Assessment of Sea Surface Heights Using GNSS Interferometric Reflectometry at Lieyu, Kinmen

Peter T.Y. SHIH, Allen C.M. LEE,
Chung-Yen KUO, Yen-Ti CHEN, Chinese Taipei

Key words: Reflectometry, Singnal-to-Noise Ratio, CSRS-PPP

SUMMARY

This study investigates the practical application of GNSS Interferometric Reflectometry (GNSS-IR) technology for tide observation by deploying a continuous GNSS station at the Nanshantou area in Kinmen National Park. We analyzed 237 days of GNSS Signal-to-Noise Ratio (SNR) data from November 6, 2024, to June 30, 2025, to derive sea surface height through the open-source software gnssrefl, and conducted harmonic analysis using the UTide program. The results demonstrate a root-mean-square error of 0.320 m between observed and reconstructed tide levels, with an average orthometric height of -0.047 m for the sea surface. The study confirms that GNSS-IR provides a stable tide observation solution with minimal environmental interference over a spatial coverage of approximately 200-400 m. Although current technological constraints prevent real-time water level acquisition, GNSS-IR is suitable for long-term monitoring applications such as mean sea level estimation and tidal analysis.

Assessment of Sea Surface Heights Using GNSS Interferometric Reflectometry at Lieyu, Kinmen

Peter T.Y. SHIH, Allen C.M. LEE,
Chung-Yen KUO, Yen-Ti CHEN, Chinese Taipei

1. INTRODUCTION

GNSS Interferometric Reflectometry (GNSS-IR) is a technique that measures sea surface height relative to the phase center of a GNSS antenna (Larson et al., 2013). As part of a charting datum enhancement program, a GNSS continuously operating reference station (CORS) dedicated to GNSS-IR-based sea surface height monitoring was established in Lieyu, Kinmen (Shih et al., 2025). As a CORS, its measurements are directly tied to the ITRF reference frame, eliminating the need for conventional surveying methods—such as differential leveling—to connect to a vertical datum. This approach removes uncertainties associated with datum connections.

This article presents a preliminary analysis of the first 237 days GNSS observations from this Lieyu station, using both GNSS positioning (ellipsoidal height of GNSS antenna) and GNSS-IR (reflector height).

2. THE GNSS HEIGHT PROCESSING RESULT

GNSS observations from the Lieyu CORS station were processed over 237 days, from November 6, 2024 (DOY 311) to June 30, 2025 (DOY 181). Two online services were used: CSRS-PPP, employing a Precise Point Positioning (PPP) strategy (Natural Resources Canada, 2025), and AUSPOS, using a relative positioning approach (Geoscience Australia, 2024). CSRS-PPP provides centimeter-level accuracy without base stations by leveraging precise satellite products.

CSRS-PPP is operated by Natural Resources Canada. This service computes absolute positions using GNSS data from a single receiver in static or kinematic modes. It supports multi-GNSS constellations and outputs coordinates in ITRF reference frames. And AUSPOS is provided by Geoscience Australia, this service processes static GNSS data relative to global IGS and APREF networks for high-accuracy positions worldwide.

As shown in Table 1, the CSRS-PPP results show higher station height by 0.027 m with lower variability, indicating stable PPP performance over the period. Daily heights exhibit tight scatter around means, consistent with CORS quality (Figure 1). The 2.7 cm offset between services may reflect reference frame realizations or processing models, warranting further investigation via GNSS-IR integration.

