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Technical Domain / Task Number 2 …………………………………

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VDE-SAT Precision Time Service test results

# Summary

A **Space Norway** led consortium with **Kongsberg Discovery - Seatex**, has under an **ESA contract** developed and tested a LEO PNT concept using existing VDE-SAT space and ground infrastructures. A standard 150 kHz waveform (Link ID 29) with a duration of 2.4 s was broadcasted every 10 s at 162 MHz to a static VDES-300 transceiver hosted in Kongsberg facilities in Trondheim. The signal contained high precision satellite position, UTC timestamp and static data optimised for good correlation properties.

Typically, 40 pseudoranges and navdata data packets were processed off-line to determine location and time through a satellite pass. The analysis of 50 NorSat-TD passes showed a UTC timing error of 1 μS RMSE and a 2D position error of 1 km. The measurements showed minor improvements using more than 20 pseudoranges. This corresponds to a 2.4 s transmission every 30s.

This type of VDE-SAT Precision Time Service may have many uses:

* Alternative PNT when GNSS is not available.
* GNSS integrity monitoring.
* GNSS spoofing detection.
* Complement to VDE-TER R-mode.
* A vessel position polling/reporting service more difficult to spoof than AIS.

We invite IALA to develop this further into the guidelines for VDES R-mode.

# introduction

The ESA project ICING (Independent Critical Navigation) has investigated the novel concept of utilizing VDE-SAT to offer a purpose-designed ranging signal. The project is conducted by a consortium consisting of Space Norway as prime contractor, and Kongsberg Discovery – Seatex as subcontractor, under the NAVISP Element 3 program.

The increasing reliance on Position, Navigation, and Timing (PNT) information, primarily sourced from Global Navigation Satellite System (GNSS) satellites, highlights a significant vulnerability due to the susceptibility of these weak signals to disturbances, including intentional jamming. This vulnerability is particularly acute in the maritime industry and defence, where loss of GNSS signals can severely impact navigation and safety systems. The UK government estimates that a five-day loss of GNSS signals could cost the maritime economy over a billion pounds [1]. Despite the existence of some alternatives like eLoran, major European countries have decommissioned these systems, further increasing reliance on GNSS.

In this context, the ICING project funded under the Navigation Innovation and Support Program (NAVISP) of the European Space Agency is seeking to address these vulnerabilities by developing new technologies for independent PNT sourcing. Recognizing the limitations and risks associated with current GNSS-dependent systems, this program aims to enhance the robustness and resilience of PNT solutions, especially in the maritime sector that is heavily reliant on precise navigation and timing information.

The importance of this project is underscored by Norway's maritime dependence on PNT information for various operations, including maritime navigation, search and rescue and air traffic control. Disruptions to GNSS signals, as evidenced by multiple incidents in recent years, pose a threat to national security and operational efficiency. This threat can be mitigated by a comprehensive space policy and PNT strategy.

The intention of project ICING was to demonstrate the use and functionality of VDE-SAT ranging signals acting as a precision time service for use in navigation, illustrated in Figure 1. This was done by defining a precision time message, transmitted from the NorSat-TD satellite VDES payload, and received at a capable R-mode receiver on the ground.

A diagram of a satellite dish

Description automatically generatedThe proposed use of VDE-SAT as a precision time service requires consideration of the timing, waveform data, and software processing. The waveform data, containing the navigation data message, is optimized for autocorrelation properties. The result is a prototype precision time service which demonstrates the use of VDE-SAT ranging as an alternative source of PNT, using only about 10% of the VDES capacity of the satellite.

1. VDE-SAT precision time broadcast service concept.

In summary, the ICING project represents a critical step towards enhancing the resilience of maritime and broader national infrastructure against GNSS signal disturbances. Through this initiative, Norway aims to reduce its vulnerability and ensure the continuous availability of reliable PNT information for various essential services and operations. The demonstrated functionality further has wide applicability for many different services, all over the world.

