On the Positioning Performance of VDES R-Mode

Markus Wirsing[1] and Armin Dammann[1] and Ronald Raulefs[1]

[1] *German Aerospace Center (DLR)*(E-mail: markus.wirsing@dlr.de)

Ships nowadays greatly rely on Global Navigation Satellite Systems (GNSSs) in order to determine their position. Since GNSS outages or jamming events do occur, there are efforts to reduce the dependency on GNSS for maritime navigation. One such effort is called R-Mode (Ranging Mode), and focuses on complementing maritime communication systems by a ranging component to enable a vessel to determine its position. One of the systems to be extended by R-Mode is the VHF Data Exchange System (VDES). The VDES communication system is currently in standardization and offers 100 kHz of bandwidth in the maritime VHF band. It utilizes single carrier modulation with $\pi/4$-QPSK. The proposed R-Mode extension works by sending a precisely timed known data sequence, so that time of arrival estimation allows determination of the range. Using software defined radios (SDR), we implemented a test setup for VDES R-Mode with three base stations on land and one receiver located on a vessel. Using this setup, we performed the first VDES R-Mode positioning trials on the Lake Ammer in Germany. By determining the time of the arrival as well as the Doppler shift of the received signals we tracked the vessels position with an Unscented Kalman Filter. The positioning accuracy performance ranged to up to $22\,\mathrm{m}$ under favourable conditions. Crucial was the consideration of the Doppler measurements to enhance tracking performance considerably.

KEYWORDS

VDES. R-Mode. Positioning.

1. INTRODUCTION. As maritime navigation nowadays strongly relies on Global Navigation Satellite Systems (GNSS), and alternatives such as LORAN are progressively being dismantled, there are concerns about being dependent on a single system, which provides accurate position information but is not free of failures (Sadlier et al., 2017). Thus, there is a need for a backup system that can be used in case of failure or jamming of the satellite systems. One such effort to provide a backup system is called R-Mode (Ranging Mode). R-Mode consists of two parts: One part that relies on Medium Frequency (MF) signal radiated by the IALA beacon system (Johnson and Swaszek, 2014), and another part that relies on the VHF Data Exchange System (VDES) that is currently in standardization (IALA, 2020). In this paper, we will consider the VDES part of R-Mode.

In Wirsing et al. (2020), we investigated the design of a suitable signal for VDES R-Mode, and in Wirsing et al. (2021), we presented an approach for the position estimation using a Kalman filter, as well as first results from our experiments on Lake Ammer. In this paper we will present more detailed results from the experiments.

The paper is structured as follows: In Section 2 we give an overview of the VDES R-Mode system. We describe our experiments on Lake Ammer in Section 3, and discuss the results in Section 4. In Section 5 we summarize our findings.

2. THE VDES R-MODE SYSTEM.

VDES is a new digital maritime communication system that comprises the existing Automatic Identification System (AIS), a satellite component, and a terrestrial component (IALA, 2017). The terrestrial component is intended to cover the same areas that are currently covered by AIS.

Terrestrial VDES will utilize a linear modulation with a bandwidth of $100\,\mathrm{kHz}$ (*IALA Guideline G1139: THE TECHNICAL SPECIFICATION OF VDES, ed. 3*, 2019). In comparison to that, AIS uses Gaussian Minimum Shift Keying (GMSK) modulation, and a bandwidth of $25\,\mathrm{kHz}$. The higher bandwidth gives VDES a significant advantage over AIS when considering its suitability for ranging purposes (Safar et al., 2020; Wirsing et al., 2019).

The concept of VDES R-Mode is to extend the VDES communication signal by a ranging component. For this ranging component, the VDES base stations will regularly transmit a precisely timed ranging signal that consists of a pre-defined data sequence. Apart from not utilizing channel coding, the ranging signal should conform to the physical layer specification of the VDES communication system. Maritime vessels can obtain an estimate on their position by estimating multiple ranges to shore based R-Mode transmitters, and performing multilateration.

The data sequence used for ranging in VDES R-Mode consists of two concatenated parts: An alternating sequence, and a pseudo-noise sequence based on a Gold code (IALA, 2020). This design was chosen due to considerations about the achievable ranging performance in different Signal to Noise Ratio (SNR) ranges (Wirsing et al., 2020). A parameter γrepresents the fraction of the alternating sequence of the total sequence, and the remainder of the sequence uses the Gold code. The advantage of the alternating sequence is the narrower main peak of the autocorrelation, but comes with a the drawback of stronger sidelobes. Therefore, depending on the SNR the joint sequence can be adapted to the local conditions.

