R-Mode receiver development for medium frequency signals

Lars Grundhöfer[*], Stefan Gewies[**]

[*]German Aerospace Center (DLR)
Institute of Communications and Navigation
Kalkhorstweg 53, 17235 Neustrelitz, Germany
email: lars.grundhoefer@dlr.de

[**]German Aerospace Center (DLR)
Institute of Communications and Navigation
Kalkhorstweg 53, 17235 Neustrelitz, Germany
email: stefan.gewies@dlr.de

Abstract: Signals from Global Navigation Satellite Systems are the primary sources for Position, Navigation and Time (PNT) information on-board any vessel today. Because these signals are prone to interferences, 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 the north of Germany.

This paper describes the current state of our research and development activities at the receiver-level for MF R-Mode signals. It introduces the receiver platform which is based on off-the-shelf components and explains the implemented algorithms for distance estimation. Furthermore, the results of first ranging measurements are presented which show the general suitability of R-Mode technology as a source for maritime positioning and timing data.

1. Introduction

With an increase in maritime traffic, the need to have a reliable navigation becomes more important. Global Navigation Satellite Systems (GNSS) such as the American Global Positioning System (GPS) are the backbone of nowadays 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 a reliable positioning of the vessel. It can provide PNT during such situations so that the already begun maritime manoeuvers can safely be finished with the help of electronic navigation support.

After the closure of most LORAN-C (LOng-RAnge Navigation) stations from 2010 to 2015, a new candidate for a backup system is under development, called R(anging)-Mode. R-Mode utilizes maritime signals-of-opportunities which are available along the main shipping routes. For the usage as R-Mode transmitter, only modifications of the signals have to be done since the complete infrastructure can be reused without disturbance of the original service of this 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 [1] [2] [3].

First detailed investigations of the potential of R-Mode technology were performed between 2012 and 2015 in the North Sea region. Different feasibility studies [4] [5] [6] show that the reuse of existing communication channels of maritime radio beacons and AIS base stations for the transmission of ranging signals enables positioning with an accuracy of 10 m to 100 m depending on conditions like geometry of transmitting stations, distance to the stations and time of day [6]. Furthermore, for an MF R-Mode, appropriate transmitter and receiver prototypes were developed, which work with combination of the legacy signal and two continuous wave signals [7]. Measurements carried out using this equipment confirm the results of the feasibility studies. The distance estimation with the R-

Mode approach is during the day below 10 m and rises at night up to about 50 m. A positioning accuracy of 11 m by day and 32 m by night was measured [8].

A major problem of MF R-Mode is the interference of the two propagation ways of the 300 kHz radio wave. At night the interference of ground wave with sky wave causes problems to measure the phase of the ground wave at the receiver side. This phenomenon is responsible for a higher observed error during the night [8]. Current investigations [3] in this technology aim to reduce the impact of the sky wave. In this context the German Aerospace Center (DLR) develops an own MF R-Mode receiver.

The paper describes the current state of our research and development activities of an R-Mode receiver for R-Mode enabled radio beacon signals. In detail, it will introduce the receiver platform which is based on off-the-shelf components and explain the receiver software implemented algorithms for the distance estimation. Finally, the results of a first measurement will be discussed.

2. R-Mode implementation on maritime radio beacons

The broadcast of maritime radio beacons is defined in the recommendation M.823-2 of the International Telecommunication Union (ITU) [9]. According to this, the code differential corrections for GNSS has to be transmitted as a minimum shift keyed (MSK) modulated signal, with a carrier frequency $\boldsymbol{f}_{\mathbf{c}}$ in the band from 283.5 kHz to 315 kHz and a bandwidth of 500 Hz in Europe. The MSK signal $\boldsymbol{s}_{\mathbf{msk}}$ for one bit duration $\boldsymbol{T}$ is described

$$\boldsymbol{s}_{\mathbf{msk}}(\boldsymbol{t}) = \boldsymbol{b}_{\mathbf{msk}} \cos\left(2\pi \boldsymbol{f}_{\mathbf{c}}\boldsymbol{t} + \boldsymbol{b}_{\boldsymbol{k}}(\boldsymbol{t})\frac{\pi \boldsymbol{t}}{2\boldsymbol{T}} + \boldsymbol{\theta}_{\boldsymbol{k}}\right), \tag{1}$$

where

$$\boldsymbol{b}_{\boldsymbol{k}}(\boldsymbol{t}) = -\boldsymbol{a}_{\mathbf{I}}(\boldsymbol{t})\boldsymbol{a}_{\mathbf{Q}}(\boldsymbol{t}). \tag{2}$$

