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Hardware in the Loop Laboratory Test Systems for Medium Frequency R-Mode Receivers †

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Abstract: Terrestrial radio navigation systems are an important data source for increasing the integrity of position, navigation, and timing information and for strengthening the immunity to the spoofing and jamming of satellite-based systems. A possible solution for maritime use is the medium frequency R-Mode. Here, the first real results were presented in the Baltic Sea within the R-Mode Baltic project. For the development of receivers and future signal evolution of R-Mode, there is a great need to provide simulated signals to the receiver hardware. For our laboratory work, we developed different hardware in the loop test systems which enable the simulation of each of the three components and the entire medium frequency R-Mode signal. With this setup, we are able to conduct reproducible tests of the R-Mode receiver's ranging and positioning performance without the necessity of field tests. Furthermore, the impact of R-Mode signal modifications can be initially analyzed without the need of an implementation in the real-world test bed. Firstly, we describe the usage of arbitrary wave generators that can be used to replay received or simulated signals. Due to their wide distribution in electronic laboratories, there are cost-efficient ways to build up test capabilities. For this work, we tested the Tektronix AFG 3022 and the Rigol DG1032. For further tests, we utilize software-defined radios that are capable of streaming continuous signals. We utilize the ETTUS N210 to directly output the simulated signals. Additionally, we test the LimeSDR with an external down-converter. To generate these signals, we utilize software packages that were created to support the development of the digital signal processing. This approach allows us to test our receiver with a continuous integration from pure software to hardware in the loop test. A comprehensive summary gives an overview of the pros and cons for the different suggested systems.

Keywords: R-Mode; medium frequency; positioning; hardware in the loop

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1. Introduction

Nowadays, high confidence and trust is placed in global navigation satellite system (GNSS) receivers to retrieve position, navigation, and timing (PNT) data. On the one hand, GNSS provides high accuracy with global coverage, which makes its usage so appealing. On the other hand, it constitutes a single point of failure due to the low power level of the satellite signal at the earth's surface, which can be easily disrupted by simple jamming techniques or more advanced and hazardous spoofing attacks. To counteract these threats and increase the resilience of maritime navigation, the idea of establishing an alternative PNT system arose under the name of R(anging)-Mode.

The general idea of R-Mode is to reuse existing infrastructure to provide positioning and timing information to mariners. Therefore, two main systems have been considered: the D(ifferential)GNSS IALA beacon, transmitting in the 300 kHz band, and the Very High Frequency Data Exchange System (VDES), which is the evolution of AIS, transmitting at around 162 MHz [1,2].

In this work, we will concentrate on the medium frequency R-Mode subsystem, which consists of several terrestrial transmitters broadcasting minimum shift key (MSK)-modulated GNSS correction. To enable ranging with sufficient accuracy, two continuous waves (CW) are included at the fourth zero crossing of the power spectra of the modulation, below (CW_1) and above (CW_2) the carrier frequency [3]. We present the resulting signal for a 500 Hz channel, which is common in Europe, in Figure 1. When these signals are synchronized over the different stations, we are able to derive ranges from the phase estimation of the CW and, consequently, positioning and timing, when we receive at least three stations [4,5].

