ENHANCING MARITIME NAVIGATION: A NOVEL APPROACH TO VALIDATE GNSS SOLUTIONS WITH A SINGLE R-MODE STATION

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DLR

The TT-Line *Marco Polo* incident – A wake-up call in the Baltic Sea

- In October 2023, the TT-Line ferry Marco Polo **ran aground** off the coast of Sweden in the Baltic Sea
- No major injuries, but vessel and **environmental damage** occurred
- Investigation pointed to **navigation system errors**, likely due to faulty GPS

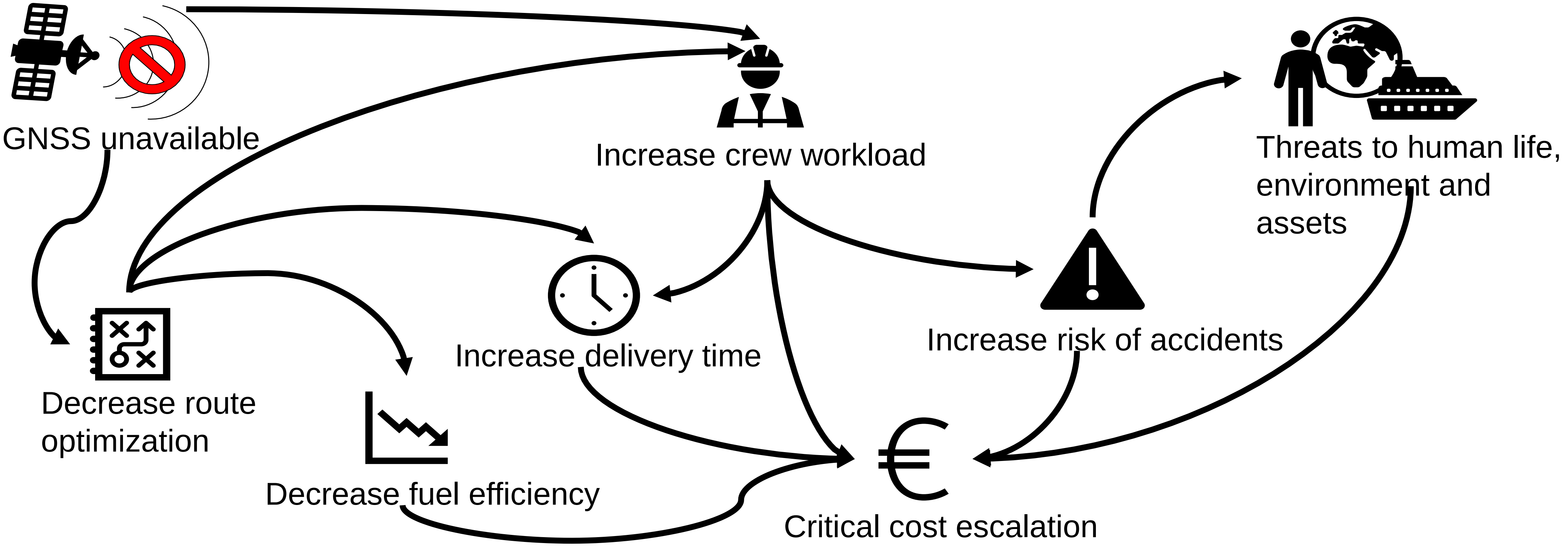
The grounded ferry Marco Polo and the tug Max are seen outside Horvik, southern Sweden, on 26 October. Photograph: Johan Nilsson/AP

The 75 people onboard, both passengers and crew, were evacuated. The ferry, operated by TT-Line of Germany, took on water but was not at risk of sinking.

The groundings released a slick of fuel that reached the shores near Solvesborg, 110km (68 miles) north-east of Malmö, Sweden's third-largest city. Swedish media carried photos of birds partly covered in oil.

Swedish prosecutors handed down fines to the captain and an officer who was in charge at the time of the grounding, saying they acted recklessly by relying on a faulty GPS.

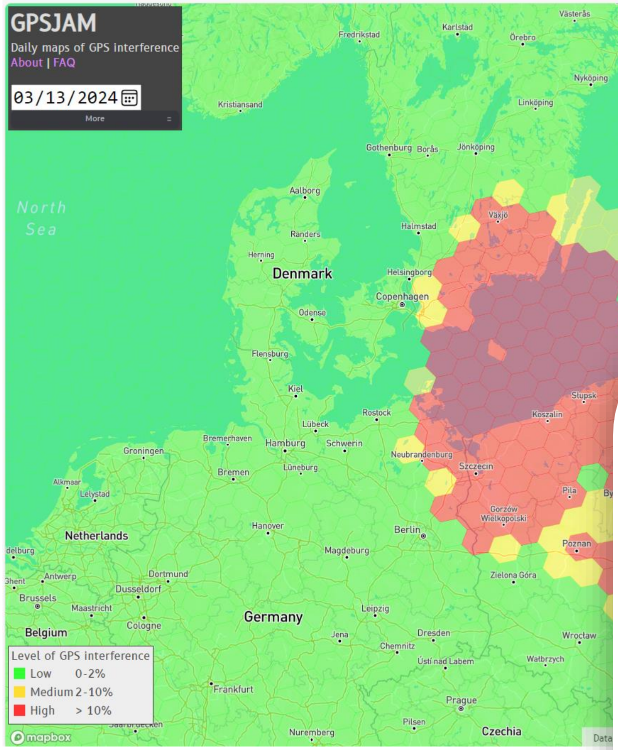
The Impact of GNSS outages on vessel operations



GNSS outages can result in significant financial losses for vessel operators, while also disrupting the entire maritime value chain and posing serious risks to the environment

Rising threats – Jamming & spoofing in the Baltic Sea

- Current Trends:
  - Global increase of threats to GNSS due to geo-political instabilities
  - Significant increase in GNSS jamming and spoofing activity in the Baltic Sea since 2022
- Facts:
  - Finland reported over 7,300 interference incidents in 2023 alone
  - Pilots, commercial vessels, and airlines are continuously reporting GNSS outages and incorrect positions