3. R-MODE EXPERIMENTS ON LAKE AMMER.

In order to experimentally determine the achievable performance of a VDES R-Mode implementation, we performed measurements on the Lake Ammer. Three transmitter stations were placed on the shore of Lake Ammer, and a receiver was placed on a boat of the Wasserwacht (water rescue). The transmitters were mounted on portable masts, with a height of approximately $10\,\mathrm{m}$. A transmitter station is shown in Figure 2a The mounting of the receive antenna is shown in Figure 2b. The location of the transmitters was chosen, so that a favourable geometry would be achieved in the northern part of Lake Ammer. Specifically, the transmitters were located in the villages Utting, Schondorf and Buch.

The transmitter hardware consisted of a USRP B210 Software Defined Radio (SDR), a power amplifier, and a laptop to control the SDR. The SDR at each station was also connected to a GNSS receiver that provided an accurate timing signal. Notably, the receiver station on the boat was also equipped with a GNSS receiver that was used as a timing source for the SDR as well as for providing a position reference. This means that, differing from

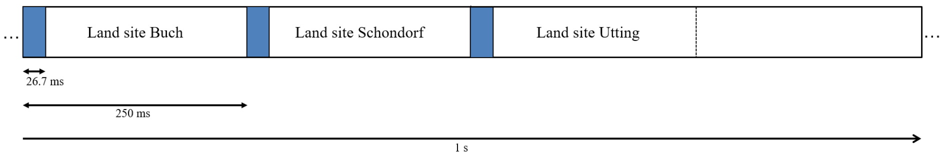
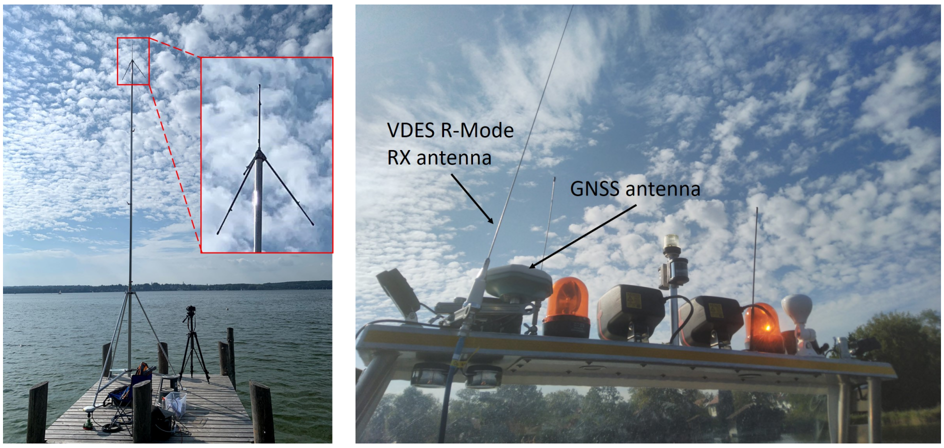


Figure 1.: Transmit schedule of the VDES base stations.



(a) Transmitter station with VDES transmitter antenna

(b) VDES R-Mode receive antenna and GNSS receiver antenna on the boat

Figure 2.: Transmitter and receiver setup at Lake Ammer.

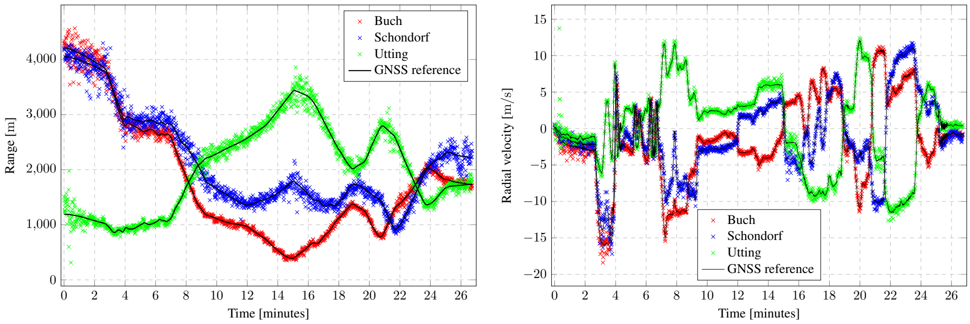
what is planned in the R-Mode standard, our receiver also had access to a stable timing source.