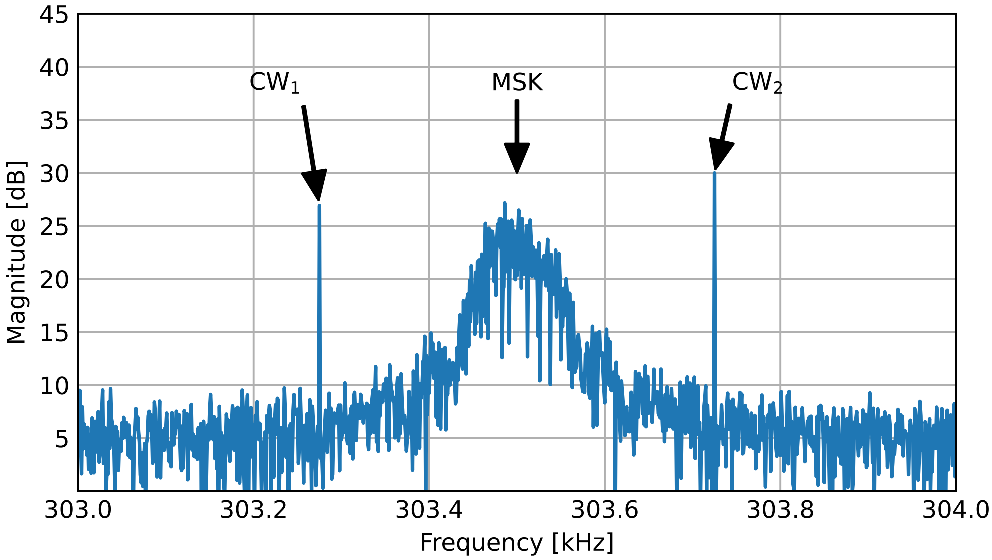

Figure 1. Example spectrum of an R-Mode MF signal.

To support our MF R-Mode receiver development, it is crucial to be able to generate signals of a single station up to a whole-system constellation. This enables us to test newly developed algorithms and verify hardware designs. The simulations described here were derived to verify our research in different publications [6–8].

In this work, we describe different forms of implementation to set up hardware in the loop simulation for different stages of development. Therefore, we introduce the general setups in Section 2. The concepts are then implemented and tested with respect to the needs of the MF R-Mode system in Section 3. Finally, we compare the results and close the paper in Section 4.

2. Simulation Setups

The simulation is oriented to the implementation of real-world R-Mode transmitters as described in [3]. In general, the report follows two possible design ideas. The first uses the existing MSK modulator and adds two continuous signals with an external signal generator. For the simulation in our laboratory, we use a software-defined radio (SDR) as a source of continuous modulated MSK signals, while the aiding carrier is provided via a signal generator that is synchronized with a precise time source. The overall setup we described is shown in Figure 2 as a block diagram. The advantage of this approach is that we can continuously stream real data. However, in the minimal configuration, only one station can be simulated, as most signal generators only provided two channels and the modulation of the messages is limited by the computational resource that drives the SDR. Moreover, not all the SDR are capable of transmitting frequencies as low as 280 kHz. When we want to utilize one of these, we need to introduce a down conversion, as shown in the block diagram in Figure 3. Additional filtering is not necessary, as the higher side band after the mixer is filtered out via the band-pass filter of the MF R-Mode receiver.

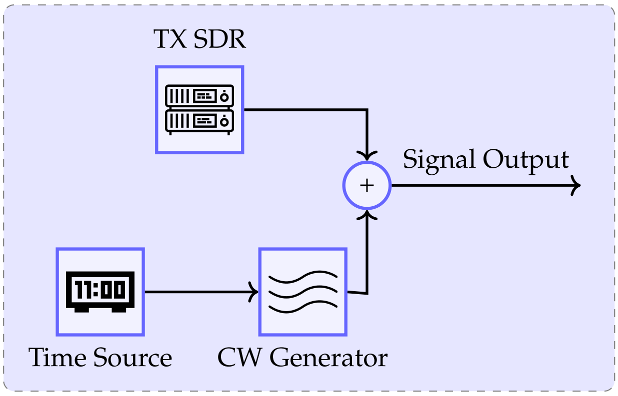

Figure 2. R-Mode signal generation with external tone generation.

This limitation can be overcome by using an arbitrary waveform generator (AWG), which replaces the aiding carrier generation with a replay of a sum of the needed carrier. Still, the number of modulated channels is limited by the computational power.