Source: gpsjam.org

- A urgent need for **redundant and alternative navigation** systems
- A strong demand to strengthen **cyber resilience** of Position Navigation and Timing (PNT) infrastructure

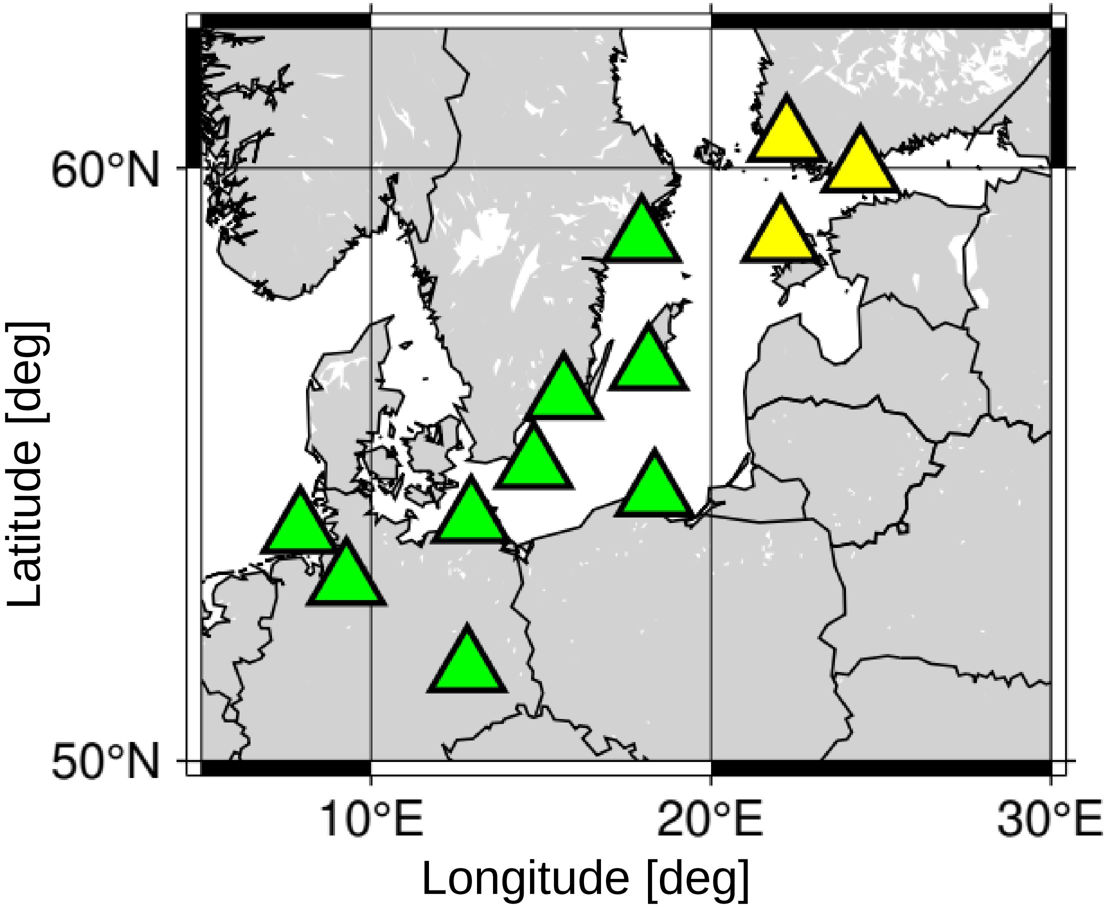
R-Mode at a glance

Based on two subsystems

MF DGNSS IALA Beacons
- FDMA @ 285.5-325 kHz
- Ground-wave propagation
- Coverage ~300 km

This talk

VHF Data Exchange System (VDES)
- Evolution of AIS
- TDMA @ 160 MHz
- LOS propagation

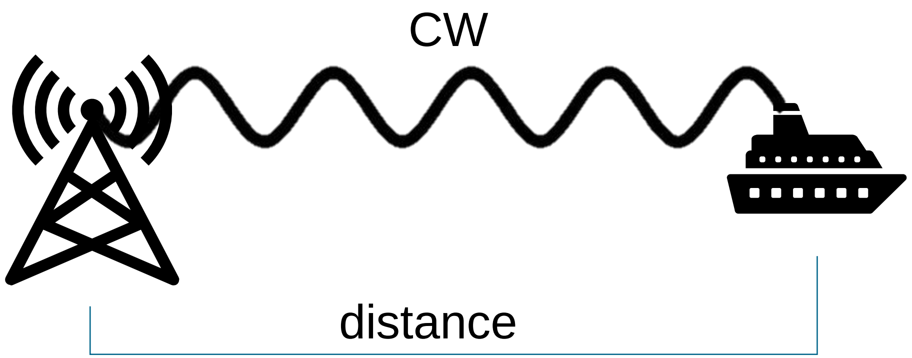


Medium Frequency (MF) R-Mode testbed in the Baltic Sea. The green transmitters are already enables while the yellow will be enabled within ORMOBASS project.

