	Scale factor and units	Range
Constant term of polynomial	32*	2^{-30} s	± 1.9999999991 s
1st order term of polynomial	24*	2^{-50} s/s	± 0.000000007451
Leap second count before leap second adjustment	8*	1 s	± 127 s
UTC data reference time of week	8	3600 s	0 – 918000 s
UTC data reference week number	12	1 week	0 – 4095 weeks
Week number of leap second adjustment	12	1 week	0 – 4095 weeks
Day number at the end of which a leap second adjustment becomes effective	3**	1 day	0 – 7 days
Leap second count after leap second adjustment	8*	1 s	± 127 s
Reserved	*13*		*For future use*
Parity	30		

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the most significant bit.

** The value range of Day Number is from 1 (Sunday) to 7 (Saturday)

The conversion between RMST and UTC is given by polynomial parameters for the deviation, parameters for the UTC reference time and week, and parameters for correct handling of leap seconds. The approach of RMST conversion to UTC is taken from the Galileo Open Service Signal in Space Interface Control Document [16] where the conversion algorithm for the Galileo System Time to UTC is described in detail. In deviation to Galileo, the modulo 256 operation for week numbers is not required because with 12 bits the real RMST week can be given (Table 7 and Figure 14).

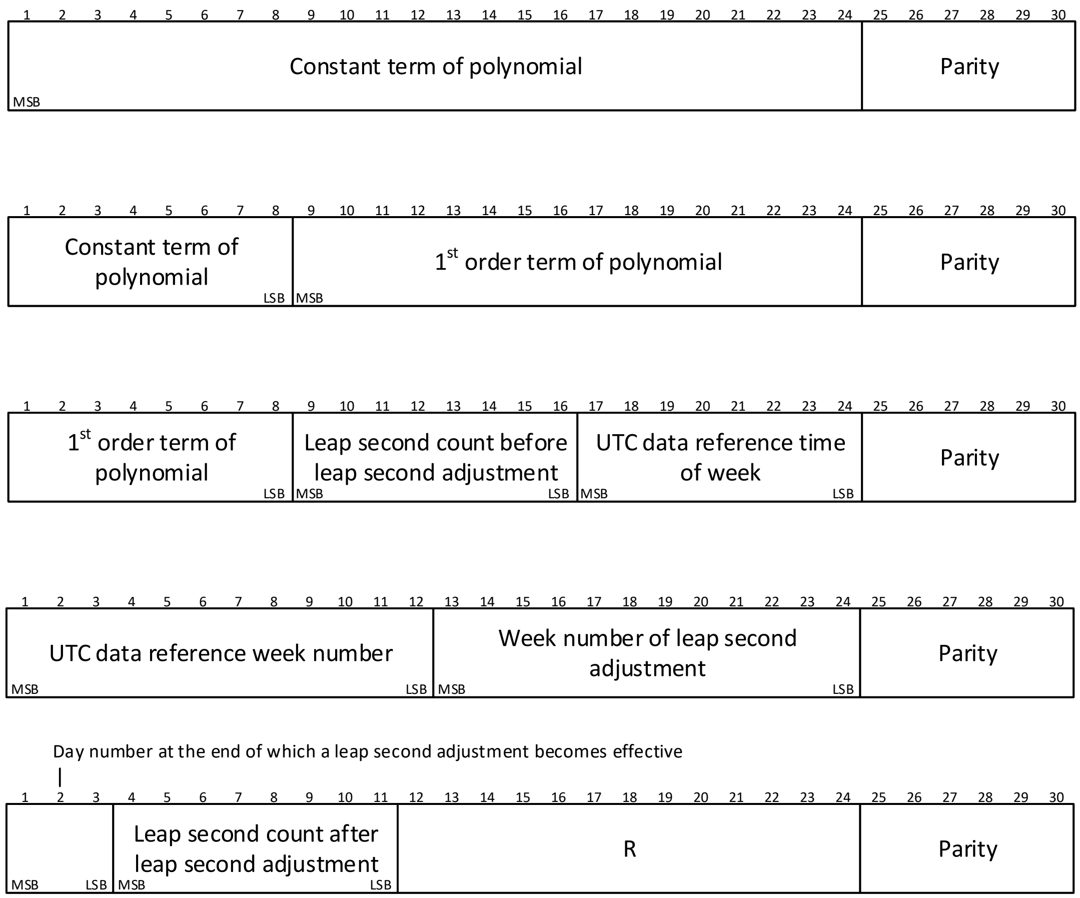

Figure 14 R-Mode submessage 3: RMST to UTC conversion

4.9. SUBMESSAGE 4: FREE RUNNING CLOCK OFFSET

When the synchronisation of the R-Mode transmitting station with the RMST is interrupted, the station uses clock hold-over capabilities to keep an accurate time. It can be assumed that for such cases, the local clock deviates further from the RMST from a certain point in time than provided for in submessage 1. Submessage 4 provides the information of larger clock errors. The local clock offset is given by the two coefficients of a 1st order polynomial and a reference time (Table 8 and Figure 15).

Table 8 Content of R-Mode submessage 4: Free running clock offset

Parameter	Number of bits	Scale factor and units	Range
Reference time	14	1 min	0 – 16383 min
Clock offset constant term of polynomial	16*	1/3 ns	± 10922.33 ns
Clock offset 1st order coefficient of polynomial	8*	1 ns / h	± 127 ns / h
Reserved	*10*		*For future use*
Parity	12		