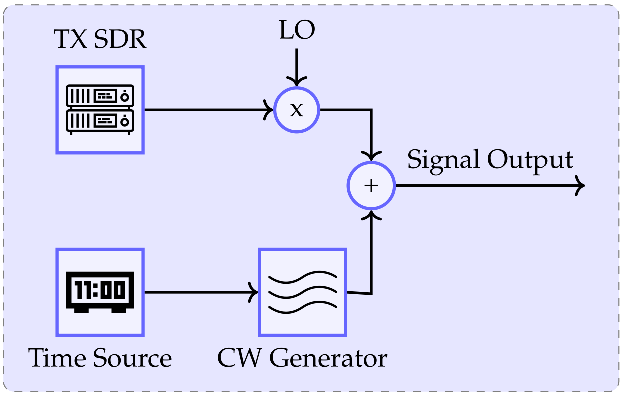

Figure 3. R-Mode signal generation with external tone generation and down conversion of the baseband.

The second approach follows the idea of utilizing an AWG to generate multiple stations by replaying the R-Mode signal for multiple channels at once. To guarantee good timing of the signal, we synchronize the AWG with an external clock source, which is described in Figure 4. The setup is similar to the transmitter station with an integrated R-Mode modulator, as described in [3]. However, with our approach, we are only able to replay recorded or pre-computed signals. These files are then repeated by continuously utilizing the sequencer of the AWG. As we simulate 16 s of the data, we assume a repeating pattern every 16 s.

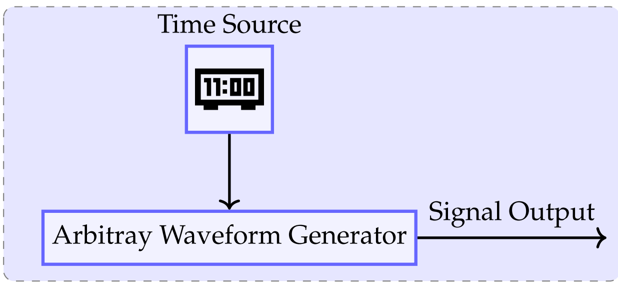

Figure 4. R-Mode signal generation with AWG.

The scenario we use for this work is obtained from the DLR simulation environment for the MF R-Mode. We have already used these methods in the past to verify different developments for the MF R-Mode [6–8].

3. Implementation

In this paper, we concentrated on the generation of a single station. In the following part, we first describe the used measurement devices. Subsequently, we discuss the result of a simulation run of half an hour, where each phase estimation considers one second of observation time. The DLR implementation of the R-Mode MF receiver based around an ETTUS N210 is used to obtain our results.

3.1. MSK Generation with ETTUS SDR

To implement the design presented in Figure 2, we utilize an ETTUS N210 with daughterboard LFTX as TX SDR. This allows us to use a baseband modulation at 300 kHz. The modulation is generated in a GNUradio flow graph, from a random byte source with a bitrate of 100 bits/s. Unfortunately, it is not feasible to generate the CW with the same SDR due to intermodulation in the generation path. As a CW generator, we use a RIGOL DG1032 two-channel generator, which is synchronized to a common oven-controlled oscillator (OCXO) shared with the receiver. The CW are generated on each channel separately with an amplitude of 100 mV and combined with the modulation signal with a Mini-Circuits ZSC-4-3-75+ signal combiner. Due to the low frequency, we neglect the mismatch between the 50 Ω signal generation and the 75 Ω of the signal combiner. Figure 5 shows the resulting setup, which is tested.

In Figure 6, we present our test run of 40 min results with zero mean. In the graph, the orange triangle indicates the results for CW_1, the blue triangle indicates CW_2 and the green points represent the beat phase, which is the phase difference between CW_1 and CW_2. We can clearly observe for the two CW a phase drift going from -0.005 rad to 0.002 rad, which corresponds to an error of 1 m. However, the phase difference is stable over the full time, with a resulting variance of 4.467×10^{-11} rad^2.