MF R-Mode positioning principles

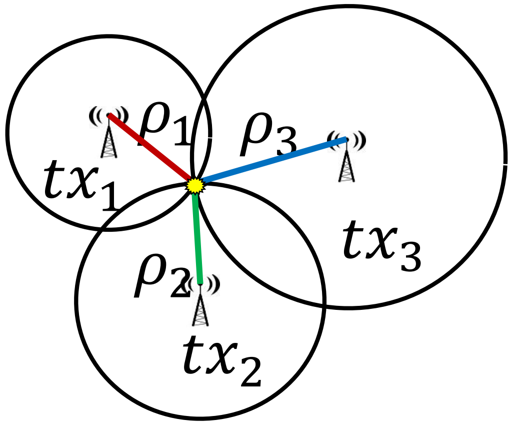
Transmitter

- Transmission of legacy DGNSS message with minimum shift keying (MSK)
- Synchronized transmission of 2 continuous wave (CW) signals



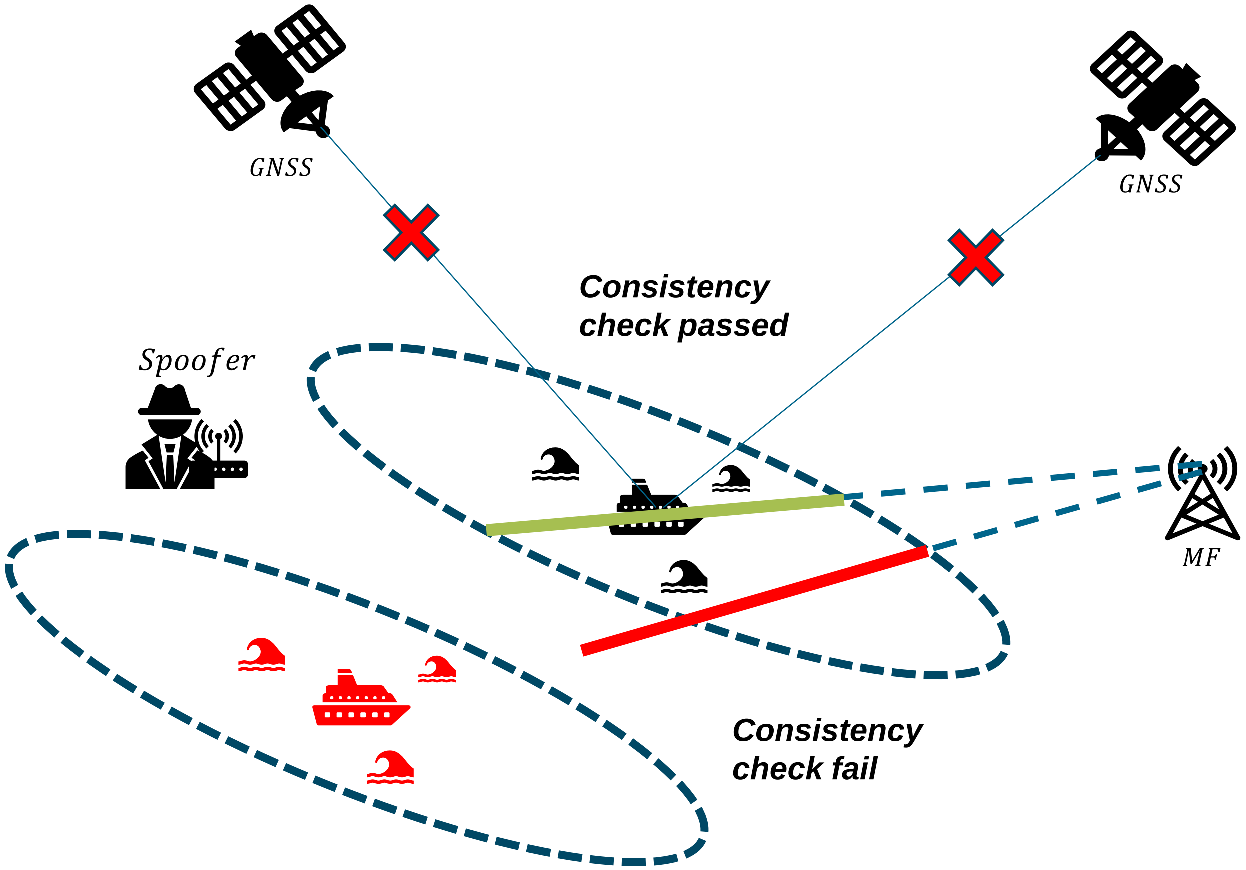
Receiver

- Phase observation $(\phi_{CW_1}, \phi_{CW_2})$
- Positioning with 3 stations in view
- **Positioning accuracies ~10-60 m (95%)**



GNSS consistency validation using R-Mode

- Ranging information from a **single R-Mode station** can be used to perform a **consistency check** of a GNSS-derived position
- To carry out this check, the following inputs are required
  - **Quality metrics** of both GNSS and R-Mode measurements
  - The **GNSS position solution** to be validated
  - A **user-defined confidence** level for the statistical test



This approach enables detection of inconsistent GNSS solutions, such as those induced by **outages** or **spoofing**, especially in environments with **limited R-Mode coverage**