Table 1: GNSS height derived from CSRS-PPP and AUSPOS

Service	Mean Height (m)	Standard Deviation (m)
CSRS-PPP	34.865	0.0056
AUSPOS	34.838	0.0077

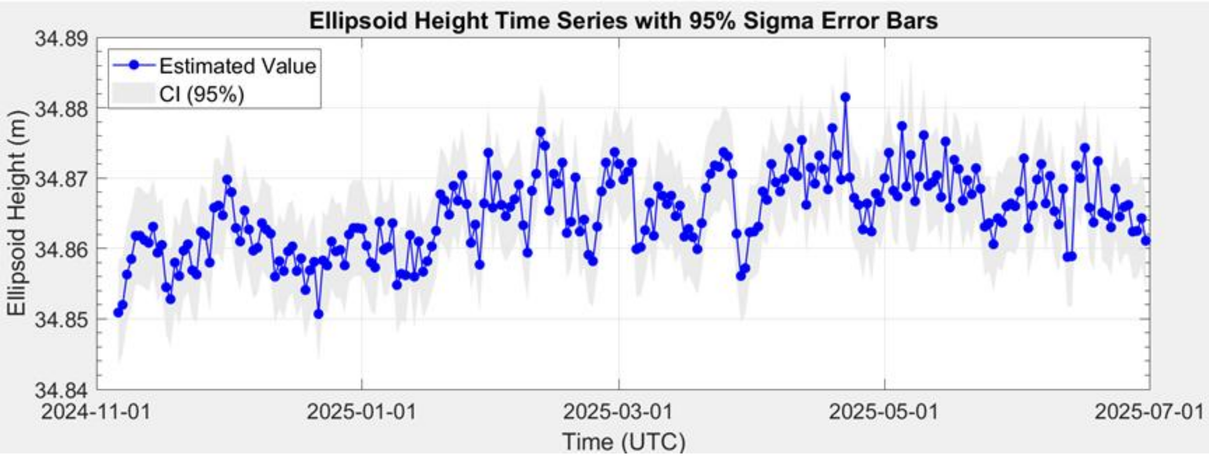

Figure 1: Ellipsoid height time series

3. GNSS-IR AND HARMONIC ANALYSIS

The gnssrefl software package (Larson, 2024) was employed for GNSS Interferometric Reflectometry (GNSS-IR) processing at the Lieyu CORS station. This open-source Python tool analyzes SNR data to estimate reflector heights, such as sea surface levels, via Lomb-Scargle Periodogram (LSP) of multipath signals. Key outputs include periodograms where reflector height corresponds to the dominant frequency peak.

A critical quality metric in gnssrefl is the Peak-to-Noise Ratio (PNR), defined as the ratio of the maximum spectral power to the average background noise. PNR assesses signal significance in the LSP, filtering out noisy reflectometry estimates. Higher PNR values indicate clearer reflector signals amid multipath interference.

Two PNR thresholds are used, 2.5 and 3.0. The PNR=2.5 yields more valid sea surface observations with negligible difference from 3.0. And, PNR=3.0 provides similar results but fewer detections. PNR=2.5 was chosen for subsequent analysis to maximize sea surface measurement count while maintaining reliability. This threshold balances sensitivity and false positives in coastal GNSS-IR applications.

The derived sea surface heights from GNSS-IR are then processed with harmonic analysis. The UTide MATLAB package (Codiga, 2011) was used to perform tidal constituent fitting on

GNSS-IR derived sea surface heights from the Lieyu station. UTide excels in analyzing irregular or gappy time series, providing robust harmonic predictions with nodal corrections. It outputs amplitudes, phases, and synthetic tide levels for model validation.

Figure 2 illustrates the time series of observed GNSS-IR heights and UTide-reconstructed tides. The Root Mean Square Error (RMSE) between observed and predicted tide levels is 0.320 m, indicating good harmonic fit. The mean predicted tide level aligns closely with the initial value derived from the first week mean, offset by just 0.002 m.

Table 2: Validation Metrics

Metric	Value	Interpretation
RMSE	0.320 m	Acceptable for GNSS-IR tides
Mean Tide Offset	0.002 m	Negligible bias

These results affirm UTide's efficacy for coastal GNSS-IR data, capturing tidal variability effectively. Residuals likely reflect non-tidal effects like weather, suitable for mean sea level estimation.