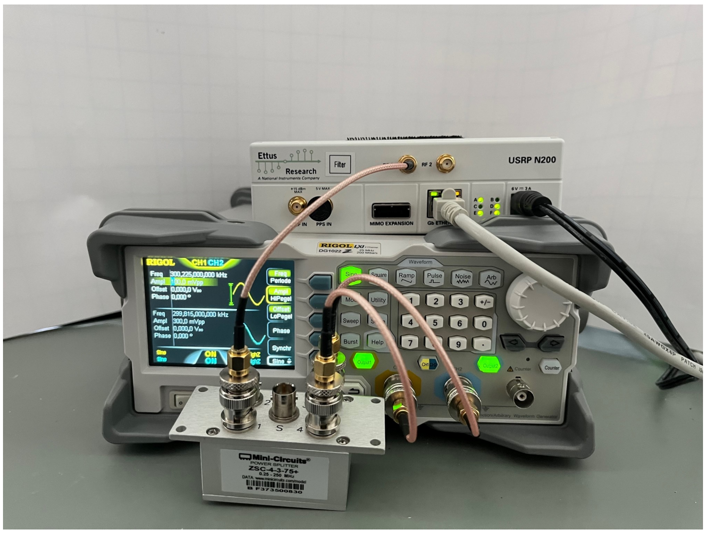

Figure 5. Test setup with ETTUS SDR.

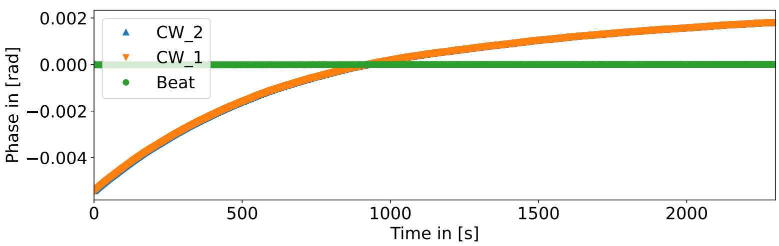

Figure 6. Phase estimation with modulation from ETTUS SDR.

3.2. MSK Generation with Lime SDR

In general, with some SDRs which do not cover the medium frequency band, a down conversion is required as described in Figure 3. As example implementation for this paper, we use the Lime SDR USB, wich is presented in Figure 7. The MSK signal is generated at a baseband frequency of 40 MHz and then down converted with the mixer Mini-Circuit ZFY-1. The local oscillator (LO) signal is generated with the Tektronix AFG31000, which is synchronized to the timing reference. The resulting intermediate frequency is then combined with two continuous signals generated using a Rigol DG1032 signal generator, corresponding to the previous setup with an amplitude of 100 mV. The result of a 40 min test run is shown in Figure 8. The orange triangles mark the estimation result with zero mean of CW_1, the blue triangle is CW_2, and the green dots are the results for the beat phase. The CWs again show a phase drift over our measurement interval, here from -0.007 rad to 0.004 rad. However, the result for CW_2 shows different outliers of the trend line after around 800 s of testing. We observe this accordingly in the result for the beat frequency, which leads to a variance of 8.528×10^{-8} rad^2. The less accurate result is potentially due to the interference with the MSK, as described in [7]. This interference occurs strongly when the carrier frequency is drifting with respect to the CWs. The problem becomes more recognizable with the mixing step, as the conversion has an influence on the stability. It is very obvious that the interference is different for the two CWs and depends on the frequency shift of the MSK. In this experiment, we can assume that the MSK has a shift towards the CW_2, producing higher interference than for the CW1.

