VDES R-Mode Flight Experiments

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***Abstract*—Aircraft navigation nowadays relies heavily on Global Navigation Satellite Systems (GNSSs). As they can be subject to jamming, spoofing, and other outages, this reliance presents a risk to safe navigation. We investigate whether the VHF Data Exchange System (VDES) R-Mode can be used on board of aircraft. VDES R-Mode is an alternative positioning, navigation and time (PNT) system to complement navigation information, primarily to support the maritime traffic. We describe a measurement campaign of VDES R-Mode signals transmitted in the port of Hamburg and received on an airplane flying at an altitude of about 400 m above the port of Hamburg. Further, we compare the positioning performance achieved during the flight experiments with previous results for VDES R-Mode. We found that we were able to achieve an accuracy better than 204 m 95% of the time despite encountering interference from other signals.**

***Index Terms*—VDES, R-Mode, APNT.**

I. Introduction

Aircraft nowadays heavily rely on Global Navigation Satellite Systems (GNSSs) for navigation. While this works well in most situations, GNSSs are subject to jamming, spoofing or other outages. Recently, GNSS jamming incidents have occured with increased frequency. Especially the Baltic sea area near Russian territories has been affected. This jamming does not only affect ships, but even more so airplanes. Due to their high altitude, they can be jammed by far away signal sources. Nonetheless, airplanes nowadays often need to rely on GPS for performing the approach to their destination airport. One example that has received a lot of publicity is Tartu Airport, where scheduled flights were suspended for a month due to jamming [1].

It is therefore desirable to have a backup positioning source available for aircraft. We had previously investigated the VHF Data Exchange System (VDES) as a source of backup position information called R-Mode. This is a terrestrial backup positioning system primarily intended for maritime applications. There is however no inherent limitation that precludes a utilization for aircraft. In this paper, we present a measurement campaign where VDES R-Mode signals were recorded on board of a small aircraft. We used the recorded data to evaluate the positioning performance of VDES R-Mode when used in an aviation context.

II. The VDES R-Mode System

VDES R-Mode [3] has been described by IALA as an alternative PNT solution for the marine systems onboard of a vessel especially to complement the satellite based GNSSs in case of disturbances. It is based on the VHF Data Exchange System, which is a recently standardised communication system for maritime applications that extends the well known Automatic Identification System (AIS) [2]. Compared to AIS, VDES offers a four times higher bandwidth of $100\,\mathrm{kHz}$ instead of $25\,\mathrm{kHz}$. It utilizes a linear modulation scheme, and is intended primarily as a maritime communication system that offers a higher communication capacity than AIS that is already often overloaded and primarily used for position reports.

VDES R-Mode is an extension of this communication system for positioning purposes. This extension works by having multiple base stations at known locations transmit known signals at well known time instances. Based on time of arrival measurements and multilateration, it is possible to determine the position at the receiver. This signal is chosen in such a way that it conforms to the standard of the VDES communication system, but also offers good properties for range estimation. We previously investigated the design of this signal and proposed a signal that depends on a design parameter γ, the optimal value for which depends on the signal to noise ratio at the receiver. [5].

In 2021 [4] a measurement campaign in Bavaria allowed for the first time to assess the positioning performance with three synchronized base stations and a vessel on the lake Ammer. The performance analysis showed positioning performances with an error in the range between $10\,\mathrm{m}$ and $100\,\mathrm{m}$.

Fig. 1. The wingpod with the VHF receiver.

III. Measurements

To practically assess the performance of VDES R-Mode for aeronautical applications, we performed a measurement