Each transmitter station transmitted R-Mode ranging sequences as described in Wirsing et al. (2020), with $\gamma = \frac{1}{3}$. Each of the stations transmitted once per second, during an assigned timeslot. Even though VDES uses a transmit power of $12\,\mathrm{W}$, the transmit power in our experiment was limited to $1\,\mathrm{W}$ due to regulatory constraints. The transmit schedule is shown in Figure 1.

We chose a maximum likelihood approach to evaluate the received signal. The time of arrival estimate $\hat{\tau}$ Doppler shift estimate $\Delta\hat{f}$ were obtained by:

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

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 $\hat{r} = c_0 \cdot (\hat{\tau} - \tau_\text{offset})$. With c_0 being the speed of light, and τ_offset being an experimentally determined offset parameter.



(a) Ranges (b) Radial velocities

Figure 3.: The range and radial velocity measurements for the scenario with good line of sight and geometry. The associated position estimation is shown in Figure 4.

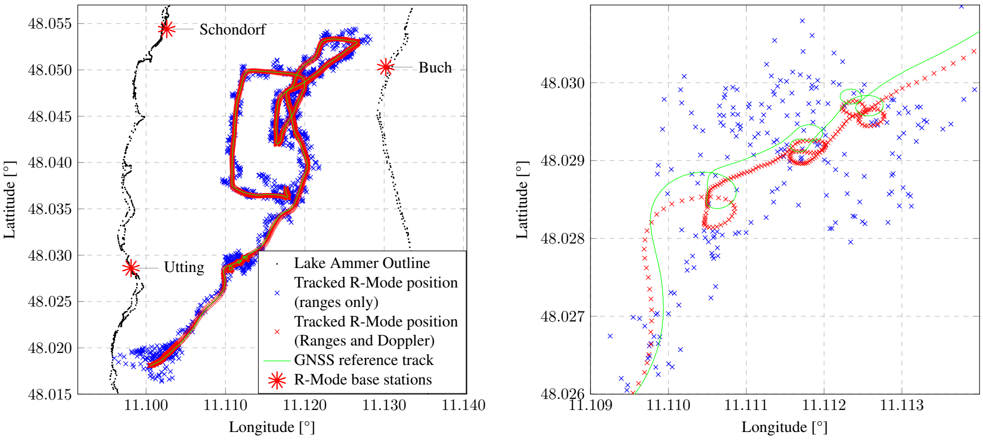
After determining the ranges and Doppler shifts, an Unscented Kalman Filter (UKF) was used to track the boats position. The UKF filter was initialized with the position and velocity from the GNSS reference. This approach allowed us to utilize the observed Doppler shift in the tracking (Wirsing et al., 2021). In order to assess the difference in achievable ranging performance, the evaluation was performed once with the Doppler measurements taken into account, and once with the Doppler measurements disregarded. The results are shown in Figures 4,6, and 9.

A number of scenarios were considered for the experiments:

1. A line of sight scenario with favourable geometry.
2. A scenario with the signal being shadowed by land areas.
3. A scenario with a passenger ship blocking the line of sight to one of the transmitters. Figure 7 shows the passenger ship next to the boat with our receiver.

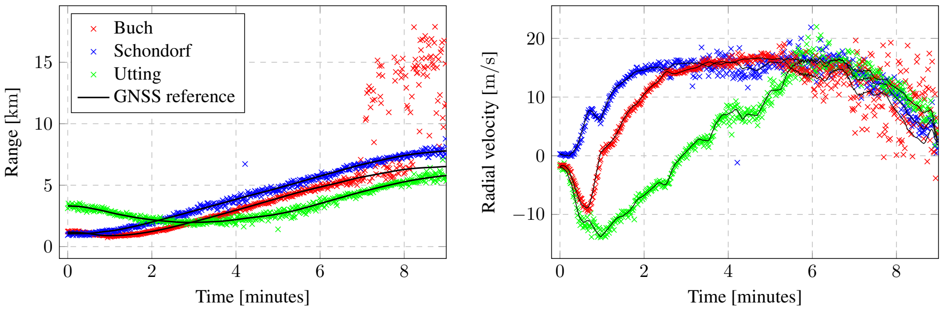
For the first scenario, we chose a path that generally stayed within or close to the triangle spanned by the three transmitter stations. The path of the boat and the result of the tracking in that scenario are shown in Figure 4a. The path starts south of Utting and continues towards the Buch station. Notably, the path of the boat also included a number of rather tight circles, which are shown in detail in Figure 4b. The associated ranges between the boat and the receiver are shown in Figure 3a, and the radial velocities in Figure 3b. It can be seen that the measurements for the Utting station show significant outliers at the beginning of the scenario. This is likely due to non line-of-sight conditions caused by buildings. Another interesting aspect of this scenario is the inclusion of tight turns, such as those shown in Figure 4b. It can be seen that they could only be resolved when the Doppler measurements were included in the evaluation.

