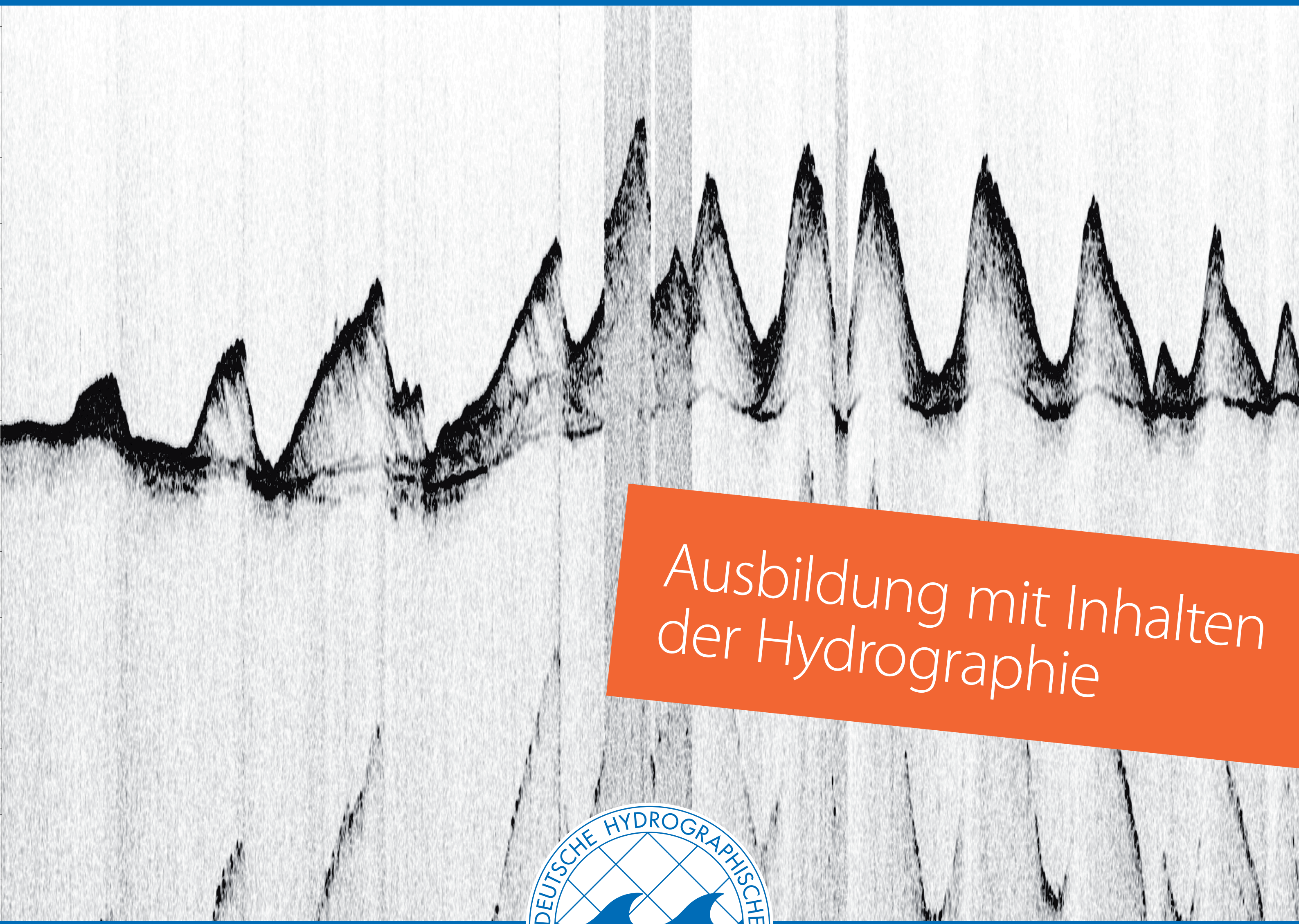
Journal of Applied Hydrography

HYDROGRAPHISCHE NACHRICHTEN 06/2025 HN 131



DEUTSCHE HYDROGRAPHISCHE GESELLSCHAFT e.V.
DHyG

DOI: 10.23784/HN131-12

Assessment of the efficacy of GNSS-interferometric reflectometry in determining water levels

