Comparing ICESat-2, SWOT, and GNSS-Reflectometry Water Surface Profiles over the Tonle Sap Lake

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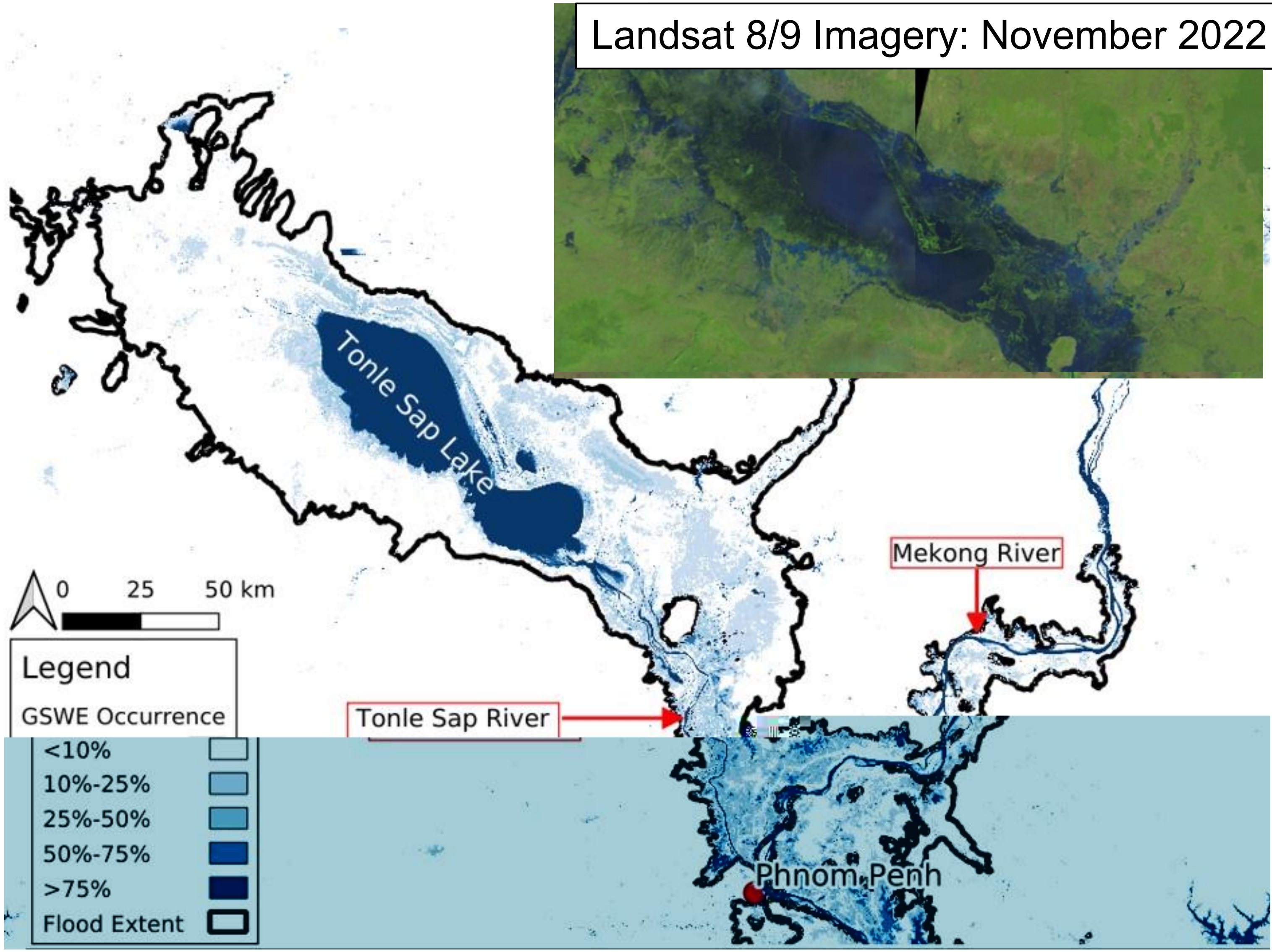
Motivation & Focus Area

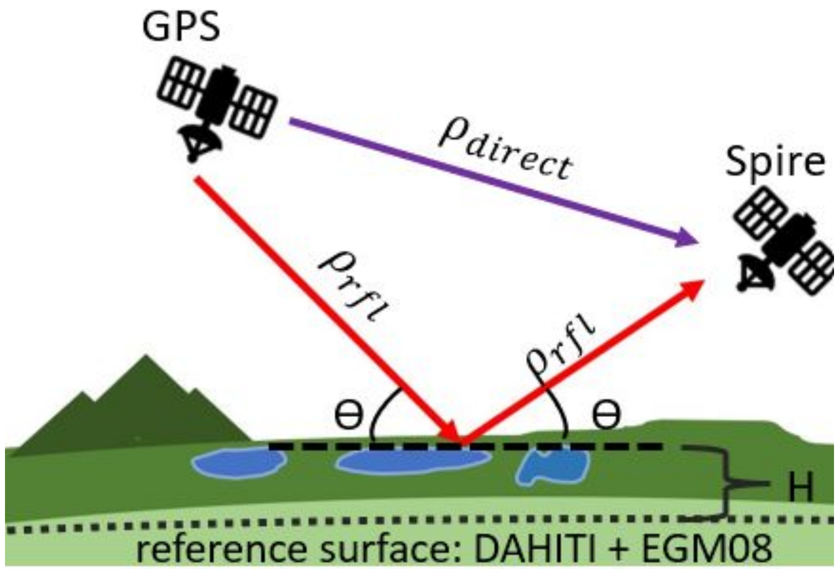
- **Motivation:**
  The impact of changing conditions (e.g., drought, damming) can be studied by looking at changes in the surface profile of inland water bodies measured by GNSS-Reflectometry

- **Focus Area: Tonle Sap Lake, Cambodia**
  – Dry season (Nov-May):
    - ***Lake drains into the Mekong River***
    - ***Water Level ~2m; 2500 km^2 surface area***
  – Rainy season (June-Oct):
    - ***Mekong floods-> Tonle Sap river reverses & fills the lake***
    - ***Water level rises to 10 m; 15000 km^2 surface area***



Dataset 1: Spire grzRfl GNSS-R

- **Polar, ~500km Orbit**
- **Dual frequency GPS L1(1575.42 MHZ) & L2 (1227.6 MHz)**
- **Grazing angle:**
  - 5-30deg elv. angle
- **Land collections Feb, 2021 – Present (our study is 2021-2023)**
- **50 Hz, L1B Product:**
  - Georeferenced excess carrier phase & power data
- **Carrier-phase height is relative**
  - Reference surface from DAHITI+EGM08



$$H = -\frac{\Delta\rho_{meas} - \Delta\rho_{mod} - B + \epsilon}{2\sin(\theta)}$$

$\Delta\rho_{meas} = \lambda_L(\phi_L^R - \phi_L^D) + \lambda_L n_L$ $\quad\epsilon = error$

$\Delta\rho_{mod}$ = *modelled bistatic delay (geometric range, troposphere, ionospheric advance, carrier ambiguity)*

C. Roesler, et al., 2022

Dataset 2: ICESat-2

- **532 nm photon-counting with 6 laser beams:**
  - 3 strong, 3 weak
- **10 kHZ PRF**
- **Absolute height measurement measuring 2-way time of flight**

- **ATL03 Product: georeferenced photon level data product**
- **Height measured as the median value between GNSS-R specular points (relative to EGM08)**