The second scenario we considered, took us further away from the base stations and into the bay near Herrsching on the eastern part of Lake Ammer. Figure 5 shows the measured range and Doppler values for this scenario. The scenario consisted of a route that started east of Schondorf and continued southwards and eastwards towards the bay. When entering the bay, the line-of-sight contact to Buch was lost. This can be seen in Figure 5a at about



(a) Tracked positon (b) Position detail

Figure 4.: The tracked position of the boat in the scenario with generally good line of sight towards the station and with favourable geometry. In (b), it can be seen that the circles in the boat's path could only be resolved when the Doppler measurements were utilized.



(a) Ranges (b) Radial velocities

Figure 5.: The range and radial velocity measurements for the scenario where the line of sight is blocked by land. The associated position estimation is shown in Figure 6.

7 minutes of elapsed time. In Figure 6, it can be seen that the R-Mode position estimate started to diverge from the true position when the line-of-sight was interrupted.

The third scenario included a passenger ship that is serving a scheduled service on Lake Ammer. The goal of the scenario was to determine whether the presence of the passenger ship within the line-of-sight path has a noticeable impact on the positioning performance. Figure 7 shows the passenger ship and the boat with our receiver next to each other. For this measurement scenario, we accompanied the passenger ship on its scheduled route between Herrsching and Stegen at the northern end of the lake. The ranges and relative velocities are shown in Figure 8. It can already be seen here that the measurements show several outliers.

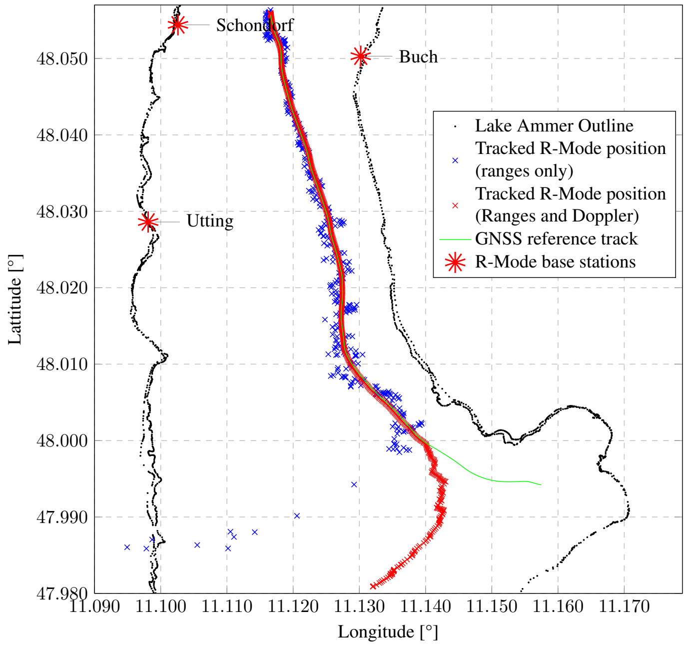


Figure 6.: The position estimate for the scenario with shadowing. The boat travels southwards. It can be seen that the position estimate becomes unreliable once the line of sight towards Buch is interrupted. Especially the estimates relying on the range only diverged to outside the scope of this figure. The associated range measurements can be seen in Figure 5.

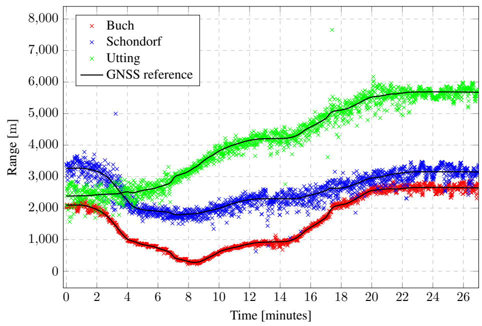
Figure 9 illustrates this even further. On several occasions, the estimated track of the boat significantly deviates from the reference track obtained from the GNSS receiver.