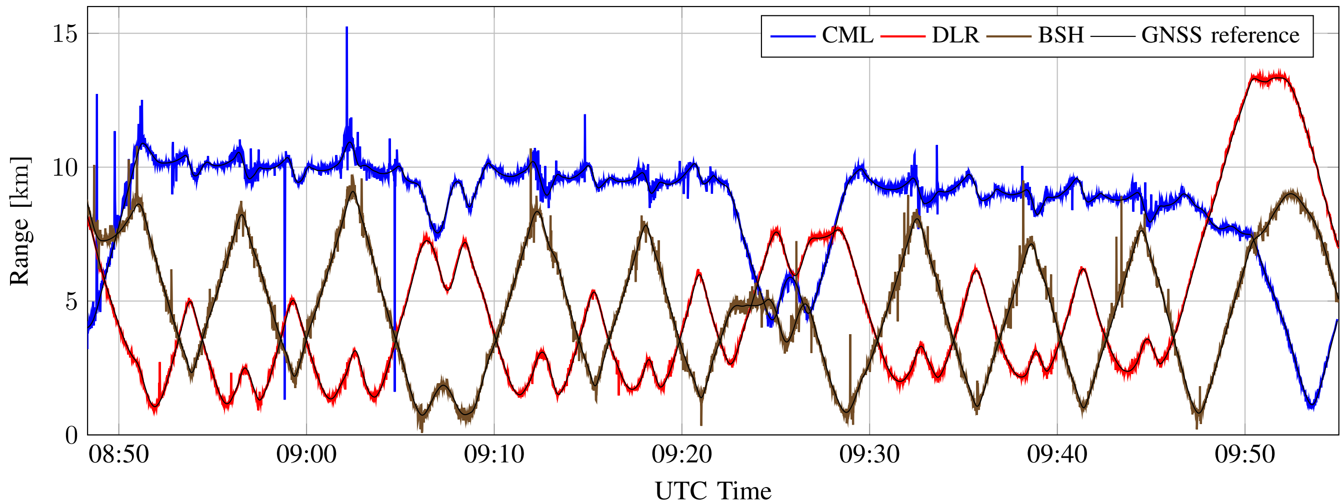

Fig. 2. The range estimates to each of the three base stations.

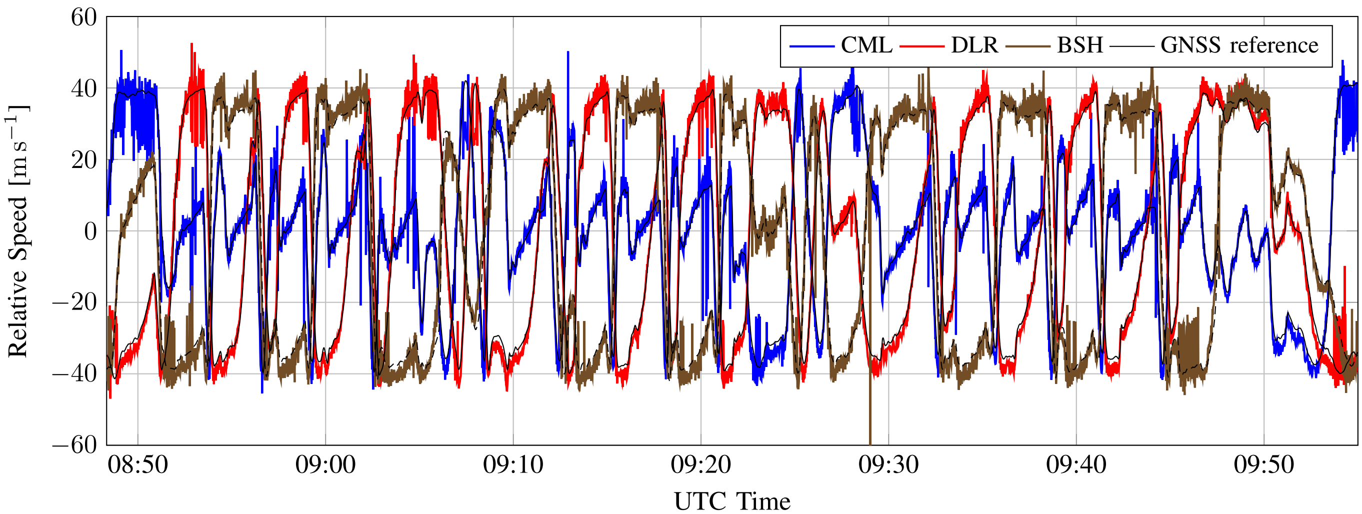

Fig. 3. The estimated relative speeds between each of the base stations and the receiver.

campaign in the area of the harbour Hamburg.

A. Measurement setup

The measurement setup consisted of three VDES R-Mode transmitters at different locations in Hamburg. Each of the transmitters consisted of an Ettus USRP B210 software defined radio to generate the VDES signals, a power amplifier with an output power of 10 W, and a GNSS-disciplined oscillator to provide an accurate timing reference. The three transmitter sites were:

- The building of the Federal Maritime and Hydrographic Agency (BSH) in Hamburg St. Pauli
- An office building of the German Aerospace Center (DLR) in Hamburg Finkenwerder.
- The building of the Fraunhofer Center for Maritime Logistics and Services (CML) in Hamburg Harburg

Their position is shown on a map in Figure 7.