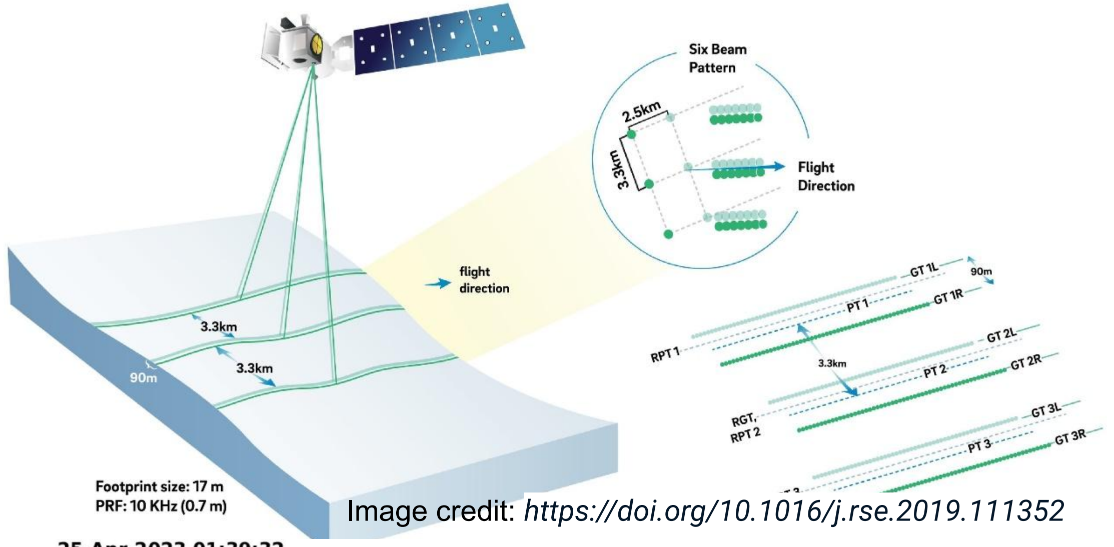
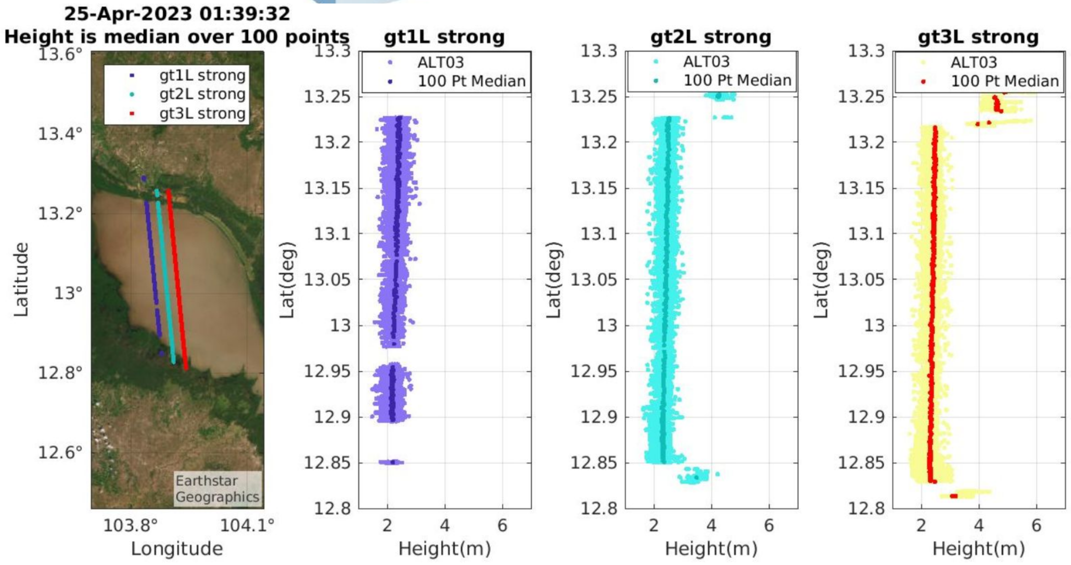


Image credit: *https://doi.org/10.1016/j.rse.2019.111352*



Dataset 3: Surface Water and Ocean Topography (SWOT)

- **Launched 2022**
- **Primary Instrument KaRIN:**
  - Near-Nadir Ka-band Interferometric SAR
  - 35.75 GHz (Ka-band)
- **Data products used:**
  - PIXC
  - L2 rasterized product

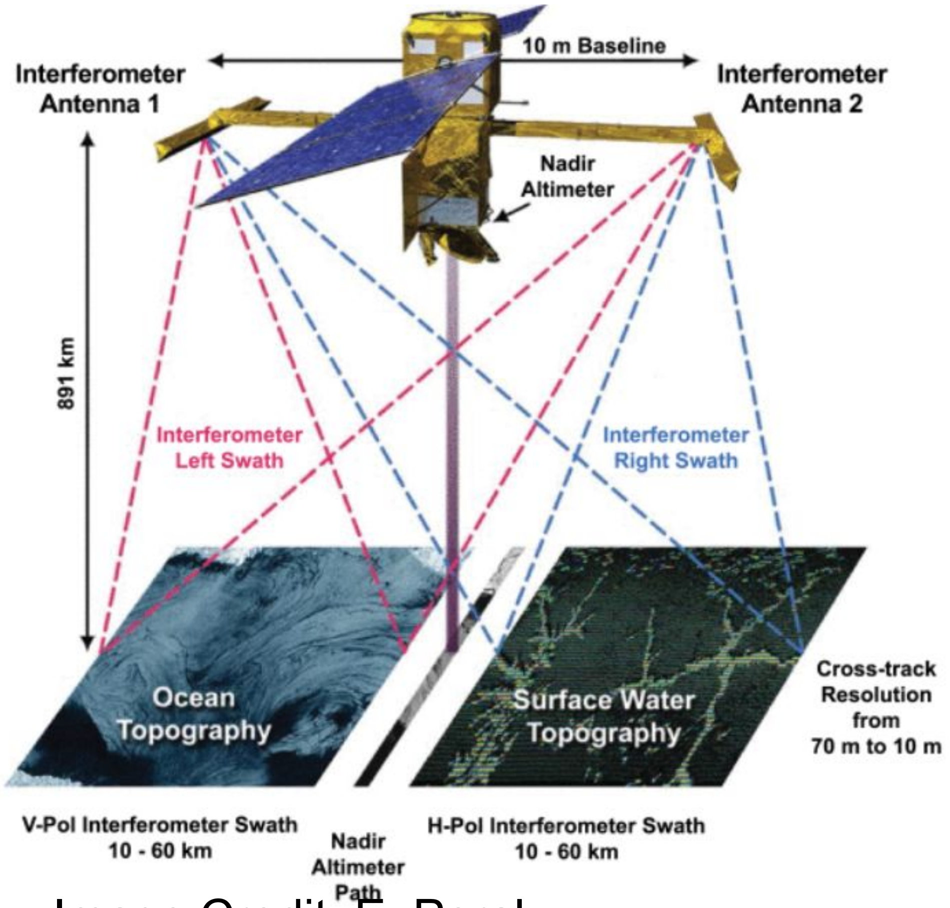
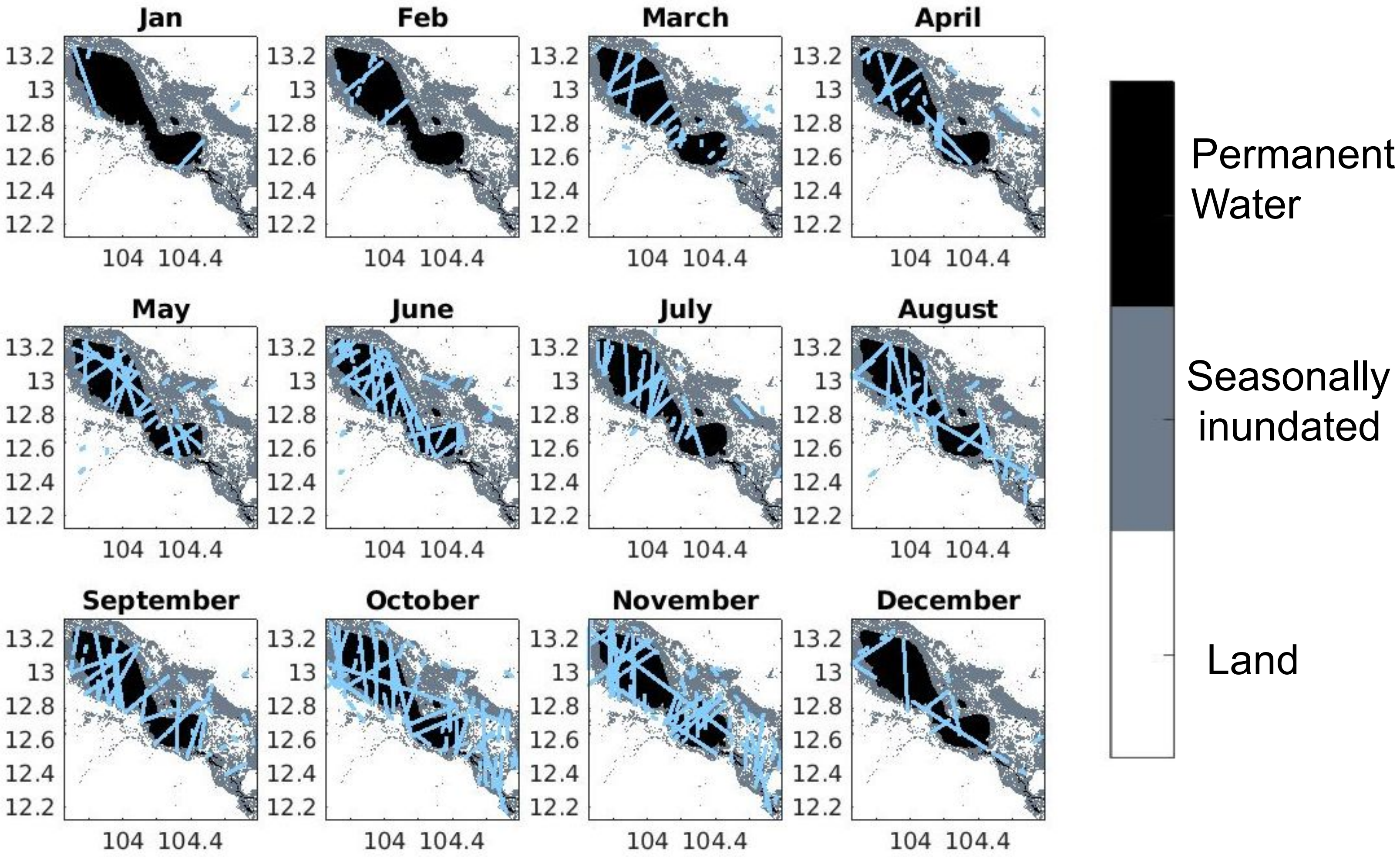