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the most significant bit.

Reference time: The reference time t_R defines the reference point of the clock offset polynomial. It is given as minutes of the current RMST week. t_R refers always to second 0 of the provided minutes.

Clock offset constant term of polynomial: Constant term of the clock offset A_0.

Clock offset 1st order coefficient of polynomial: 1st order coefficient of the clock offset A_1.

The corrected time t_{corr} is computed from estimated time t_E (given as seconds of RMST week) according to the following equations:

$$t_{corr} = (t_E - t_{offset}) \quad \text{Eq. 3}$$

$$t_{offset} = A_0 + A_1\,(t_E - t_R * 60 \text{ s/min}) \,. \quad \text{Eq. 4}$$

t_E and t_R must be in the same RMST week.

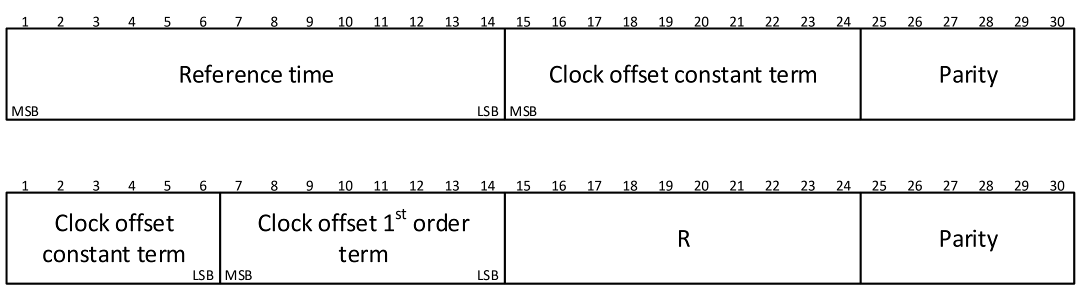

Figure 15 R-Mode submessage 4: Free running clock offset

4.10. SUBMESSAGE 5: DYNAMIC DR-MODE DATA

Submessage 5 aims to improve the positioning accuracy, providing integrity information, and can be optionally generated depending on the system architecture. This message is requested to be broadcasted within a minute. It should be broadcasted within less than a minute for better performance during night. To reduce the impact on the provision of DGNSS service, the DR-Mode message transmission period must be set to an optimal value according to the used transmission data rate of the service provider.

The details of the submessage 5 are shown in Table 9 and Figure 16. Corrections and user defined range error (UDRE) must be provided for lower CW and higher CW respectively. And since there may be multiple DR-Mode stations within the transmitting station coverage, station ID information is also provided.

Table 9 Content of R-Mode submessage 5: Dynamic DR-Mode data

Parameter	Number of bits	Scale factor and units	Range
Differential R-Mode station ID	10		
DR-Mode health status	2	-	0 – usable 1 – not monitored 2 – clock error (reference station or monitor) 3 – under test
Correction for lower CW	12*	1 ns	± 2,047 ns
Correction for higher CW	12*	1 ns	± 2,047 ns
UDRE for lower CW	3	1 m	See text below
UDRE for higher CW	3	1 m	See text below
Reserved	*6*		*For future use*
Parity	12		

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the most significant bit.