An article by PAVLOS PETROGKONAS

Accurate and continuous water level monitoring is fundamental in hydrography. While conventional methods such as tide gauges, satellite altimetry and airborne LiDAR remain valuable, they are often constrained by spatial coverage, temporal resolution and operational cost. This study investigates the potential of GNSS-interferometric reflectometry (GNSS-IR) as a complementary method for water level determination in urban, tidally influenced environments. GNSS-IR observations were carried out during multiple sessions in spring 2024 in Hamburg's HafenCity, using a geodetic GNSS antenna to capture reflected signals from the water surface. The collected data were processed with the open-source software gnssrefl to derive water level estimates. These were subsequently validated against measurements from two nearby tide gauges and interpolated tide levels at the receiver site. Statistical analysis showed strong agreement between datasets, with a correlation coefficient exceeding 0.99 and a root mean square error (RMSE) of 14.9 cm. Despite signal interference from urban infrastructure and vessel traffic, GNSS-IR demonstrated robust performance, confirming its applicability as a cost-effective solution for enhancing hydrographic monitoring in complex coastal environments.

GNSS-IS | water level | gnssrefl software | tide gauge | remote sensing | HafenCity
GNSS-IS | Wasserstand | Software gnssrefl | Gezeitenpegel | Fernerkundung | HafenCity

Eine genaue und kontinuierliche Überwachung des Wasserstands ist für die Hydrographie von grundlegender Bedeutung. Herkömmliche Methoden wie Gezeitenpegel, Satellitenaltimetrie und luftgestütztes LiDAR sind zwar nach wie vor wertvoll, doch sind sie häufig durch die räumliche Abdeckung, die zeitliche Auflösung und die Betriebskosten eingeschränkt. Diese Studie untersucht das Potenzial der GNSS-interferometrischen Reflektometrie (GNSS-IR) als ergänzende Methode zur Bestimmung des Wasserstands in städtischen, gezeitenbeeinflussten Gebieten. GNSS-IR-Beobachtungen wurden im Frühjahr 2024 in der Hamburger HafenCity durchgeführt, wobei eine geodätische GNSS-Antenne installiert wurde, um von der Wasseroberfläche reflektierte Signale zu erfassen. Die gesammelten Daten wurden mit der Open-Source-Software gnssrefl verarbeitet, um Wasserstandsschätzungen abzuleiten. Diese wurden anschließend mit Messungen von zwei nahe gelegenen Gezeitenpegeln und interpolierten Wasserständen am Empfängerstandort abgeglichen. Die statistische Analyse ergab eine hohe Übereinstimmung zwischen den Datensätzen, mit einem Korrelationskoeffizienten von über 0,99 und einem mittleren quadratischen Fehler (RMSE) von 14,9 cm. Trotz der Signalstörungen durch die städtische Infrastruktur und den Schiffsverkehr zeigte GNSS-IR eine robuste Leistung und bestätigte seine Anwendbarkeit als kosteneffiziente Lösung zur Verbesserung der hydrographischen Überwachung in komplexen Küstengebieten.

Author
Pavlos Petrogkonas studied Hydrography at HafenCity University Hamburg. He is currently assigned to the Hellenic Navy Hydrographic Service.

pa.petrogkonas@hotmail.com

Motivation

The precise and continuous determination of water levels is a critical requirement in vulnerable urban coastal areas such as Hamburg's HafenCity. Situated along the Lower Elbe River, the district is directly influenced by tidal dynamics, meteorologically induced storm surges and the broader impacts of sea level rise. As a coastal economic hub with vital infrastructure, including ports, shipyards and commercial facilities, HafenCity is exposed to significant hydrological risks. It experiences an average tidal range of 3.66 metres and tidal currents of up to 2.5 knots, increasing the threat of flooding.

Traditionally, water levels have been monitored using tide gauges, and more recently, LiDAR and satellite altimetry. However, each technique demonstrates specific limitations when applied in dense urban coastal environments. Tide gauges offer limited spatial coverage, LiDAR involves high operational costs and satellite altimetry is constrained by coarse spatial resolution and infrequent revisit times – limitations that are particularly pronounced in narrow and hydrologically complex water bodies like the Elbe. HafenCity's intricate infrastructure and canal network further complicate the applicability of these conventional approaches.

GNSS-interferometric reflectometry presents a promising alternative delivering continuous, high-resolution water level observations. Its flexibility allows deployment on existing infrastructure such as quay walls or buildings, offering a scalable, cost-effective monitoring solution with minimal installation requirements.