Image Credit: E. Peral (2024)

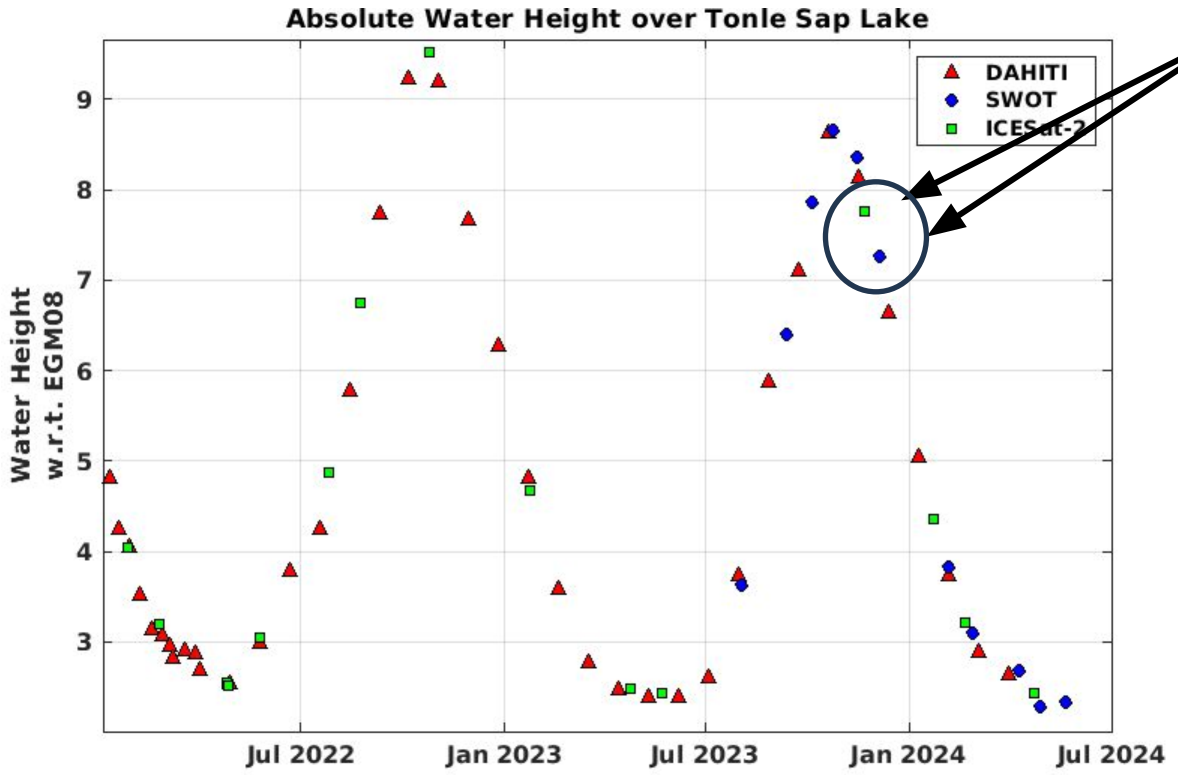
Why GNSS-R?

- **High spatial & temporal resolution**
- **Diverse look directions across lake**
- **Penetrates cloud and vegetation cover**