Here $a_{\mathrm{I}}(t)$ and $a_{\mathrm{Q}}(t)$ describe the in phase and quadrature data bits, which lead to then a phase shift in (1). b_{msk} is the amplitude of the MSK signal. θ_k is a special parameter in a continuous phase modulation (CPM) as MSK. It is called memory of the MSK, and describes the accumulated phase of the modulation and an additional part of the phase propagation [10]. Both components of θ_k have to be estimated when using the MSK signal for distance measurements. Due to the CPM characteristic, an ambiguity occurs every 250 m in the distance estimation for a carrier frequency of about 300 kHz. To overcome the ambiguities an approach is to introduce for two continuous wave (CW) signals for R-Mode within the channel [5]. The CW is placed at 225 Hz beside the carrier frequency as shown in (3) and (4).

$$s_{\mathrm{cw1}}(t) = b_{\mathrm{cw1}} \sin(2\pi(f_{\mathrm{c}} - 225 \text{ Hz})t + \theta_{\mathrm{cw1}}) \tag{3}$$

$$s_{\mathrm{cw2}}(t) = b_{\mathrm{cw2}} \sin(2\pi(f_{\mathrm{c}} + 225 \text{ Hz})t + \theta_{\mathrm{cw2}}) \tag{4}$$

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 depend only on time because there is no phase shifting due to a modulation. The overall signal $s(t)$ of a modified radio beacon transmitter is given by

$$s(t) = s_{\mathrm{msk}}(t) + s_{\mathrm{cw1}}(t) + s_{\mathrm{cw2}}(t)\ . \tag{5}$$

In Fig. 1 the spectrum of a simulated R-Mode signal is presented. It shows clearly the three components of the signal within the 500 Hz width channel. Even if the CW signals overlap with the MSK signal, the low energy in the CW signals do not affect the performance of legacy equipment [8] which works with the MSK signal component.

3. Theory of distance estimation

In order to derive distance estimation from the modified radio beacon signal, it was suggested to use the phase or edges of the bit transitions [5]. Some estimation techniques to derive phase information are discussed, using the signal representation defined in Section 2.

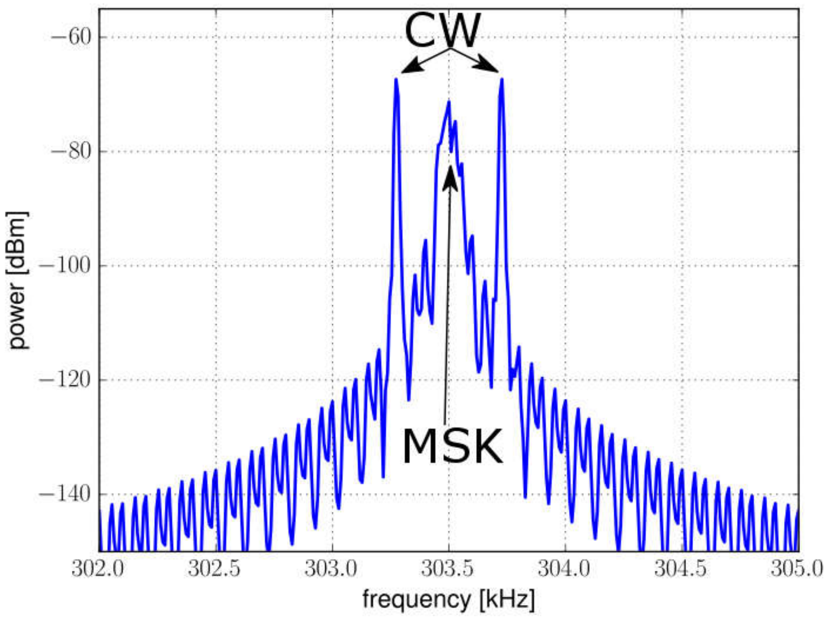

Figure 1. Power spectrum of radio beacon R-Mode signal.