The receiver also consisted of an Ettus USRP B210 software defined radio together with a small form factor computer. The receiver also had an integrated GPS disciplined oscilator that provided an accurate timing reference. The receiver was mounted in the wingpod of a small research airplane, together with other scientific payloads. The wingpod with the receiver can be seen in Figure 1 A small Ettus VERT400 antenna was used for the receiver, mounted on the bottom of the wingpod. The route of the airplane is shown in Figure 7.

B. Transmitted signal

Each base station transmitted a number of different signals. Among them:

- A 100 kHz VDES R-Mode signal r_γ^{100} with $\gamma \in \{0.0, 0.3, 0.7, 1.0\}$
- A 25 kHz VDES R-Mode signal r^{25}
- A standard AIS signal a
- An AIS+ signal $a^+_{\mathrm{d}A}$ with $\mathrm{d}A \in \{0.2, 0.4, \ldots, 1.0\}$

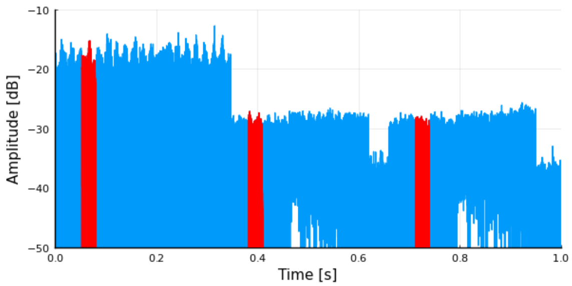

Fig. 4. An example of interference affecting part of the ranging signal. The evaluated time slots are marked red.

The transmitted AIS signal and its AIS+ variations are mentioned for completeness, but are out of scope for this article.

As mentioned in section II The parameter γ for the VDES R-Mode signal is a design parameter between 0 and 1 that influences the spectrum of the signal. Lower values of γ cause a more uniform spectrum, while higher values cause a spectrum with most of the signal energy at the edge of the spectrum. The optimal value of γ depends on the Signal to Noise Ratio at the receiver [5]. For this article, the signals with $\gamma = 0.7$ were evaluated.

C. Data Evaluation

In order to evaluate the data, a maximum likelihood approach was used for estimating the delay τ and the Doppler shift Δf of the received signal.

$$(\hat{\tau}, \Delta\hat{f}) = \underset{\tau, \Delta f}{\arg\max} \sum_{k} x[k] \cdot s^{*}(kT_{\mathrm{s}} - \tau)\, \mathrm{e}^{\mathrm{j}2\pi k T_{\mathrm{s}} \Delta f} \quad (1)$$

with $x[k]$ being the received samples from the software defined radio receiver, and $s(t)$ being the transmitted signal. A numerical optimization method was used to evaluate the $\arg\max$ operation. From the estimated time of arrival, a range r was estimated as

$$\hat{r} = c_0 \cdot (\hat{\tau} - \tau_{\text{offset}}). \quad (2)$$

With c_0 being the speed of light, and τ_{offset} being an experimentally determined offset parameter. As described in section III-B, multiple R-Mode signals with different parameters of the parameter γ were transmitted. For this article, we evaluated the signals with $\gamma = 0.7$. The results of the range estimation can be seen in Figure 2, and the results of the speed estimation in Figure fig:speeds. Implausible negative range estimates were discarded. Other outliers were not removed.

The estimated range $\hat{r}$ and the estimated Doppler shift $\Delta\hat{f}$ for each station are then used to track the position with an unscented Kalman filter. The Kalman filter was initialized with the true position and velocity that was obtained from the GNSS reference. The estimated track after Kalman filter tracking can be seen in Figure 7.

IV. Results and Discussion

In the results of the range estimation, that are shown in Figure 2, we observe a few obvious outliers, such as shortly before 09:00 in the CML range. We observed that some of these outliers correlated with interference events that were noticable in the received signal. Figure 4 shows an example where the first third of one second is affected by interference. We have not yet identified the source of the interference events. Obviously implausible outliers that resulted in negative range estimates were discarded after estimation, otherwise no measures were taken to identify or reject outliers in the measurements.