Accumulated Coherent Spire GNSS-R Tracks, 2021-2024



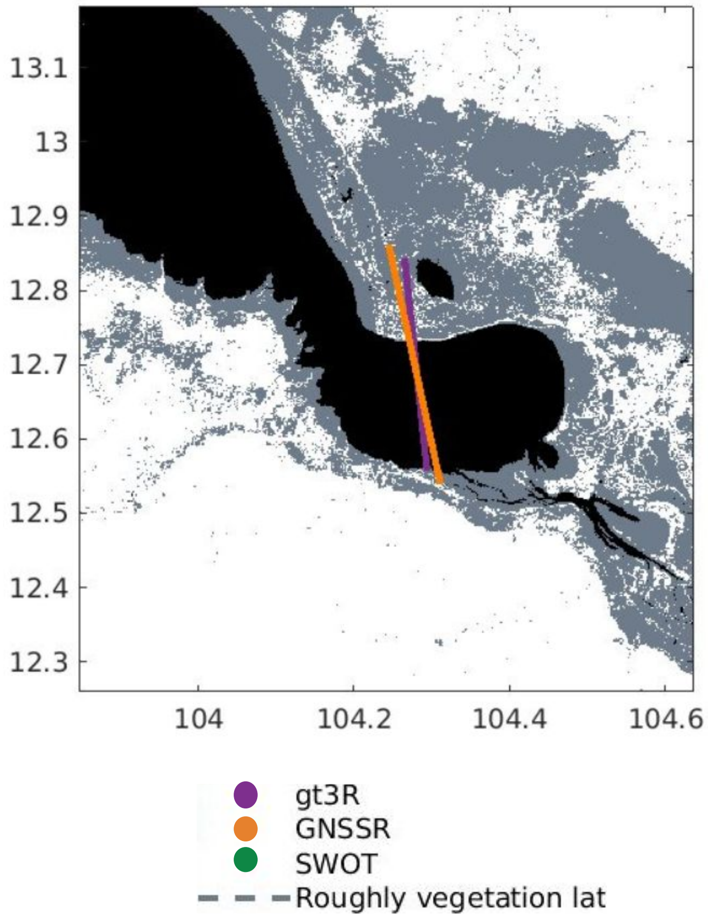
Motivation Methods Results Summary

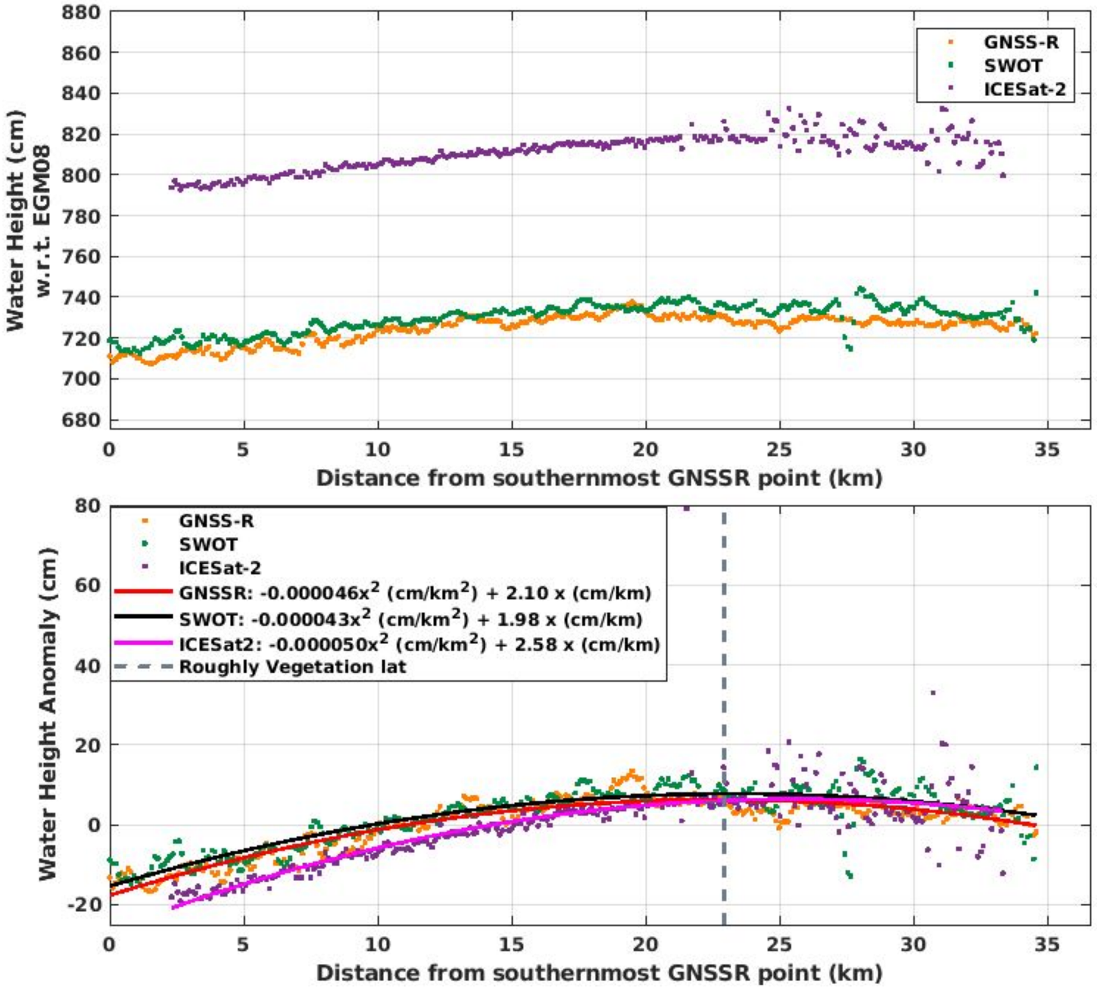


Nov/Dec, 2023
(8→7.3m)

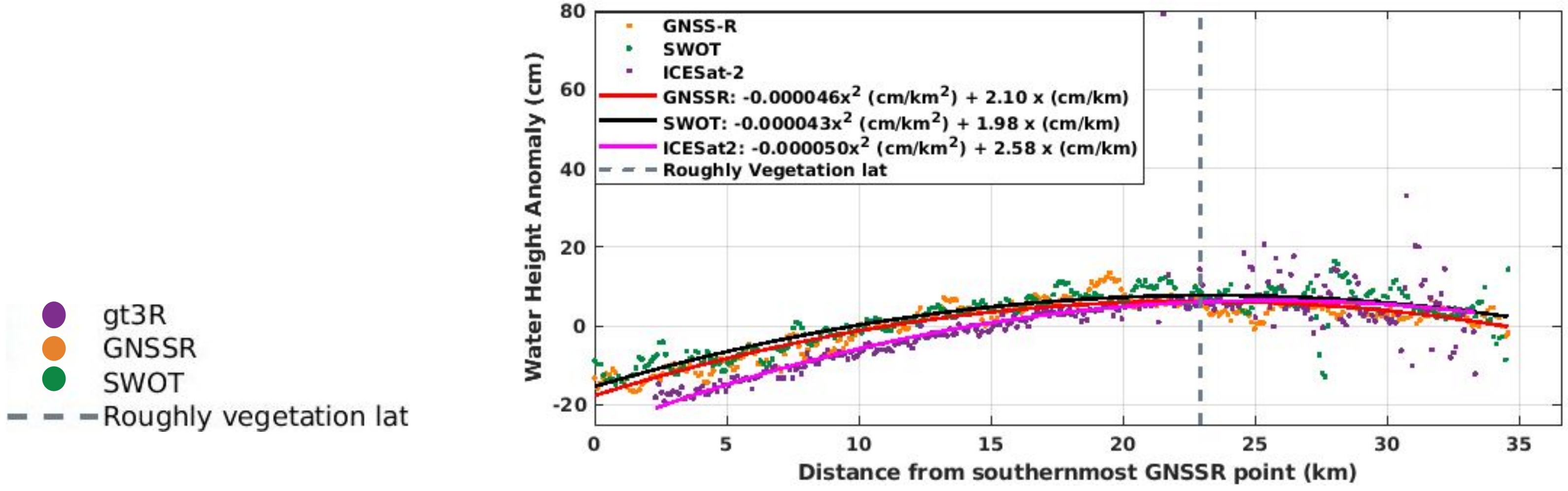
Results: 1 Case Study

November 21, 2023 (ICESat-2), December 2, 2023 (GNSSR), & December 4, 2023 (SWOT)