3.1 Maximum likelihood approach

For CW signals an estimation of θ_{cw1} and θ_{cw2} is needed. In [11] a maximum likelihood approach is described with the likelihood function

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

where

$$A(\omega_i) = \frac{1}{N} \sum_{n=0}^{N-1} (X_n - \mathrm{j}Y_n) e^{-\mathrm{j}n\omega T} \ . \quad (7)$$

θ_i and b_i correspond to 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 are the sampled data which might be provided by a software defined radio (SDR). The samples Y_n are the Hilbert transforms of X_n. The values $\tilde{b}_i$ and $\tilde{\theta}_i$ which maximize (6) can be found by (8) and (9).

$$\tilde{b}_i = |A(\omega_i)| \quad (8)$$

$$\tilde{\theta}_i = \mathrm{j} \arg[A(\omega_i)] \quad (9)$$

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 wavelength multiplied by the wavelength and a part of the wavelength which corresponds to θ_i. Further 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 at every full second. The number of complete wavelengths can be calculated with the help of the beat frequency of both R-Mode CW signals. By calculating the phase difference between s_{cw1} and s_{cw2} we get a new signal at 450 Hz, also called the beat signal. Ambiguities in the beat signal are larger than the range of the transmitter (around 300 km), therefor the ambiguities for a single CW signals can be resolved.

3.2 Hilbert transformation approach

Another way to derive a distance 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 (10) with real valued samples $\mathrm{X}(\mathrm{j}\omega_{\mathrm{c}})$ at angular frequency ω_{c} we derive complex valued signal samples $\hat{X}$ with

$$\hat{X}(j\omega_c) = -j\, X(j\omega_c)\, \text{sgn}(\omega_c)\,. \tag{10}$$

Signal $\hat{X}$ is called the analytical signal. The complex phase corresponds to the phase of the sampled signal. Assuming that there is only one channel left containing only a MSK signal, we can neglect the carrier phase and use the continuous phase characteristic of the MSK to derive the distance. This is done by comparing the transform of the signal to a generic signal generated on the receiver site. To get a clean MSK signal it is necessary to filter the signal to one channel of 500 Hz width and subtract the CW signals within the channel. For this cancelation we can use the estimation results from (8) and (9). Due to the memory of the MSK modulation ambiguities occur every 250 m.

4. R-Mode receiver platform

The DLR is developing an R-Mode receiver using an SDR platform. Fig. 2 shows the block diagram of the receiver approach. Currently only two radio beacons in Zeven and Heligoland transmit an MF R-Mode signal. In order to time synchronize the transmitter and receiver, respectively the GNSS stabilized rubidium frequency standard LL-3760 of Lange Electronic is used, represented by the clock block in Fig. 2.

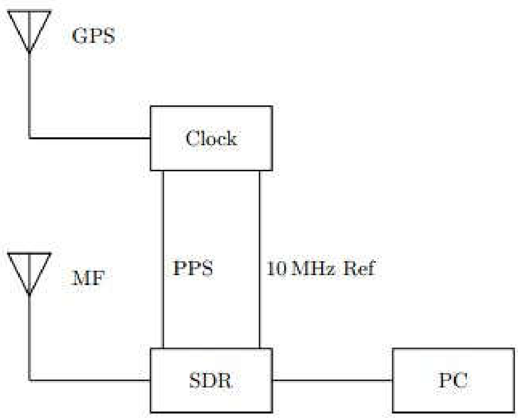

Figure 2. Block diagram of the SDR based R-Mode receiver.

An Ettus N210 with an LFRX daughterboard is used as SDR. It is synchronized to the Universal Coordinated Time (UTC) via a pulse per second (PPS) signal from local clock. On second output the clock provides a 10 MHz sine-wave signal. This enables phase stable measurements when it is connected to the SDR. Furthermore, this timing reference is a prerequisite for equal-distanced samples, which is important for the estimation theory introduced in Section 3. On the MF front end, we use a custom made H-field loop antenna with two amplification stages. An H-field antenna is preferred because it is more rugged against interference noise than other types of antennas.

5. First R-Mode distance estimation with receiver platform

5.1 Measurement

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

For this purpose the receiver platform was installed into the DLR measurement vehicle. During the measurements the H-filed antenna was mounted on a tripod some meters away from the vehicle. 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, is assumed to be lower than in the night.