Correction for CWs: Time varying correction data of signal propagation delay for each CW generated at the DR-Mode station.

UDRE: UDRE is calculated after applying the MF DR-Mode correction for each CW at the DR-Mode monitoring station. UDRE provides the 95% ranging error bound for the last 60 s. The level of UDRE is expressed in 2^n m, where n = 0, 1, 2, …, 6 (When n = 2, 2 m < UDRE ≤ 4 m). If the error bound exceeds 64 m, then n = 7 is sent, which means 'Do not use'.

Differential R-Mode Station ID: Station ID of DR-Mode reference station which generates the corrections.

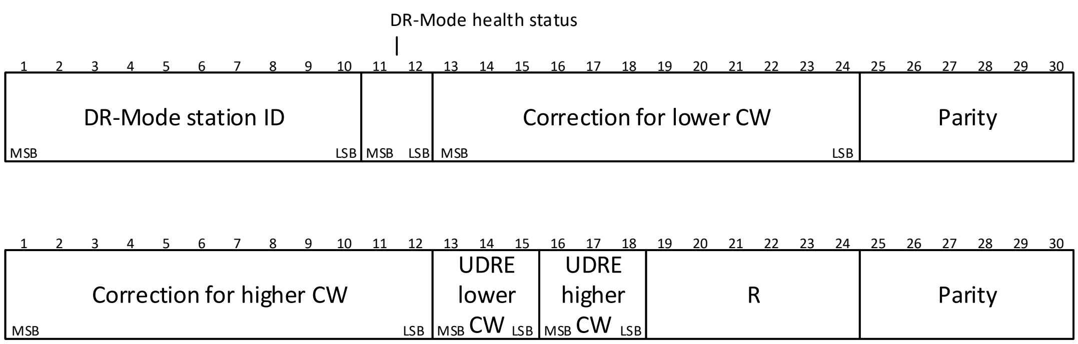

Figure 16 R-Mode submessage 5: Dynamic DR-Mode data

4.11. SUBMESSAGE 6: STATIC NAVIGATION DATA OF DR-MODE STATION

To apply the DR-Mode corrections properly a few basic information has to be provided to the mobile MF R-Mode receiver. This includes the location of the DR-Mode reference station MF reception antenna. This is important for the selection of the nearest DR-Mode site which should be used by the mobile receiver to reduce the impact of spatial decorrelation of the error components. The spatial decorrelation causes deviating signal delays for received signals at the DR-Mode sites and the user location.

Additionally, an information is given about the used spatial correction map which was used at the DR-Mode reference station, when estimating the CW offset, and at the DR-Mode monitor, when estimating the UDRE. It is important that the DR-Mode reference station and monitor as well as the R-Mode receiver use the same version of spatial MF R-Mode correction maps. At the moment ASF (known from eLoran [14] [17]) and AGDF [18] based correction maps are proposed. The correction maps are assigned to the transmitting stations. They provide corrections for that transmitting station in its service area. This means, the same correction map ID can be used for different transmitting stations in the same service area.

Details about submessage 6 can be found in Table 10 and Figure 17.

Table 10 Content of R-Mode submessage 6: Static navigation data of DR-Mode station

Parameter	Number of bits	Scale factor and units	Range
DR-Mode station ID	10	-	
Latitude MF R-Mode reference antenna	20*	$90 / (2^{19}-1)$ °	± 90 °
Longitude MF R-Mode reference antenna	21*	$180 / (2^{20}-1)$ °	± 180 °
Spatial MF R-Mode correction map ID	4	-	0 to 15
Type of MF R-Mode spatial correction map	2	-	0 – ASF 1 – AGDF 2, 3 – for future use
Separate correction maps for lower and higher CW	1	-	0 – one map to correct both CW 1 – two correction maps to correct both CW independently
Reserved	*14*		*For future use*
Parity	18		

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the most significant bit. "+" values indicate North Latitude or East Longitude.

DR-Mode Station ID: Station ID of the station which generates the DR-Mode corrections.