To compare the performances achieved in the different scenarios, with and without the Doppler measurements, Figure 10 shows a cumulative distribution function of the positioning error that was achieved during our trials. For the first scenario, the beginning of the data, where non line-of-sight conditions where observed, was disregarded for the calculation of the CDF, so that the first scenario represents line-of-sight conditions. The other two scenarios are shown in full, so that the effect of the non line-of-sight conditions are included. In the LOS scenario, a 95th percentile error of $22\,\mathrm{m}$ was achieved when the Doppler measurements were utilized. When only the range measurements were used, $144\,\mathrm{m}$ were achieved. In case of the scenario with the passenger ship, the error was below $84\,\mathrm{m}$ 95% of the time with the Doppler data, and below $443\,\mathrm{m}$ without the Doppler data.

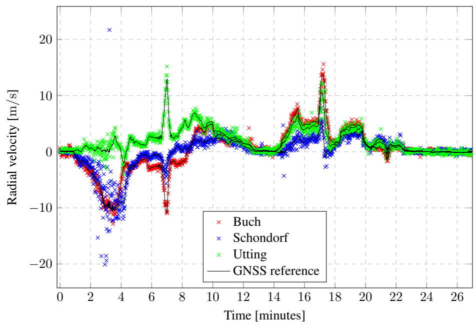
4. DISCUSSION. Our measurement results show that it is possible to achieve a good positioning accuracy using VDES R-Mode under line-of-sight conditions when utilizing the Doppler effect measurements. In our first measurement scenario, line-of-sight conditions were present most of the time. When only the line-of-sight part of the data was considered, a 95th percentile positioning error of $22\,\mathrm{m}$ was achieved.

The two scenarios with obstructions in the line-of-sight path showed that environmental factors such as other ships need to be considered when implementing an R-Mode system.

Figure 7.: The boat with our receiver, next to a larger passenger ship. The ship served as an obstacle in the line of sight path between the boat and the land stations.



(a) Ranges



(b) Radial velocities

Figure 8.: The range and radial velocity measurements for the scenario where the line of sight is blocked by another ship. The associated position estimation is shown in Figure 9.

This seems especially relevant in environments close to harbours, where an accurate position information is vital, and at the same time many environmental factors such as other ships are present. In case of a harbour located in a bay, receiving VDES stations located elsewhere can become challenging if buildings are located in between the transmitter and the receiver.

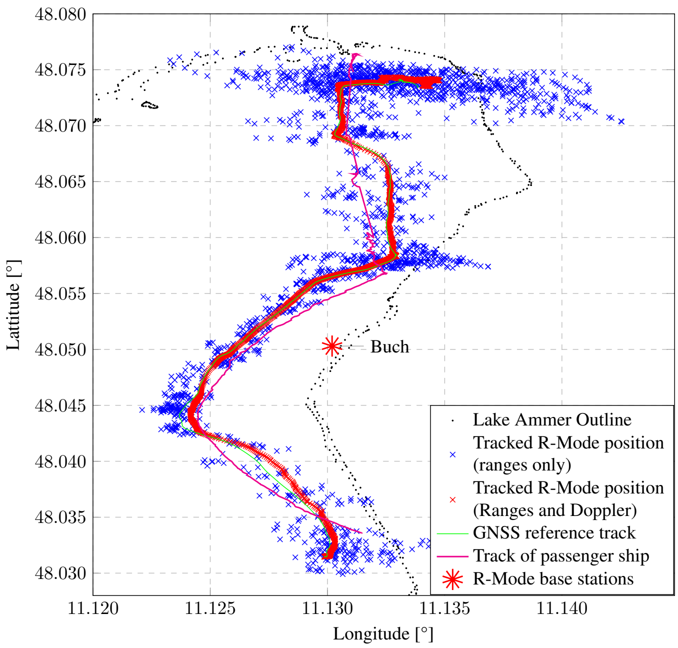


Figure 9.: The position estimate for the scenario with shadowing by a passenger ship and the track of the passenger ship. The boat travels northwards. The associated range measurements can be seen in Figure 8.