5.2 Data processing

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

Fig. 3 shows, 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 Zeven. Both curves were freed from their mean value for a clearer comparison. Within an interval of 240 s both curves show similar temporal dependency and vary in a range of about 3.6 m with a standard deviation of 1.7 m. The standard deviation was calculated before the sliding window was applied.

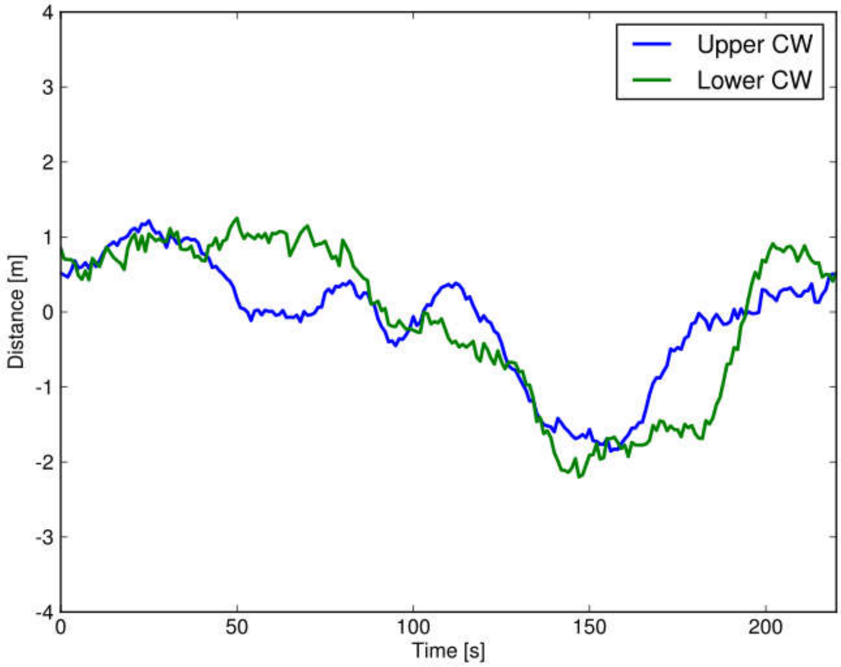

Figure 3. Distance relative to the mean derived from the CW signals.

As described in Section 2., when calculating the distance between transmitter and receiver, one CW signal is only unique within the wavelength. To solve the ambiguity of complete wavelengths, the beat frequency of both CW signal components is used. Fig. 4 shows the calculated distance from 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 of Fig. 3, so that an increase in phase difference between upper and lower CW (see Fig. 3 where the phase depends on the distance over the wavelength) causes the distance derived from beat signal to increase (see Fig. 4 at around 180 s). The distance of beat signal varies in a range of 2.0 km with a standard deviation of 1.0 km.

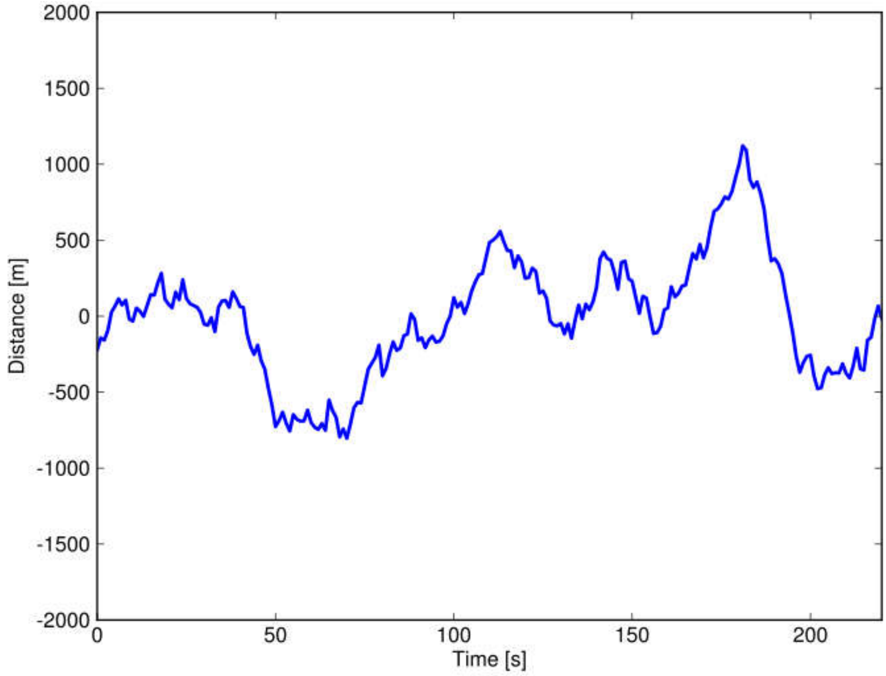

Figure 4. Distance relative to the mean derived from beat signal.