# System specification and ranging signals

This section will summarise the implemented system and details of the transmitted ranging signals. All infrastructure is developed by Kongsberg Discovery, Seatex. The ground station comprises of a modified Kongsberg VDES 300 ship-terminal, connected to a standard maritime VHF antenna. This station received the ICING messages on the ground and further the data was processed on a computer. The antenna's location is in Trondheim, Norway, at the Kongsberg Discovery, Seatex offices, where the antenna was strategically positioned to optimize sky view on the roof.

The test setup in space involved the Kongsberg VDES satellite transceiver VST x50 on NorSat-TD, transmitting range and position over VHF frequencies. The satellite also housed a GNSS receiver for position, velocity, and time data. The satellite test campaign for NorSat-TD's VDES payload was a comprehensive process, ensuring the effectiveness of its ICING functionality. In this work, end-to-end communications tests and satellite commissioning were most critical. All tests were successfully passed, and the system verified ready for testing.

Ranging measurements were collected over the four months of July, August, September and October, for all satellite passes on certain measurement days. VDES ranging sequences were transmitted every 10 seconds during satellite passes. Each measurement, derived from the time offset between transmission and reception, generated a pseudorange. The analysis involved 50 passes, yielding 1121 reliable pseudorange observations, as the basis of a comprehensive analysis of the performance of VDE-SAT ranging signals.

# performance analysis

The analysis of collected data focuses on assessing the system's performance as an independent source of PNT in two main parts. First, the measured pseudoranges are compared to the true geometric range between the NorSat-TD satellite and the static receiver, forming the elementary residual measurements. This aspect is explored in the signal performance analysis. Secondly, the system's positioning performance is assessed in the context of contemporary IALA requirements for a GNSS backup system.

## Signal performance

The further study was concerned with the statistical properties of the pseudorange measurements gathered during the test campaign. The pseudorange measurements are susceptible to influences from the environment and equipment, and it was of particular interest to evaluate the current performance level, as well as identifying any critical error sources. Pseudorange residuals, representing the difference between measured and true distance between the satellite and ground station, were analysed through a parametric analysis, revealing the correlation between the residuals and parameters associated with different error sources.

The distribution of pseudorange residuals, shown in Figure 2, and parametric correlations indicate the current 1-σ accuracy of the VDE-SAT range measurements are 335.2 m, and that the performance is susceptible to fixed biases. First, a large and constant bias is visible in the residuals, associated with a systematic and correctable transmit bias. Pseudorange residuals also varied similarly through a satellite pass. Notably, the consistent bias and a U-shaped trend linked to satellite elevation was quickly identified. The variation with elevation angle was hypothesized to come from time-delay due to the ionosphere.

A diagram of a normal distribution

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1. Histogram representations with overlaying normal distribution of the residual measurements, before and after correcting for ionospheric time-delay.

The findings of the analysis support the hypothesis that the errors follow from time-delay due to the ionosphere. The results of the parametric analysis are visualized in Figure 3. Simple linear regression indicates a confident increase in residuals with higher pseudorange and a confident decrease with higher elevation angle, aligning with the hypothesis of larger errors with longer propagation paths. The elevation angle shows a stronger correlation, evident in a steeper trend and results from multiple linear regression, where the pseudorange trend is opposite and less confidently modelled. Limited observations at all hours impact the analysis of time-of-day variation, but a trend emerges around mid-day, correlating with higher residuals, supporting the ionospheric time-delay hypothesis. The weak trend in increasing SNR, as seen in both simple and multiple linear regression, suggests that multipath error is unlikely as a source of systemic error. However, the variation in the residuals appears to decrease with higher SNR, as expected.

A group of graphs with blue and red lines

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1. The residual measurements plotted as a function of the parameters SNR, pseudorange, elevation angle and time-of-day. Trend lines are shown for the parameters included in the regression analysis.