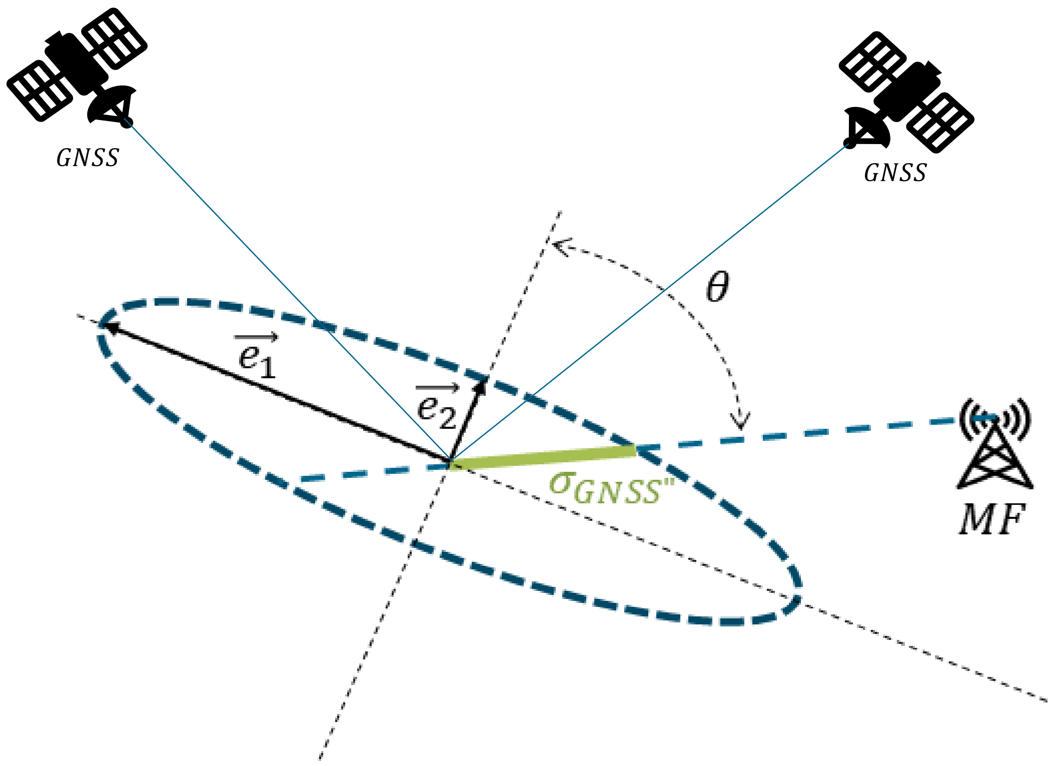
The approach in details

- Let e_1, e_2 be the eigenvectors of the GNSS **variance-covariance matrix**, representing the principal axes of positional uncertainty
- To evaluate consistency between GNSS and R-Mode measurements, we define the **dispersion of the GNSS solution** in the direction of the R-Mode station ($\sigma_{GNSS''}$)
- The GNSS to R-Mode one dimensional error ε is computed
- Under nominal conditions, this error follows as a **zero-mean Gaussian distribution**
- We define a **confidence** level β, and compute the threshold σ_β such that

$$P(-\sigma_\beta < \varepsilon < \sigma_\beta) = \beta$$

- The **consistency decision rule** is then

$$T = \frac{|\varepsilon|}{\sigma_\beta} = \begin{cases} \text{Consistent} & if \;\; T \leq 1 \\ \text{Non consistent} & if \;\; T > 1 \end{cases}$$



The Digital Spree-Oder Waterway

DigitalSOW

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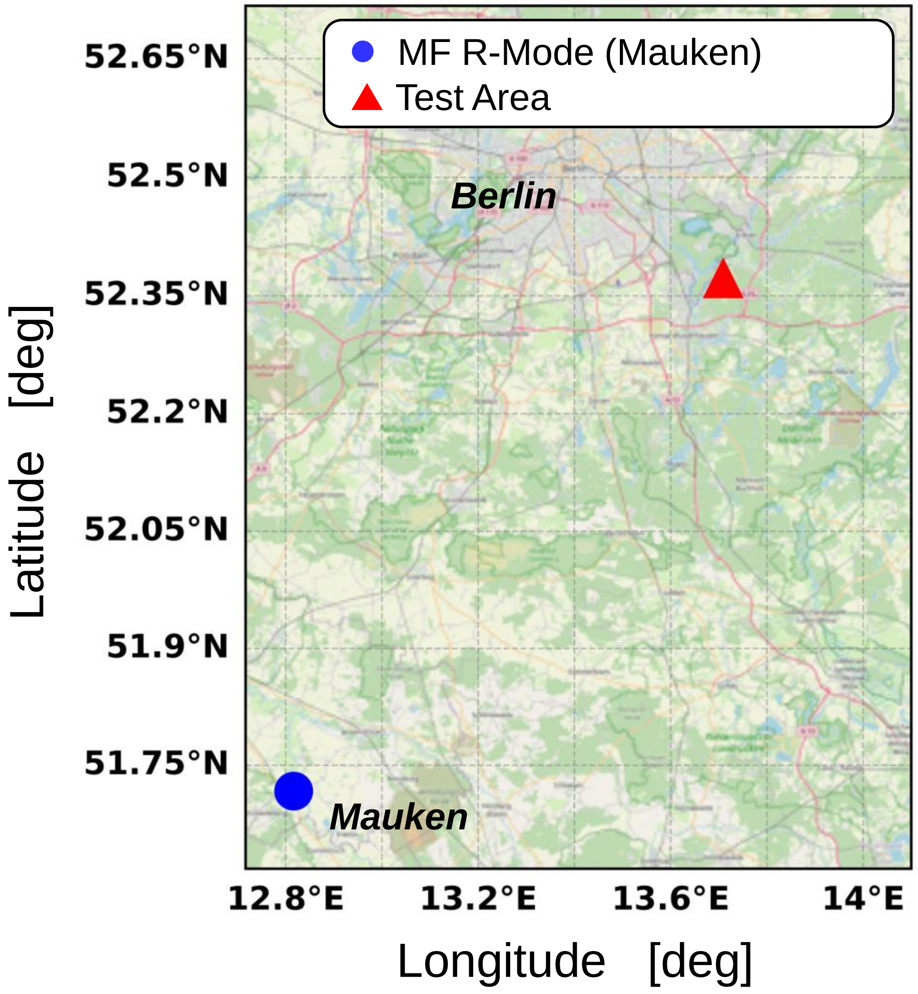
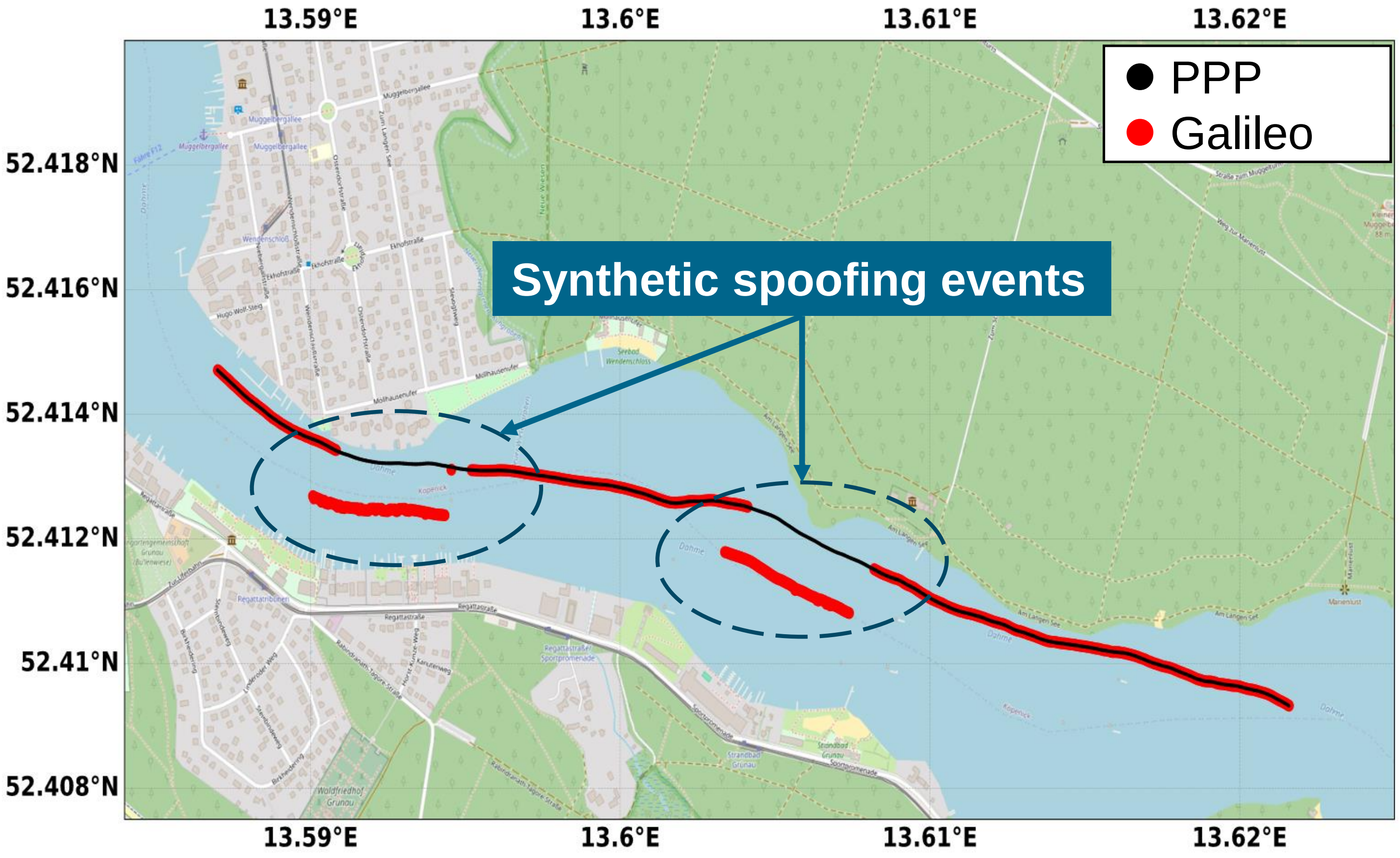


