

Time Synchronization and Recovery Using R-Mode

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Abstract—Time synchronization is a fundamental requirement for modern maritime navigation, supporting accurate positioning, operational coordination, and navigational safety. Although Global Navigation Satellite Systems (GNSS) provide the primary source for positioning and timing, their susceptibility to interference, including jamming and spoofing, particularly in regions such as the Baltic Sea, has motivated the development of complementary technologies such as R-Mode. This work presents methods for extracting timing information from Minimum Shift Keying (MSK) signals used within the R-Mode system. It evaluates the achievable synchronization accuracy and investigates approaches for stabilizing a local clock oscillator using remote atomic clock references in order to maintain a stable and continuously updated time source.

Index Terms—PNT, R-Mode, MSK signals, maritime navigation, timing synchronization, GNSS backup

I. INTRODUCTION

While GNSS provides high accuracy and global coverage [1], its signals are inherently weak at the Earth's surface and therefore vulnerable to interference, jamming, spoofing, or signal obstruction [2] [3] [4]. These vulnerabilities pose significant risks for safety-critical systems, particularly in maritime environments where reliable navigation and timing are essential. Consequently, the development of complementary terrestrial technologies capable of maintaining PNT services during GNSS disruptions has increased in importance.

One promising approach is Ranging Mode (R-Mode), a terrestrial navigation concept designed to provide positioning and timing capabilities by reusing existing maritime radio infrastructure. In the Baltic Sea region, R-Mode implementations are based on medium-frequency (MF) maritime radio beacon transmissions that incorporate two signal components [2].

The first component consists of Minimum Shift Keying (MSK) signals used for broadcasting differential GNSS corrections in accordance with Radio Technical Commission for Maritime Services (RTCM) standards. These MSK-modulated transmissions provide a continuous data stream that can be processed to extract timing information [5]. The second component comprises continuous wave (CW) signals transmitted alongside the MSK signal, which serve as stable spectral references that allow precise phase measurements for ranging applications (See Fig. 1.). By combining the phase information from the CW tones with the timing information derived from the MSK signal, R-Mode systems enable terrestrial positioning and time synchronization capabilities.

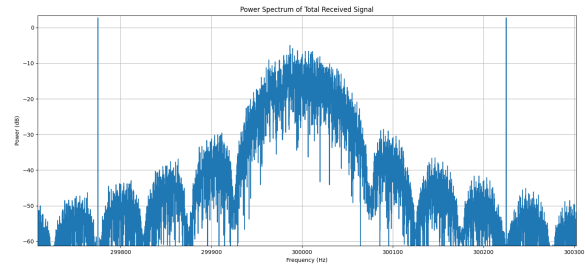


Fig. 1. R-Mode spectrum, with the MSK at a 300,000 Hz carrier and the two continuous waves (CW) at 299,775 Hz and 300,225 Hz respectively

This work focuses specifically on the extraction of precise timing information from the MSK-modulated RTCM transmissions of maritime radio beacons operating in the Baltic Sea. The objective is to investigate methods for recovering accurate time references from these signals and to evaluate their suitability for stabilizing local oscillators relative to remote atomic clock references. Through analytical modeling, simulation, and experimental measurements, the study evaluates the feasibility of using terrestrial R-Mode signals as reliable timing sources, contributing to the development of resilient maritime PNT systems capable of operating independently of GNSS.

II. ACQUISITION OF ABSOLUTE TIME

DGNSS beacons broadcast corrective messages, and a parameter of interest is called the z-count [6]. This parameter alone cannot be used to extract absolute time because it does not represent the actual transmission time. Rather, it corresponds to the message generation time. For the purposes of this paper, the z-count will be considered the transmission time despite the fact that it is not designed to be. In the future, the R-Mode message 55 will be used to enhance the current DGNSS system. This message will be sent every minute, and the contained time will reflect the current R-Mode system time at transmission. This allows the user to unambiguously retrieve the absolute timing at reception. At the time of writing this paper, the R-Mode message 55 is not available, so the implementation is designed to work with R-Mode message 55 at its release. However, the implementation is currently being tested using the z-count parameter broadcast by existing DGNSS stations, assuming it represents the absolute time, solely as a proof of concept.

III. PRELIMINARY RESULTS

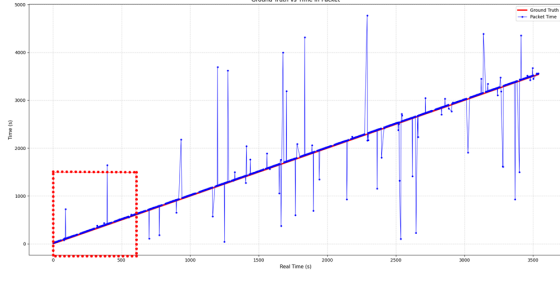


Fig. 2. True UTC time (red) and time extracted from the Groß Mohrdorf station (blue)

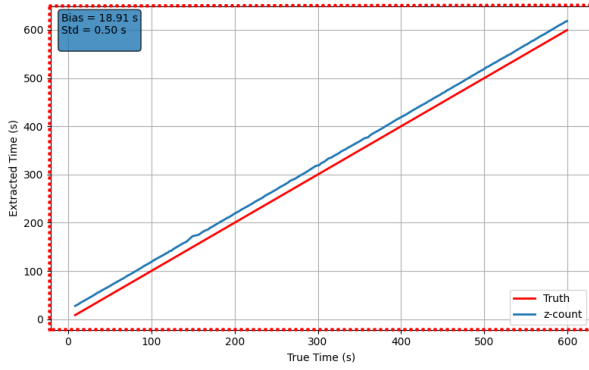


Fig. 3. Zoomed-in view of the first 10 minutes of the experiment (Fig. 2)

We were able to approximate the time using real measured signals. A residual bias remains after removing the outliers. The calculated bias between the extracted time and the actual UTC time is 18.91 s and the standard deviation is 0.50 s. The bias, visible as an offset between the true time (red line) and the extracted time (blue line), can be explained by many factors. A substantial part of it comes from the difference between UTC and GPS time of 18 seconds. Correcting for the constant GPS–UTC offset, we see that the new value for our bias is $18.91\text{ s} - 18\text{ s} = 0.91\text{ s}$. The remaining 0.91 s bias is influenced by the following factors, listed in order of decreasing magnitude: The filters used to isolate the signal and the station’s z-count time alignment with GPS time (order of hundreds of milliseconds), the processing delay at the receiver level (order of milliseconds), the transmission delay and the propagation delay over the channel from the station to the receiver (order of microseconds).

Further results from Jammertest 2025 in a GNSS-denied environment will be presented in the full paper, together with an extended description of R-Mode message 55. This message mitigates reference-station timing biases, removing a large portion of the observed error. The remaining biases will be reduced through improved control of the processing chain, including the filtering stages and the computation time, potentially lowering the timing bias to a few microseconds to hundreds of nanoseconds.

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