# 利用GNSS-IR和GNSS浮標監測海水面變化

## 中央氣象署114年三十九屆天氣分析與預報研討會

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2025/09/04

# Why Monitor Coastal Sea Level?

**Climate Change**

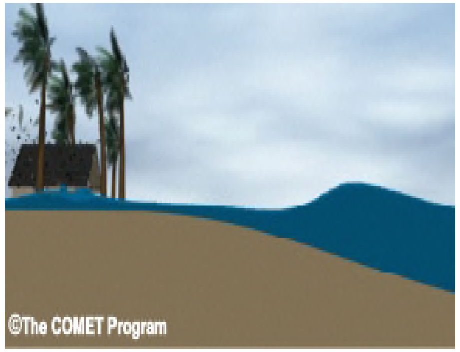
Sea Level Rise Impacts

SLR: 1 m by 2100
[DeConto & Pollard, 2016]

- Low-Lying Areas Inundation
- Intrusion of Seawater
- Wetland Destruction
- Coastal Erosion

Living Environment, Economic Issue…etc.

[Bindoff et al., 2007;Watkins, 2007; ESA, 2018, NOAA, 2022]




[Credit: IPCC, USGS, NOAA]

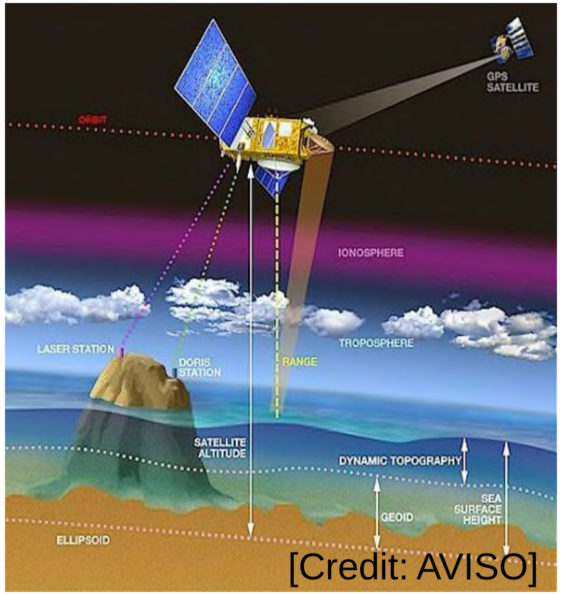
# How to Monitor Sea Level?

**1. Tide Gauge → Relative Sea Level Changes**

- Uneven distribution
- Incomplete and inconsistent data
- Measurements contain land motion effects
- Maintenance issue

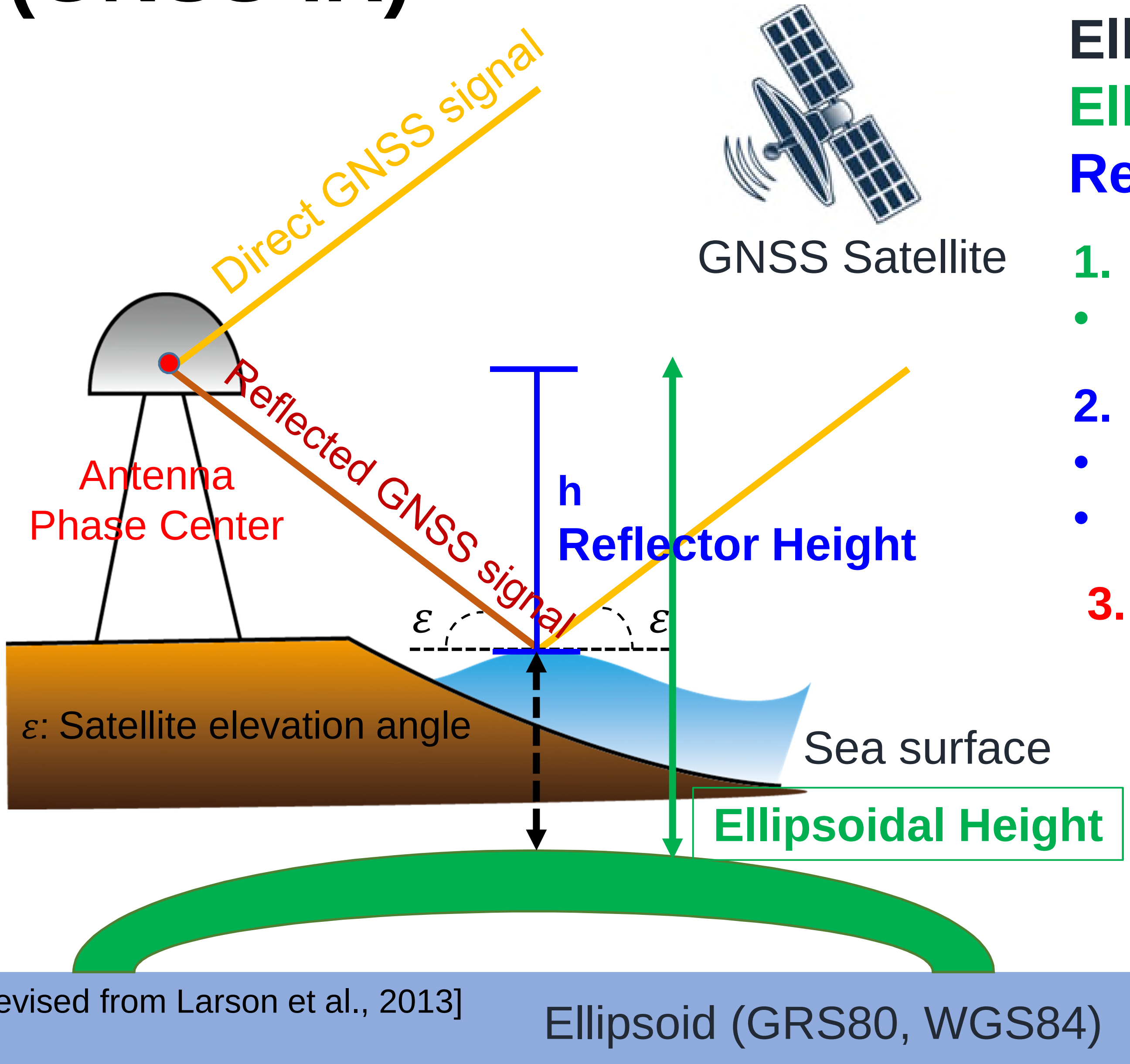
**2. Satellite Altimetry → Absolute Sea Level Changes**

- Low accuracy in coastal regions
- Low temporal resolution (limited repeated cycle)
- Limited satellite altimetry data in polar regions



[Credit: AVISO]

# Ground-based GNSS Interferometric Reflectometry (GNSS-IR)




[Revised from Larson et al., 2013]

**Ellipsoidal Height of sea surface = Ellipsoidal Height of antenna − Reflector Height**

1. **Ellipsoidal Height of antenna:**
   - **Acquired by GNSS positioning**

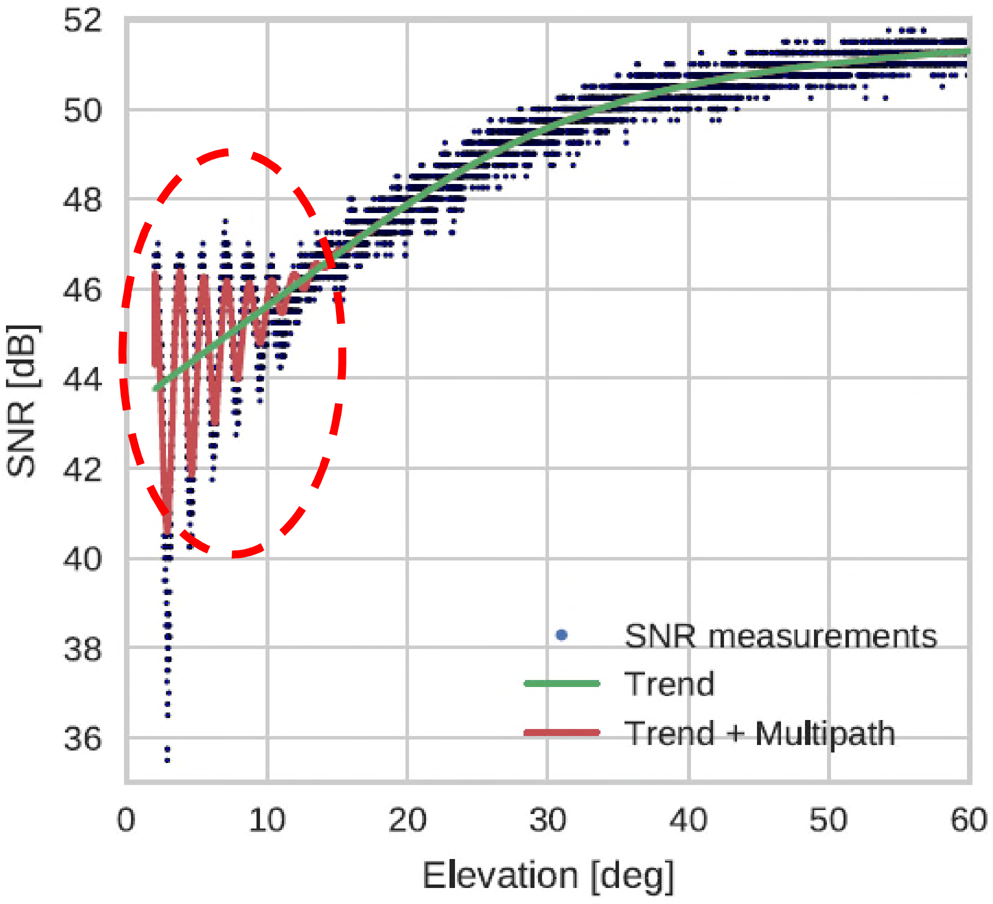
2. **Reflector Height:**
   - **Obtained via GNSS-IR technique**
   - **Signal-to-Noise Ratio (SNR) Data**

3. **Atmospheric correction**

➢ **Issues:**

1. **Optimal way to separate the reflected signals**
2. **Integration of Multi-frequency and Multi-constellation observables**

# GNSS-IR based on SNR Data




[Strandberg et al., 2019]

from reflected signal — from direct signal

$$\delta \text{SNR} = \text{SNR} - \textbf{low order polynomial (quadratic fitting/2}^{\textbf{nd}}\textbf{ order)}$$
$$= A\cos(\boldsymbol{\psi} + \varphi)$$
$$= A\cos(\mathbf{4\pi h\lambda^{-1} \sin \varepsilon} + \varphi)$$

[Larson et al., 2013]