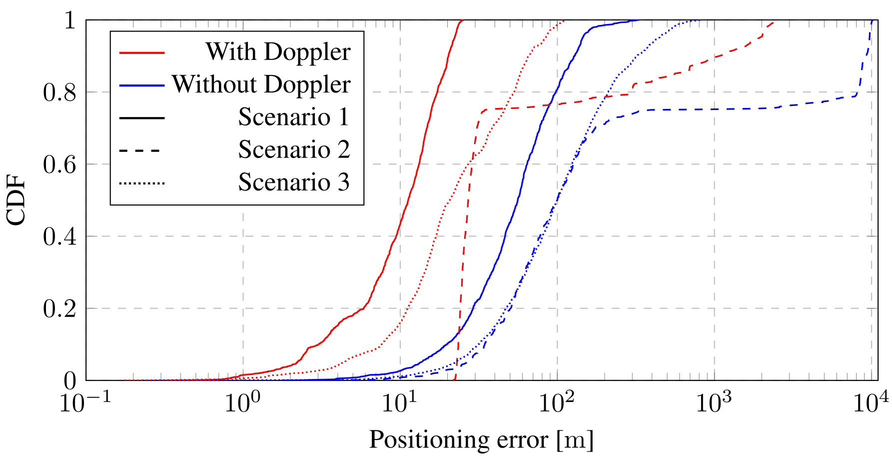


Figure 10.: Error CDF for the different scenarios

The influence of the Doppler measurements on the achievable accuracy was considerable in all of the considered measurement scenarios. The difference was especially high in the third considered scenario with a larger ship in the vicinity of the receiver.

Our measurements still differed from how a finished R-Mode system would be implemented. One important difference was that our receiver was time synchronized to the transmitter stations by means of GNSS. Due to the nature of a GNSS backup system, a production R-Mode receiver will not have that option. When the synchronization is not available, the time offset of the local clock will need to be estimated from the received signal. Another difference was that our transmit power was limited to $1\,\mathrm{W}$, while VDES can use $12\,\mathrm{W}$ according to the standard. This means that the performance could be improved by utilizing the full transmit power.

5. CONCLUSION. We performed experiments on Lake Ammer to practically evaluate the performance of VDES R-Mode, using range and Doppler measurement data, We found that utilizing the Doppler measurements can improve the performance by a factor of 5 to 6. In our experiments, we were able to achieve a 95th percentile accuracy of $22\,\mathrm{m}$ under line-of-sight conditions. In the more challenging scenario with the passenger ship close to the receiver, $84\,\mathrm{m}$ were achieved.

Acknowledgment We would like to thank the staff of the Wasserwacht Utting for their valuable support during the experiment at Lake Ammer.

REFERENCES

IALA (2017), 'IALA guideline g1117: VHF data exchange system (VDES) overview ed.2.0'.
URL: *https://www.iala-aism.org/product/vhd-data-exchange-system-vdes-overview-1117/*

IALA (2020), 'Iala guideline g1158: VDES R-Mode ed. 1'.
URL: *https://www.iala-aism.org/product/g1158-vdes-r-mode/*

IALA Guideline G1139: THE TECHNICAL SPECIFICATION OF VDES, ed. 3 (2019).
URL: *https://www.iala-aism.org/product/g1139-technical-specification-vdes/*

Johnson, G. and Swaszek, P. (2014), Feasibility study of R-Mode using MF DGPS transmissions, Technical report, Accseas Project.
URL: *https://www.iala-aism.org/content/uploads/2016/08/accseas_r_mode_feasibility_study_mf_dgps_transmissions.pdf*

Sadlier, G., Flytkjær, R., Sabri, F. and Herr, D. (2017), The economic impact on the UK of a disruption to GNSS, Technical report, Innovate UK.
URL: *https://www.gov.uk/government/publications/the-economic-impact-on-the-uk-of-a-disruption-to-gnss*

Safar, J., Grant, A., Williams, P. and Ward, N. (2020), 'Performance bounds for VDES r-mode', *Journal of Navigation* **73**(1), 92114.

Wirsing, M., Dammann, A. and Raulefs, R. (2019), Investigating R-Mode signals for the VDE system, *in* 'OCEANS 2019 MTS/IEEE SEATTLE', pp. 1–5.

Wirsing, M., Dammann, A. and Raulefs, R. (2020), Designing a ranging signal for use with VDE R-Mode, Proceedings IEEE/ION Position, Location and Navigation Symposium (PLANS), pp. 822–826.

Wirsing, M., Dammann, A. and Raulefs, R. (2021), VDES R-Mode Performance Analysis and Experimental Results.
URL: *https://doi.org/10.1002/sat.1424*