Improving near real-time GNSS-IR sea level retrievals with robust outlier detection

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1. Motivation

- Reliable, timely sea-level observations are vital for coastal hazards, navigation, and climate monitoring.
- GNSS-IR has been used for ~15 years to measure sea level, snow depth, and soil moisture.
- Most studies rely on archived data and post-processing, limiting timeliness and operational use.
- NRT GNSS-IR provides sea-level data within minutes, but detecting outliers is more challenging compared to post-processing due to sea-level variability in near-real-time results.
- This study adapts a median-based robust outlier detection (ROD) method, previously used for snow depth [1], to improve NRT sea-level estimates.

2. Objectives

1) **Develop an NRT workflow** that processes 1 Hz GNSS SNR data every 15 mins using the latest 60 mins.
2) **Integrate the ROD method to identify outliers** before providing each set of estimates.
3) **Test the method** using 30 days of data (Nov 2024) from PTLD GNSS and nearby PORL tide gauge.
4) **Evaluate different look-back windows (1–24 h),** representing the amount of past data used in ROD, to assess their impact on estimate quality and count.
5) **Recommend a practical setup** for accurate, low-latency GNSS-IR sea-level monitoring.

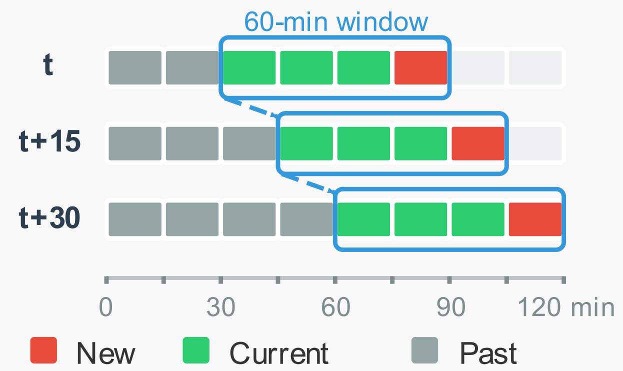
3. Materials and Methods

- **GNSS site:** Portland (PTLD), south-eastern Australia
- **Orbit products:** Wuhan University MGEX ultra-rapid
- **Tide gauge:** PORL
- **Period analysed:** 1-30 Nov 2024

Data filtering	Constellation	G+R+E+C
	Elevation Limits (°)	0-15
	Azimuth Limits (°)	130-270
	Polynomial Degree	2
LSP analysis	Minimum H (m)	0
	Maximum H (m)	10
	Precision (m)	0.01
Quality control	Min. Elevation Range (°)	5
	Min. PBNR	4

The analysis was performed separately for;

- Short Wavelength Group (SWG): λ<20 cm
  - $H_0 = 4.90$ m
- Long Wavelength Group (LWG): λ>20 cm
  - $H_0 = 5.01$ m



Robust Outlier Detection (ROD)

Let $\mathbf{H}(t) = \{h_i | t_i \le t \wedge t_i \ge t - \tau\}$ be the set of H estimates within the look-back window τ (for 1 h, 3 h, 6 h, 12 h, 24 h).

1. **Sort heights:** $h_{(1)} \le \cdots \le h_{(n)}$.
2. **Consecutive differences:** $d_j = h_{(j+1)} - h_{(j)}, \quad j = 1, \ldots, n-1.$
3. **Median residuals:** $r_j = d_j - median(\mathbf{d})$
4. **Median Absolute Deviation (MAD):**

