Geodetic Reference Instrument Transponder for Small Satellites (GRITSS)

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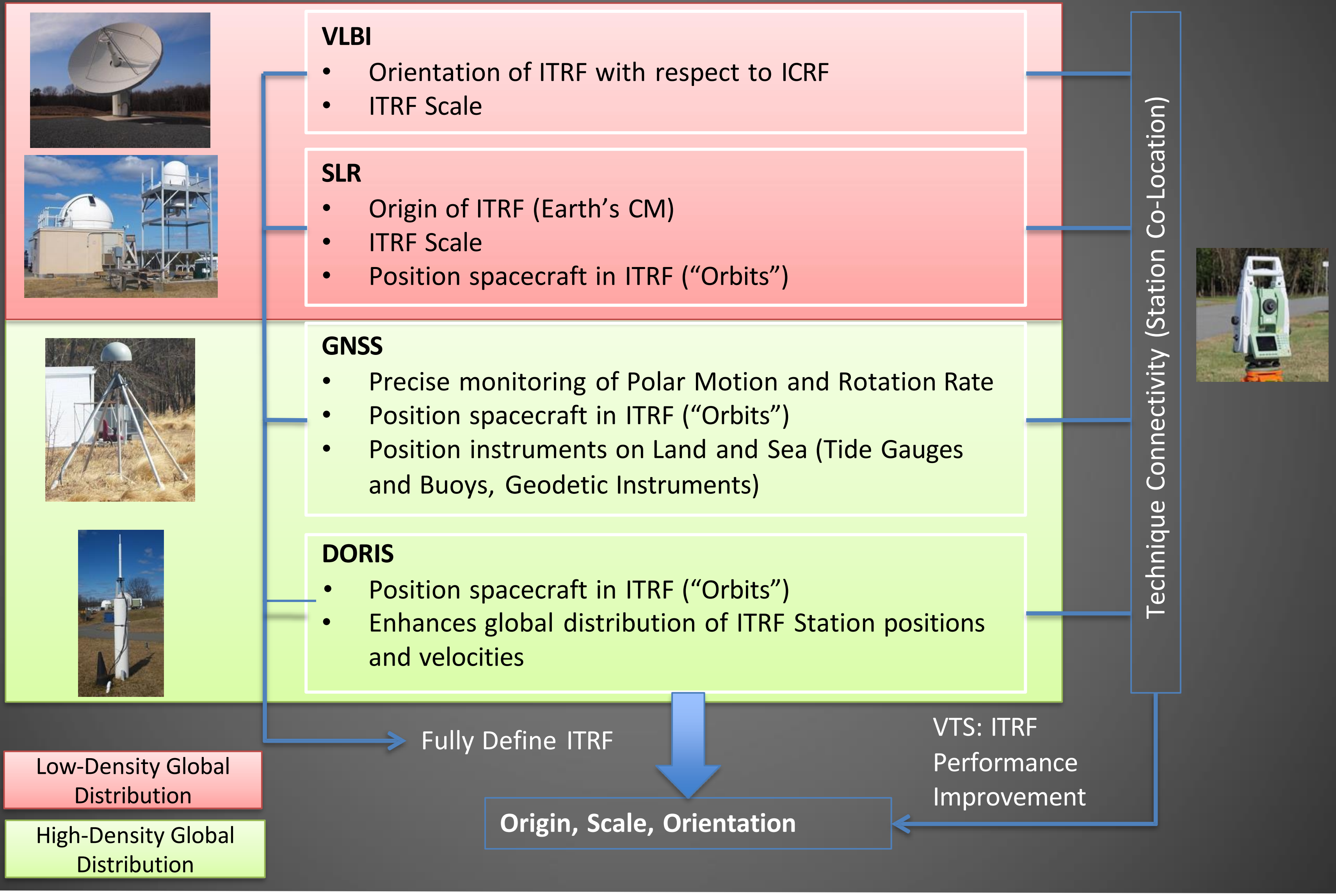
NASA Goddard Space Flight Center

April 20, 2026

The Geodetic Measurement System



VLBI
- Orientation of ITRF with respect to ICRF
- ITRF Scale

SLR
- Origin of ITRF (Earth’s CM)
- ITRF Scale
- Position spacecraft in ITRF (“Orbits”)