Spatial MF R-Mode correction map ID: For accurate MF R-Mode positioning the impact of the signal propagation over land which causes a signal time delay has to be compensated by a spatial MF R-Mode correction map. This map has to be provided by the R-Mode or DR-Mode service provider and it is used in the mobile receiver and the DR-Mode reference station and its monitor. The correction map ID is the indicator for the correction map for one transmitting station It has to be increased when a new correction map is made available for the transmitting station. The correction map ID has to be evaluated together with the "Type of MF R-Mode spatial correction map".

Type of MF R-Mode spatial correction map: The DR-Mode and R-Mode service providers have different options to make the spatial correction maps available to the user. The type of the correction map together with the map ID has to be used to consider which correction map has to be used in the receiver to be in accordance with the version used at the DR-Mode reference station and its monitor.

Separate correction maps for lower and higher CW: With a frequency difference of less than 1 kHz between both CWs of one transmitting station the difference of propagation time delays of both CWs caused by over land propagation are quite low. It is up to the service provider to decide, if they will provide two correction maps (one for each CW frequency) or only one, which has to be used to correct lower and higher CW range estimations.

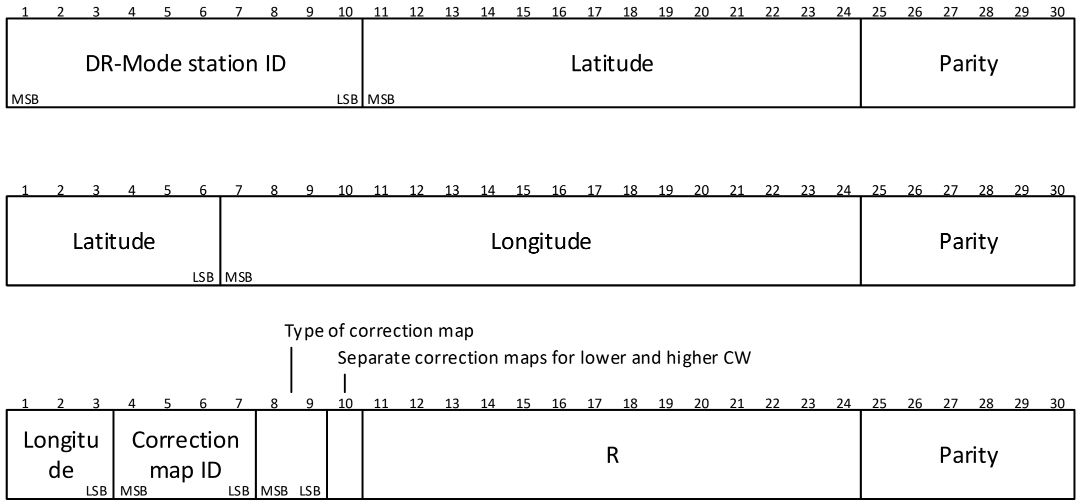

Figure 17 R-Mode submessage 6: Static navigation data of DR-Mode station

5. DEFINITIONS

The definitions of terms used in this Guideline can be found in the International Dictionary of Marine Aids to Navigation (IALA Dictionary) and were checked as correct at the time of going to print. Where conflict arises, the IALA Dictionary should be considered as the authoritative source of definitions used in IALA documents.

6. ACRONYMS

AGDF	Atmospheric Ground and Delay Factor
ASF	Additional Secondary Factor
ATU	Antenna Tuning Unit
CW	Continuous Wave
DGNSS	Differential GNSS
DR-Mode	Differential R-Mode
GPS	Global Positioning System of the United States; originally Navstar GPS
GNSS	Global Navigation Satellite System
ITU	International Telecommunication Union
ITU-R	Radiocommunication Sector of ITU
LSB	Least Significant Bit
MF	Medium Frequency
MSB	Most Significant Bit
MSK	Minimum-Shift Keying
RMST	R-Mode System Time
RTCM	Radio Technical Commission for Maritime Services

UDRE	User Defined Range Error
UTC	Universal Coordinated Time
VDES	VHF data exchange system
VHF	Very High Frequency

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ANNEX A EXAMPLE FOR R-MODE MODULATOR SPECIFICATION

The R-Mode modulator shall enable the transmission of standard RTCM messages used for the DGNSS service. Further the modulator shall provide two independent CW signals with adjustable frequency and output level. The signal generation for MSK and the two CW signals shall be based on the same signal clock which is provided from an external clock, providing 10 MHz and 1 PPS (aligned to RMST which is a realisation of UTC). Figure A1 provides a schematic of the R-Mode/MSK-Modulator and the external equipment required to transmit an R-Mode signal. The output signal should be provided similar to a legacy MSK modulator, as typically used in standard DGNSS radio beacon reference stations.