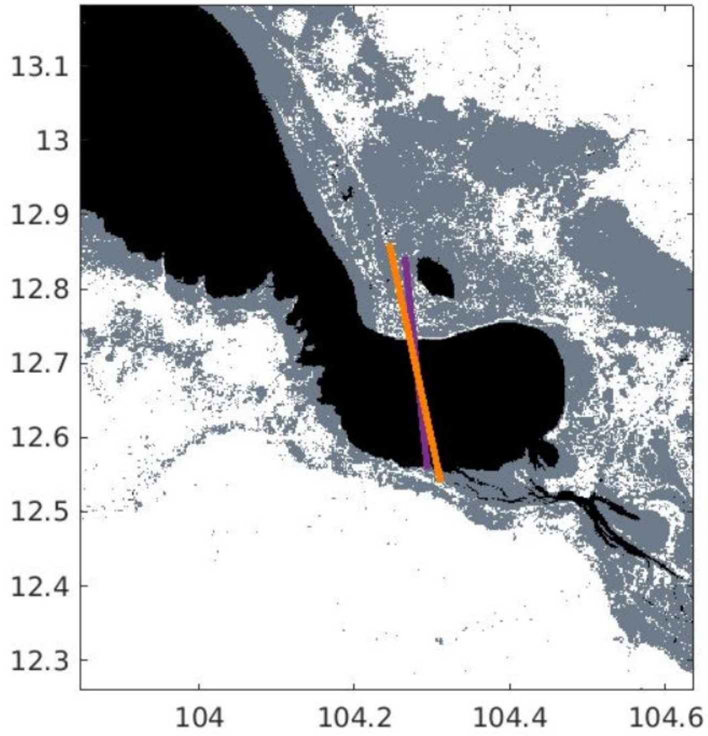


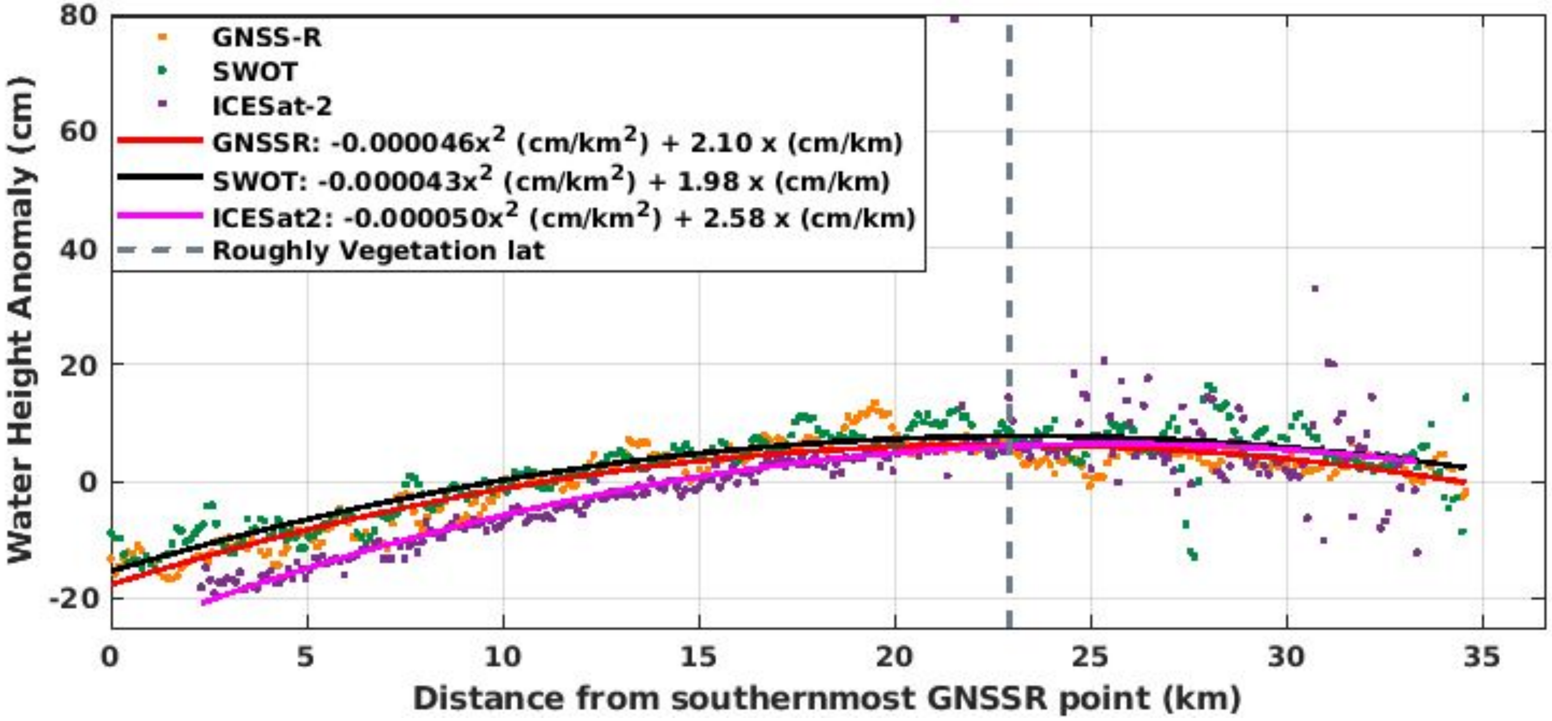


November 21, 2023 (ICESat-2), December 2, 2023 (GNSSR), & December 4, 2023 (SWOT)



Date	Sensor	Open Water σ_{rms} (cm)	Water under Vegetation σ_{rms} (cm)	Open water R (GNSS,SWOT) ($\alpha = 0.05$)	Open water R (ICESat-2,SWOT) ($\alpha = 0.05$)	Open water R (GNSS,ICESat-2) ($\alpha = 0.05$)
November/ December, 2023	ICESat-2	1.6 cm	6.9 cm	0.91	0.94	0.93
	GNSS-R	2.6 cm	2.2 cm			
	SWOT	2.3 cm	4.6 cm			





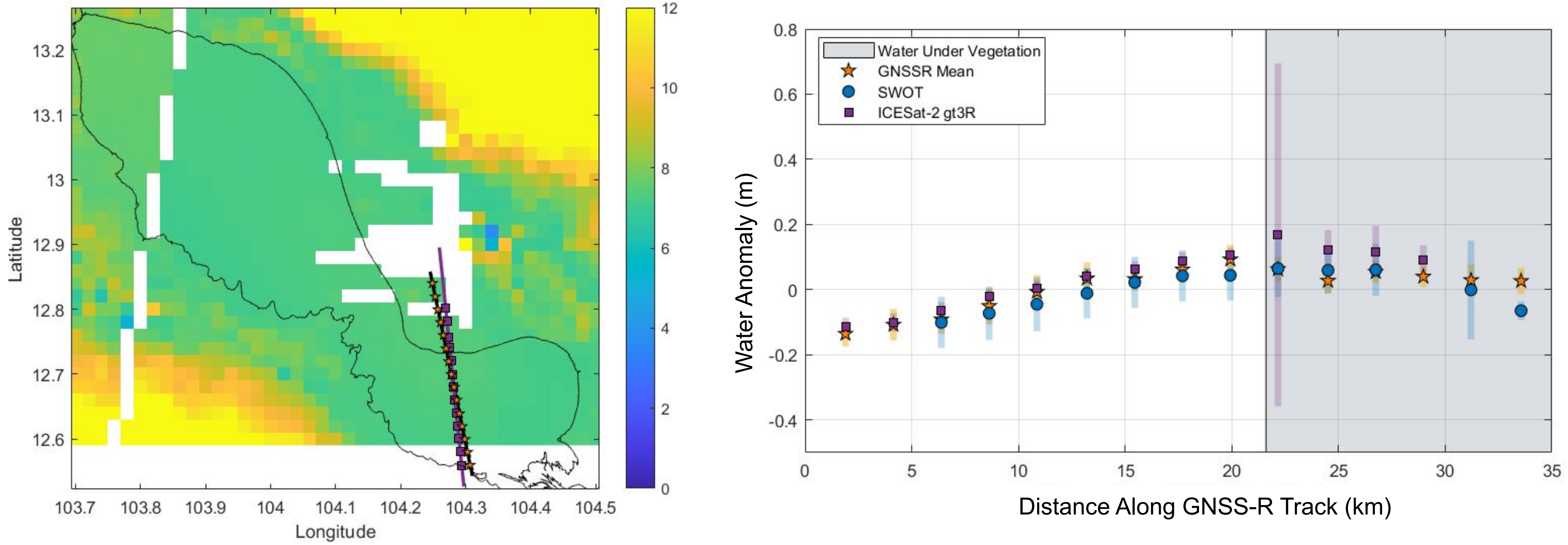
Interpreting Slope

Measurements important to freshwater resources are height (h), change of height of space (dh/dx), and change of height over time (dh/dt)

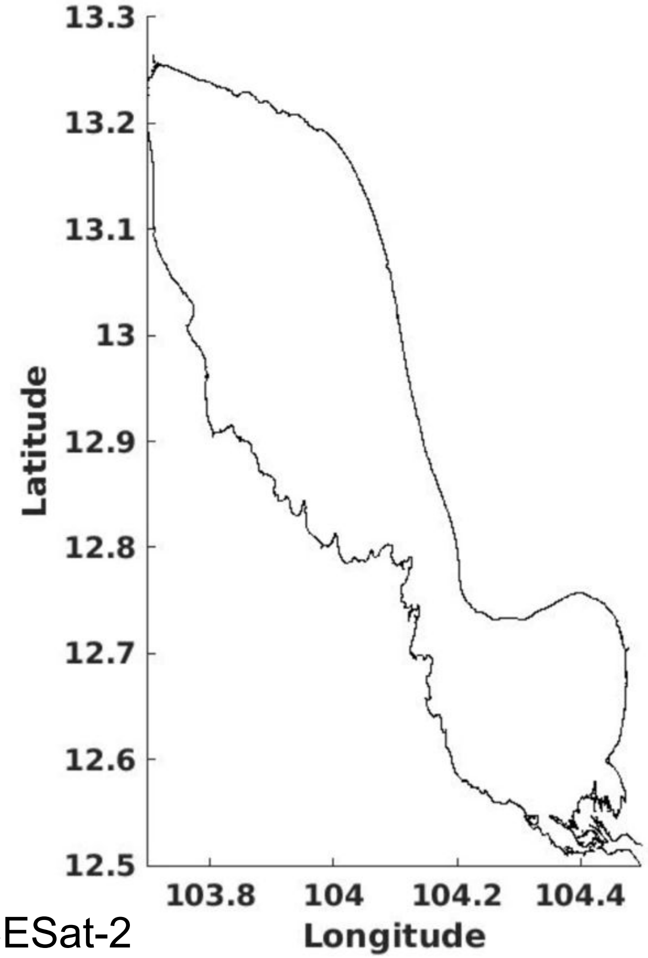
HOWEVER! It is well-established that geoid anomalies not captured at the resolution of geoid models such as EGM08 can exist over large lakes

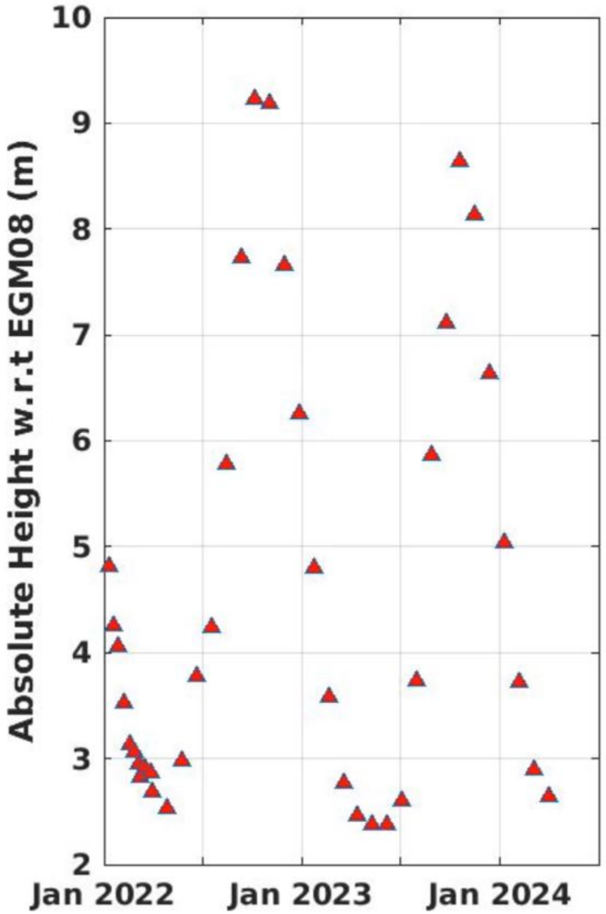
PIXC → L2 Rasterized data from SWOT
0.02º x 0.02º gridding