Although GNSS-IR has been successfully applied in lakes, reservoirs and various coastal and riverine settings, its implementation in urban estuarine environments remains limited. The closest regional application, conducted by Larson (2023) along the Elbe River, is located approximately 40 km from the present study site. HafenCity, however, presents distinct challenges due to its dense built environment and frequent signal interference from surrounding infrastructure and maritime activity. This study aims to address the existing research gap by evaluating the performance of GNSS-IR in HafenCity through comparative analysis with tide gauge data and interpolated tidal estimates. The findings are intended to support the integration of GNSS-IR into coastal water level monitoring frameworks, enhancing flood risk management amid ongoing sea level rise.

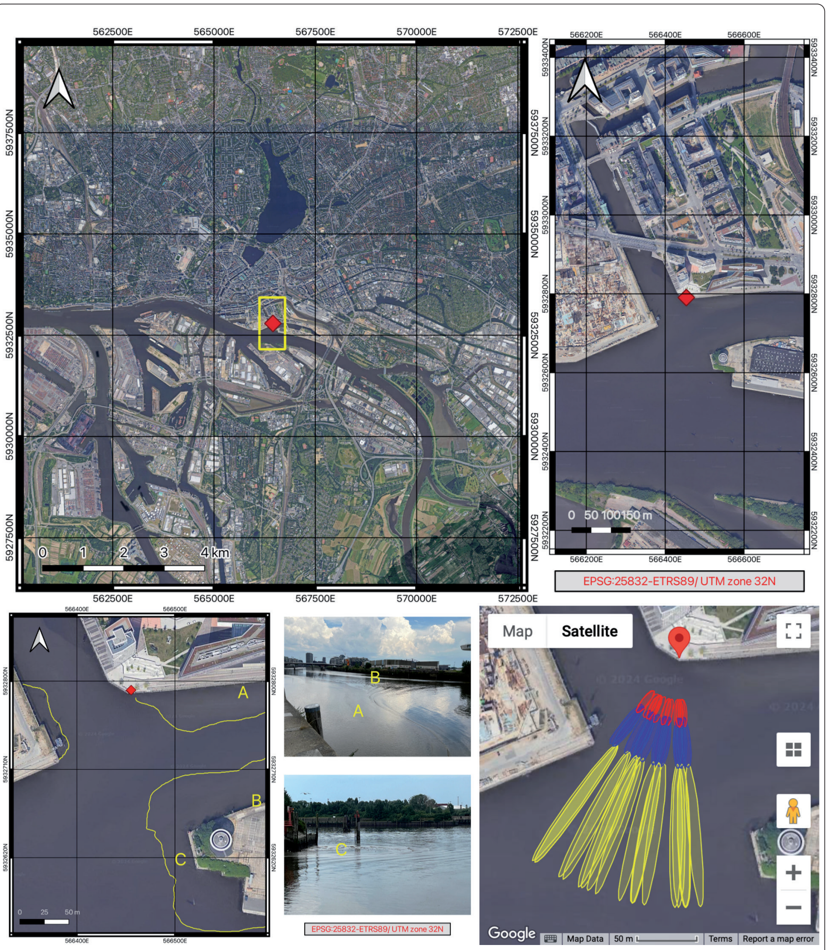


Fig. 1: Study area along the Elbe River near Buenos Aires Kai in HafenCity, Hamburg (top). Delineated dried areas during low tide (bottom left) and representative Fresnel zones for the GPS L1 frequency (bottom right)

Materials and methods

The selection of the measurement site was guided by operational, environmental and geometric considerations to ensure the integrity and continuity of GNSS-IR observations. The location near Buenos Aires Kai in HafenCity was chosen for its proximity to HafenCity University, allowing convenient access for equipment maintenance and real-time monitoring. Situated along the Lower Elbe River, the site offers suitable conditions for water level measurements in a tidally influenced environment. The GNSS antenna was installed with an unobstructed line of sight to the water surface and minimal environmental interference, ensuring optimal satellite elevation angles between 5° and 25° for effective signal reflection and reception. Geometric constraints, as defined by Geremia-Nievinski and Hobiger (2019), were applied to determine the appropriate antenna height and horizontal offset from the water surface. The final location was validated through field inspection during low tide to eliminate interference from dry surfaces, combined with a detailed assessment of the Fresnel zones, as illustrated in Fig. 1. The antenna was ultimately positioned at 53.5398012° N, 10.0027483° E, at an elevation of 51.7012 m (WGS-84).