**ψ: Phase angle** — φ: Phase offset

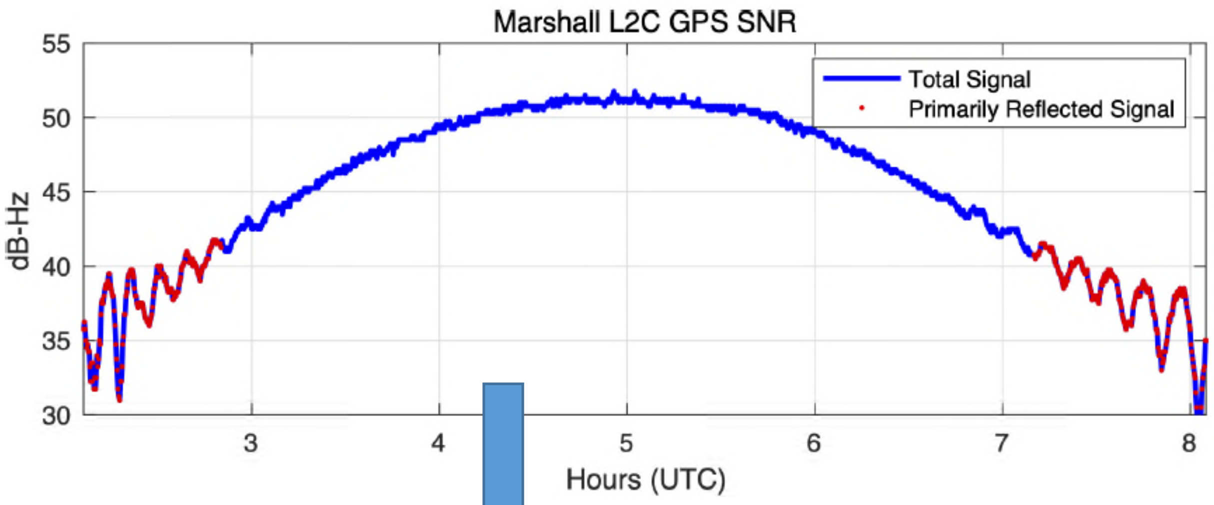
**h: Reflector height** — λ: Wavelength

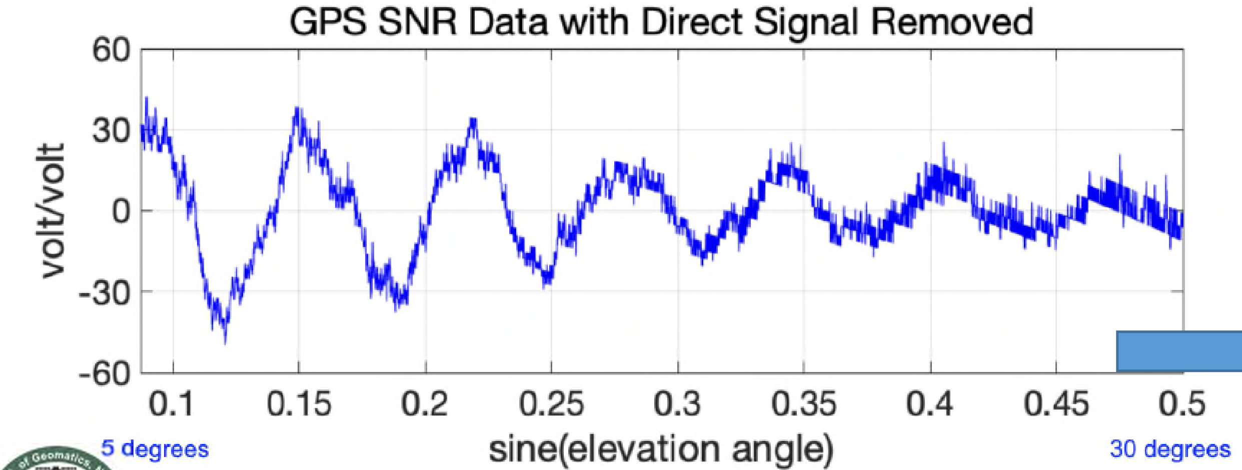
$\varepsilon$: Satellite elevation angle — f: Frequency

| Assumption | Static ($\dot{h} = 0$) | Dynamic ($\dot{h} \neq 0$) |
|---|---|---|
| Frequency | $f = \frac{2h}{\lambda}$ | $f = \frac{2\dot{h}}{\lambda}\frac{\tan\varepsilon}{\dot{\varepsilon}} + \frac{2h}{\lambda}$ |
| Reflector height | $h = \frac{f * \lambda}{2}$ | $h = \frac{f * \lambda}{2} - \dot{h}\frac{\tan\varepsilon}{\dot{\varepsilon}}$ |

**Stations with large tidal variations**

# Extract Reflected Signals and Spectral Analysis

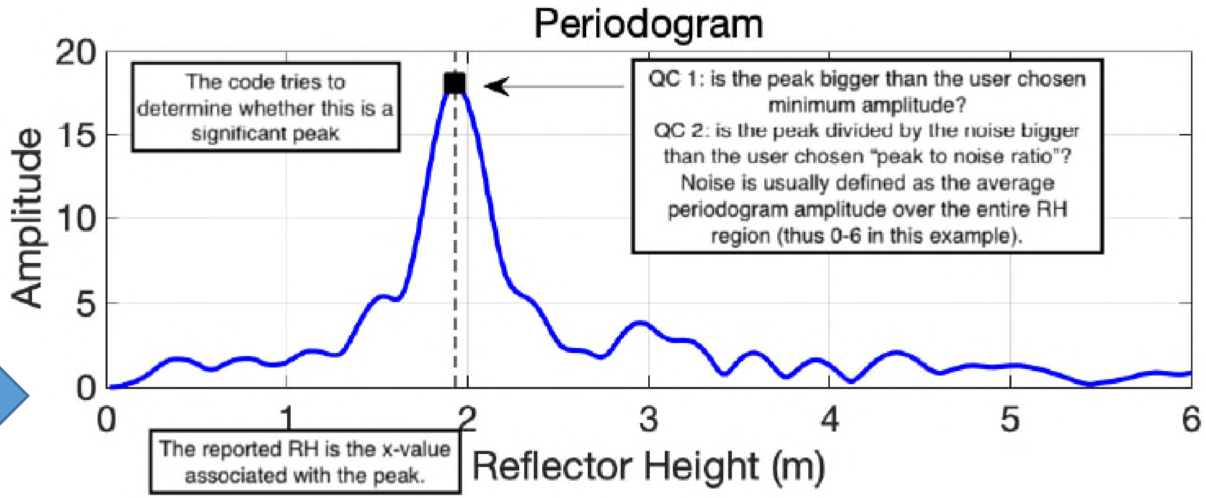



## ■<u>Lomb-Scargle Periodogram(LSP)</u>

- The **dominant frequency** of **δSNR**
- The observations can be **unevenly sampled** and **have gaps**

[Lomb, 1976; Scargle, 1982]



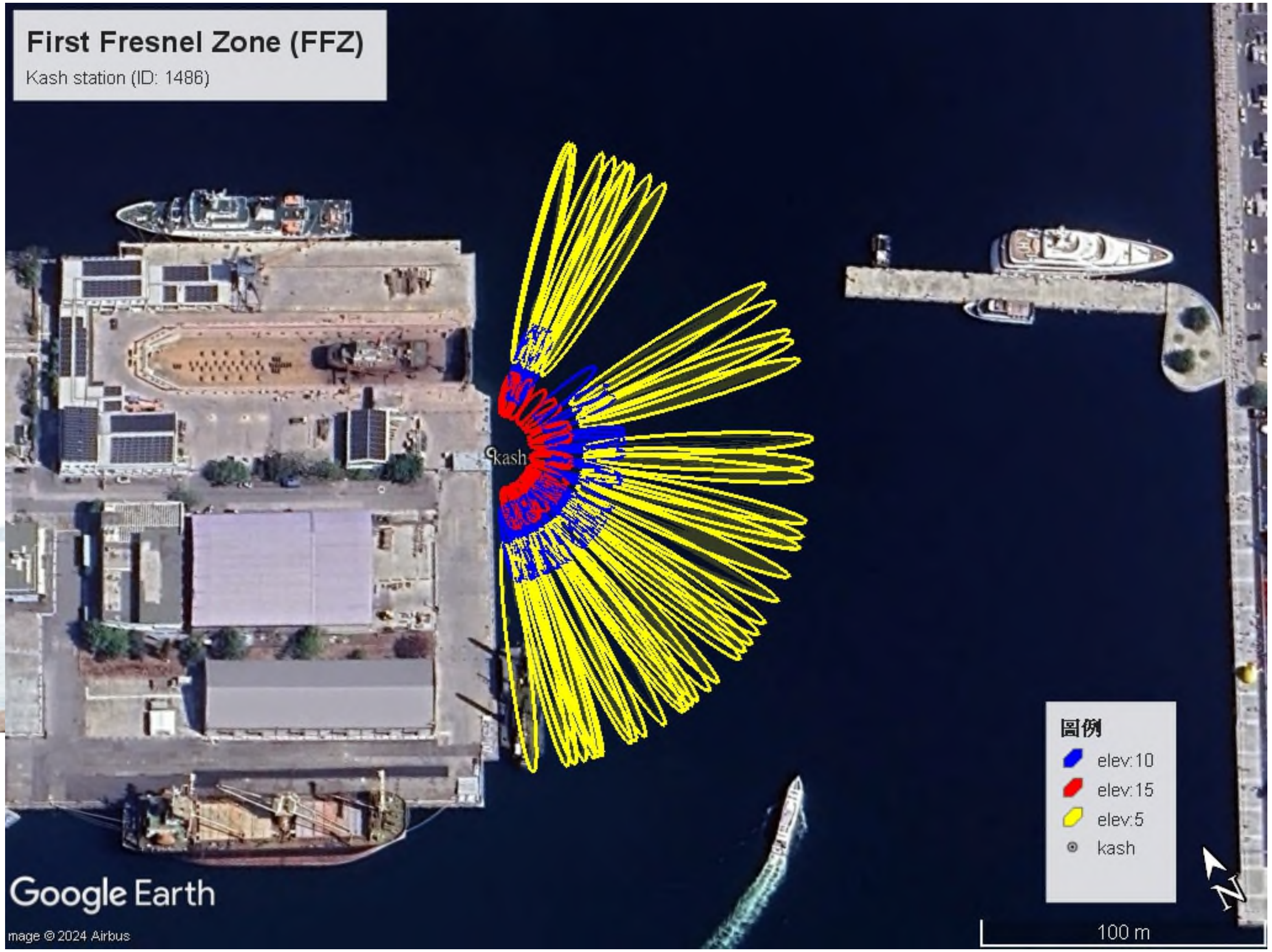

https://gnssrefl.readthedocs.io/en/latest/

# Part I

## Feasibility Assessment of Defining Taiwan's Vertical and Depth Datums using Coastal GNSS-IR Altimetry

④ Establishing long-term GNSS-IR sea level monitoring and assessing the feasibility of using GNSS-IR retrievals for determination of **vertical and depth datums in Taiwan**.

# Study Area and Data




[Base map: Google Earth]

**Datasets:**

**① GNSS SNR**

**② Tide Gauge**

**③ Sea Level Anomaly**

**- AVISO & CMEMS**

**④ Meteorological Data**

- Data interval: 2005/11-2022/09
- Constellation:

✓ GPS (2005/11-2013/06)

✓ GPS+GLO(2013/06-2020/05)

✓ GPS+GLO+GAL(2020/05-2022)

- Azimuth: 40-200 (deg.)
- Elevation: 5-15 (deg.)

# MSS and Tidal Surfaces Computation

① Arithmetic mean [Pugh, 1987]

② Six parameter fitting

Annual Signal — Semi-annual Signal

$$TG\ (t) = \boldsymbol{a} + bt + \underbrace{c\sin(2\pi t) + d\cos(2\pi t)}_{\text{Annual Signal}} + \underbrace{e\sin(4\pi t) + f\cos(4\pi t)}_{\text{Semi-annual Signal}}$$

③ Tidal harmonic analysis + Nodal Tide Correction [Foreman et al., 2009, Chang & Shih, 2022]

$$TG(t) = \boldsymbol{a} + b(t) + \sum_{k=1}^{n} \boldsymbol{f_k}(t) C_k \cos(\omega_k(t) + V_k + \boldsymbol{u_k}(t) - g_k)$$

→ **Tidal Surfaces for Depth datum**

④ Multiple variable fitting [Liu, 1998]

$$TG(t) = \boldsymbol{a} + b(t) + c_1\boldsymbol{T}(t) + c_2\boldsymbol{P}(t) + c_3\boldsymbol{R}(t) + \sum_{i=1}^{m=5}[A_i \sin(\omega_i(t)) + B_i\cos(\omega_i(t))]$$