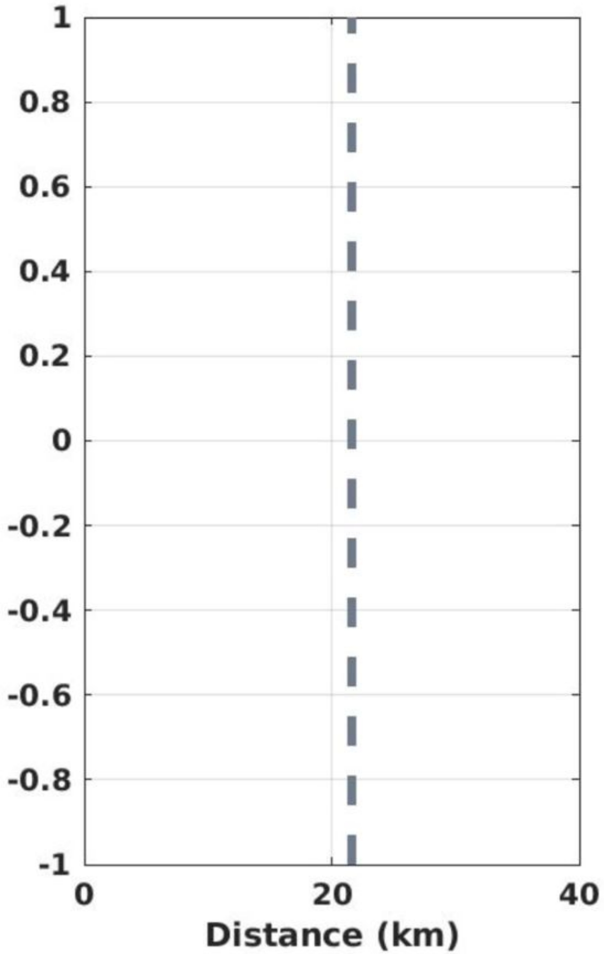
ICESat-2 (November 21, 2023), GNSS-R (December 2, 2023) and SWOT (December 4, 2024) Comparison



Comparing across Distance, Height, and Time

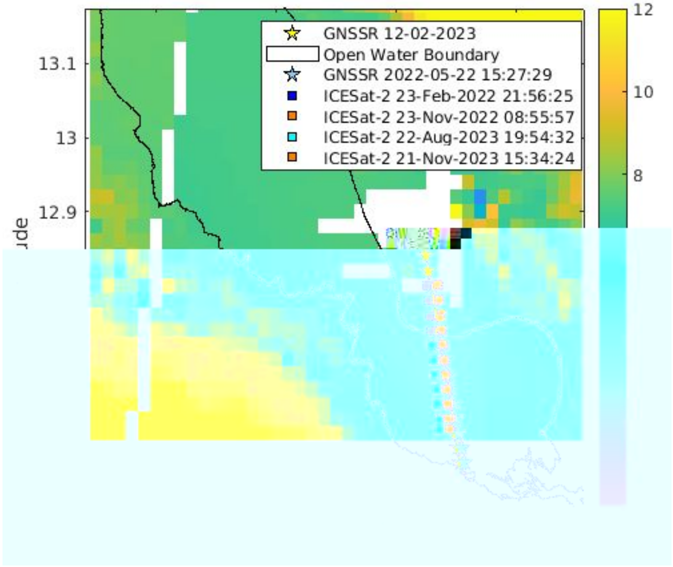


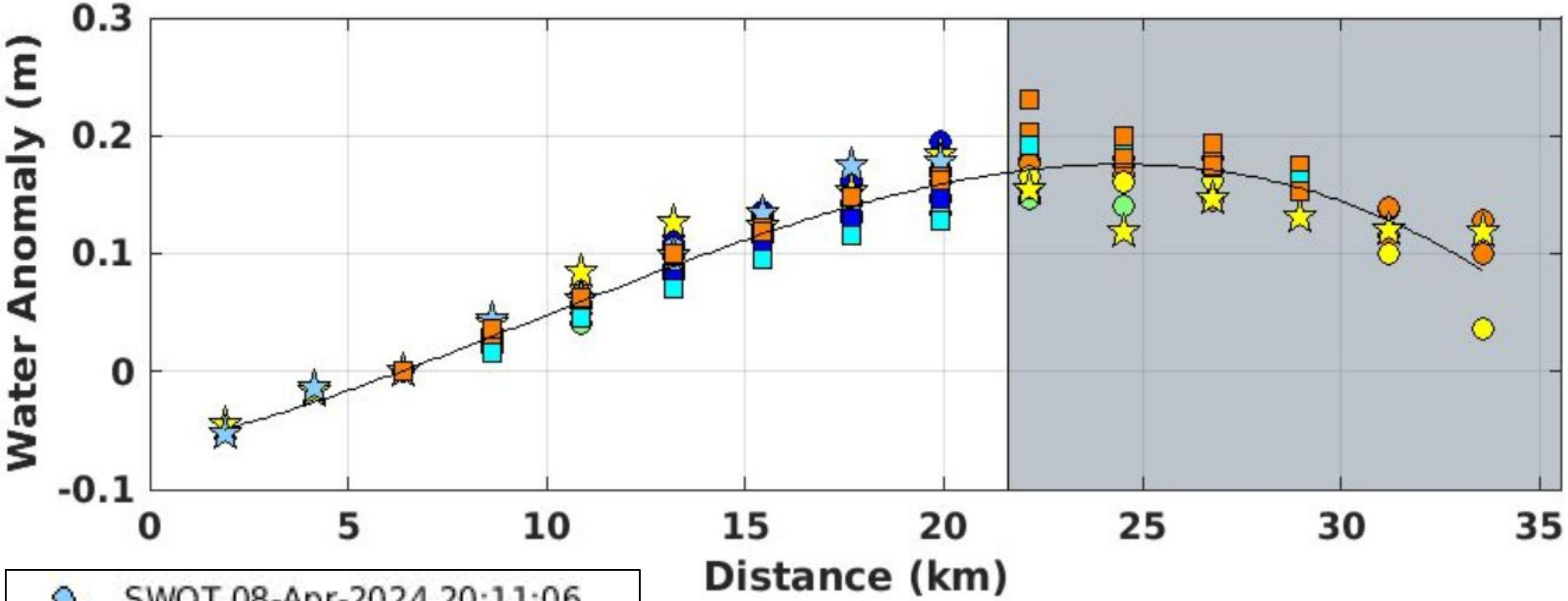


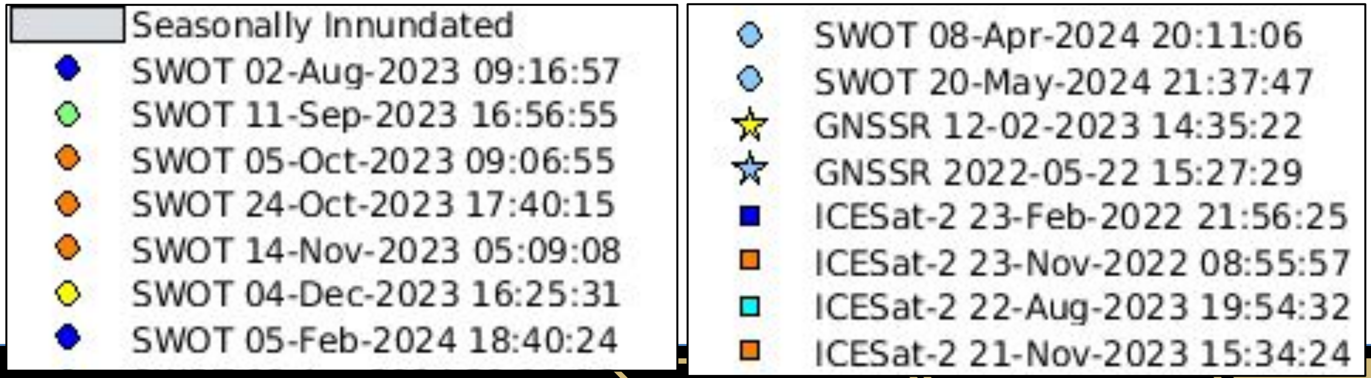


□ ICESat-2
☆ GNSS-R
○ SWOT

Stable structure strongly suggestive of a geoid anomaly



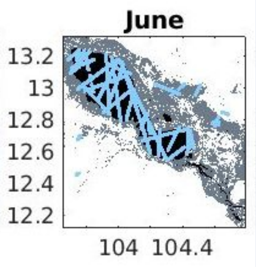




Importance: Without removing stable structures, comparing water height measurements collected at different regions of a lake may lead to biased results