For data acquisition, the Trimble R-10 GNSS receiver was selected due to its capability to track multiple GNSS constellations (GPS, GLONASS, Galileo and BeiDou), high sampling rate and ability to log SNR data – parameters essential for GNSS-IR water level estimation (Geremia-Nievinski 2023; Geremia-Nievinski and Hobiger 2019). Furthermore, it delivers high positioning performance under static and fast-static configurations, with documented accuracies of 3 mm + 0.5 ppm RMS horizontally and 5 mm + 0.5 ppm RMS vertically (Trimble 2018). To ensure optimal data quality, the device underwent a three-step calibration process consisting of tilt calibration, magnetometer calibration and magnetometer alignment.

Data acquisition and preprocessing

GNSS-IR data acquisition was conducted in 2024 on April 23 (four observations), April 30 (12), May 6 (16), May 13 (22), June 24 (repetitive calibration) and June 27 (70). Measurement durations progressively increased from 2 to 24 hours, culminating in a full-day session to ensure sufficient temporal coverage and data reliability.

Following data acquisition, the raw GNSS data stored in Trimble's T02 format was converted into RINEX 2.11 format using Trimble Business Center (TBC) and was prepared with strict adherence to naming conventions for compatibility with the gnssrefl software (Larson and GNSS-IR community 2024). The different RINEX files from the 24-hour measurement campaign were merged into a single dataset using the KernelSat web tool to enable continuous analysis. The merged file was then prepared for reflection analysis by defining appropriate elevation and azimuth masking based on site geometry and signal reflection theory. Fresnel zones were computed using the GNSS Reflections online tool to verify the visibility and quality of the reflection area.

Data processing

The processing phase focused on extracting meaningful water level information from the GNSS data using the open-source gnssrefl software, as shown in Fig. 2. Raw GNSS observations were converted to signal-to-noise ratio (SNR) outputs and analysed through structured modules that applied satellite geometry filtering, signal quality evaluation and reflector height estimation. The Lomb-Scargle periodogram was employed to identify dominant reflection frequencies and assess signal coherence across multiple GNSS constellations. Further refinement was achieved using interfrequency bias corrections, quality control thresholds and spline fitting techniques to mitigate outliers and improve temporal resolution. Subsequently, the subdaily command was used to model tidal dynamics and generate high-resolution water level time series.

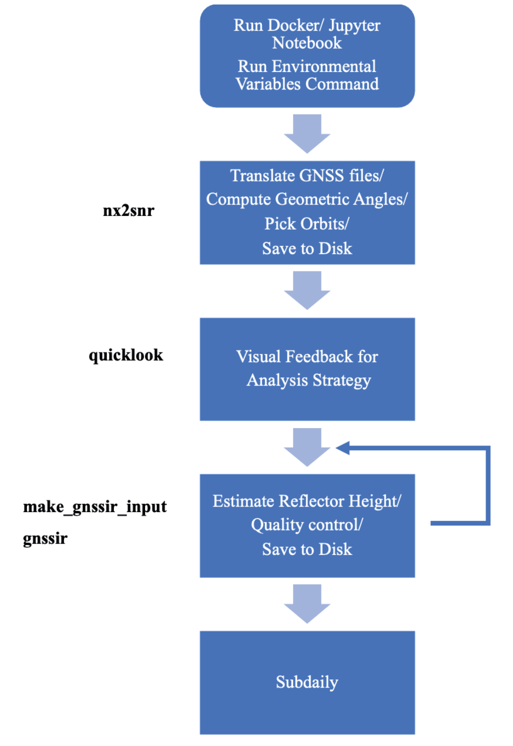


Fig. 2: gnssrefl software processing workflow (Larson 2024)

Statistical Analysis

All GNSS-IR-derived water level outputs were cross-validated against records from the nearby tide gauges at St. Pauli and Schöpfstelle to assess their consistency and accuracy. Validation was performed using statistical analysis, including linear regression, correlation coefficient and root mean square error (RMSE), to quantify the agreement between the datasets. To further enhance the spatial relevance of the comparison, an interpolated tide dataset was generated for the GNSS antenna location. This was achieved by implementing a custom two-dimensional linear interpolation function that accounted for the geodesic distances between the GNSS site and both tide gauges, mitigating tidal phase shifts associated with spatial separation.