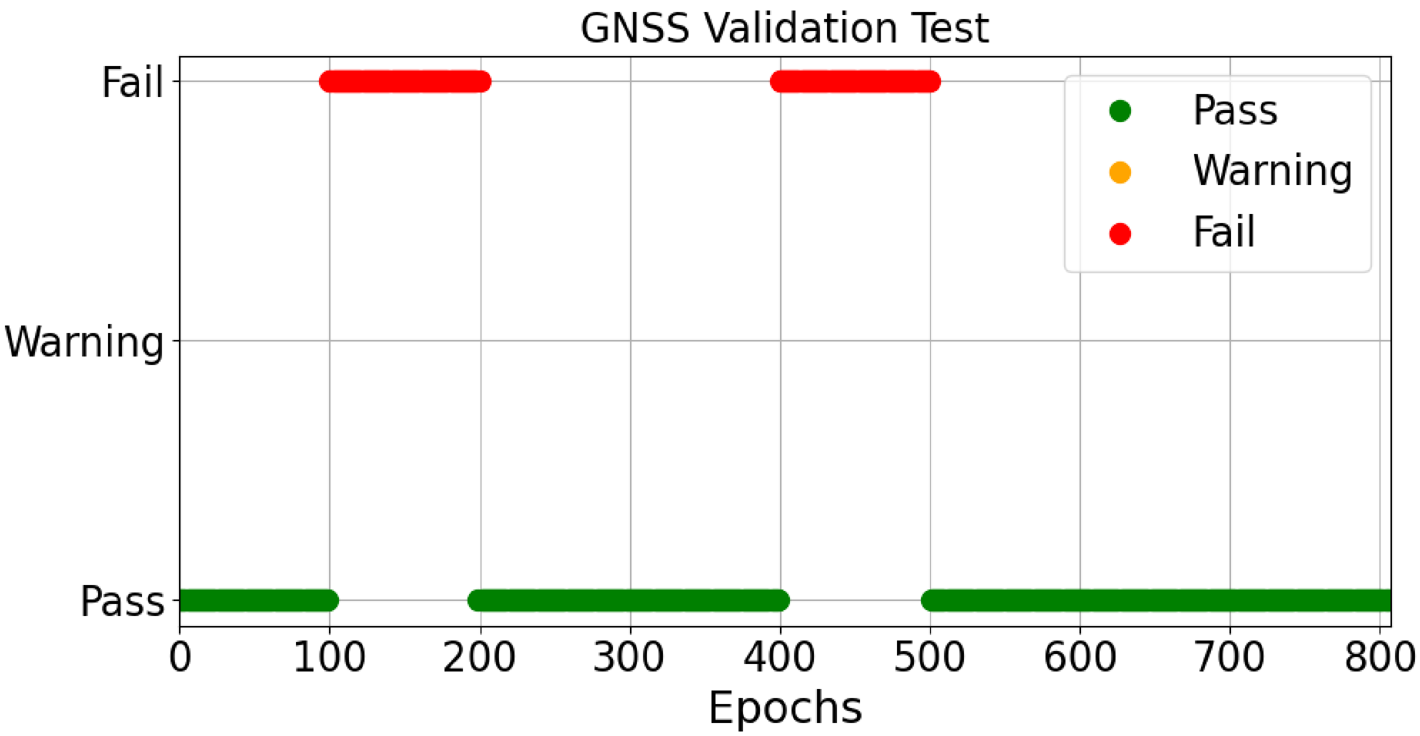
Data gathering and operational scenario

- Real measurement on the Dahme river
- Reference track obtained with PPP (black line)
- Positioning solution based on Galileo E1 SPP (red line)
- Spoofing included in post-processing in two events of 100 s each