$\boldsymbol{T}$: Temperature

$\boldsymbol{P}$: **Pressure**

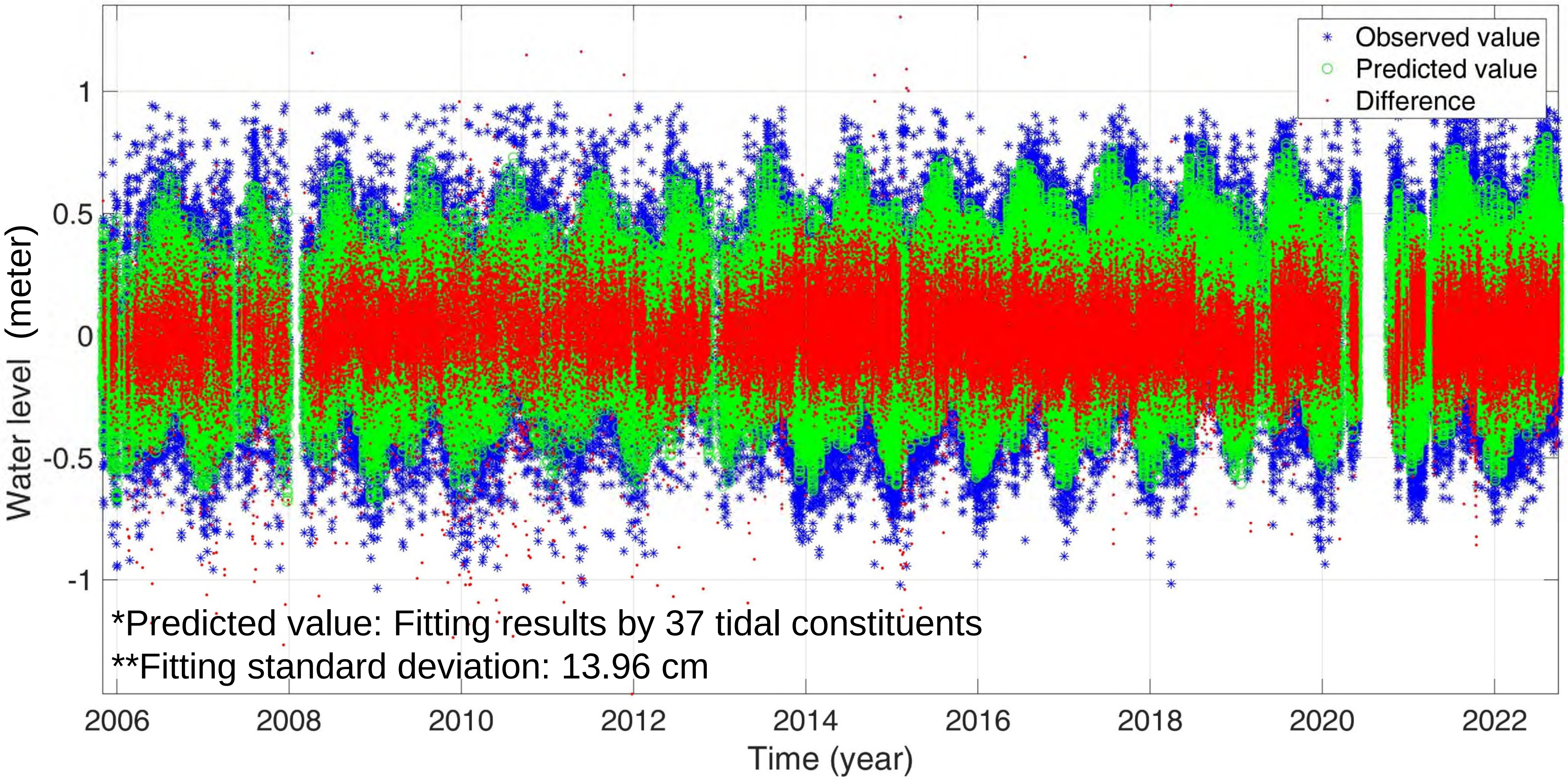
$\boldsymbol{R}$: Rainfall

**$M_f$ (13.6612 day), $M_m$ (27.5533 day), $S_a$ (364.9635 day), $S_{sa}$ (182.7040 day), and $M_N$ (18.6672 year)**

# GNSS-IR sea level retrieval

GNSS-IR related corrections:

① Tropospheric correction
② Dynamic sea surface (rhdot) correction
③ Inter-frequency bias correction
④ Inverse Barometer (IB) correction (monthly data)
⑤ APC to ARP correction
⑥ Nodal tide correction



# Compare with long-term tide gauge records

Tide gauge data
(referenced to geoid)

↓ TWVD2001

① Vertical land motion correction

② IB correction

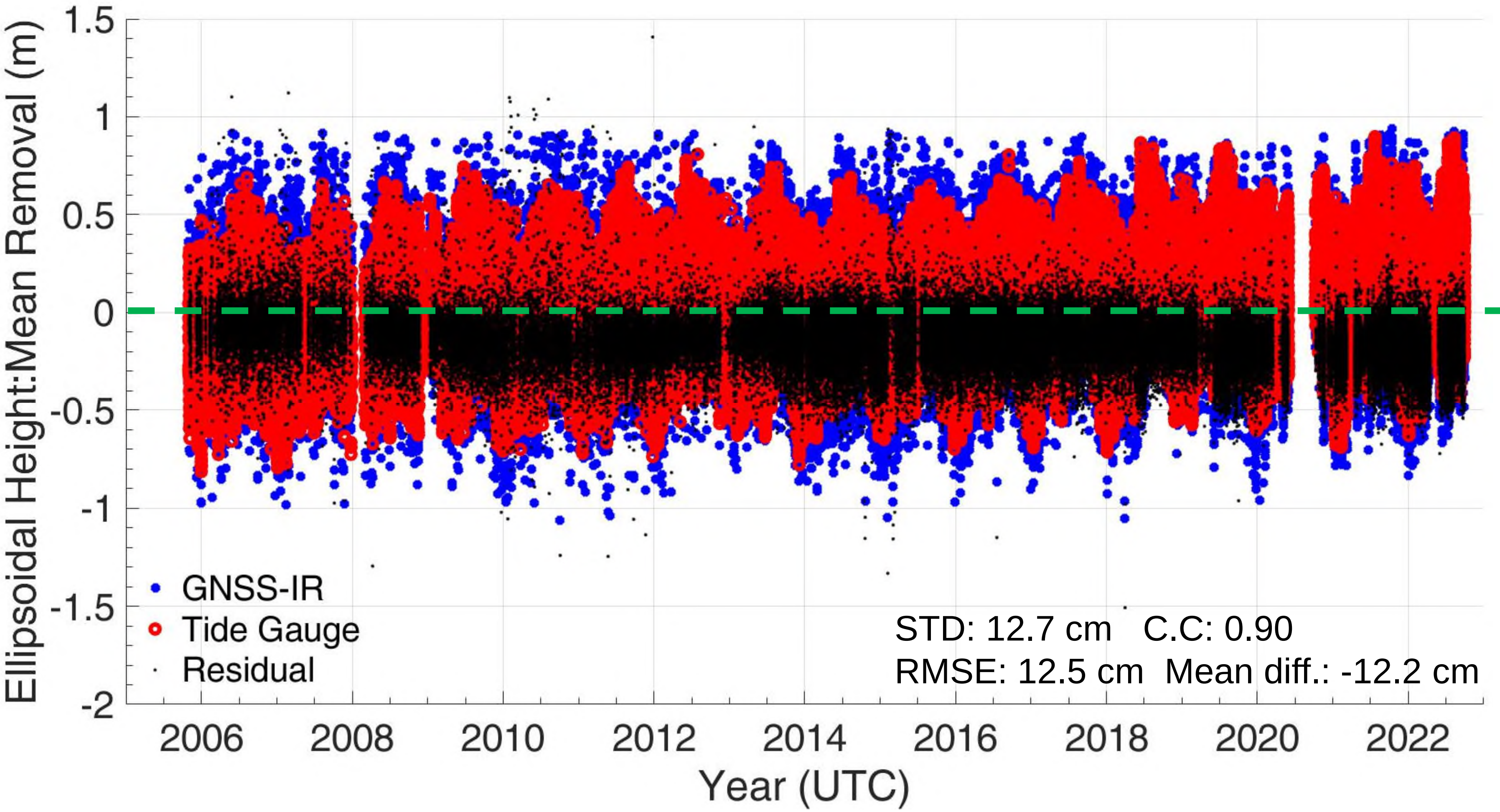
③ Add geoid undulation

↓

Tide gauge data
(referenced to ellipsoid)

↓

Compare with GNSS-IR result
(served as ground truth)




| KASH geoid Undulation | EGM96 | EGM2008 | 2015 Hybrid Geoid | 2021 Hybrid Geoid | Ellip.-Ortho. |
|---|---|---|---|---|---|
| | 20.300 m | 19.681 m | 20.287 m | 20.290 m | **20.240 m** |

# MSS results

| Method | Referenced Epoch | Mean sea level (m±mm) | | | | Mean |
|---|---|---|---|---|---|---|
| | | Arithmetic mean (Monthly data) | Six parameter fitting (Monthly data) | Tidal harmonic analysis (hourly data) | Multiple variable fitting (daily data) | |
| TG | 2025.0 (2025/1/1) | 20.535 m | 20.533m± 8.4 mm | 20.535m± 0.10 mm | 20.535m±7.0 mm | 20.535 |
| GNSS-IR | | 20.425 m | 20.423m± 8.1 mm | 20.404m± 0.40 mm | 20.423m±8.0 mm | 20.419 |
| Difference (GNSS-IR-TG) | | -0.110 m | -0.110 m | -0.131 m | -0.112 m | -0.116 m |

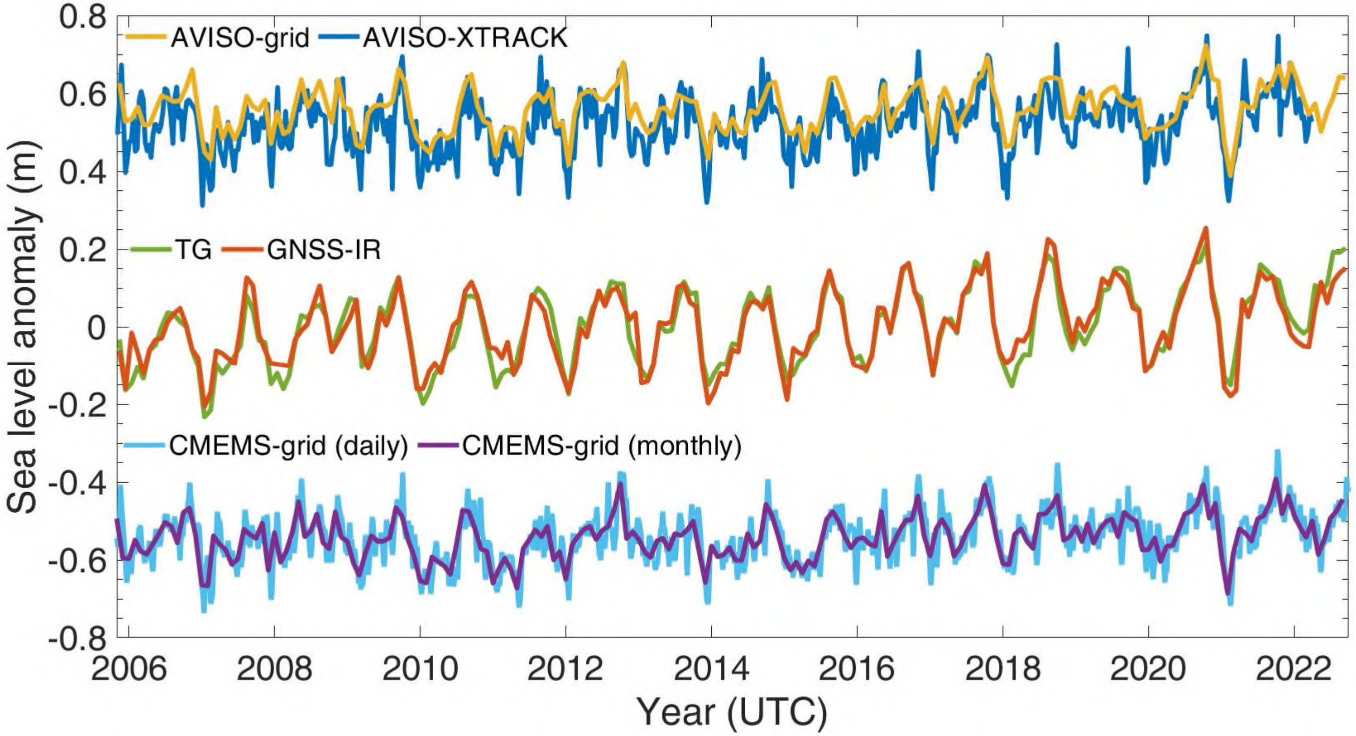
- Vertical discrepancy (datum shift)