Results and discussion

The results presented in this subsection are supported by figures that depict key parameters and their respective values, essential for drawing meaningful conclusions. Fig. 3 (top) illustrates the relative contribution of each GNSS constellation to the dataset, comprising a total of 70 observations, with a notable absence of BeiDou signals. The reduced number of recorded observations is primarily attributed to the limited azimuth range (170 to 220 degrees), the geographic latitude of the receiver, located near the polar gap, and two specific time intervals during which data were unavailable. The first occurred during the early morning hours (00:27 to 00:57 CEST), when the data logging indicator was active but no data were recorded. The second was an afternoon interruption, during which measurements were suspended for approximately one hour due to a thunderstorm.

An essential correction applied during processing is the RHdot correction, which accounts for water level variations along the satellite track within a given arc. The application of this correction led to a 2 % improvement in the RMSE between the GNSS-IR observations and the applied spline fit, as shown in Fig. 3 (middle). The absence of outliers (red dots; > 3-sigma) highlights the robustness of the geodetic GNSS receiver compared to low-cost alternatives.

Furthermore, given the inclusion of multiple constellations and frequencies, applying an interfrequency bias correction further improved the RMSE by approximately 30 %, as illustrated in Fig. 3 (bottom).

The most consistent results were achieved by comparing GNSS-IR observations with interpolated tide values derived from St. Pauli and Schöpfstelle stations, yielding an RMSE of 14.9 cm and a correlation coefficient of 0.994 (Fig. 4). Comparisons with individual tide gauges showed slightly reduced accuracies: St. Pauli data resulted in an RMSE of 15.8 cm (Fig. 5,top), while Schöpfstelle comparisons produced the highest RMSE of 16.9 cm with a slightly lower correlation of 0.992 (Fig. 5, bottom). These variations, particularly in tidal range, were primarily linked to discrepancies in low-water levels. The reduced performance in some cases can be attributed to signal attenuation due to increased path length after reflection and environmental multipath effects. During low tide, exposed structures like quay walls and pillars may act as secondary reflectors, introducing additional interference and degrading the GNSS-IR signal quality.

Despite the achieved results, as illustrated in Fig. 6, the lack of a permanent power supply for the antenna and the reliance on batteries with a lifespan of approximately five hours, requiring successive replacements, resulted in multiple RINEX files. A fluctuation in the recorded position of the receiver's antenna was observed across the individual RINEX files. Although relatively small, this variation nonetheless affected the overall measurement accuracy.

Consequently, maritime traffic in HafenCity introduced additional multipath effects from passing vessels, negatively impacting signal quality. Moreover, personnel fatigue during the 24-hour measurement campaign affected data quality, as a longer observation period was required. While daily GNSS-IR observations typically achieve an RMSE of 1 to 5 cm, extending measurement campaigns over several months is recommended to enhance accuracy, reducing the RMSE to a range of 1 to 2 cm (Williams 2024).

Conclusion

This study evaluated the application of GNSS-interferometric reflectometry (GNSS-IR) for water level determination in the urban, tidally influenced environment of HafenCity, Hamburg. Data

