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R-Mode receiver development for medium frequency signals

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Abstract

Signals from Global Navigation Satellite Systems are the primary source for Position, Navigation and Time (PNT) information onboard any vessel today. As these signals are prone to interference, a maritime backup system is needed to provide reliable PNT data, R(anging)-Mode is such a system. It utilizes existing maritime radio beacons or base stations of the Automatic Identification System (AIS) by adding ranging components to the legacy signals. The first modified radio beacons transmit medium frequency (MF) R-Mode signals in northern Germany. This paper has described the current state of the authors' research and development activities at the receiver level for MF R-Mode signals. The receiver platform has been introduced, which was based on off-the-shelf components and the implemented algorithms for distance estimation have been explained. Furthermore, the results of the first ranging measurements have been presented, which have shown the general suitability of the R-Mode technology as a source for maritime positioning and timing data.

Introduction

With an increase in maritime traffic, the need to have reliable navigation has become more important. Global Navigation Satellite Systems (GNSS) such as the American Global Positioning System (GPS) are the backbone of present-day marine navigation and other important bridge systems. However GNSS is prone to jamming, spoofing and natural incidents like ionospheric storms. In such cases, a terrestrial backup system would help to identify situations when GNSS signals are altered and not usable for the reliable positioning of a vessel. It could provide PNT during such situations, allowing already begun maritime manoeuvers to be finished safely with the help of electronic navigation support.

After the closure of most LORAN-C (LOng-RAnge Navigation) stations from 2010 to 2015, development began for a new candidate for a backup system. This system, called R(anging)-Mode utilizes maritime signals-of-opportunity that are available along the main shipping routes. For their use as an R-Mode transmitter, only modifications of the signals are required, since the complete infrastructure can be reused without disturbing the original service of these signals-of-opportunity. This is a cost efficient way to establish a backup system because no new stations have to be built. The signals of the Automatic Identification System (AIS) and maritime radio beacons are currently being considered as candidates for R-Mode (Johnson et al., 2014; Gewies et al., 2018; Hoppe et al., 2018).

The first detailed investigations of the potential of the R-Mode technology were performed between 2012 and 2015 in the North Sea region. Different feasibility studies (Johnson & Swaszek, 2014a; 2014b; 2014c) showed that the reuse of existing communication channels of maritime radio beacons and AIS base stations for the transmission of ranging signals enabled positioning with an accuracy of 10 m to 100 m, depending on conditions such as the geometry of the transmitting stations, the distance to the stations and the time of day (Johnson & Swaszek, 2014b). Furthermore, for an MF R-Mode system, appropriate transmitter and receiver prototypes have been developed, which work with a combination of the legacy signal and two continuous wave signals (Swaszek et al., 2014). Measurements that were carried out using this equipment confirmed the results of the feasibility studies. The accuracy of the distance estimation with the R-Mode approach was less than 10 m during the day and increased at night to approximately 50 m. A positioning accuracy of 11 m by day and 32 m by night was measured in the literature (Johnson et al., 2017).

A major problem of the MF R-Mode is interference from the two ways of propagation of 300 kHz radio waves. At night the interference of the ground waves with the sky waves causes problems in measuring the phase of the ground waves on the receiver side. This phenomenon is responsible for the higher observed error at night (Johnson et al., 2017). Current investigations (Gewies et al., 2018) into this technology aim to reduce the impact of the sky waves. In this context the German Aerospace Center (DLR) is developing its own MF R-Mode receiver.

The paper has described the current state of the authors' research and development activities of an R-Mode receiver for R-Mode enabled radio beacon signals. It has introduced the receiver platform in detail, it is based on off-the-shelf components and the algorithms implemented in the receiver software for distance estimation have been explained. Finally, the results of the first measurements have been discussed.

R-Mode implementation for maritime radio beacons

The broadcast of maritime radio beacons is defined in recommendation M.823-2 of the International Telecommunication Union (ITU) (ITU-R, 2006). According to this, the code differential corrections for GNSS are required to be transmitted as a minimum shift keyed (MSK) modulated signal, with a carrier frequency f_c in the band of 283.5 kHz to 315 kHz and a bandwidth of 500 Hz in Europe. The MSK signal s_{msk} for the duration of one bit T is described as:

$$s_{\text{msk}}(t) = b_{\text{msk}} \cos\left(2\pi f_c t + b_k(t)\frac{\pi t}{2T} + \theta_k\right) \quad (1)$$