1. Sea state bias (EM bias)
2. Vertical components

- ✓ Geoid undulation
- ✓ Benchmark change
- ✓ Equipment setting
- ✓ Etc.

| Date | Issue |
|---|---|
| 2015/08 | 1. Rebuild tide gauge benchmark (TG12)<br>2. Lose of first-order benchmark |

# Absolute Sea Level Changes




| Data Sources | Absolute sea level trend (mm/yr) |
|---|---|
| **Tide Gauge** | **5.32±0.65** |
| **GNSS-IR** | 3.93±0.69 |
| **AVISO (0.25°)** | 2.77±0.69 |
| **AVISO-XTRACK (100 km)** | 3.18±0.53 |
| **CMEMS-Monthly (0.125°)** | 3.35±0.59 |
| **CMEMS-Daily (0.125°)** | 3.36±0.13 |

# Tidal Surfaces in Depth Datum

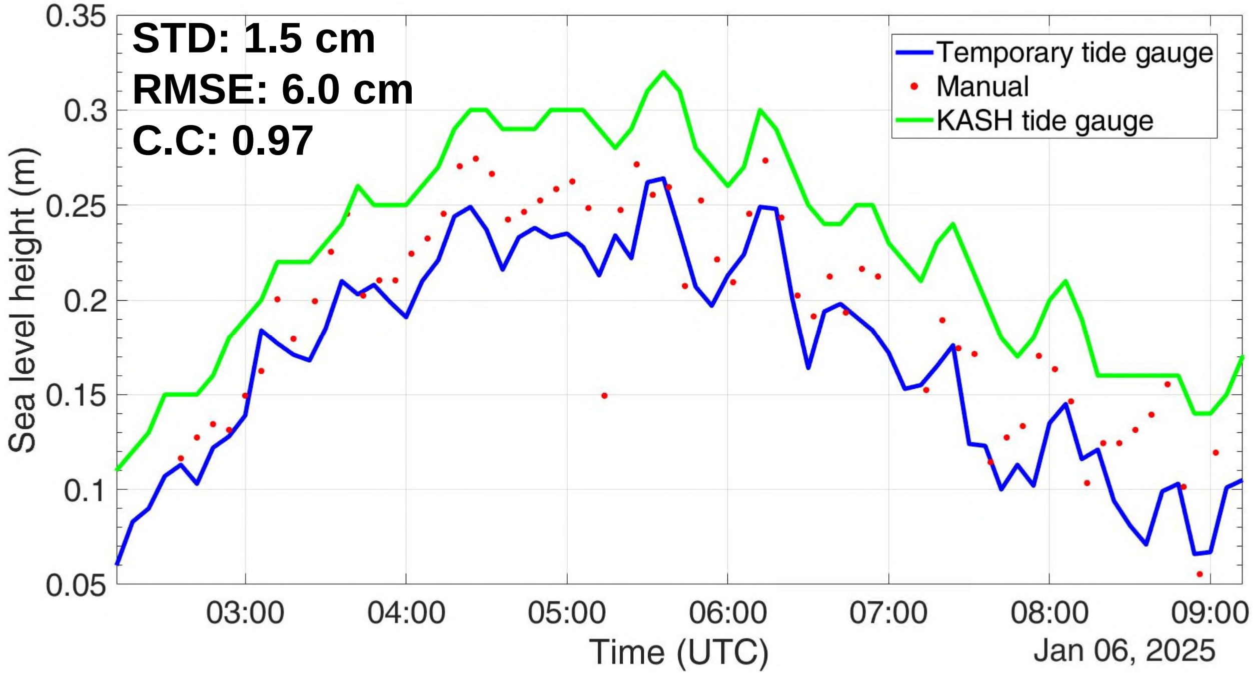
| Tidal Surfaces | GNSS-IR (m) | TG (m) | Differences (m) [GNSSIR－TG] |
|---|---|---|---|
| LAT | -0.676 | -0.673 | -0.003 |
| Highest Astronomical Tide (HAT) | 0.776 | 0.782 | -0.006 |
| Mean High Water (MHW) | 0.237 | 0.241 | -0.004 |
| Mean Low Water (MLW) | -0.235 | -0.242 | 0.007 |
| Mean High Water Springs (MHWS) | 0.254 | 0.253 | 0.001 |
| Mean Low Water Springs (MLWS) | -0.254 | -0.253 | -0.001 |
| Mean High Water Neaps (MHWN) | 0.119 | 0.114 | 0.005 |
| Mean Low Water Neaps (MLWN) | -0.119 | -0.114 | -0.005 |
| Indian Spring Low Water (ISLW) | -0.578 | -0.585 | 0.007 |
| Lowest Low Water (LLW) | -1.045 | -0.773 | -0.272 |
| STD | | | 0.005 |
| RMSE | | | 0.005 |

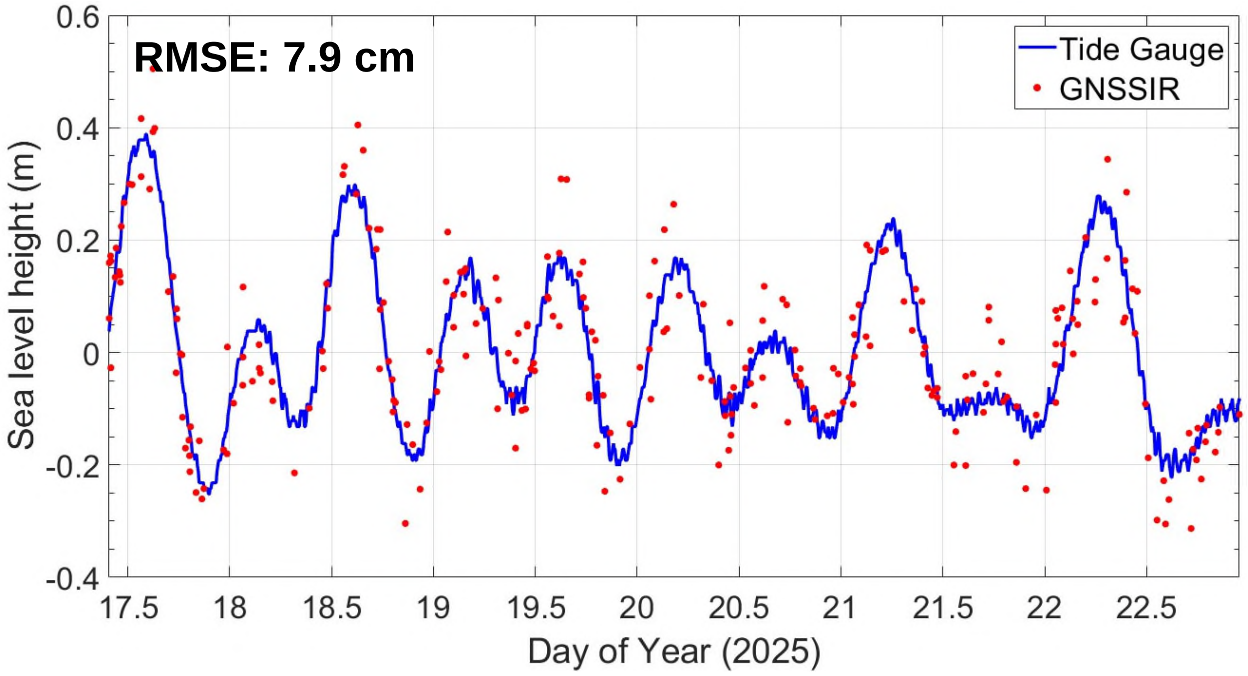
Note:

① MSS in each dataset is removed for comparison.

② The value of each tidal surface is the relative range to MSS

# Discussion




Elevation difference between TG12 and temporary tide gauge:

① Leveling: 2.5 cm

② e-GNSS: 2.9 cm

# Part I – Summary

① The findings reveal an average **datum offset** of **11.6 cm** between the measurements obtained from tide gauge and those derived from GNSS-IR.

② The sea level trend (3-4 mm/yr) derived from observations compared to trend computed from tide gauge data. **GNSS-IR demonstrates a better agreement with satellite altimetry**

③ GNSS-IR can effectively **capture most of the tidal characteristics and patterns**, achieving the **similar precision** comparable to conventional tide gauge.

④ A **datum issue** is identified in this study, indicating the need for further researches to analyze the underlying reasons and address potential inconsistencies in tide gauge measurements.

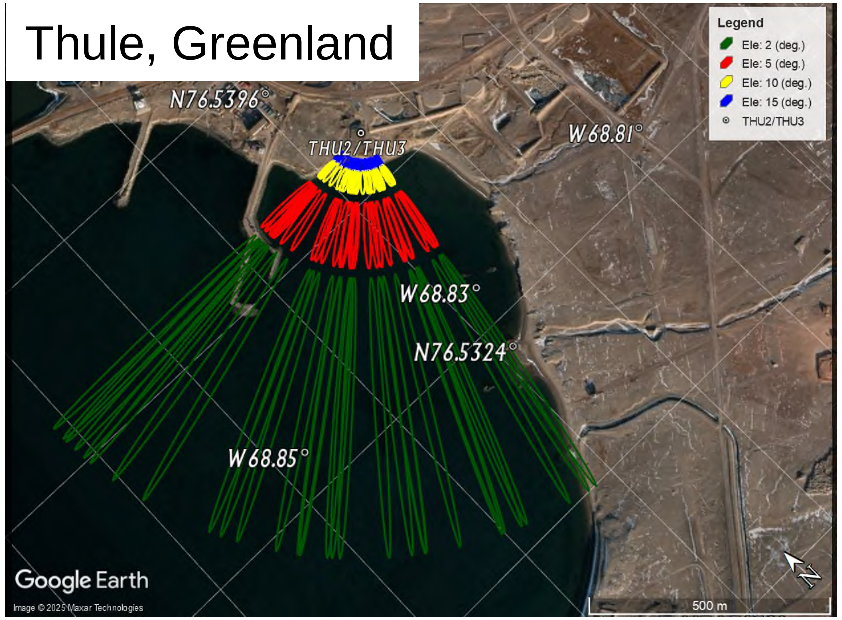
# Part II

## Monitoring Coastal Sea Level and Sea Ice Freeboard Variations in Polar Regions using GNSS Interferometric Reflectometry Technique

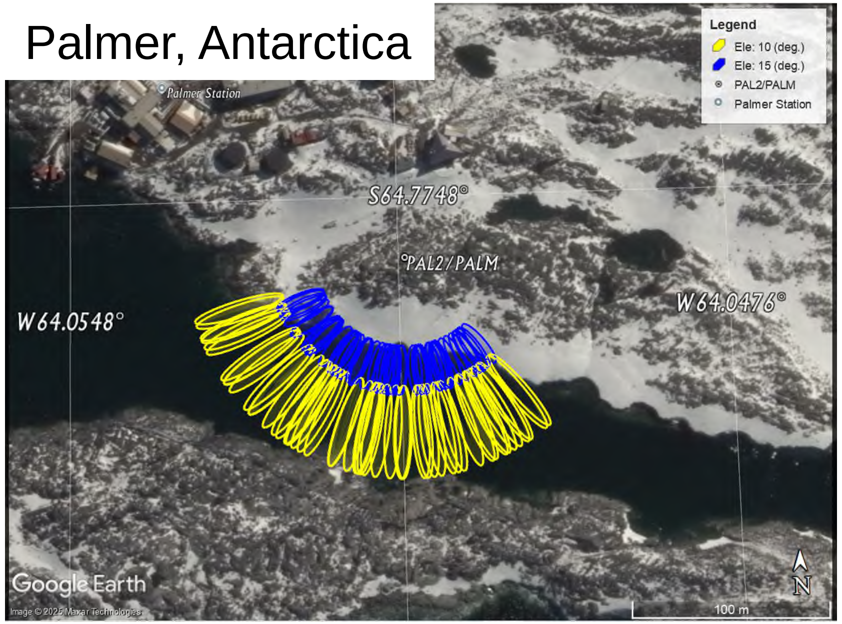
② Integrating **multi-frequency** and **multi-constellation** GNSS SNR data.