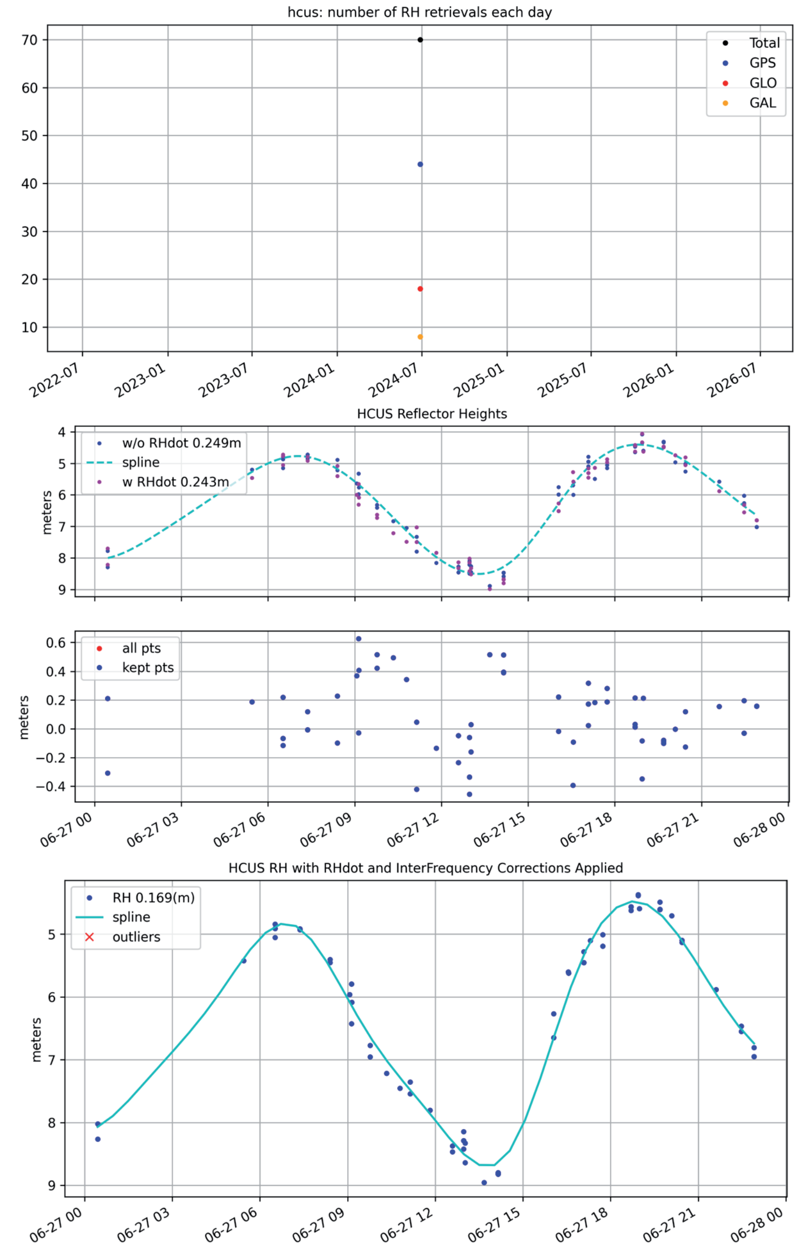


Fig. 3: Contribution of individual GNSS constellations to the observations (top), application of RHdot correction resulting in an improvement of RMSE relative to the spline fit curve (middle), final GNSS-IR-derived water level after application of interfrequency bias correction (bottom)

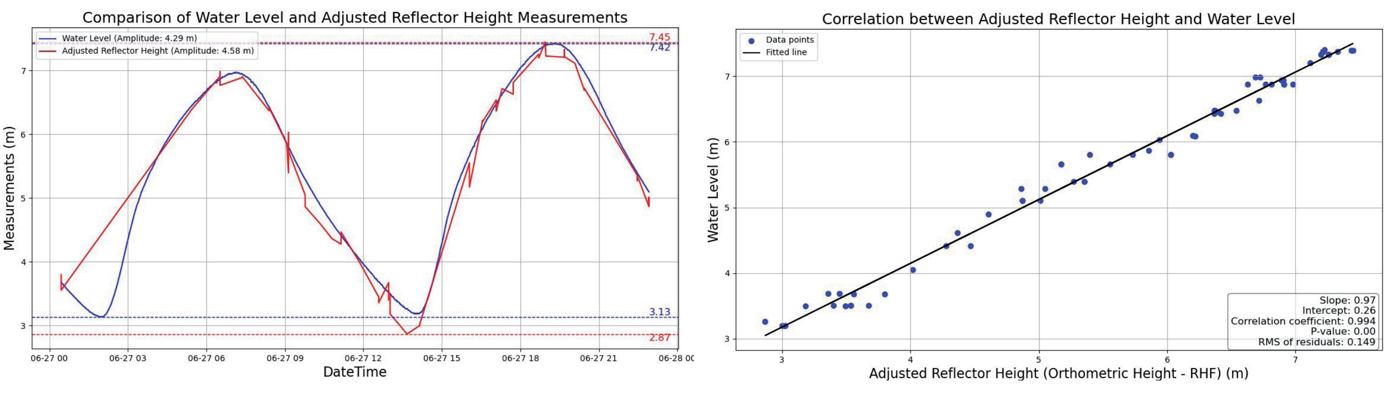


Fig. 4: Comparison of the two water level time series derived from GNSS-IR (red) and interpolated tide data (blue), highlighting maximum and minimum values as well as tidal ranges for each dataset (top). Statistical analysis between interpolated tide measurements (Y-axis) and GNSS-IR observations (X-axis) (bottom)