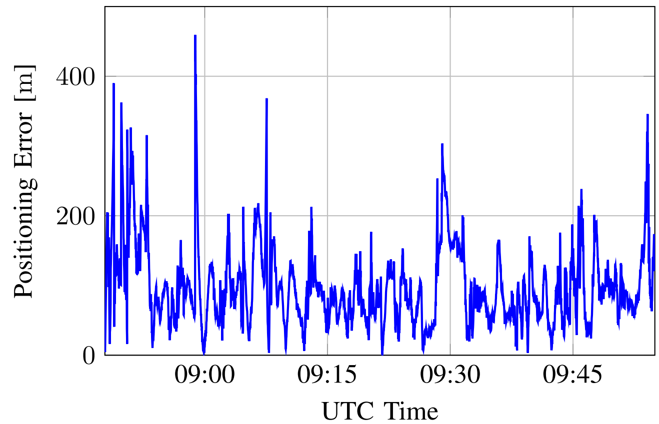

Fig. 5. The absolute error of the position estimation over time.

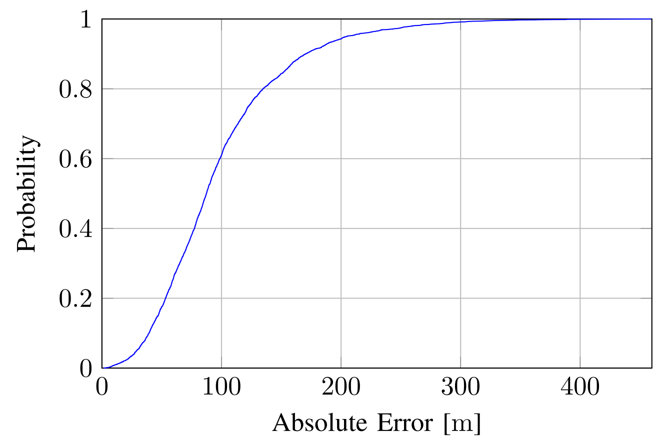

Fig. 6. The distribution of the positioning error.

Figure 6 shows the distribution of the absolute estimation error after Kalman filter tracking. It can be seen from that figure that the error was below $204\,\mathrm{m}$ for $95\,\%$ of the time. It can also be seen that errors up to $470\,\mathrm{m}$ were observed during the measurement.

In Figure 5, the absolute error can be seen over the course of the measurement. We can see that errors above $250\,\mathrm{m}$ only occured during a few instances. Many of the increases in the absolute error also correlate to outlier events that are visible in the range or speed measurements. It is therefore plausible that the accuracy can be improved further by introducing plausibility checks and rejecting outlier measurements that might have been affected by interference.

In previous measurements, we observed that including Doppler observations in the tracking of the position, significantly improved its accuracy [6]. Since the observed relative

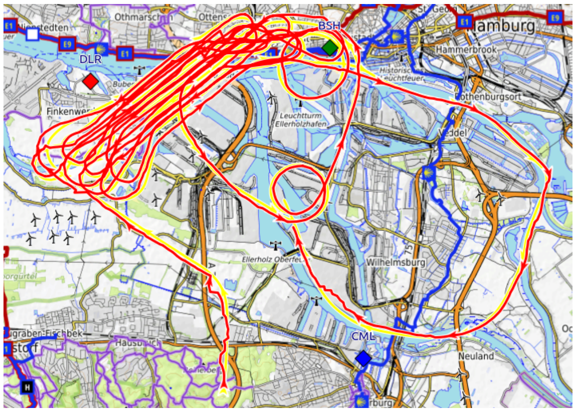

Fig. 7. The flightpath of the motorglider. The GNSS reference track is shown in Yellow. The R-Mode estimation is shown in red. The transmitter stations are shown as colored diamonds. CML in blue, DLR in red, and BSH in green.

speeds in an aeronautical scenario are much higher than the speeds in a typical maritime scenario, we expect the influence of the Doppler observations to be even more important. Indeed, we can see that most larger positioning errors occur at times where a significant error in the speed estimates can be seen in Figure 3.

V. Conclusion

VDES R-Mode is a part of an alternative PNT system that eases the single dependency on GNSS in the maritime domain. For the first time, we applied VDES R-Mode to an aeronautical application and performed a flight measurement campaign over the harbour of Hamburg that demonstrates the feasibility of utilizing VDES R-Mode for aeronautical applications. We analyzed the received signals to estimate ranges and Doppler information. Using these data, we were able to track the airplanes position with an Unscented Kalman filter. We found that the achieved positioning accuracy was better than $204\,\mathrm{m}$ for $95\,\%$ of the time. We also found that the estimated position is occasionally affected by outliers in the range and Doppler measurements that are probably caused by interference. We expect that further accuracy improvements are possible if interference events are detected and affected measurements discarded.

The performed measurement campaign shows that it is feasible to utilize VDES R-Mode not only for maritime positioning, but also for airplanes.

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