③ Simultaneous monitoring of **sea ice and sea level variations in polar regions**.

# Study Area and Data




**Station: THU2 (Main) & THU3**
**RH: 19.5 m**
**Ele.: 2° ~ 15°**
**Azi.: 190° ~ 270°**




**Station: PAL2 (Main) & PALM**
**RH: 15.4 m**
**Ele.: 10° ~ 15°**
**Azi.: 140° ~ 250°**

## Datasets:

① **GNSS SNR Data**
- **Multi-constellation and Multi-frequency**

② **Tide Gauge Data**
- **403 m → Thule Station**
- **214 m → Palmer Station**

③ **Sea Ice Concentration**
- **Evaluation of the sea ice dynamics**

④ **GNSS Velocity Field**
- **Estimation of vertical land motion (VLM)**

# Methodology

## ① Multi-frequency and Multi-constellation Integration Composite weighted scheme

$$\omega_i^{(short)} = \frac{Amp_i}{\max(Amp_{f_i})} * \frac{PNR_i}{\max(PNR_{f_i})}$$ → Short-term (instantaneous signal properties)

$$\omega_i^{(long)} = \frac{1}{\sigma_{f_i}{}^2}$$ → Long-term (stability of the corresponding frequency)

## ② K-Means Clustering for Reflective Surface Classification

Features: (1) **LSP amplitude** and (2) **Peak-to-noise ratio (RNR)**

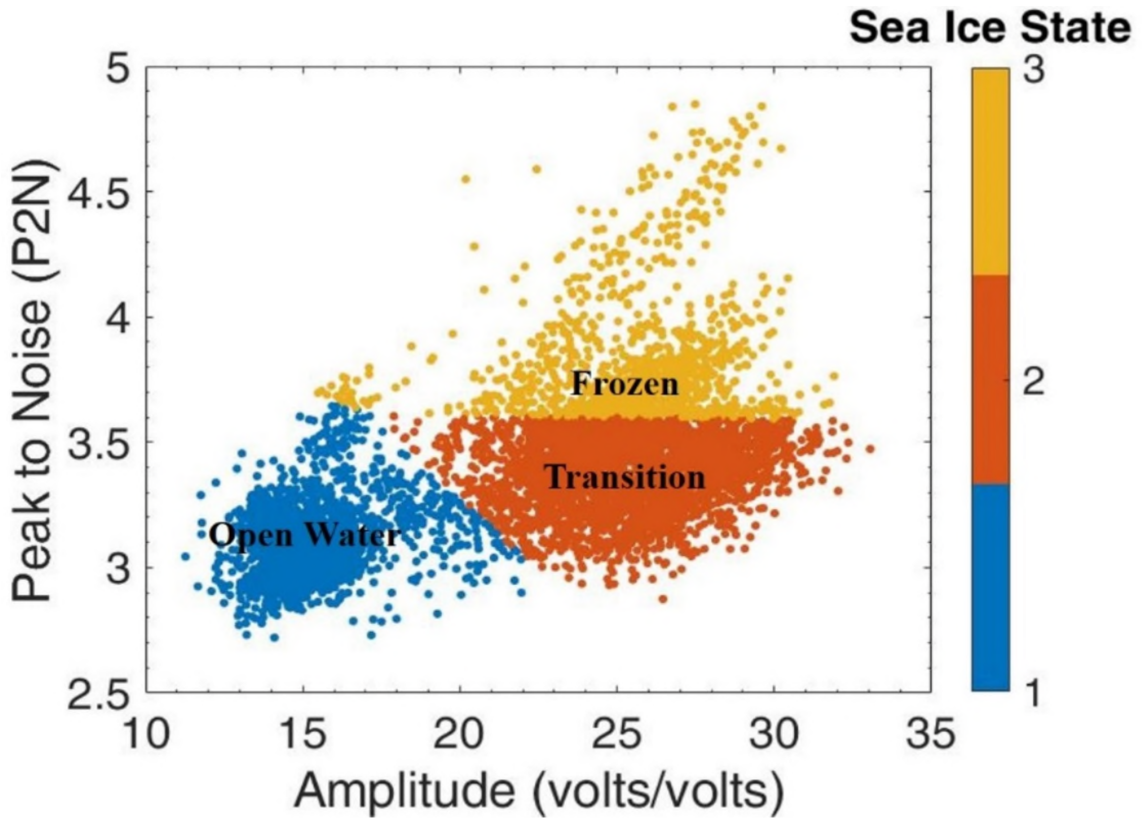
$$J = \sum_{k=1}^{K} \sum_{x_i \in C_k} \|x_i - \mu_k\|^2$$ [MacQueen, 1967]

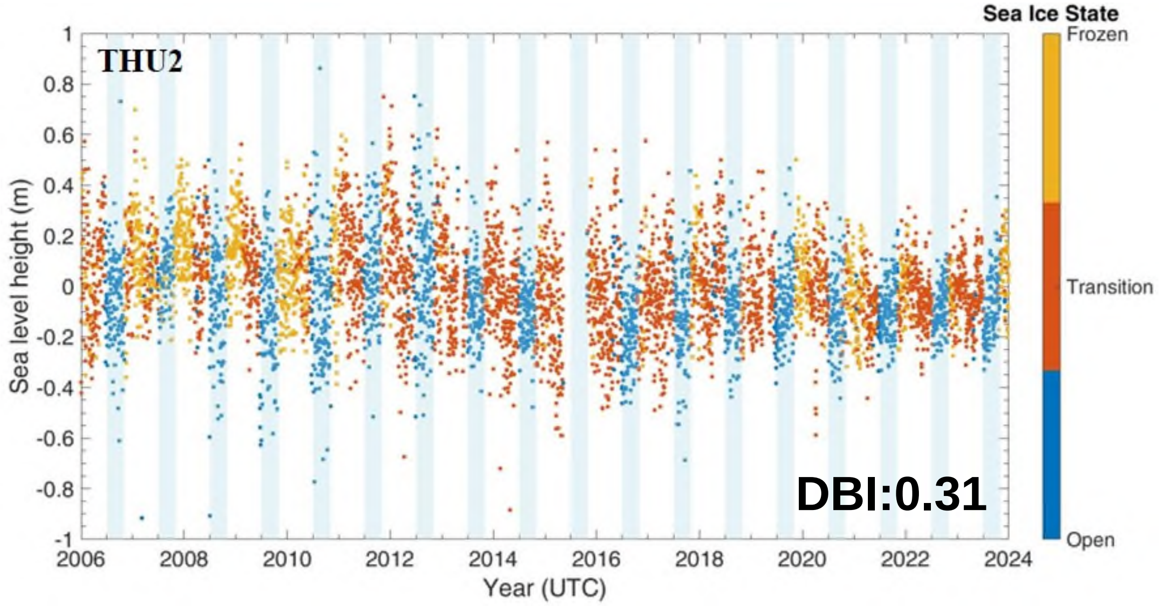
**Evaluation Index: Davies-Bouldin Index (DBI)→ [0,+∞)**

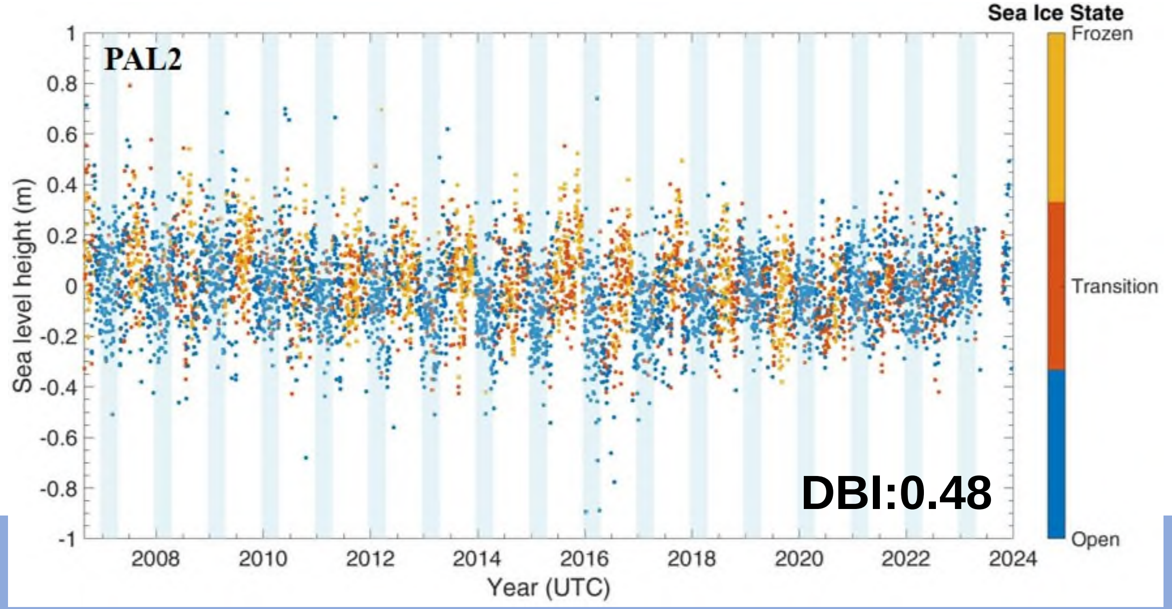
$$\bar{R} = \frac{1}{C} \sum_{i=1}^{C} R_i$$ [Davies & Bouldin, 1979; Vergani & Binaghi, 2018]

✓ **Smaller values → Better results**

# Reflective Surface Clustering




① Open Water: Sea water-only

② Transition: Sea water + Sea ice

③ Frozen: Sea ice-only

# Sea Level Monitoring

## ➢ Independent GNSS-IR Comparison

| THU2 vs. THU3 | | | | | | |
|---|---|---|---|---|---|---|
| **System** | RMSE (cm) | STD (cm) | Max. err. (cm) | C.C | $R^2$ | Slope |
| **GPS** | 13.2 | 13.2 | 40.8 | 0.98 | 0.96 | 0.98 |
| **ALL** | 13.4 | 13.4 | 41.8 | 0.98 | 0.96 | 0.98 |

| PAL2 vs. PALM | | | | | | |
|---|---|---|---|---|---|---|
| **System** | RMSE (cm) | STD (cm) | Max. err. (cm) | C.C | $R^2$ | Slope |
| **GPS** | 12.6 | 12.6 | 35.7 | 0.96 | 0.92 | 0.94 |
| **GLO** | 13.4 | 13.4 | 35.9 | 0.95 | 0.90 | 0.93 |
| **ALL** | 13.7 | 13.7 | 38.5 | 0.95 | 0.90 | 0.93 |

## ➢ Compare with Tide Gauge

**(Key info from Table 4-4)**

① GPS system, especially **GPS-L5 (Best RMSE: 13.3 cm)** and **GPS-L2C (Best RMSE: 14.1 cm)** frequencies, remains the most reliable system for GNSS-IR retrievals in polar regions.

② Long-term monitoring accuracy of approximately **20 cm (17.1 ~ 20.1 cm)** among the four stations.

③ GNSS-IR technique is capable of delivering **10 cm** or even **centimeter-level** accuracy under favorable conditions (sea water only).