where

$$b_k(t) = -a_{\text{I}}(t)\, a_{\text{Q}}(t) \quad (2)$$

Here $a_{\text{I}}(t)$ and $a_{\text{Q}}(t)$ describe the in phase and the quadrature data bits, which then lead to a phase shift in equation (1). b_{msk} is the amplitude of the MSK signal, θ_k is a special parameter in a continuous phase modulation (CPM) as the MSK signal. It is called the memory of the MSK signal, and describes the accumulated phase of the modulation and an additional part of the phase propagation (Pasupathy, 1979). Both components of θ_k must be estimated when using the MSK signal for distance measurements. Due to the CPM characteristics, an ambiguity occurs every 250 m in the distance estimation for a carrier frequency of approximately 300 kHz. To overcome the ambiguities, one approach is to introduce two continuous wave (CW) signals for the R-Mode within the channel (Johnson & Swaszek, 2014c). The CW is placed at 225 Hz beside the carrier frequency as shown in (3) and (4):

$$s_{\text{cw1}}(t) = b_{\text{cw1}} \sin\left(2\pi\left(f_c - 225\text{ Hz}\right)t + \theta_{\text{cw1}}\right) \quad (3)$$

$$s_{\text{cw2}}(t) = b_{\text{cw2}} \sin\left(2\pi\left(f_c + 225\text{ Hz}\right)t + \theta_{\text{cw2}}\right) \quad (4)$$

The CW signals s_{cw1} and s_{cw2} have independent amplitudes b_{cw1} and b_{cw2} and phase offsets θ_{cw1} and θ_{cw2}. The offsets only depend on time because there is no phase shifting due to modulation. The overall signal $s(t)$ of a modified radio beacon transmitter is given by:

$$s(t) = s_{\text{msk}}(t) + s_{\text{cw1}}(t) + s_{\text{cw2}}(t) \quad (5)$$

In Figure 1 the spectrum of a simulated R-Mode signal has been presented. It clearly shows the three components of the signal within the 500 Hz width channel. Even if the CW signals overlap with the

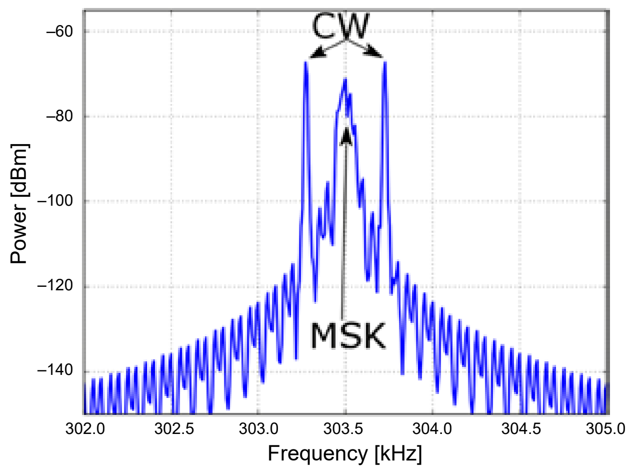

Figure 1. Power spectrum of the radio beacon's R-Mode signal

MSK signal, the low energy in the CW signals does not affect the performance of legacy equipment (Johnson et al. 2017) that works with the MSK signal component.

Theory of distance estimation

In order to derive distance estimation from the modified radio beacon signal, the use of the phase or edges of the bit transitions has been suggested (Johnson & Swaszek, 2014c). Some estimation techniques to derive the phase information have been discussed, using the signal representation defined in the previous section.

Maximum likelihood approach

For CW signals, an estimation of θ_{cw1} and θ_{cw2} is needed. In the literature (Rife & Boorstyn, 1976) a maximum likelihood approach has been described with the likelihood function:

$$L = \sum_{i=1}^{d} 2b_i \operatorname{Re}\left[\mathrm{e}^{j\theta_i} A(\omega_i)\right] - b_i^2 \tag{6}$$

where:

$$A(\omega_i) = \frac{1}{N}\sum_{n=0}^{N-1}(X_n - jY_n)\,\mathrm{e}^{-jn\omega T} \tag{7}$$