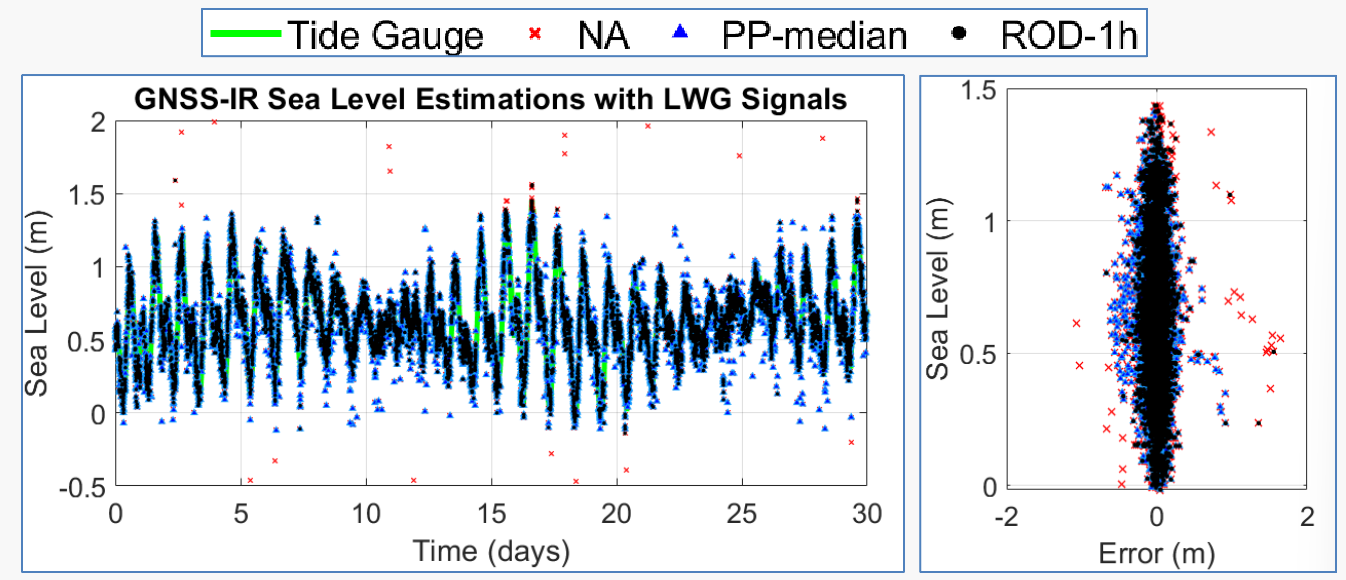
$$MAD = \begin{cases} 1.4826 \times median(|\mathbf{r}|), if\ median(|\mathbf{r}|) \neq 0 \\ 1.2533 \times \dfrac{1}{n-1} \sum_{j=1}^{n-1} |r_j|, otherwise \end{cases}$$

4. Results

Outlier Analysis Options	
NA	Not Applied
PP-median	Outliers are identified as reflector height estimations more than 3×MAD from the median, after 30-day estimation process.
ROD-τ	ROD with different look-back window lengths (ROD-1h, ROD-3h, ROD-6h, ROD-12h, ROD-24h)

- GNSS-IR RH estimates were aligned with the datum of the PORL TG measurements using the Vertical Local Tie (VLT) approach [2].
- LWG signals provided both a higher number of estimates and greater accuracy compared to SWG signals.
- The ROD method effectively identified outliers and improved NRT GNSS-IR sea level estimates in both signal groups.
- Due to the dynamic nature of the sea surface, it was observed that using a look-back window longer than 6 hours decreases accuracy. Therefore, it is recommended to use ROD with look-back windows of 6 hours or less in NRT analysis.
- ROD-1h, ROD-3h, and ROD-6h gave similar accuracy, but ROD-1h offers higher temporal resolution due to more estimates.

	SWG (λ<20 cm)				LWG (λ>20 cm)			
	Num. of Est.	Corr. (%)	RMSE (cm)	Bias (cm)	Num. of Est.	Corr. (%)	RMSE (cm)	Bias (cm)
NA	9129	73.79	22.5	0.2	11452	89.61	12.0	-0.4
PP-median	9067	89.05	12.2	-0.6	11390	91.89	10.3	-0.6
ROD-1h	7424	85.69	14.6	-0.3	9198	94.01	8.8	-0.1
ROD-3h	7092	85.81	15.0	-0.5	6260	94.58	8.9	-0.1
ROD-6h	5534	85.77	16.0	-0.3	4748	95.24	8.5	-0.1
ROD-12h	3344	82.42	16.2	-0.2	4719	92.05	7.9	0.0
ROD-24h	4638	81.33	13.1	-0.1	7548	92.09	8.5	-0.4



- Van de Casteele diagram shows the error distribution of sea level estimates for NA, PP-median, and ROD-1h. ROD-1h estimates are tightly clustered around zero, indicating higher accuracy and low bias.

5. Conclusions

- The 1-hour observation window provides the most consistent results with both high accuracy and a sufficient number of estimates.
- Longer windows (e.g., 3 or 6 hours) maintain similar accuracy but result in fewer estimates and reduced temporal coverage.
- The adapted ROD method is effective in detecting outliers in NRT GNSS-IR sea-level estimates, and holds potential for improved performance through further methodological refinement.

Ref.

[1] Altuntas, C., Erdogan, B., & Tunalioglu, N. (2024). Implementing robust outlier detection to enhance estimation accuracy of GNSS-IR based seasonal snow depth retrievals. *International Journal of Remote Sensing, 45*(11), 3648-3663.

[2] Altuntas, C., Tunalioglu, N., & Ocalan, T. (2025). Datum Alignment Between GNSS-IR Sea Level Estimations and Tide Gauges in Türkiye: A Vertical Local Tie Approach. *Marine Geodesy, 48*(1), 2-20.

Ack.

GNSS Data: Geoscience Australia
Orbit Products: Wuhan University (WHU-GRC)
TG Data: IOC Sea-Level Monitoring Facility