Summary

1. **Good agreement across ICESat-2, GNSS-R, and SWOT**
   - Started with case-studies comparing data collected in similar place & time
2. **Extended analysis over the same location to a diverse range of times to understand the result, which strongly suggests a geoid anomaly**
   - *9 SWOT*
   - *2 GNSS-R*
   - *4 ICESat-2*
3. **Moving forward:**
   - **Expand to studying more of the lake**
   - **Determine best way to combine measurements and separate seasonal signatures from geoid signatures**

Mission	Advantages	Challenges
ICESat-2	• Lowest noise over open water • Dense photon cloud w/in a track • 3-6 laser tracks in 1 pass	• Fewer total number of useable tracks (clouds) • Strongly influenced by vegetation
GNSS-R	• Low-cost • Many tracks, diverse orientations • Penetrates vegetation, clouds	• Relative nature of carrier-phase altimetry 
SWOT	• Swath data • Frequent repeat	• Influenced by emergent riparian vegetation • Ka-band attenuated by rain

Acknowledgements

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- **A portion of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration**

Data References

- **ICESat-2 ATL03:** T. A. Neumann, A. Brenner, D. Hancock, J. Robbins, J. Saba, K. Harbeck, A. Gibbons, J. Lee, S. B. Luthcke, T. Rebold, et al, "ATLAS/ICESat-2 L2A Global Geolocated Photon Data, Version 5 [Data Set]". *Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center*, 2021. https://doi.org/10.5067/ATLAS/ATL03.005
- **SWOT:** JPL D-105504,SWOT Algorithm Theoretical Basis Document: Level 2 KaRIn High Rate Pixel Cloud Science Algorithm Software, *Jet Propulsion Laboratory Internal Document.* (2023)

JPL D-105501,SWOT Algorithm Theoretical Basis Document: Level 2 KaRIn High Rate Raster (L2 HR Raster) Science Algorithm Software,*Jet Propulsion Laboratory Internal Document.* (2023).

Water Mask: J.F. Pekel, A. Cottam, N. Gorelick, and A. S. Belward, "High-resolution mapping of global surface water and its long term changes," *Nature,* vol. 540, pp. 418- 422, 2016

  - ***Data access: EC JRC/Google***

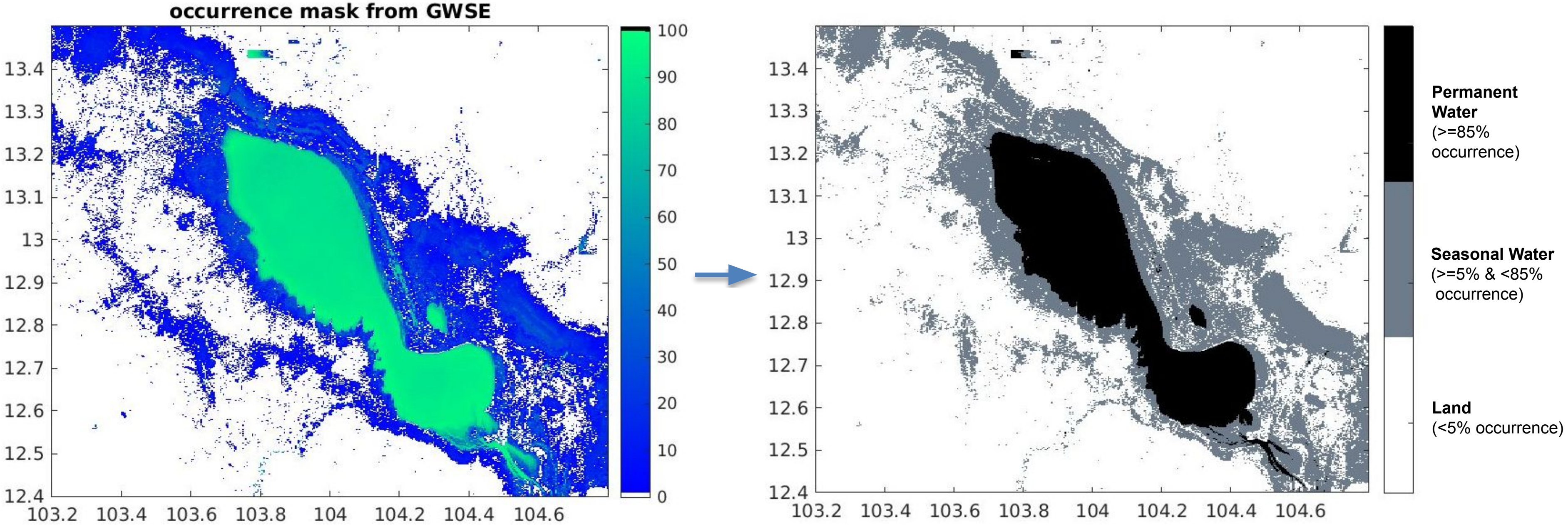
- **DAHITI:** C. Schwatke, D. Dettmering, W. Bosch, and F. Seitz, "Dahiti– an innovative approach for estimating water level time series over inland waters using multi-mission satellite altimetry," Hydrol. Earth Syst. Sci., vol. 19, pp. 4345–4364, 2015.

Back-up Slides

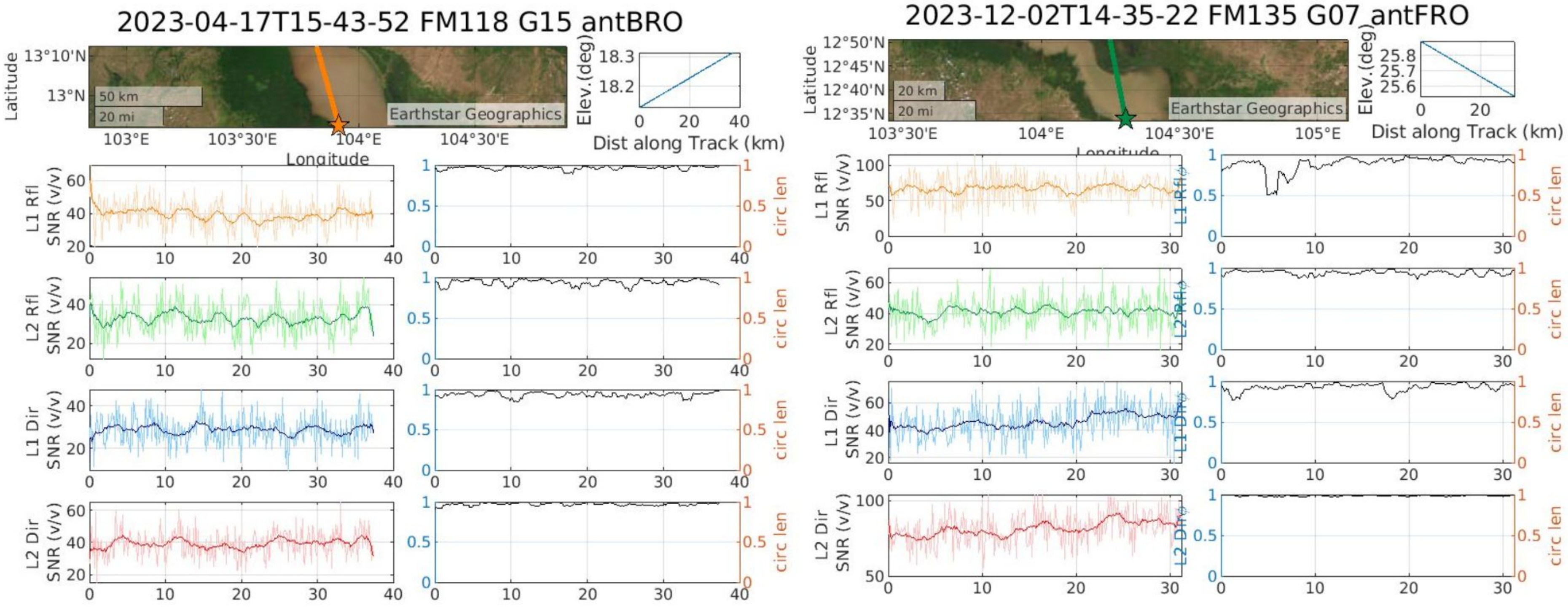
Water Mask from Global Water Surface Explorer