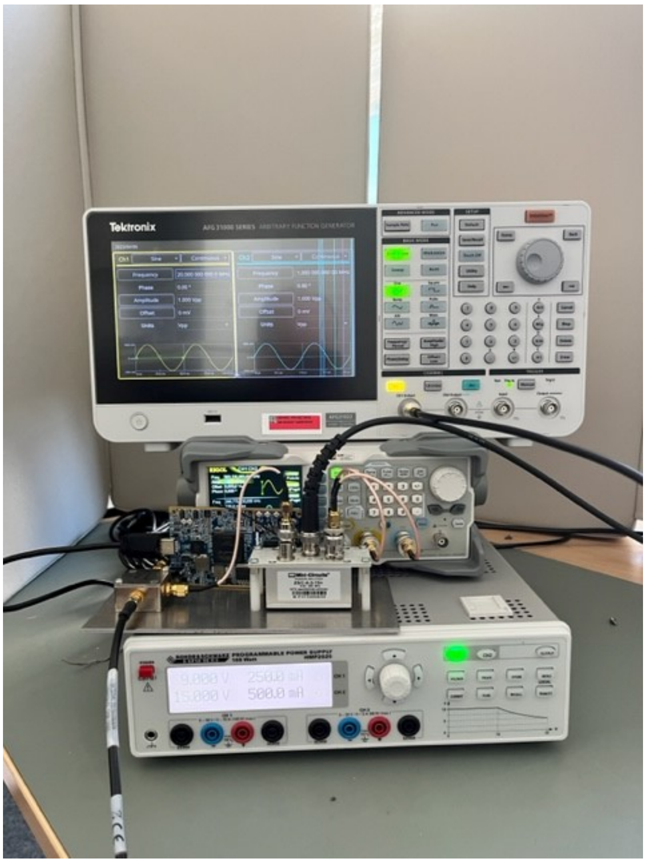

Figure 7. Test setup with Lime SDR.

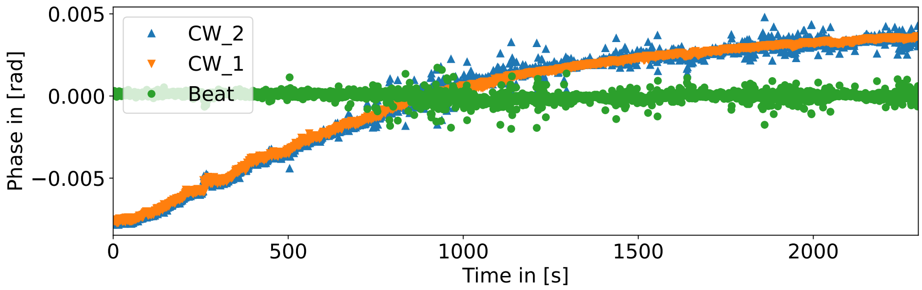

Figure 8. Phase estimation with modulation from Lime SDR.

3.3. Data Replay with AWG

The last setup is fundamentally different to those previously used. Instead of generating the signals in real time, we replay pre-simulated or recorded signals as described in Figure 4. Our setup utilizes the Tektronix AFG31000 with a common OCXO to our receiver. We obtain a single R-Mode station from the DLR python simulation environment with a sample rate of 5 Msamples/s in four comma-separated value (CSV) files. Each of the files holds 4 s of data and is loaded into the sequencer of the AWG. The corresponding CWs have an amplitude of 100 mV for CW_1 and 200 mV for CW_2. The 16 s of total data are repeated endlessly. The generated output is fed directly to the MF R-Mode receiver, as shown in Figure 9.

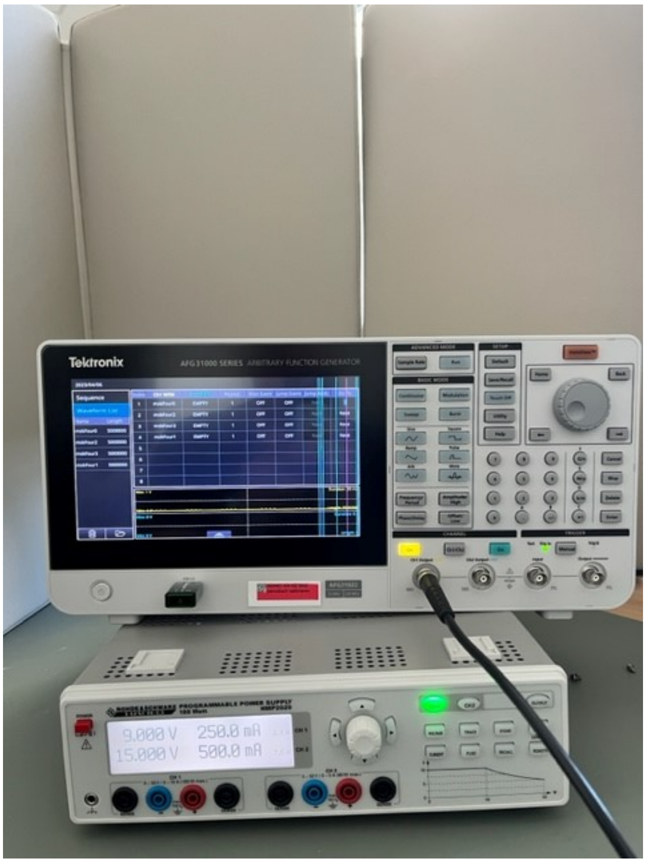

Figure 9. Test setup with AWG.