GNSS validation test outcome

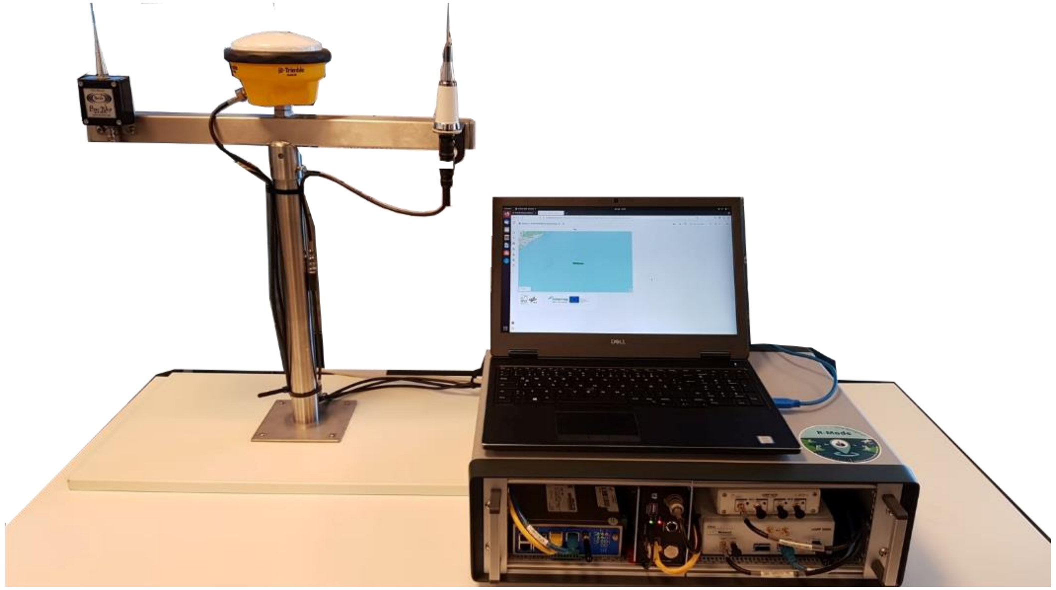
- Algorithm settings:
  - Galileo measurement quality is modeled as a function of satellite elevation
  - MF R-Mode ranging accuracy is derived from previous empirical measurements
  - Confidence parameter $\beta = 4\sigma_\beta$



A single R-Mode station provides an independent reference for identifying **GNSS outages or spoofing events**

Summary & conclusion

- **GNSS alone poses a single point of failure**, especially due to the increasing risk of jamming and spoofing
- R-Mode offers a **promising alternative positioning** source in the Baltic Sea
- **R-Mode enhances safety** both at sea and on inland waterways
- Our proposed approach enables users to **validate GNSS positioning** using just a single R-Mode station, making it particularly relevant in areas with limited R-Mode coverage
- Future work:
  - Conduct **detailed simulations** to further characterize the proposed approach
  - Increase dataset volume
  - **Extend the method** to support **multiple R-Mode stations** and **additional sensors** for increased robustness and accuracy



R-Mode-enabled resilient maritime receiver setup.

Reliable Positioning, Navigation, and Timing (PNT) data will increasingly be provided by integrated multisensor systems incorporating GNSS, R-Mode, IMU, LiDAR, and cameras

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Interreg Baltic Sea Region
Co-funded by the European Union
BLUE ECONOMY ORMOBASS

ORMOBASS - Interreg Baltic Sea Region (interreg-baltic.eu)

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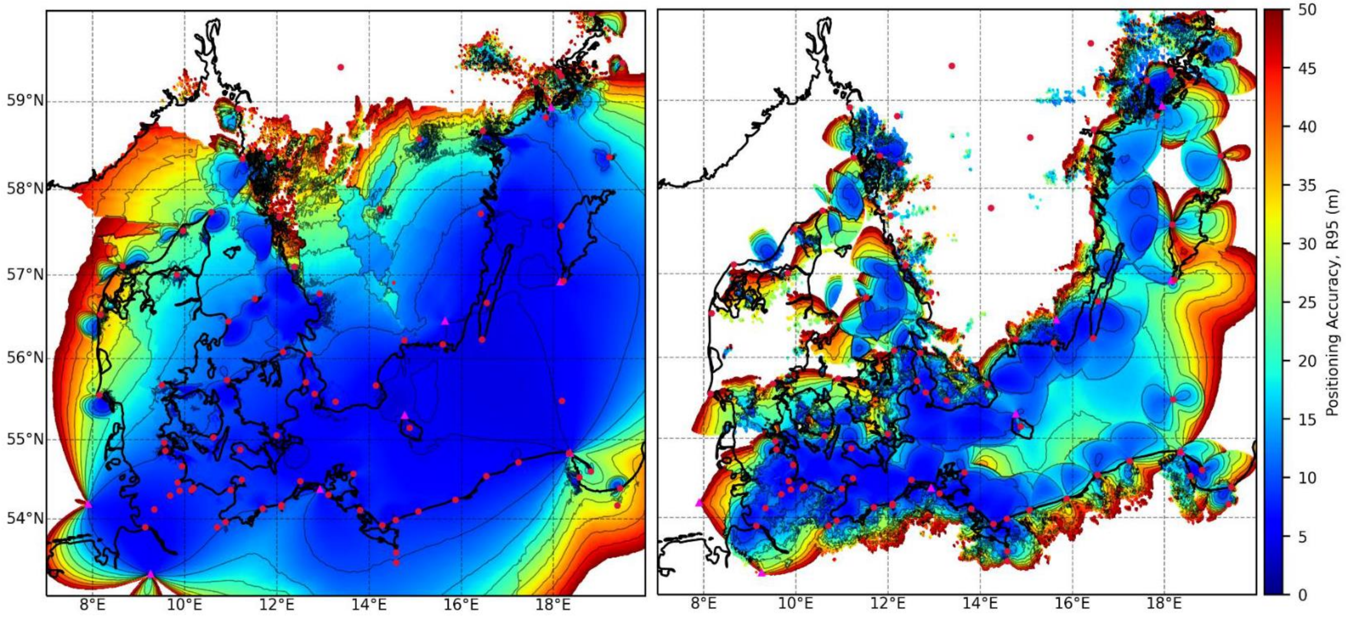
Theoretical accuracy prediction