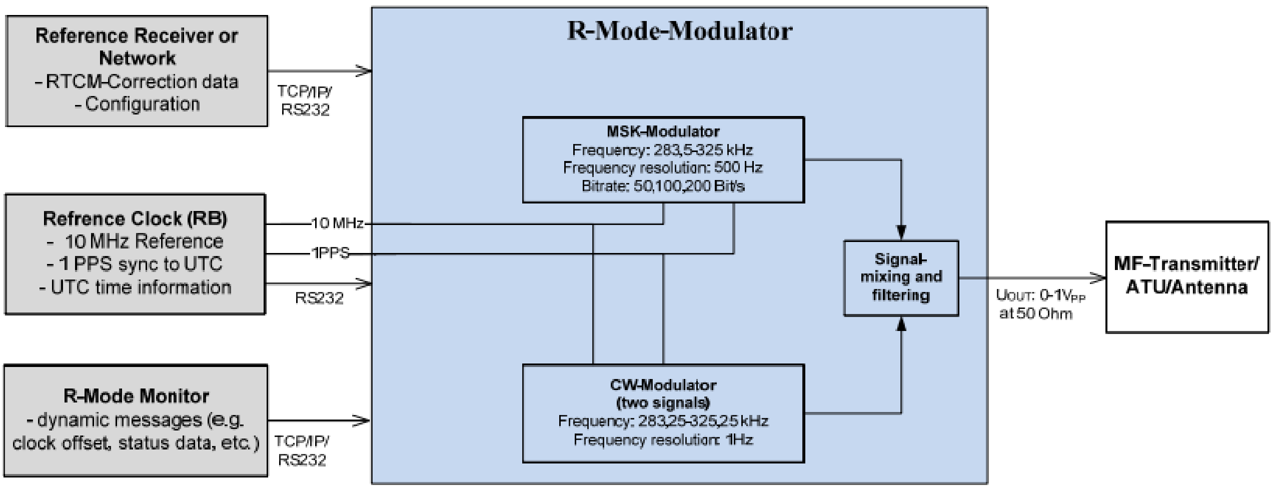

Figure A1 R-Mode/MSK-Modulator as part of the signal generation and transmitting chain [15]

The MF R-Mode signal modulator should comply with ITU-R M.823-3 [11] DGNSS standards while satisfying the following specifications.

- The frequency range of MSK should be adjustable in the range between 283.5 kHz and 325.0 kHz and have a channel spacing of 500 Hz.
- The RTCM data rate should follow legacy DGNSS RTCM service data rates of 50, 100, and 200 bps.
- The modulator should process RTCM 10402.3 message types and the proposed R-Mode specific RTCM message types.
- The modulator shall enable the internal generation of two CW signals.
- The frequency range of CW signals should be adjustable in the range between 283.25 kHz and 325.25 kHz and have a frequency resolution/increment of 1 Hz.
- The CW signals start with the phase 0.0 and a rising edge at integer RMST seconds with a maximum jitter of 1 ns.
- The CW signals should be positioned at the same distance on both sides from the MSK centre frequency and the possible CW spacings for 100 bps RTCM transmissions are:
    - MSK ±175 Hz
    - MSK ±225 Hz (recommended for 500 Hz bandwidth)
    - MSK ±275 Hz

  - MSK ±325 Hz
  - MSK ±375 Hz
  - MSK ±425 Hz
- Possible CW spacings for 200 bps RTCM transmissions are:
  - MSK ±250 Hz
  - MSK ±350 Hz
  - MSK ±450 Hz
- The total amplitudes of the two CW signals and the MSK should be 1.0 Vpp (for example, 0.6 Vpp of MSK and 0.2 Vpp of each CW signal is required when the signal ratio is 3:1).
- The modulator shall enable the generation of R-Mode signals following this Guideline on MF R-Mode signal structure and navigation message.