To further investigate the influence of the ionosphere, an ionospheric correction technique is applied to the observations. The applied model is the NeQuick-G ionospheric correction technique used in the European Galileo navigation system [2]. The corrected range measurements were obtained by adding the NeQuick-G-equated time-delay to pseudorange measurements. The result is a reduced 1-σ variation to 262.9 m standard deviation in the residual distribution.

The trends linked to ionospheric time-delay were notably reduced after applying the correction model. Figure 2 shows the shifted distribution with the reduced variance of 262.9 m standard deviation. The time-of-day variation in residuals is affected, with no significant difference around mid-day. Overall, the analysis indicates significantly less variation in the chosen parameters, suggesting the successful removal of ionospheric time-delay when using a correction technique.

## Positioning performance

A positioning tool has been developed for the evaluating of the positioning performance of VDE-SAT ranging acting in a variety of systems. The evaluation of VDE-SAT's autonomous positioning performance focuses on assessments using only NorSat-TD VDE-SAT range observations in a single-satellite system. The result is a decreasing surface position error with an increasing number of consecutive observations, both with and without a ground constraint, as visible in Figure 4. The errors with a ground constraint consistently prove to be 10-100 times smaller than those without. The lowest surface position error achieved with a ground constraint falls below 100 m using 35 observations. However, in general, little improvement is observed beyond N > 20, both with and without a ground constraint. The single satellite system's performance falls just short of consistent navigation backup system requirements of 1000 m for navigation at ocean [3]. Occasional positioning within the required ocean navigation range is achieved with a ground constraint. However, the majority of considered satellite passes meet the 1000 m requirement, indicating a potential benchmark for future navigation systems with advancements in VDE-SAT ranging.

A graph showing different colored lines

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1. All passes equated with a mean rolling performance metric, for a varying number of observations N.

The study also explored the contemporary application of VDE-SAT in combination with partial GNSS coverage. Results reveal that while all passes exhibit a mean error near or below the standard deviation of a single range measurement, the mean surface position error is 229.0 m with a standard deviation of 338.4 m. The findings emphasize the dominance of VDES range error over GPS range errors in surface position error.

# achievements and lessons learned

This work has been an important first step in the development of an alternative navigation system, independent of GNSS. It has characterized the performance of VDE-SAT ranging signals that are physical-layer compatible with the VDES standard and determined the critical influence of ionospheric time-delay on measured pseudoranges. It has been shown that VDE-SAT acting as a PNT-source can serve as a contemporary navigational backup system that, under the right conditions, meet the minimum requirements for navigation at ocean. Further, we have highlighted key next steps in the development of an autonomous and alternative navigation system, and as part of the project, developed, verified, and validated the prototype software for such as system.

# Related developments and future work

The consortium has also detailed the next steps for the evolution of project ICING. The measurements were static on a rooftop in Trondheim harbour, we propose to extend this using the Kongsberg Discovery, Seatex Ocean Space lab vessel, Norwegian Coastal Administration test site and then to at least one vessel in the Artic for an extended period of one year. It would be highly desirable to also include two terrestrial VDES R-mode base stations. The further goal is to improve the precision of the pseudorange measurements for an improved functionality. Additional topics include improvements to ground hardware and software, and to operationalize the service at the user. We also want to synchronize local UTC time and measure drift vs time, as well as analyse further what parameters can be used to filter out bad data at the receiver.

Space Norway, Kongsberg Discovery – Seatex, and Comrod are also carrying out a project with the goal of developing a new VHF antenna, supressing specular reflections, and specifically built for Arctic environments. The design is expected to improve the link by 5 dB, allowing a lower timing error, lower packet loss, or alternatively a higher throughput.

# Proposed action

The consortium asks IALA to take the presented work into consideration for future developments. In particular, the presented work should be considered in the development of guidelines for VDES R-mode.

# Acknowledgements

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# References

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