θ_i and b_i correspond to the phase and amplitude of a CW signal with frequency ω_i. It is assumed that the received signal, represented by N samples, consists of up to d CW signals. X_n is the sampled data that might be provided by a software defined radio (SDR). The samples Y_n are the Hilbert transforms of X_n. The values $\widetilde{b_i}$ and $\widetilde{\theta_i}$ that maximize (6) can be found from equations (8) and (9):

$$\widetilde{b_i} = |A(\omega_i)| \tag{8}$$

$$\widetilde{\theta_i} = j\arg[A(\omega_i)] \tag{9}$$

To calculate the distance between the user and the R-Mode transmitter, two pieces of information are needed; the distance is the sum of the number of complete wavelengths multiplied by the wavelength and the part of the wavelength that corresponds to θ_i. Additionally, it is assumed that at a certain well-known time the CW signals have a zero crossing at the transmitter side. This is the case for the R-Mode signals every full second. The number of complete wavelengths can be calculated with the help of the beat frequency of both of the R-Mode CW signals. By calculating the phase difference between s_{sw1} and s_{sw1} a new signal at 450 Hz is obtained, also called the beat signal. Ambiguities in the beat signal are larger than the range of the transmitter (around 300 km), therefore the ambiguities for a single CW signal can then be resolved.

Hilbert transformation approach

Another way to derive a distance measurement from ambiguities is to directly use the MSK modulated signal. Unfortunately, there is no known maximum likelihood estimation solution. By using the Hilbert transformation, described by equation (10) with real valued samples $X(j\omega_c)$ with angular frequency ω_c the complex valued signal samples $\hat{X}$ can be derived from:

$$\hat{X}(j\omega_c) = -jX(j\omega_c)\operatorname{sgn}(\omega_c) \tag{10}$$

The signal $\hat{X}$ is called the analytical signal; the complex phase corresponds to the phase of the sampled signal. Assuming there is only one channel left only containing the MSK signal, the carrier phase can be neglected and the continuous phase characteristic of the MSK can be used to derive the distance. This is done by comparing the transformation of the signal to a generic signal generated at the receiver site. In order to get a clean MSK signal it is necessary to filter the signal to one channel with a width of 500 Hz and then subtract the CW signals within the channel. For this cancellation the estimation results from equations (8) and (9) can be used. Due to the memory of the MSK modulation, ambiguities occur every 250 m.

R-Mode receiver platform

The DLR has been developing an R-Mode receiver using an SDR platform. Figure 2 has shown the block diagram of the receiver approach. Currently only two radio beacons in Zeven and Heligoland transmit an MF R-Mode signal. To time synchronize the transmitter and receiver respectively, the GNSS stabilized rubidium frequency standard LL-3760 of Lange Electronic was used, as represented by the clock block diagram in Figure 2.

An Ettus N210 with an LFRX daughterboard was used as the SDR. It was synchronized to Universal Coordinated Time (UTC) via a pulse per second (PPS) signal from a local clock. On the second output the clock provides a 10 MHz sine-wave signal. This enables phase stable measurements when connected to the SDR. Furthermore, this timing reference

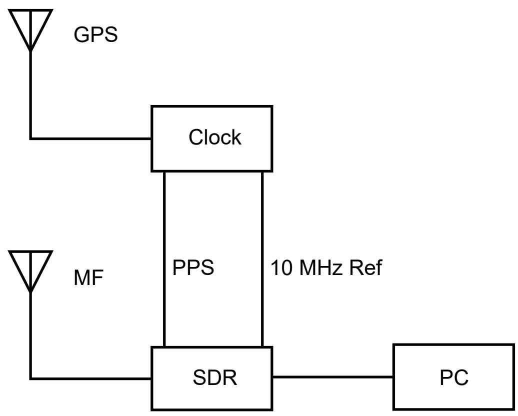

Figure 2. Block diagram of the SDR based R-Mode receiver

is a prerequisite for equidistant samples, which is important for the estimation theory introduced in the section: *Theory of distance estimation*. On the MF front end, a custom made H-field loop antenna with two amplification stages was used. An H-field antenna was preferred because it is less susceptible to interference noise than other types of antennas.

The first R-Mode distance estimation with the receiver platform

Measurement

MF R-Mode signals are currently available only in northern Germany; up to 280 km around the North Sea island of Heligoland and in Zeven (a town near Hamburg). Therefore, the first measurements of the signals were performed at the river Elbe at a distance of 70 km to the R-Mode transmitter in Zeven. The goal was to prove the concept of the receiver.

For this purpose the receiver platform was installed in the DLR's measurement vehicle. While taking the measurements, the H-field antenna was mounted on a tripod at a safe distance away from the vehicle. The sampled data was recorded at 1 million samples per second (MSs) at 13:00 UTC+1. This particular time was chosen, because the impact of the sky wave propagation, which disturbs the measurements, was assumed to be lower during the day than at night.