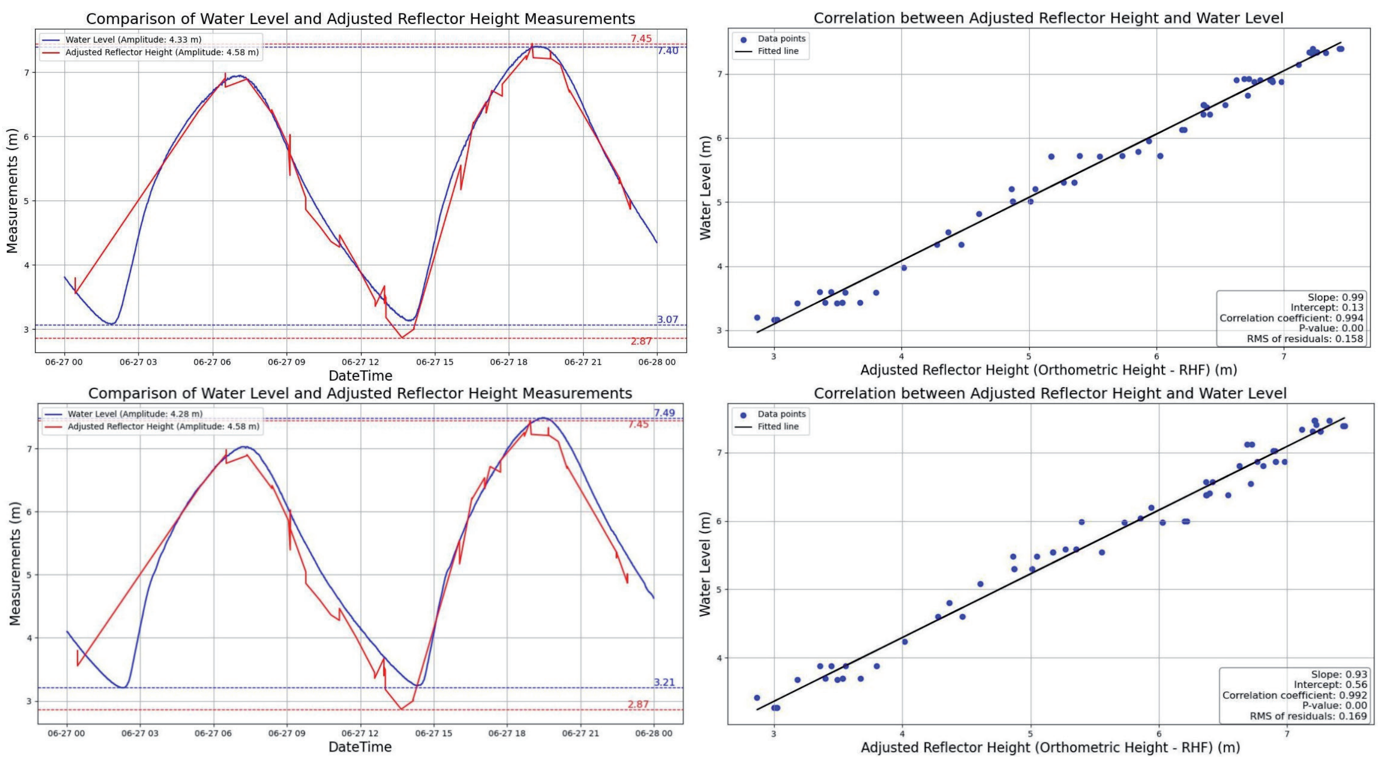


Fig. 5: Comparison and statistical analysis of datasets (St. Pauli on top and Schöpfstelle bottom)