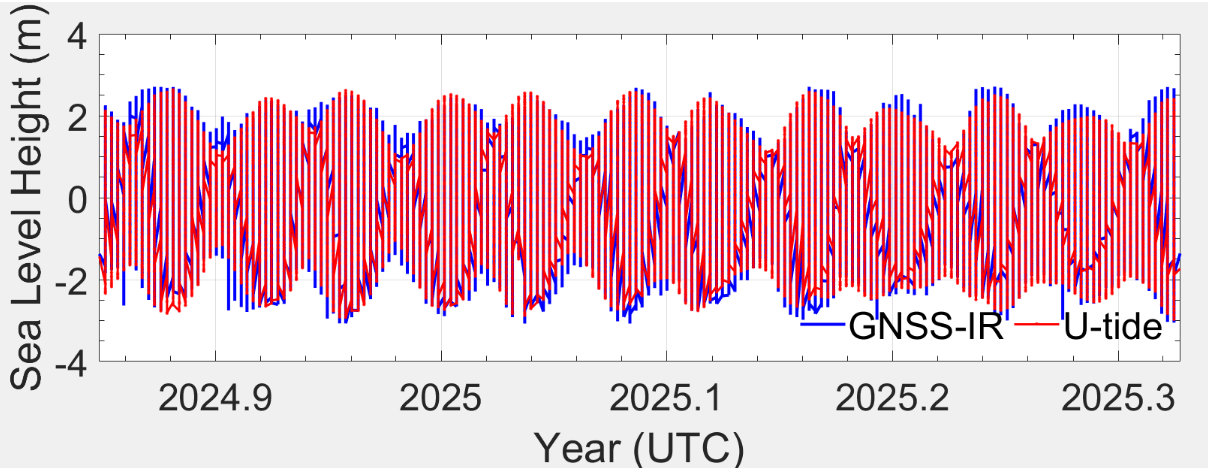

Figure 2: UTide Analysis

Based on the analysis, the ellipsoidal height of the phase center was recorded at 34.865 m, while the height from the mean sea level to the antenna was 24.434 m. After applying a harmonic analysis offset of 0.002 m, the calculated ellipsoidal height of the mean sea level (h) during the observation period is 10.433 m (34.865 - 24.434 + 0.002). According to the MOI-109 geoid model, the geoid undulation (N) at this location is 10.48 m. By applying the fundamental geodetic formula H = h - N, the resulting orthometric height (H) is determined to be -0.047 m (10.433 - 10.48).

4. CONCLUDING REMARKS

The primary findings and advantages identified in this deployment include:

- Geodetic Integration: Because the measurements are conducted at a CORS station, they are directly tied to the ITRF reference frame. This eliminates the need for traditional differential leveling and removes uncertainties typically associated with connecting to a vertical datum.
- Performance Stability: Processing GNSS data through services like CSRS-PPP provided stable station height results with low variability (standard deviation of 0.0056 m), ensuring a precise baseline for reflectometry.
- Harmonic Accuracy: The integration of gnssrefl for height estimation and UTide for harmonic analysis yielded an RMSE of 0.320 m. The negligible mean tide offset of 0.002 m confirms the efficacy of these tools for coastal tidal analysis.
- Operational Resilience: The system proved to be a stable observation solution with minimal environmental interference, covering a spatial area (the First Fresnel Zone, FFZ) of approximately 200–400 m.

While current technological constraints prevent GNSS-IR from acquiring real-time, high-frequency data, the technique nevertheless proves to be an excellent tool for long-term monitoring applications, including mean sea level estimation and the refinement of charting datums. Future work may further investigate the 2.7 cm offset observed between different processing services to refine the integration of GNSS height and GNSS-IR models.