Data processing

The phase of the two CW signal components was estimated in post processing for every second of data using the maximum likelihood approach. To get an impression of the temporal behavior of the estimated distance a sliding window average filter was implemented, which calculated the average reading from 15 consecutive phase estimations.

Figure 3 has shown, in blue and green, the distance variation calculated for the upper and lower CW signal components (303.725 and 303.275 kHz) of the radio beacon in Zeven. Both curves were freed from their mean value for a clearer comparison. Within an interval of 240 s, both curves showed similar temporal dependency and a range variation of approximately 3.6 m with a standard deviation of 1.7 m. The standard deviation was calculated before the sliding window was applied.

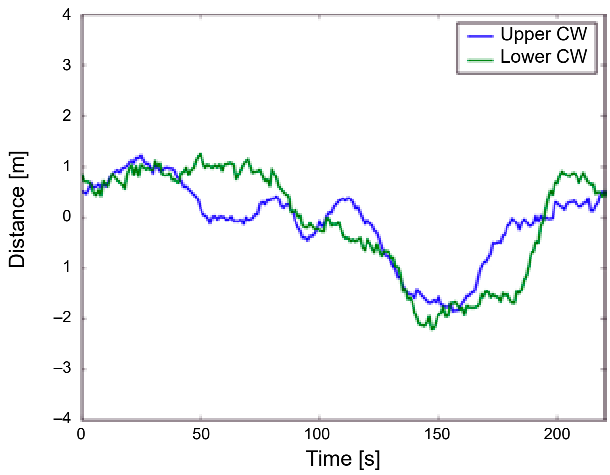

Figure 3. The distance relative to the mean derived from the CW signals

As described in the section: *R-Mode implementation on maritime radio beacons*, when calculating the distance between the transmitter and the receiver, only one CW signal was unique within the wavelength. To resolve the ambiguity of the complete wavelengths, the beat frequency of both CW signal components was used. Figure 4 has shown the calculated distance from the phase estimation of the beat signal, which was freed from the mean value. It reflects the phase difference between the upper and lower CW signal in Figure 3, so an increase in the phase difference between the upper and lower CW signals (see Figure 3, where the phase depended on the distance over the wavelength) caused the distance derived from the beat signal to increase (see Figure 4 at approximately 180 s). The distance of the beat signal varied within a range of 2.0 km with a standard deviation of 1.0 km.

As a third approach and using the MF R-Mode signal for the distance estimation between the transmitter and receiver, the MSK signal component was analyzed with the help of the algorithm outlined in the subsection: *Hilbert transformation approach*.

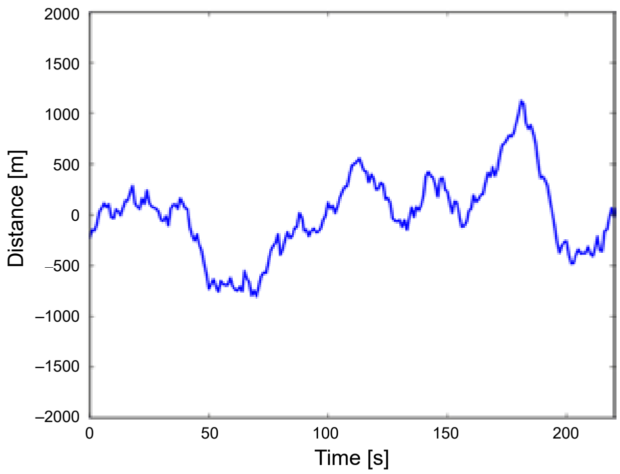

Figure 4. The distance relative to the mean derived from the beat signal

To reduce the impact of the signals outside the frequency band of the radio beacon, a channel filter was applied at around 303.5 kHz. Figure 5 has shown the distance relative to the mean derived from the MSK signal component. For each second of data, the distance was estimated. To better show the temporal behavior, a sliding window of 15 calculations was implemented.

Within the 240 s interval the distance varied within a range of 140 m with a standard deviation of approximately 100 m. Some irregular spikes occurred, which are currently subject to further analysis.