As a third approach, using the MF R-Mode signal for the distance estimation between transmitter and receiver, the MSK signal component was analyzed with the help of the algorithm outlined in Section 3.2. To reduce the impact of signals outside the frequency band of the radio beacon a channel filter around 303.5 kHz was applied. Fig. 5 shows the distance relative to the mean derived from the MSK signal component. For each second of data, a distance was estimated. To better show the temporal behavior, a sliding window of 15 calculations was implemented.

Within the 240 s interval the distance varies in a range of 140 m with a standard deviation of around 100 m. Some irregular spikes occur which are currently subject to further analysis.

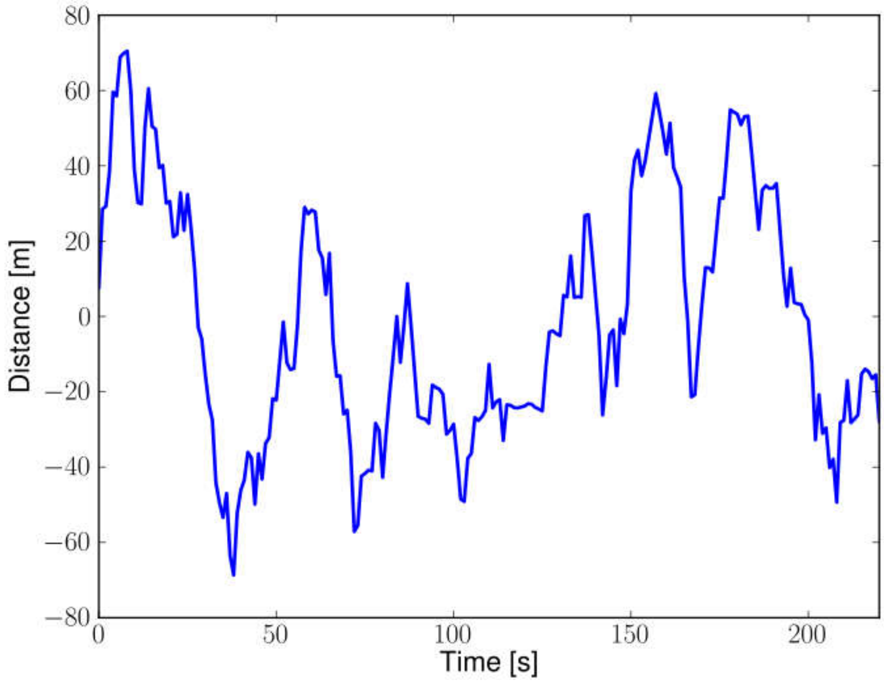

Figure 5. Distance relative to the mean derived from MSK signal.

5.2. Discussion

Fig. 3 shows the variation of the distance estimation over a time interval of 4 min for two MF CW signals which propagated 70 km over land. Johnson et.al. presented in [8] the results of a similar measurement with an R-Mode receiver of the ACCSEAS project. Here the R-Mode signal of the Heligoland radio beacon was received in different distances. At the reception site Tönning one site was at a distance of 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 estimation are based on sampled MF signals of 5 s length.

Johnson et.al. [8] calculated, for Tönning, the average standard deviation for the distance over a four day period based on CW phase estimation to a value of 2.3 m by day and values between 1 m and 6 m for the hourly average. With 1.7 m standard deviation, our presented receiver platform shows similar performance within the measurement time.