# Tidal Analysis

➢ **Solve the GPS orbital error**

**THU2 (2022-2023)**

| Tide | TG | | GPS-only | | | | GNSS(G+R+E+C) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Amp. | Pha. | Amp. | Diff. | Pha. | Diff. | Amp. | Diff. | Pha. | Diff. |
| **K1** | 37.5 | 137.1 | 36.2 | **-1.3** | 136.4 | **-0.7** | 37.0 | **-0.5** | 137.1 | **0.0** |
| **K2** | 11.0 | 152.0 | 10.3 | **-0.7** | 147.4 | **-4.6** | 11.2 | **0.2** | 153.3 | **1.3** |

**PAL2 (2019-2023)**

| Tide | TG | | GPS-only | | | | GNSS(G+R) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Amp. | Pha. | Amp. | Diff. | Pha. | Diff. | Amp. | Diff. | Pha. | Diff. |
| **K1** | 31.9 | 287.9 | 29.4 | **-2.5** | 285.6 | **-2.3** | 30.2 | **-1.7** | 285.9 | **-2.0** |
| **K2** | 5.0 | 145.5 | 6.0 | **1.0** | 183.3 | **37.8** | 5.3 | **0.3** | 166.6 | **21.1** |

**PALM (2019-2023)**

| Tide | TG | | GPS-only | | | | GNSS(G+R+E+C) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Amp. | Pha. | Amp. | Diff. | Pha. | Diff. | Amp. | Diff. | Pha. | Diff. |
| **K1** | 31.9 | 287.9 | 30.1 | **-1.8** | 286.1 | **-1.8** | 32.1 | **0.2** | 288.8 | **0.9** |
| **K2** | 5.0 | 145.5 | 6.3 | **1.3** | 187.8 | **42.3** | 5.5 | **0.5** | 191.8 | **46.3** |

Amplitude Improvement (%) (on average)
**61% for K1**
**68% for K2**

Note: The units for Amp. and Pha. are cm and degree (°)

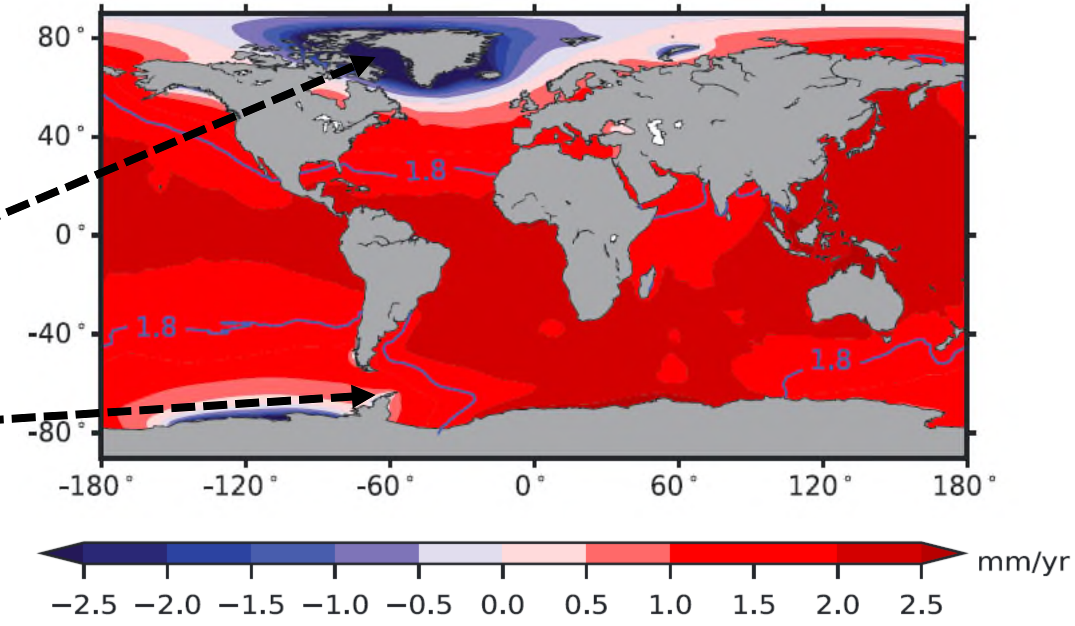
# Long-term sea level trend

| Region | Station | Relative trend | VLM | Absolute trend |
|---|---|---|---|---|
| Arctic | Thule TG | -8.69±1.29 | - | -2.30±1.39 |
| | THU2 | -7.94±0.85 | 6.39±0.51 | -1.55±0.99 |
| Antarctica | Palmer TG | -3.07±0.40 | - | 1.40±0.72 |
| | PAL2 | -3.66±0.53 | 4.47±0.60 | 0.81±0.80 |
| | PALM | -4.18±0.40 | 4.39±0.50 | 0.21±0.64 |

**Sea level fingerprint (SLF)**

↓

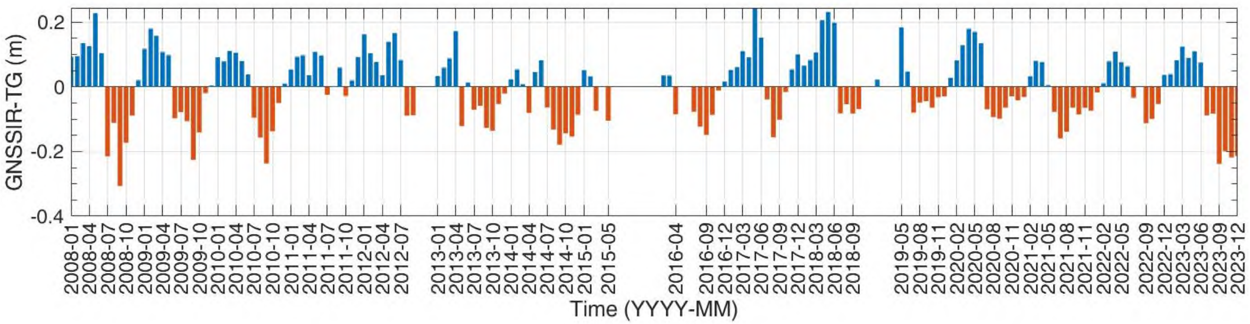
**Non-uniform sea level trend**

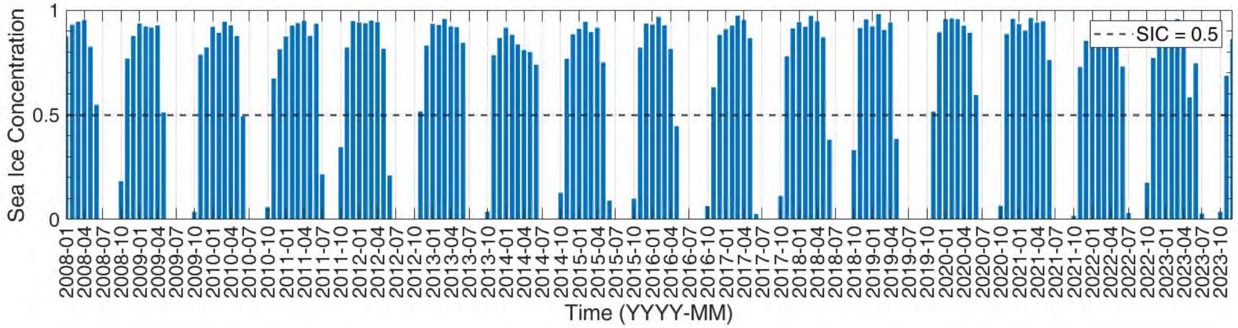



[Revised from Hsu & Velicogna, 2017 (Fig. 1)]

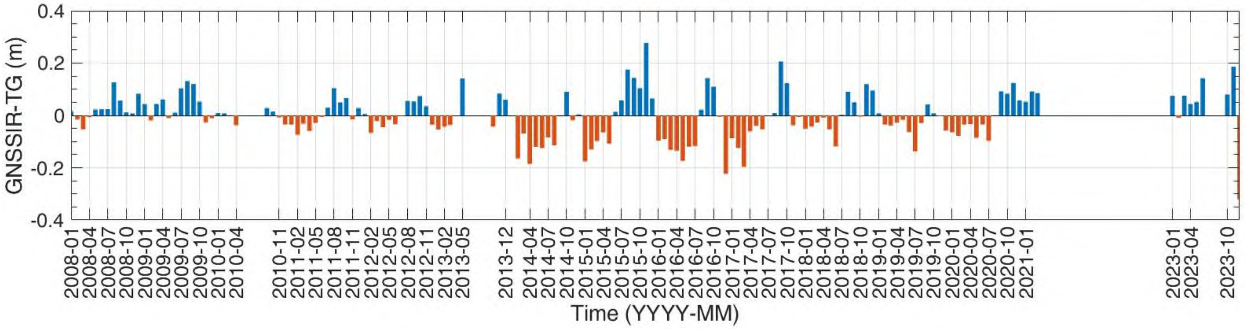
# Sea Ice Freeboard Variations

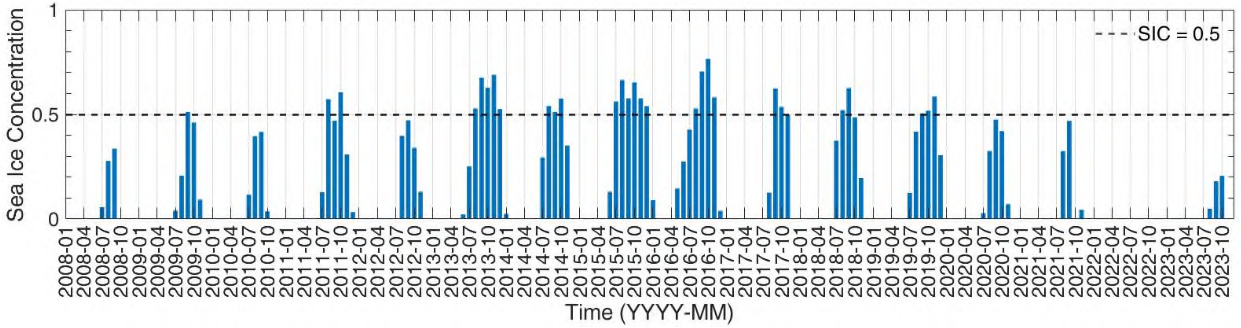
## THU2




## PAL2




| | Sea ice – THU2 | Open water – THU2 |
|---|---|---|
| Sea ice – SIC index (> 0.5) | 87/91 (96%) | 25/81(31%) |
| Open water – SIC index (< 0.5) | 4/91 (4%) | 56/81 (69%) |

| | Sea ice –PAL2 | Open water – PAL2 |
|---|---|---|
| Sea ice – SIC index (> 0.5) | 46/75 (61%) | 4/84 (5%) |
| Open water – SIC index (< 0.5) | 29/75 (39%) | 80/84 (95%) |

# Polar GNSS-IR Stations Deployment

➢ Recommendations:

① Location: The **western coast of Greenland** and the **Antarctic Peninsula**

② Instrumentation: **Multi-frequency**, **Multi-constellation** (at least two) GNSS receivers

③ Data Frequency: Ideally recorded at **1 Hz** sampling rates

⬇ Integrate to existing observation networks

✓ Polar Earth Observing Network (POLENET)
✓ Greenland GNSS-Network (GNET)
✓ GNSS-IR portal under Permanent Service for Mean Sea Level (PSMSL)

# Part II – Summary

① This study accomplished reflective surface clustering based on **LSP amplitude** and **PNR** features using **K-means clustering**.