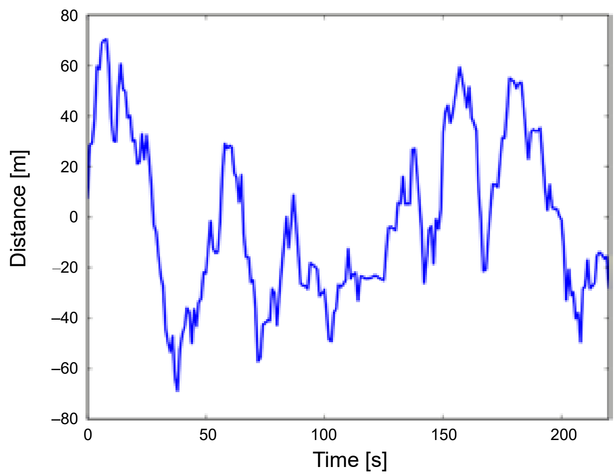

Figure 5. The distance relative to the mean derived from the MSK signal

Discussion

Figure 3 has shown the variation of the distance estimation over a time interval of 4 min for two MF CW signals which propagated a distance of 70 km over land. The results of a similar measurement with an R-Mode receiver of the ACCSEAS project have been presented in the literature (Johnson et al., 2017). Here the R-Mode signal of the Heligoland radio beacon was received at different distances. At the reception site in Tönning, one receiver was located 66 km from the transmitter. In contrast to the measurements and results presented in this paper, the propagation path was mostly over sea and the phase estimations were based on sampled MF signals that were 5 s in length.

The average standard deviation of the distance was calculated for Tönning, over a four-day period based on the CW phase estimation, to have a value of 2.3 m by day and values between 1 m and 6 m for the hourly average in the literature (Johnson et al., 2017). With a 1.7 m standard deviation, the receiver platform presented in this paper showed a similar performance within the measurement time.

In Figure 3, both of the distance estimations shown within the 4 minutes had a similar tendency to increase and decrease. This can be explained by certain effects, which had a simultaneous impact on both of the CW signal components e.g. the clock error at the transmitter and receiver sites. The relative deviation of the two distances needs further investigation.

Figure 4 has shown the one big challenge of the two CW approach. Due to the small bandwidth of 500 Hz for each radio beacon transmission channel, and the fact that the CW tones on the band boundary would interfere with other radio beacon's CW signals, they were placed slightly inside the band with a difference of 450 Hz. Therefore, the beat signal had a wavelength of approximately 670 km. To solve the challenge of the ambiguity of the CW signals, the phase of the beat signal was estimated to be approximately 1.0 km, which was 1/670th of the wavelength. The current implementation of the receiver platform and data processing nearly reached this accuracy (see Figure 4). Further investigation is also necessary to reduce the variation, which is a precondition for stable ranging and positioning with an R-Mode receiver.

Besides the two CW signal components, the MF R-Mode signal contains the MSK legacy signal that could also be used for distance estimation. The first approach using the Hilbert transformation on 1s long data samples showed, with a standard deviation of 100 m, a much worse performance in comparison to the two CW tones approach, which provided an accuracy of 1.7 m; this clearly justified the use of the CW approach. On the other hand, using the MSK signal itself would reduce the need for the modification of the radio beacon legacy signal (MSK only), which would be beneficial for the national maritime administration's plan to upgrade their maritime infrastructure with R-Mode technology.

Conclusions

The paper has presented the basic concept for an R-Mode receiver in the MF band that is based on a signal model for the modified transmission of maritime radio beacons with two CW signal components. In the mathematical foundation of the paper, two estimation methods for the CW and the modulated signal components have been shown. These were applied to the data, which was measured with an SDR receiver platform around 70 km away from the R-Mode transmitter in Zeven.

The results of the data processing with a 4 minute interval showed that the distance estimation based on the CW signals, with a standard deviation of 1.7 m, was very accurate within the uncompleted wavelength. However solving the ambiguity is a big challenge, because fixing the right ambiguities is not certain with a standard deviation of 1.0 km for the distance calculated with the beat signal. The MSK approach exhibited worse accuracy compared to the CW approach in the first data analysis. Overall, the receiver measured in this paper performed in a similar manner to other measurements in the literature (Johnson et al., 2017).

In all of the measurements an unknown phase offset was still included, which was caused by delays in the transmitter chain of each radio beacon and on the receiver platform. A future task is to characterize all components. Furthermore, the received MF signal is always the sum of a ground wave and a sky wave. The resulting signal strongly depends on the amplitudes of both components, which showed an amplitude variation throughout the day. Finding a good channel model for the signal propagation is a major task in the further development of the R-Mode system.

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