ACKNOWLEDGEMENT

This project was conducted with invaluable support from the Department of Land Administration (Ministry of the Interior), Lieyu Workstation of Kinmen National Park Administration, Kinmen County Government Land Administration Bureau, Yohung Surveying Co., Ltd. (https://www.yuhung-surveying.com.tw/), Data Surpass Technology Co., Ltd. (http://www.formosatrend.com/), and Taiwan Baiyue Technology Co., Ltd. We extend sincere gratitude for their collaboration. This GNSS-IR CORS deployment forms part of the Ministry of the Interior's Advanced Benchmarking and System Enhancement Project.

Technical editing of this manuscript utilized Gemini and Perplexity AI services.

REFERENCES

Geoscience Australia, 2024. AUSPOS - Online GPS processing service. https://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/auspos, Last accessed on 2026/01/05.

Codiga, D.L., 2011. Unified Tidal Analysis and Prediction Using the UTide Matlab Functions. Technical Report 2011-01. Graduate School of Oceanography, University of Rhode Island, Narragansett, RI. 59pp. https://www.po.gso.uri.edu/~codiga/utide/2011Codiga-UTide-

Report.pdf, Last accessed on 2026/01/05.
Larson, K.M., Lofgren, J., & Haas, R., 2013. Coastal sea level measurements using a single geodetic GPS receiver, Adv. Space Res., 51(8):1301-1310, doi:10.1016/j.asr.2012.04.017.
Larson, K.M., 2024. Gnssrefl: an open source software package in python for GNSS interferometric reflectometry applications, GPS Solutions, 28:165, https://doi.org/10.1007/s10291-024-01694-8, Last accessed on 2025/01/20.
Larson, K.M., 2024a. Kristine M. Larson and GNSS-IR community, https://gnssrefl.readthedocs.io/_/downloads/en/1.3.21/pdf/, Last accessed on 2024/12/05.
Natural Resources Canada, 2025. *Precise Point Positioning (CSRS-PPP)*. Canadian Spatial Reference System. https://webapp.csrs-scrs.nrcan-rncan.gc.ca/geod/tools-outils/ppp.php, Last accessed on 2026/01/05.
Shih, Peter T.Y., Lin, Y.N., Lee, C.M., Kuo, C.Y., Chen, Y.T., 2025. GNSS-R Deployment for Enhanced Sea-Level Monitoring in Lieyu, Kinmen County, Taiwan, FIG Working Week 2025, 2025/4/6-2025/4/10, Brisbane, Australia.

BIOGRAPHICAL NOTES

Peter T.Y. Shih is a Professor Emeritus at the Department of Civil Engineering of the National Yang Ming Chiao Tung University, Taiwan. He received his PhD degree from the Department of Surveying Engineering, University of New Brunswick, Canada in 1989. His main research and teaching interests are in the fields of photogrammetry, terrain mapping, satellite positioning and navigation, and hydrography.

Allen C.M. Lee received PhD degree from the Department of Geomatics, National Cheng Kung University (NCKU). He currently serves as the postdoctoral research fellow at Research Institute for Applied Mechanics, Kyushu University, Japan. He has been focusing on GNSS-IR technology since 2015.

Chung-Yen Kuo became a full Professor in the Department of Geomatics, NCKU in 2015. He received PhD degree from Ohio State University in 2005. His research interests include, Geodesy, Sea level, Climate Change, Gravity, GNSS-R, Hydrographic survey and Unmanned Surface Vehicle.

Yen-Ti Chen received Master degree from the Department of Geomatics, NCKU in 2007. He is a senior officer in the Department of Land Administration, Ministry of the Interior. His work includes to serve as a leader in the Taiwan ENC Center.

CONTACTS

Prof. Peter T.Y. Shih
Department of Civil Engineering
National Yang Ming Chiao Tung University

1001 Ta-Hsueh Road
Hsinchu
300093, TAIWAN
Tel. +886 3 5712121 #54957
Fax +886 3 5716257
Email: tyshih@nycu.edu.tw
Web site: https://ce.nycu.edu.tw/en/member/educators/4