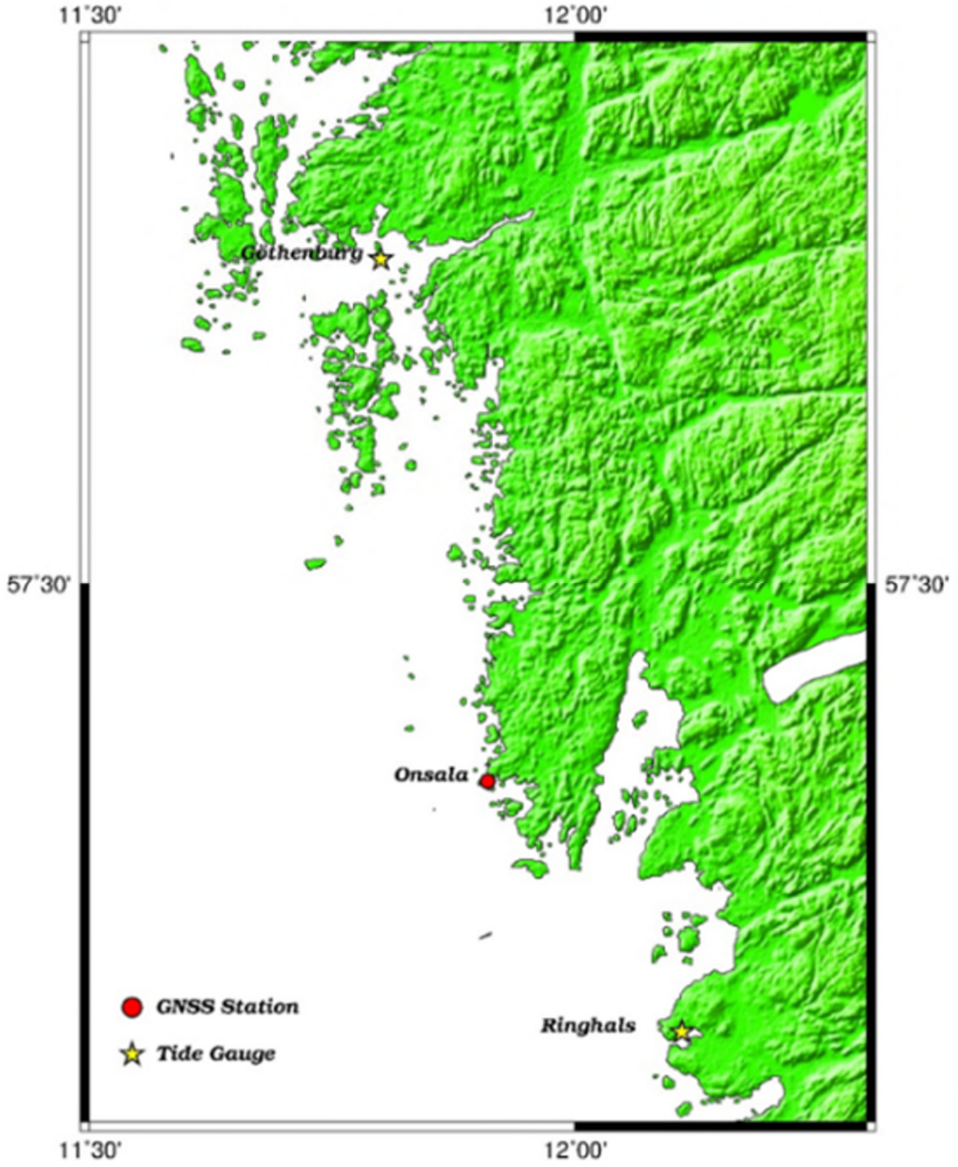
② GPS signals, particularly those at **GPS-L5** and **GPS-L2C** frequencies, yielded the most stable and accurate results.

③ **Multi-constellation** and **multi-frequency** integration significantly improved tidal constituents' **resolution** and mitigated **system-specific biases**. Additionally, the proposed **weighted scheme** was shown to maintain the overall accuracy of GNSS-IR observables by minimizing the influence of lower-precision retrievals.

④ This study demonstrated the feasibility and robustness of applying GNSS-IR techniques for **coastal sea level monitoring** and **sea ice characterization** in polar environments, where traditional observation methods are often logistically challenging and sparse.

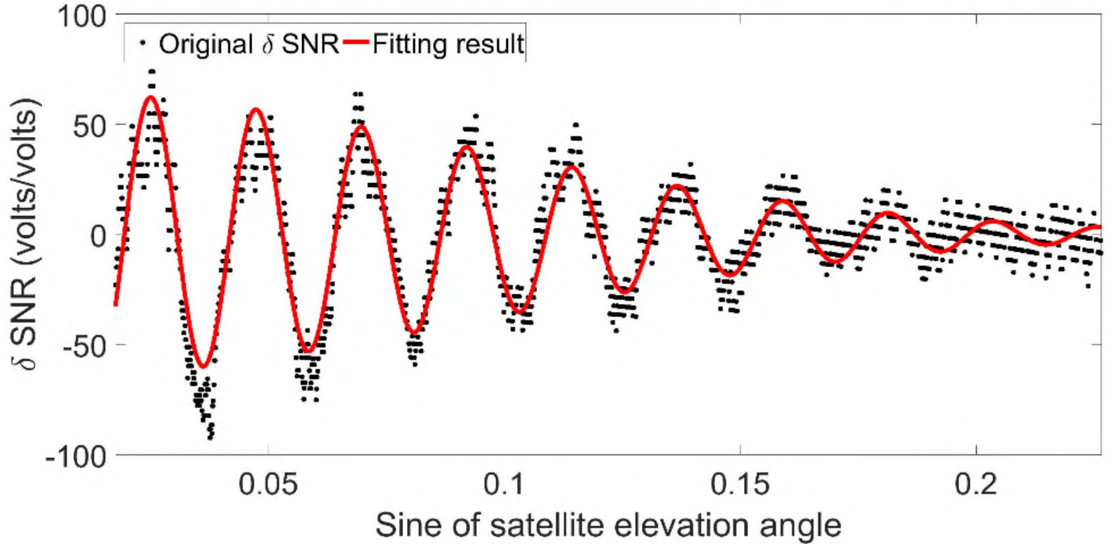
# Study areas

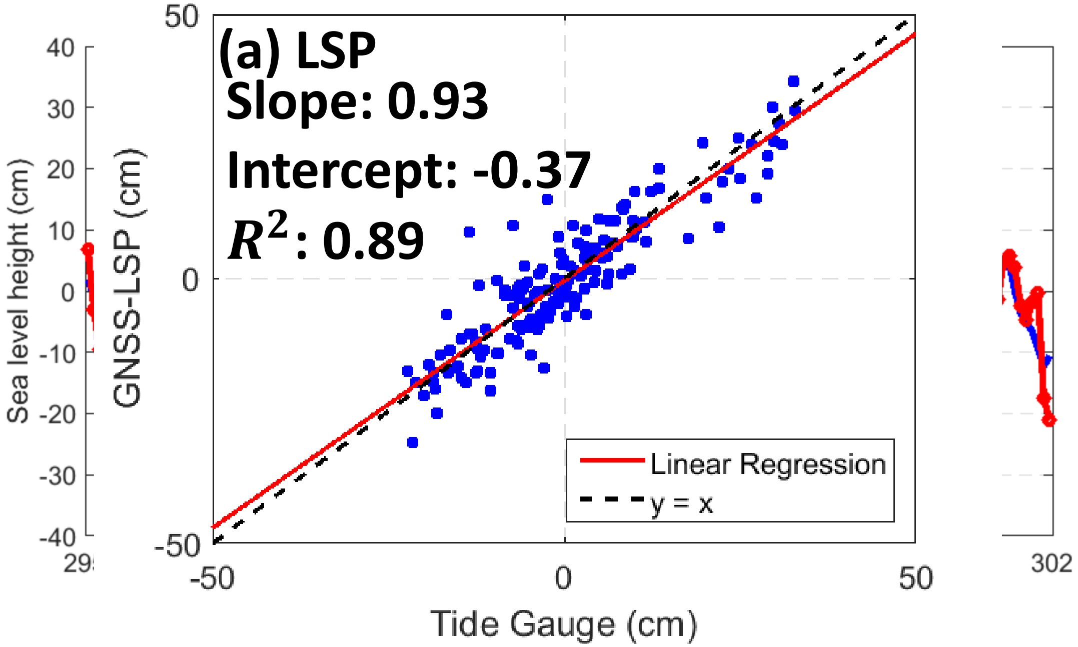
Onsala - Sweden

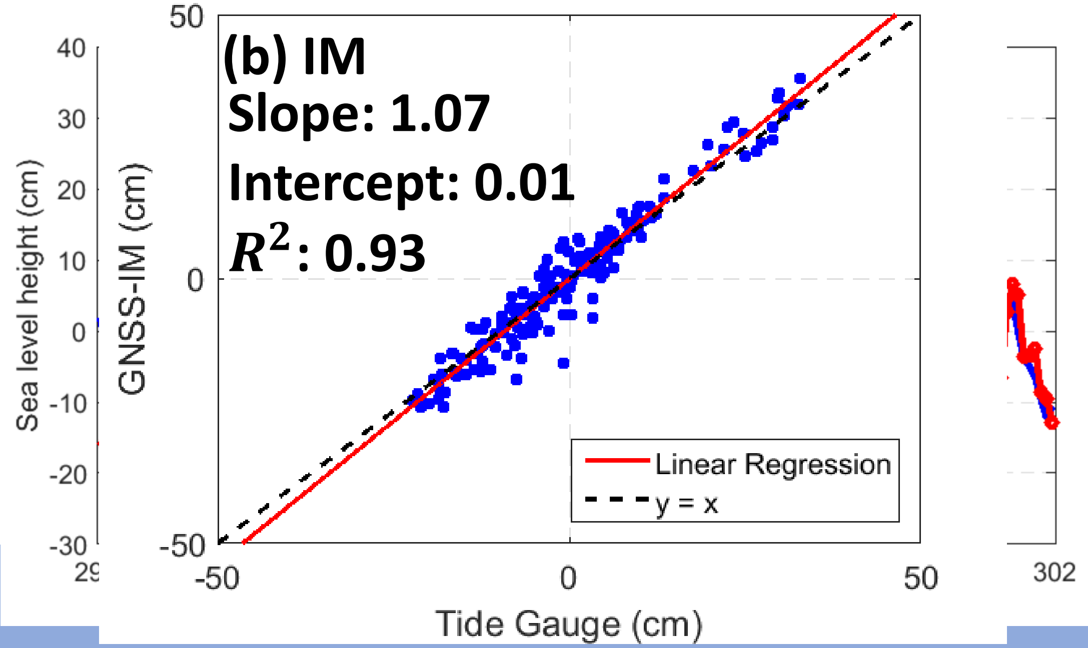



[Resource: http://wx.oso.chalmers.se/data/gnss_tide_gauge/]

# Onsala result – LSP vs IM




| Method | LSP | IM |
|---|---|---|
| Number of solutions | 157 (93%) | 167 (99%) |
| STD (cm) | 5.5 | 3.5 |
| Mean diff. (cm) | < 0.0 | < 0.0 |
| Max. diff (cm) | 22.2 | 15.1 |
| C.C | 0.91 | 0.97 |

# GNSS Buoy: PPP 與 PPK 優缺點比較表

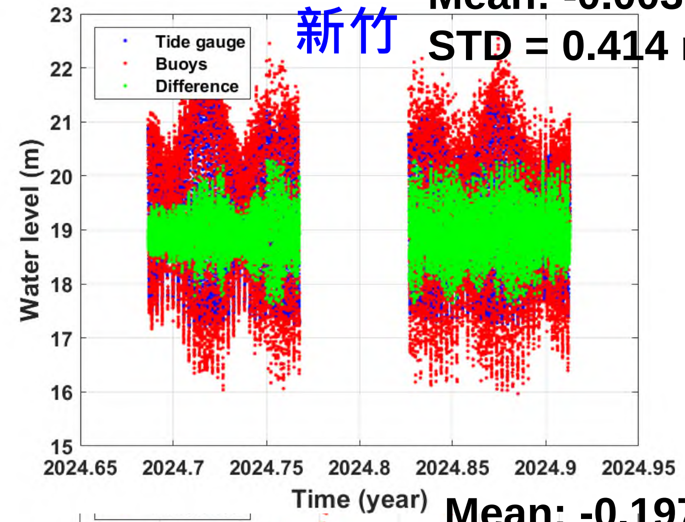
| 項目 | PPP（精密單點定位） | PPK（後處理動態差分定位） |
| --- | --- | --- |
| 是否需基準站 | 不需要 | 需要（自建或使用 CORS） |
| 適用範圍 | 全球皆可（不限距離） | 基準站附近（10–50 公里內最佳） |
| 精度 | 公分級～數公分級 | 公分級～公釐級 |
| 收斂時間 | 長（約 15–60 分鐘才能穩定） | 短（幾分鐘內即可） |
| 優點 | 成本低、全球適用、單機即可 | 精度高、收斂快、適合高精度需求 |
| 缺點 | 收斂時間長、動態精度受限 | 需基準站資料、作業範圍受限 |
| 適合場景 | 偏遠地區、海上作業、飛行定位 | 測量放樣、航拍測圖、工程應用 |