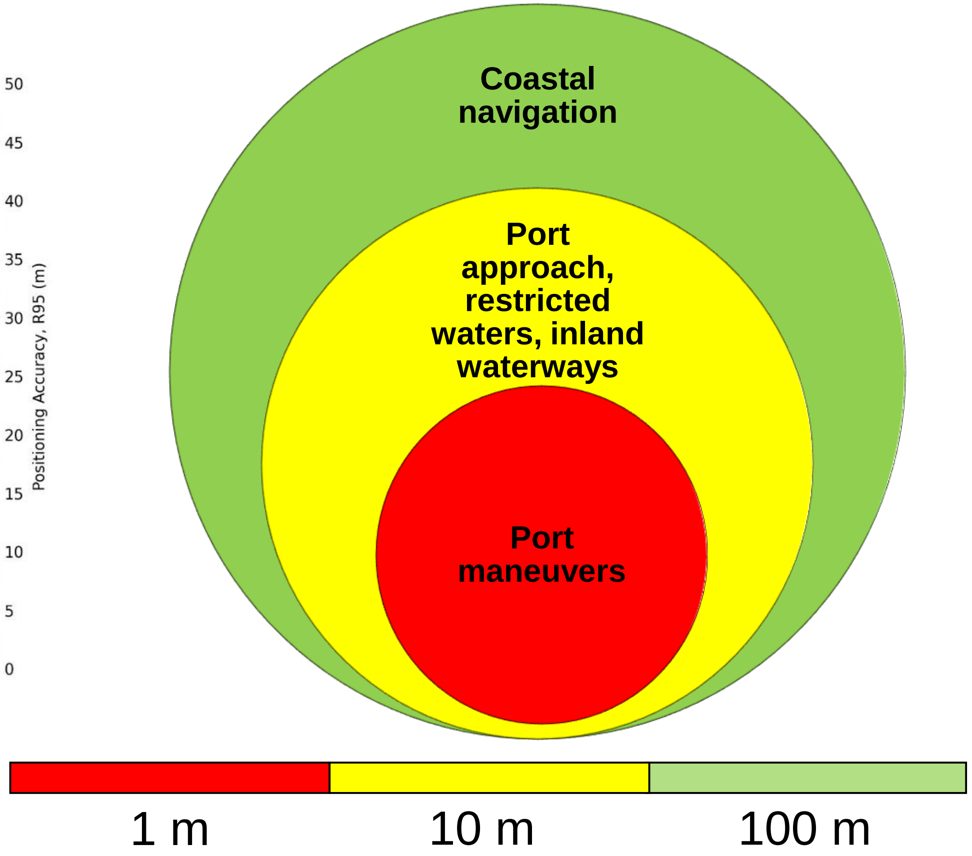
Horizontal accuracy prediction

Day-time   Night-time



Horizontal accuracy prediction (95%) based on available MF and AIS transmitters in the Baltic Sea region.

Horizontal accuracy requirements (95%) for backup-systems [IALA R-129]