To proof the repeatability of the pattern, we compare the phase estimation of the first and second replay of the files in Figure 10. We indicate the first replay with red dots and the second replay with blue crosses. All signals have discrete values that appear repeatedly in the range of −0.2 rad to 0.2 rad. The overlay shows a good agreement.

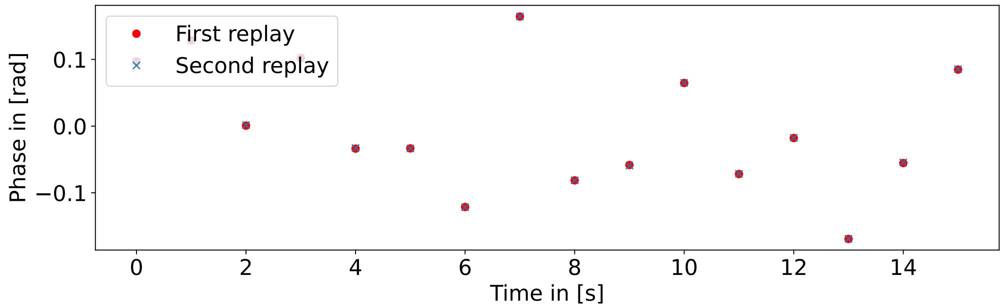

Figure 10. Phase estimation with modulation from replayed CSV files for first and second replay.

To show the attainable performance, the result of the conducted half-hour test run is shown in Figure 11 for every 16th estimation. By only evaluating at certain time steps, the repetition pattern is not visible and we only evaluate the expected performance. The estimation results are represented by orange dots for the CW_1, blue dots for the CW_2, and green dots for the beat frequency. The CW appear to drift in the range of -0.0075 rad to 0.0025 rad. Despite the issue encountered, this approach has the big advantage of generating several R-Mode stations with a predefined configuration. Therefore, it is useful to test the R-Mode receiver positioning engine, as long as we only consider snapshot solutions.

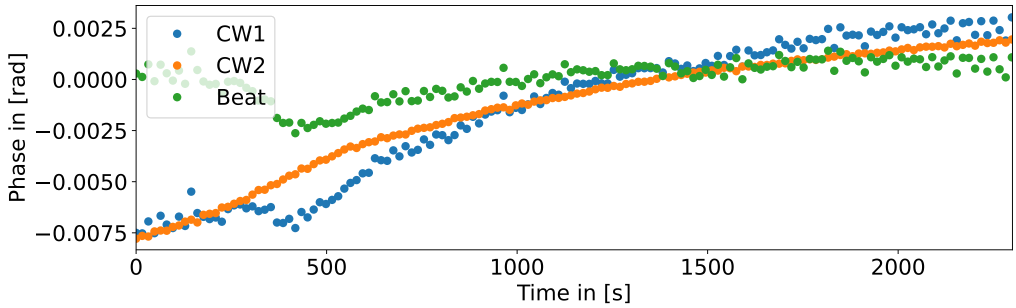

Figure 11. Phase estimation with modulation from replayed CSV files for every 16th estimation.

4. Conclusion

We introduced three different approaches for simulating R-Mode signals in a laboratory environment. We were able to generate R-Mode signals with a medium frequency baseband, a baseband conversion, and the replay of pre-processed files. Overall, the use of an external generator and an SDR that is able to transmit in the medium frequency baseband provides the highest phase stability and can therefore be used to detected even small improvements. However, this approach is limited to the simulation of a single, station, and when more stations are required, the amount of hardware grows. As an alternative, the AWG can be used to simulate multiple stations, even if the observed performance is limited.

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