Pekel, 2016 (doi:10.1038/nature20584). Source: EC JRC/Google

Landsat-derived Occurrence from 1984 - 2021

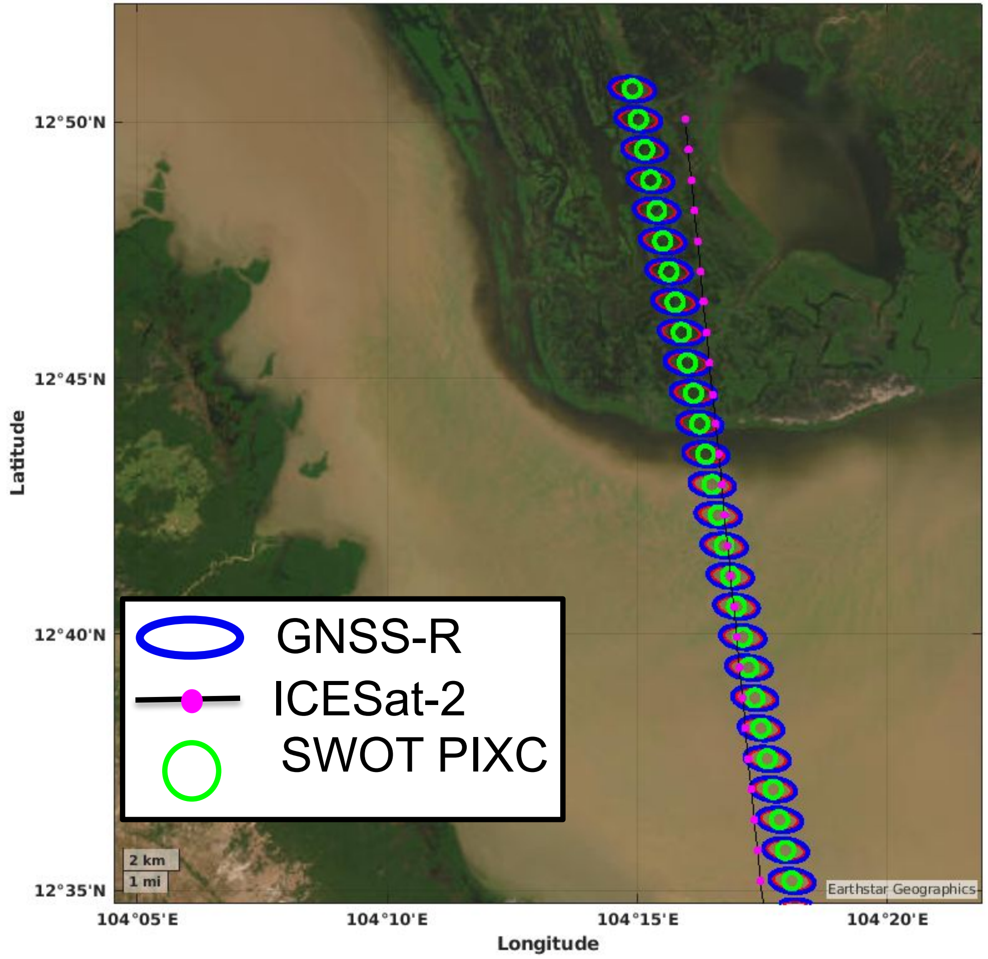


GNSS-R Track Comparisons



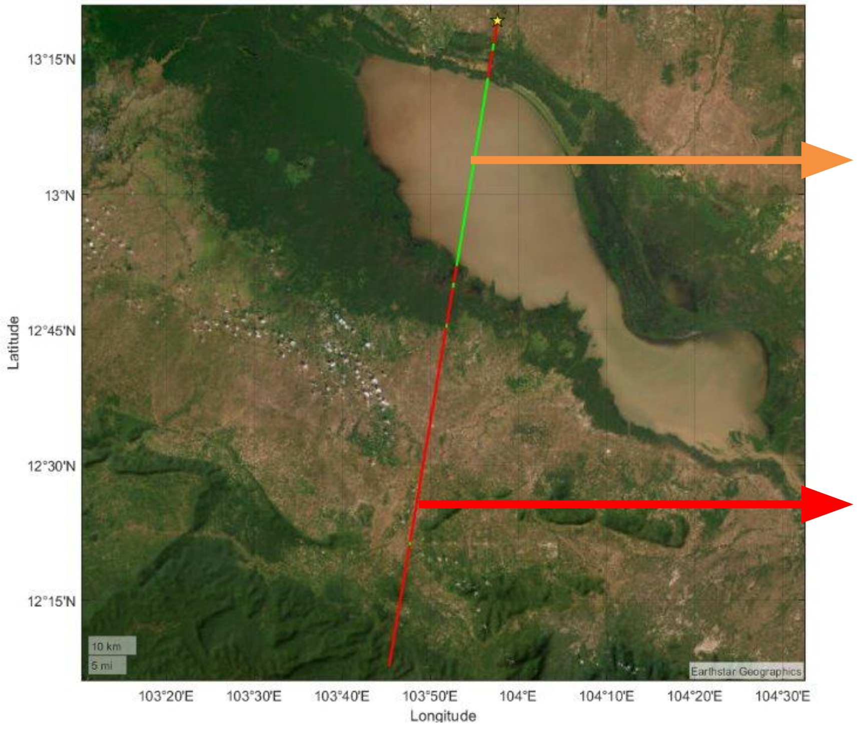
Data Match-up Strategy

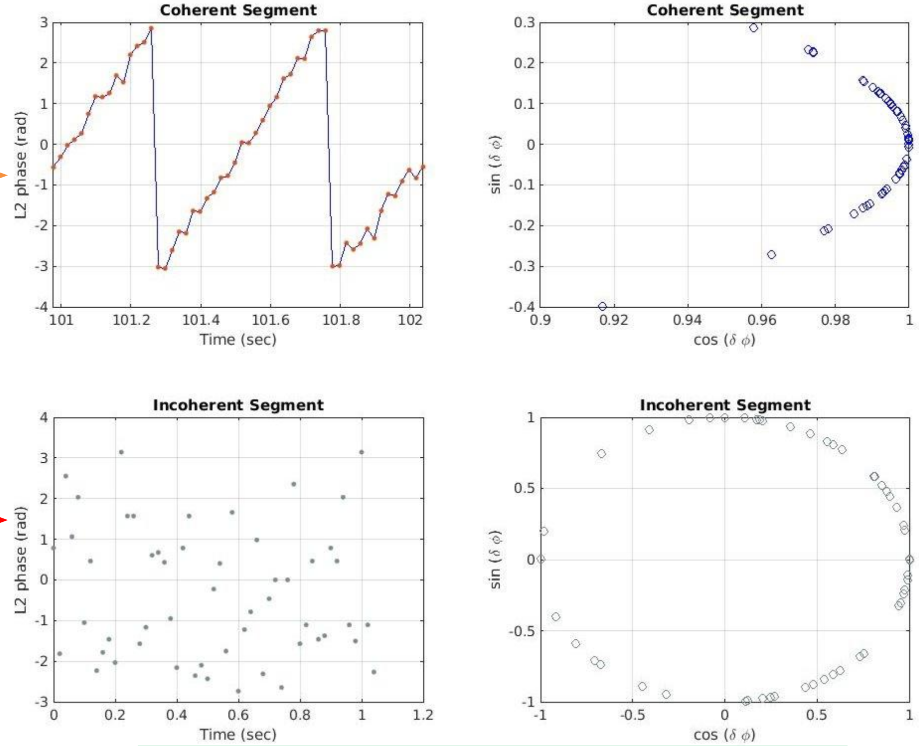
- **Compare tracks within:**
  - 3 km separation (max)
  - 2 weeks



Definition of Circular Length

$$\zeta = \frac{1}{N}\left|\sum_{1}^{N} \cos\delta\phi_i + \sum_{1}^{N} \sin\delta\phi_i\right|, \quad \zeta \in \left[0, 1\right]$$





Higher ζ indicates a more coherent phase