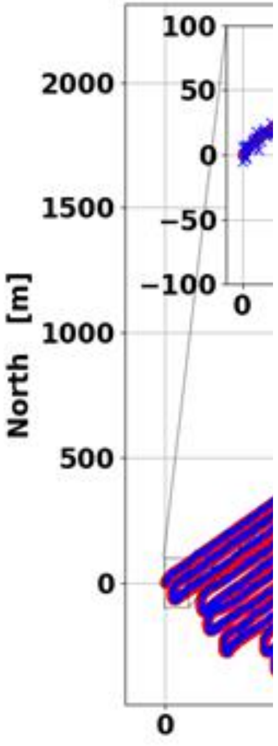


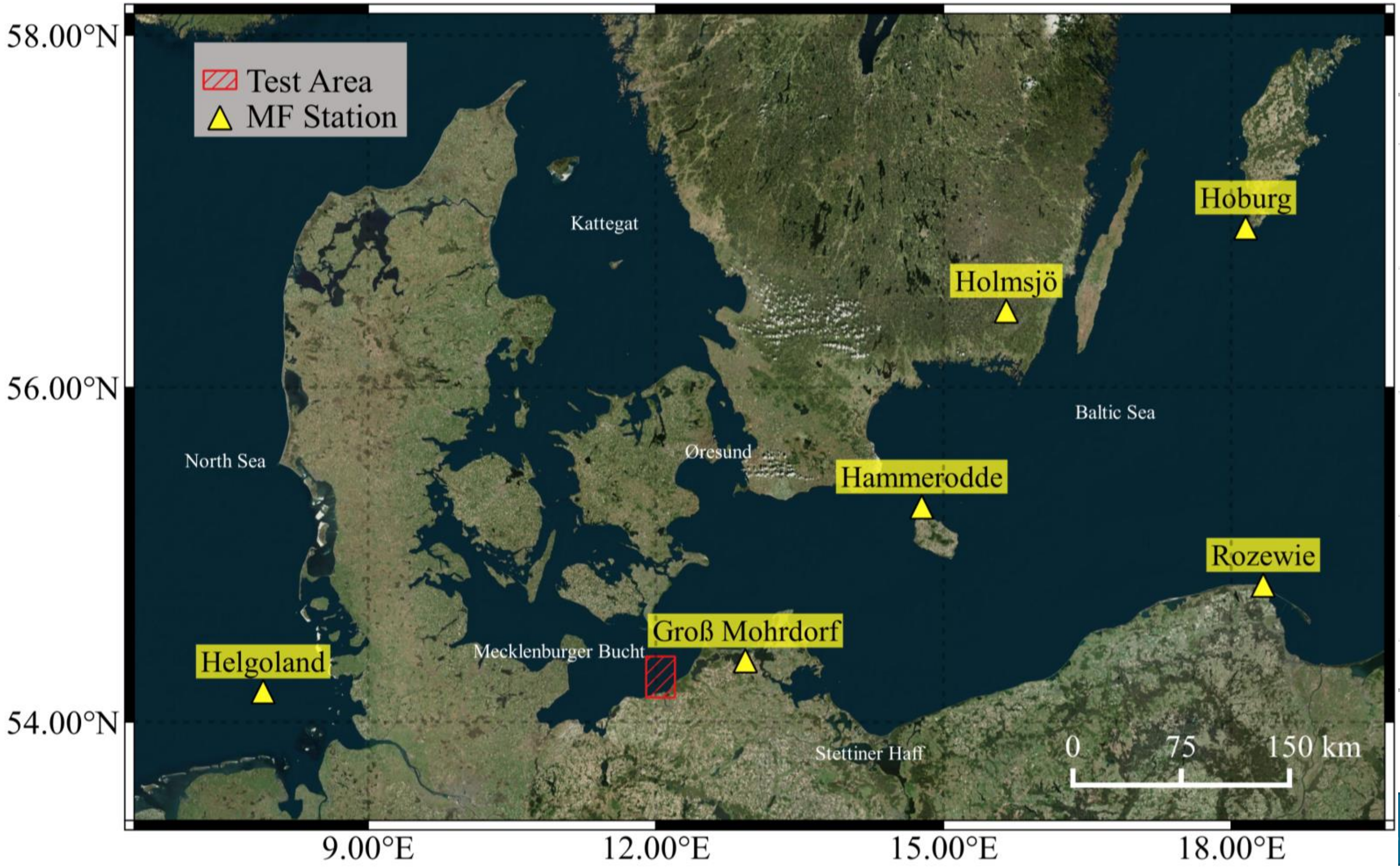
Real-testbed performance

[Applied Sciences | Free Full-Text | Performance Assessment of the Medium Frequency R-Mode Baltic Testbed at Sea near Rostock (mdpi.com)](mdpi.com)

Hoburg	Rozewie	Holmsjö	Helgoland	Hammerodde	Groß Mohrdorf
486 km	414 km	334 km	267 km	211 km	67 km

Day-… UTC)





Hori… $): 55.3\ m$

MF R-Mode Positioning Principles

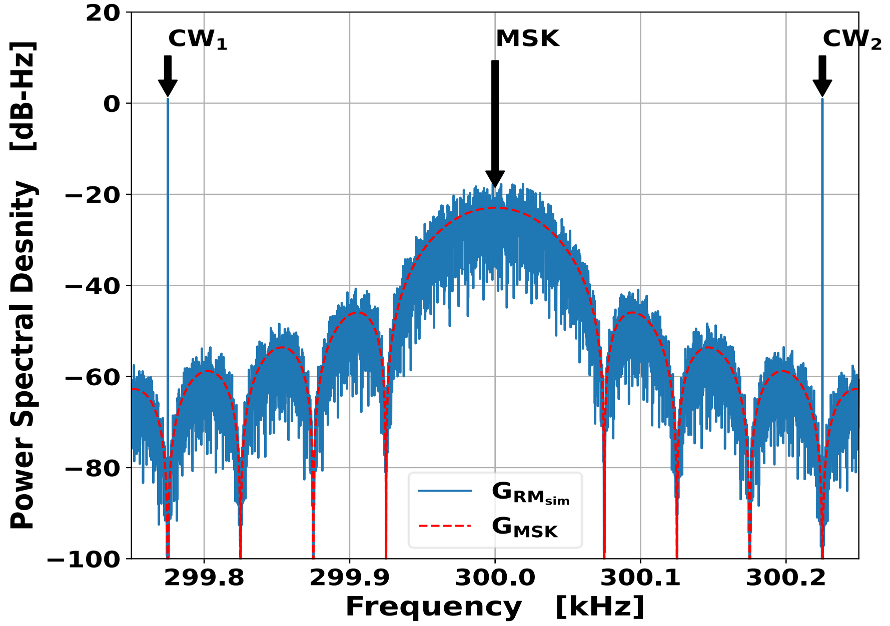
Transmitter

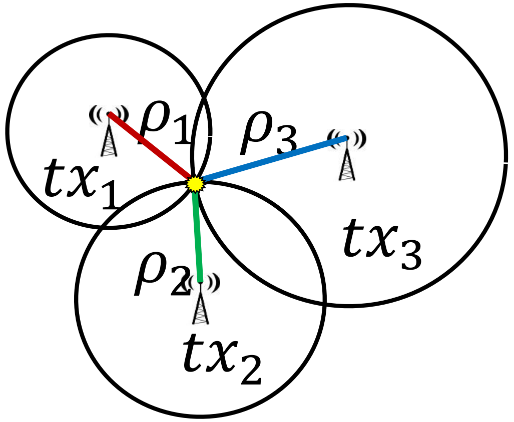
- Transmission of legacy DGNSS information with minimum shift keying (MSK)
- Synchronized transmission of continuous wave (CW) signals

Receiver

- Phase observation $\left(\phi_{CW_1}, \phi_{CW_2}\right)$
- Phase estimated through Fast Fourier Transform (FFT)
- Ambiguity resolved by using beat signal phase or initial calibration (with a known location)
- Pseudorange are generated by tracking the phase

Position and time estimation with weighted least squares or Kalman filter





Impressum

Thema: Enhancing maritime navigation: a novel approach to validate GNSS solutions with a single R-Mode station.

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