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

Fig. 4 shows 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 CW tones on the band boundary would interfere with other radio beacon CW signals, they are placed a slightly inside the band at a difference of 450 Hz. Therefore, the beat signal has a wavelength of about 670 km. To solve the ambiguity challenge of CW signals, the phase of beat signal has to be estimated to about 1.0 km, which is 1/670th of the wavelength. The current implementation of the receiver platform and data processing nearly reach this accuracy (see Fig. 4). Further investigations are 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 which could also be used for distance estimation. The first approach using the Hilbert transformation on 1s long data samples shows with a standard deviation of 100 m a much worse performance in comparison to the two tones CW approach which provides 1.7 m accuracy. This clearly justifies use of the CW approach. On the other hand using the MSK signal itself would reduce the need for modification of the radio beacon legacy signal (only MSK) which would be beneficial for national maritime administrations planning to upgrade their maritime infrastructure with R-Mode technology.

6. Summary

The paper shows the basic concept for an R-Mode receiver in the MF band which 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 are shown. These were applied on the data, measured with a SDR receiver platform around 70 km away from the R-Mode transmitter in Zeven.

The results of data processing of a 4 min interval show that the distance estimation based on the CW signals is, with a standard deviation of 1.7 m, very accurate within the uncompleted wavelength. But solving the ambiguity is a big challenge, because fixing the right ambiguities is not sure with a standard deviation of 1.0 km for the distance calculated with the beat signal. The MSK approach exhibits a worse accuracy as compared to the CW approach in the first data analysis. Overall, our receiver performs similar to other measurements [8].

In all measurements an unknown phase offset is still included which is caused by delays in the transmitter chain of each radio beacon and on the receiver platform. It is a future task 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 show an amplitude variation over the day. Finding a good channel model for the signal propagation is a major task of the further development in R-Mode.

References:

[1] G. Johnson, P. Swaszek, J. Alberding, M. Hoppe and J.-H. Oltmann, "The Feasibility of R-Mode to Meet Resilient PNT Requirements for e-Navigation," in *ION-GNSS+*, Tampa, 2014.

[2] M. Hoppe, A. Grant, C. Hargreaves and P. Williams, "R-Mode: The Story so far," in *IALA Conference*, Incheon, 2018.

[3] S. Gewies, A. Dammann, R. Ziebold, J. Bäckstedt, K. Bronk, B. Wereszko, C. Rieck, P. Gustafson, C. G. Eliassen, M. Hoppe and W. Tycholiz, "R-Mode Testbed in the Baltic Sea," in *IALA Conference*, Incheon, 2018.

[4] G. Johnson and P. Swaszek, "Feasibility Study of R-Mode using AIS Transmissions," 2014.

[5] G. Johnson and P. Swaszek, "Feasibility Study of R-Mode using MF DGPS Transmissions," 2014.

[6] G. Johnson and P. Swaszek, "Feasibility Study of R-Mode combining MF DGNSS, AIS, and eLoran Transmissions," 2014.

[7] D. P. Swaszek, "Analysis of MF-DGNSS modifications for improved ranging," in *ENC*, Rotterdam, 2014.

[8] G. Johnson, P. Swaszek, M. Hoppe, A. Grant and Š. Jan, "Initial Results MF DGNSS R-Mode Alternative Position Navigation and Timing Service," in *ITM*, Monterey, 2017.

[9] ITU-R, "Recommendation M.823-3: Technical characteristics of differential transmissions for global navigation satellite systems from maritime radio beacons in the frequency band 283.5-315 kHz in Region 1 and 285-325 kHz in Regions 2 and 3," 2006.

[10] S. Pasupathy, "Minimum shift keying: A spectrally efficient modulation," *IEEE Communications Magazine,* vol. 17, pp. 14-22, 7 1979.

[11] D. C. Rife and R. R. Boorstyn, "Multiple tone parameter estimation from discrete-time observations," *The Bell System Technical Journal,* vol. 55, pp. 1389-1410, 11 1976.

About the Authors:

Lars Grundhöfer is a Scientist working for the German Aerospace Center in the Institute of Communications and Navigation. After he received his Master degree in electrical engineering in 2017, he is working on terrestrial maritime navigation in the medium frequency band.

Stefan Gewies is a Scientist working for the German Aerospace Center in the Institute of Communications and Navigation. He is there Head of the Working Group Maritime Services of the Department of Nautical Systems and Project Manager of an international project that aims to build an R-Mode testbed in the Baltic Sea. His current research focus is on terrestrial maritime navigation systems using signals-of-opportunity. He received his PhD degree in Physics from Heidelberg University in 2009.