GNSS
- Precise monitoring of Polar Motion and Rotation Rate
- Position spacecraft in ITRF (“Orbits”)
- Position instruments on Land and Sea (Tide Gauges and Buoys, Geodetic Instruments)

DORIS
- Position spacecraft in ITRF (“Orbits”)
- Enhances global distribution of ITRF Station positions and velocities

Technique Connectivity (Station Co-Location)

Fully Define ITRF

VTS: ITRF Performance Improvement

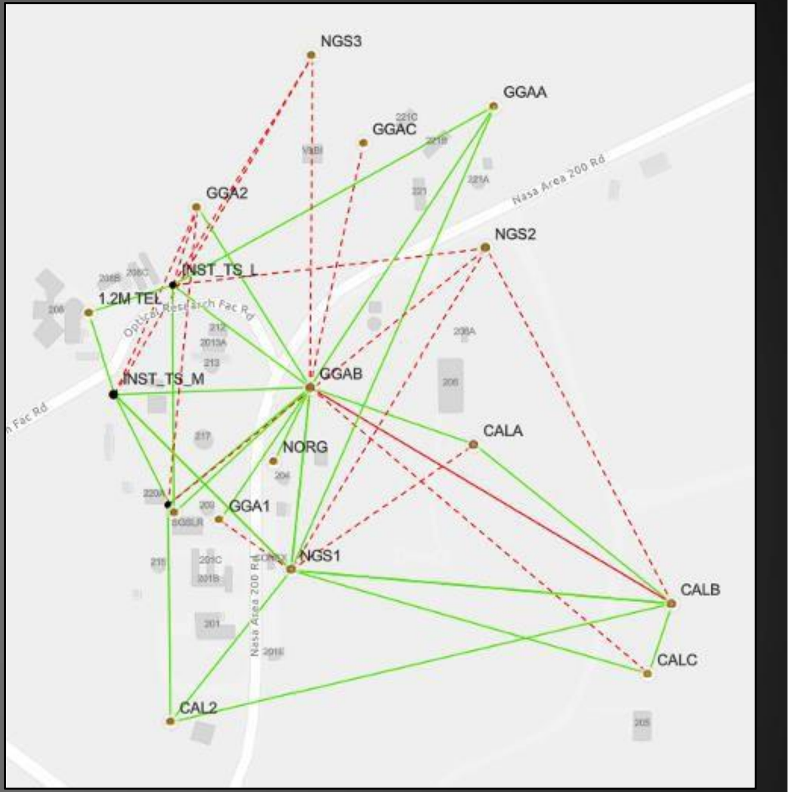
Origin, Scale, Orientation

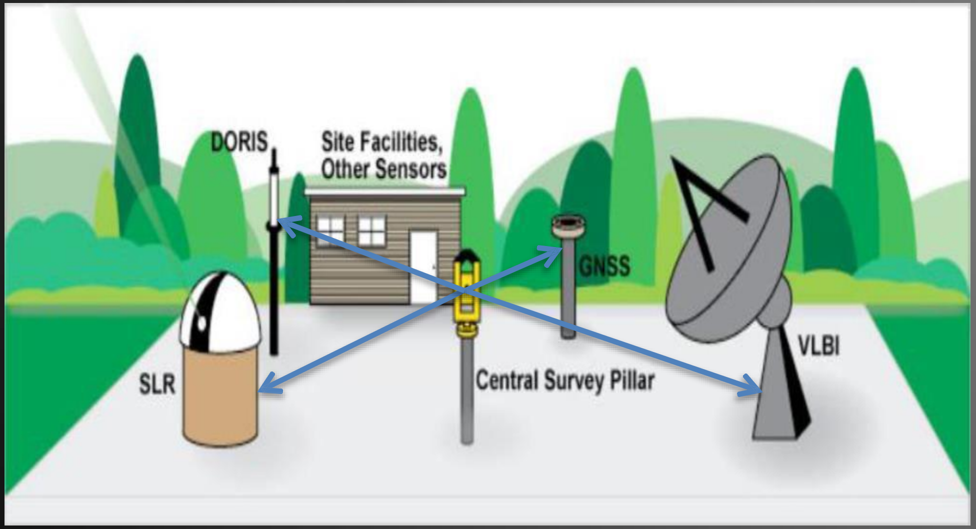