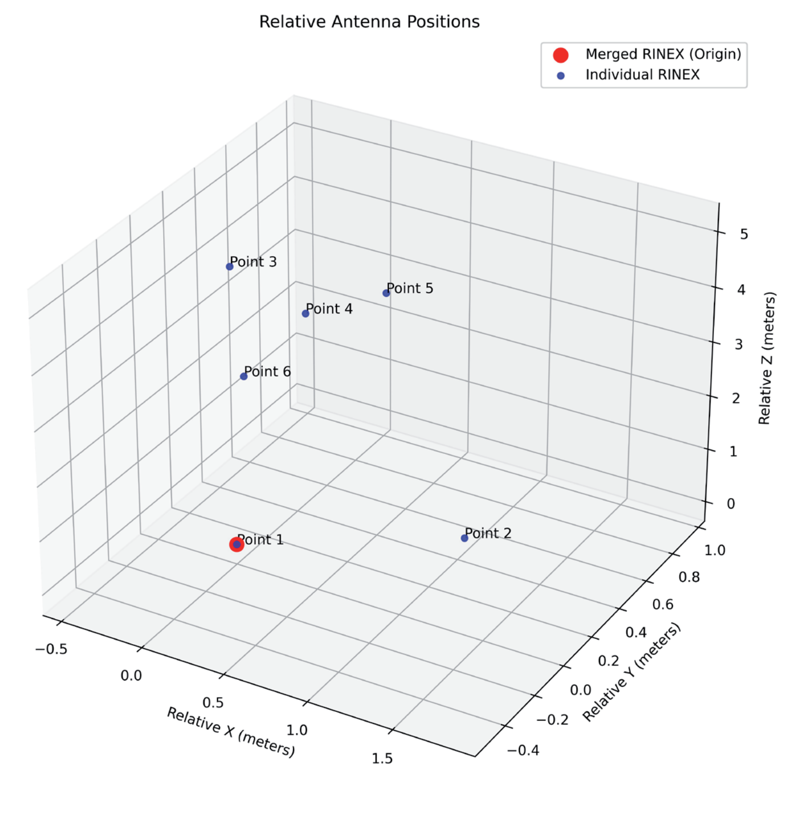


Fig. 6: Spatial distribution of antenna positional errors. The six points represent the recorded antenna positions from each RINEX file, while the red point denotes the merged position used as the reference for subsequent water level processing

collected during a 24-hour observation period were processed using the gnssrefl software and validated by comparison with measurements from the St. Pauli and Schöpfstelle tide gauges, as well as interpolated tidal data. Results demonstrated a high correlation (up to 0.994) and an RMSE of 14.9 cm, confirming the method's robustness even under challenging urban conditions. Limitations affecting performance included multipath interference from maritime traffic, personnel fatigue that restricted observation time, unfavourable weather conditions, and site-specific constraints such as the limited azimuth range. Despite these challenges, GNSS-IR proved to be an effective and reliable method for deriving water-level time series in complex coastal environments. The findings underline the technique's potential as a complementary tool for enhancing conventional water level monitoring systems, particularly in dynamic and infrastructure-dense settings like HafenCity.

Outlook

While this study confirmed the reliability of GNSS-IR for water level determination in complex urban environments, opportunities for further development remain. Future work could involve establishing a permanent GNSS-IR station on the roof of HafenCity University, offering continuous, long-term measurements under stable conditions with an external power supply. Additionally, developing an IoT-based laser rangefinder system would enable real-time ground-truth water level data collection, reducing dependence on external tide gauge interpolation. Addressing dynamic interference caused by maritime traffic through machine learning techniques, supported by AIS data, could also improve data quality in real time. Finally, integrating real-time GNSS data streams with Kalman filtering techniques would facilitate near-real-time water level estimation, significantly advancing the operational application of GNSS-IR for hydrological monitoring. //

References

Geremia-Nievinski, Felipe (2023): Low-Cost Ground-Based GNSS Reflectometry. In: Michael G. Sideris (Ed.): Encyclopedia of Geodesy. Springer International Publishing, DOI: 10.1007/978-3-319-02370-0_175-1

Geremia-Nievinski, Felipe; Thomas Hobiger (2019): Site guidelines for multi-purpose GNSS reflectometry stations. DOI: 10.5281/ZENODO.3660744

Larson, Kristine M. (2023): TGGO: GNSS-Reflectometry Use Case. https://gnssrefl.readthedocs.io/en/latest/use_cases/use_tggo.html

Larson, Kristine M. (2024): Running the gnssrefl code. https://gnssrefl.readthedocs.io/en/latest/pages/sc_media2024.html

Larson, Kristine M.; GNSS-IR community (2024): Welcome to the gnssrefl documentation! https://gnssrefl.readthedocs.io/en/latest/index.html

Williams, Simon (2024): GNSS-IR water levels – Background on models and methods needed/used for water monitoring. National Oceanography Centre, https://morefunwithgps.com/public_html/sc2024/Day2-Williams.pdf

Trimble (2018): Trimble R10 Model 2 GNSS System. https://geomaticslandsurveying.com/product/trimble-r10