# GNSS Buoy

- 氣象署目前已有GNSS浮標在新竹(儀器於2024年12月故障，但於2025年第三季剛更換)和臺南安平外海進行資料收集，彰化外海GNSS浮標尚未取得資料。以下成果並未修正浮標傾斜。

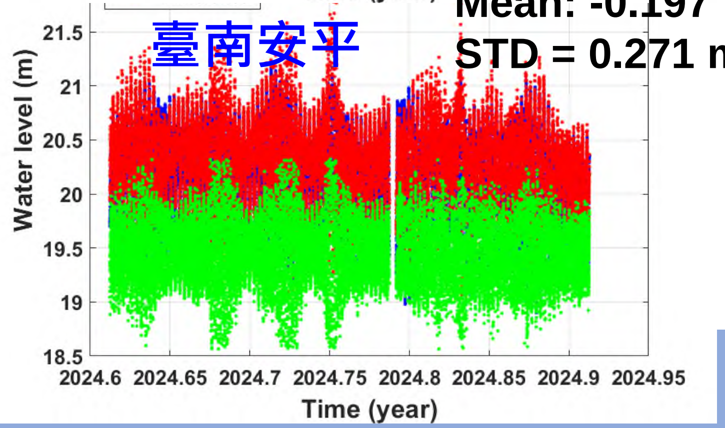
新竹

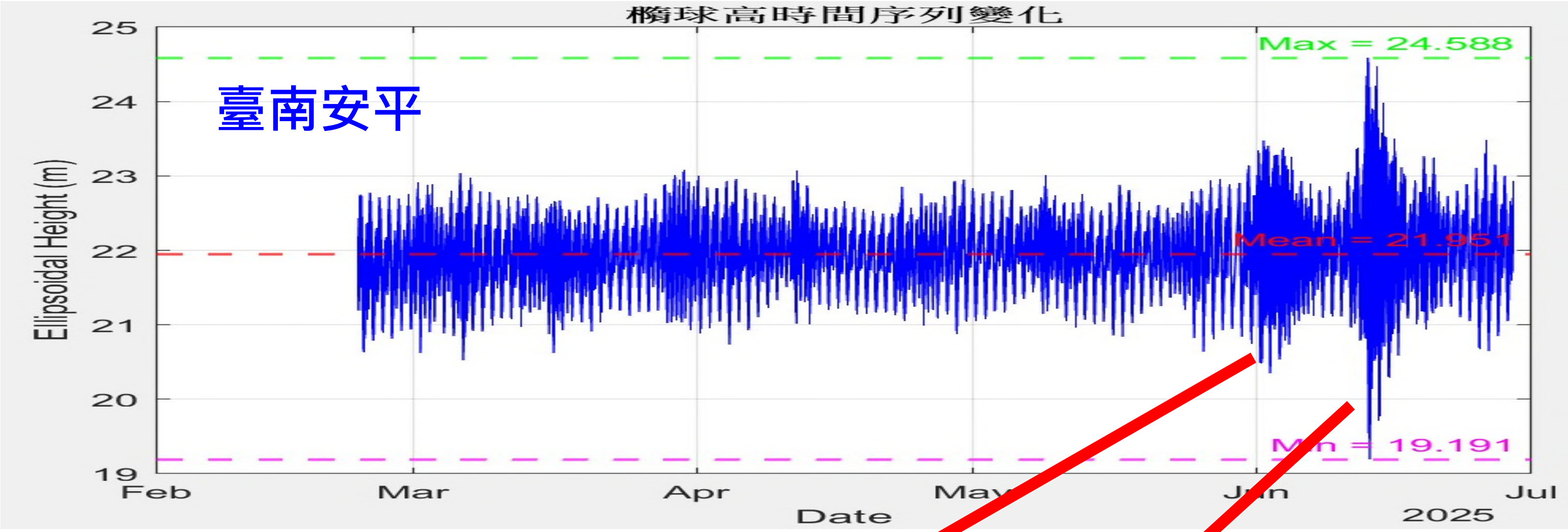
Mean: -0.003m
STD = 0.414 m



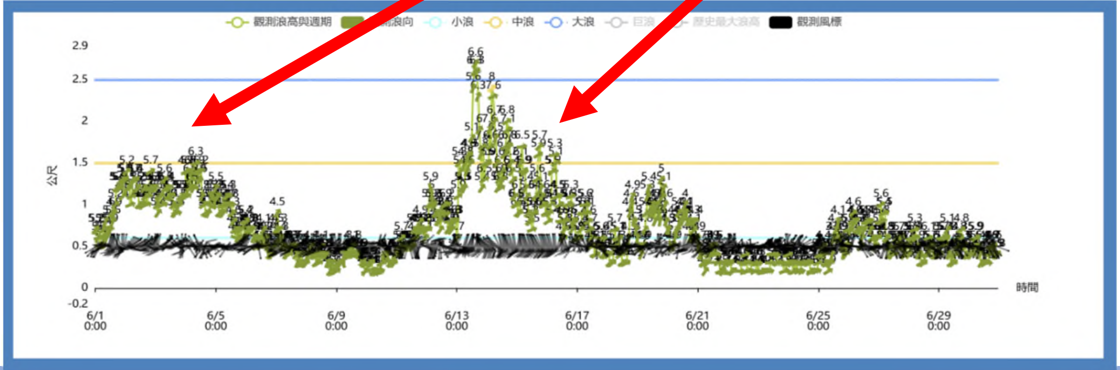

臺南安平

Mean: -0.197 m
STD = 0.271 m



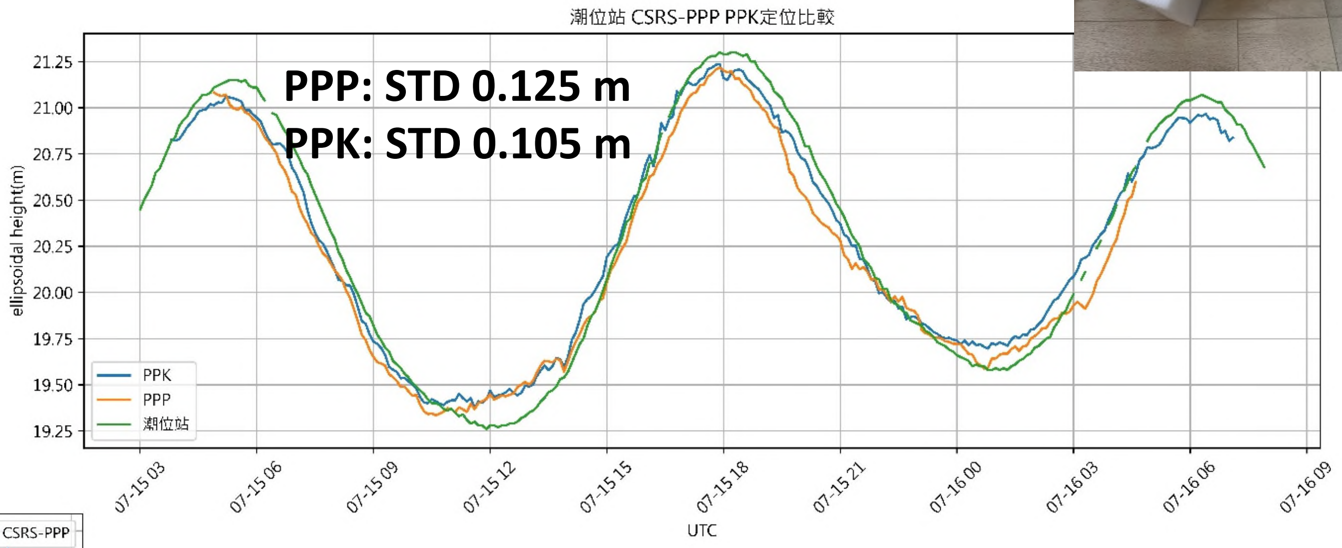

臺南七股中央氣象署資料浮標2025年6月浪高與週期觀測量

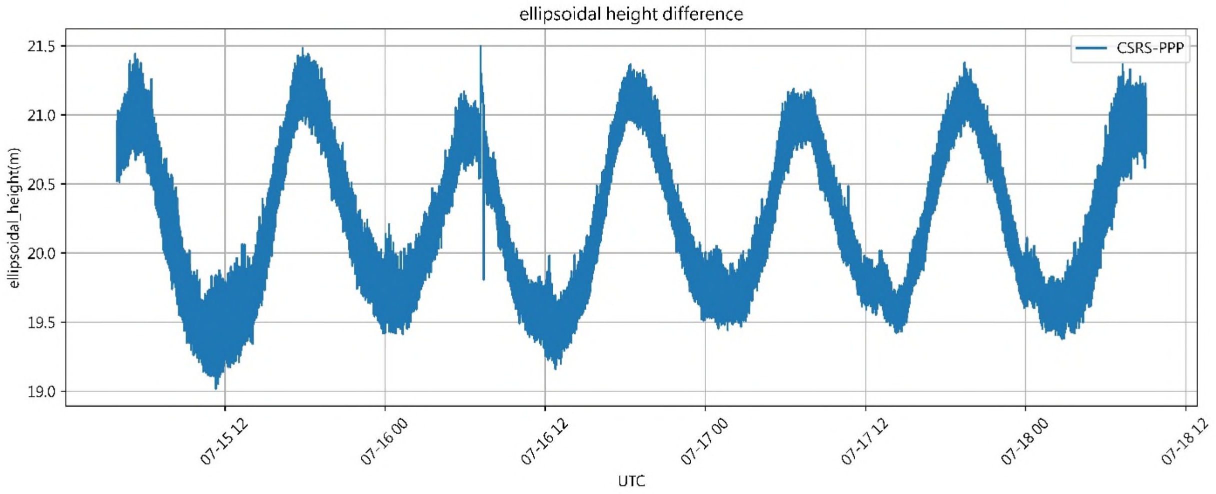


# GNSS Buoy

- 流浪者小型GNSS浮標於新北白沙灣外海置設測試。

GNSS浮標
設置位置




GNSS浮標PPP和PPK(相對於石門站)定位解和麟山鼻潮位站計算之大地起伏分別為19.713m和19.776m，內政部[2018a]提供之麟山鼻潮位站觀測大地起伏19.722m

# Conclusions

1. GNSS-IR能有效提供海水面高度觀測量
2. GNSS浮標能有效提供海水面高度觀測量

## Future work

- Real-time GNSS-IR and GNSS Buoy monitoring systems

# Conclusions

➢ **Contributions of this research**

1. **Evaluation and Comparisons of Signal Extraction Methods**

✓ SSA can address **low-frequency interference** and **multi-peak issues**

2. **Automated and Objective Classification of Reflective Surfaces**

✓ K-means clustering enhances **GNSS-IR data interpretation** and facilitates more accurate monitoring of **sea level and sea ice dynamics**.

3. **Multi-frequency and Multi-constellation Integration and Its Impact on Tidal Constituents**

✓ Improve the accuracy of **tidal constituents** determination

✓ Mitigate the **system-specific bias**

# Conclusions

➢ **Contributions of this research**

4. **Sea Ice Freeboard Monitoring by GNSS-IR Technique**

✓ A significant novel application of GNSS-IR in this study is the **successful detection of sea ice freeboard variations**.

5. **Determination of Vertical and Depth Datums by utilizing GNSS-IR**

✓ The research successfully established reference surfaces such as the **MSS** and **LAT** using GNSS-IR data

# Future Work

1. **Advanced signal extraction algorithms**

✓ Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs)

2. **Enhanced surface classification with machine learning techniques**

✓ Support Vector Machines (SVMs), Random Forests (RF)

3. **Multi-GNSS data fusion and error modeling**

✓ Atmospheric, instrumental errors, and sea state bias (SSB) corrections

4. **Real-time GNSS-IR monitoring systems**

✓ Kalman filtering, sequential least squares estimation, recursive Bayesian methods