Low-Density Global Distribution

High-Density Global Distribution

Traditional Local Tie Surveys

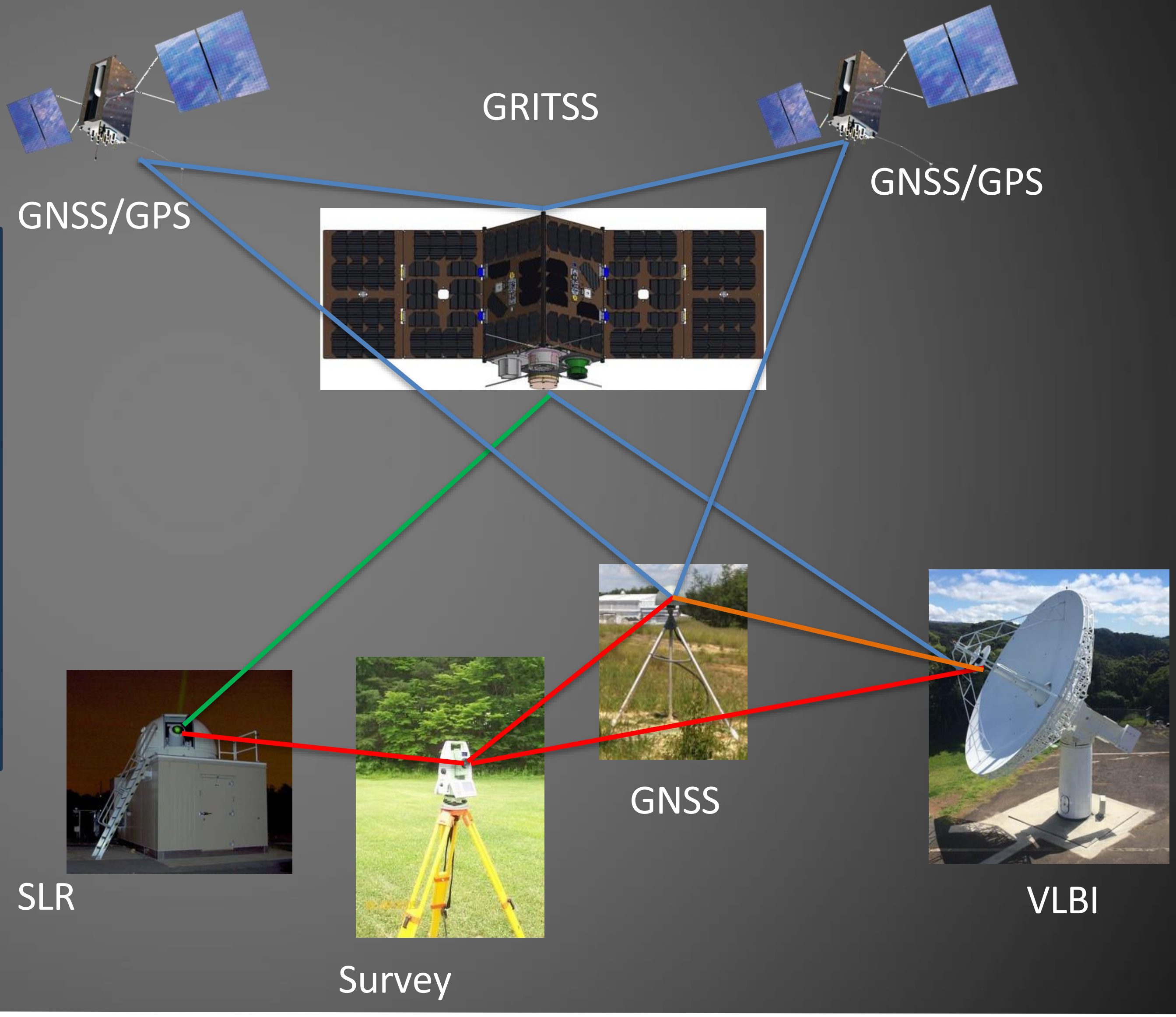
- Survey of site ground control network, site reference, optical access points, and supplemental targets to estimate the measurement points of space geodesy instruments.
- The actual instrument measurement point is often not accessible to survey techniques and must be estimated, introducing errors in the local tie.
- Surveys are only performed periodically further introducing the possibility of errors.





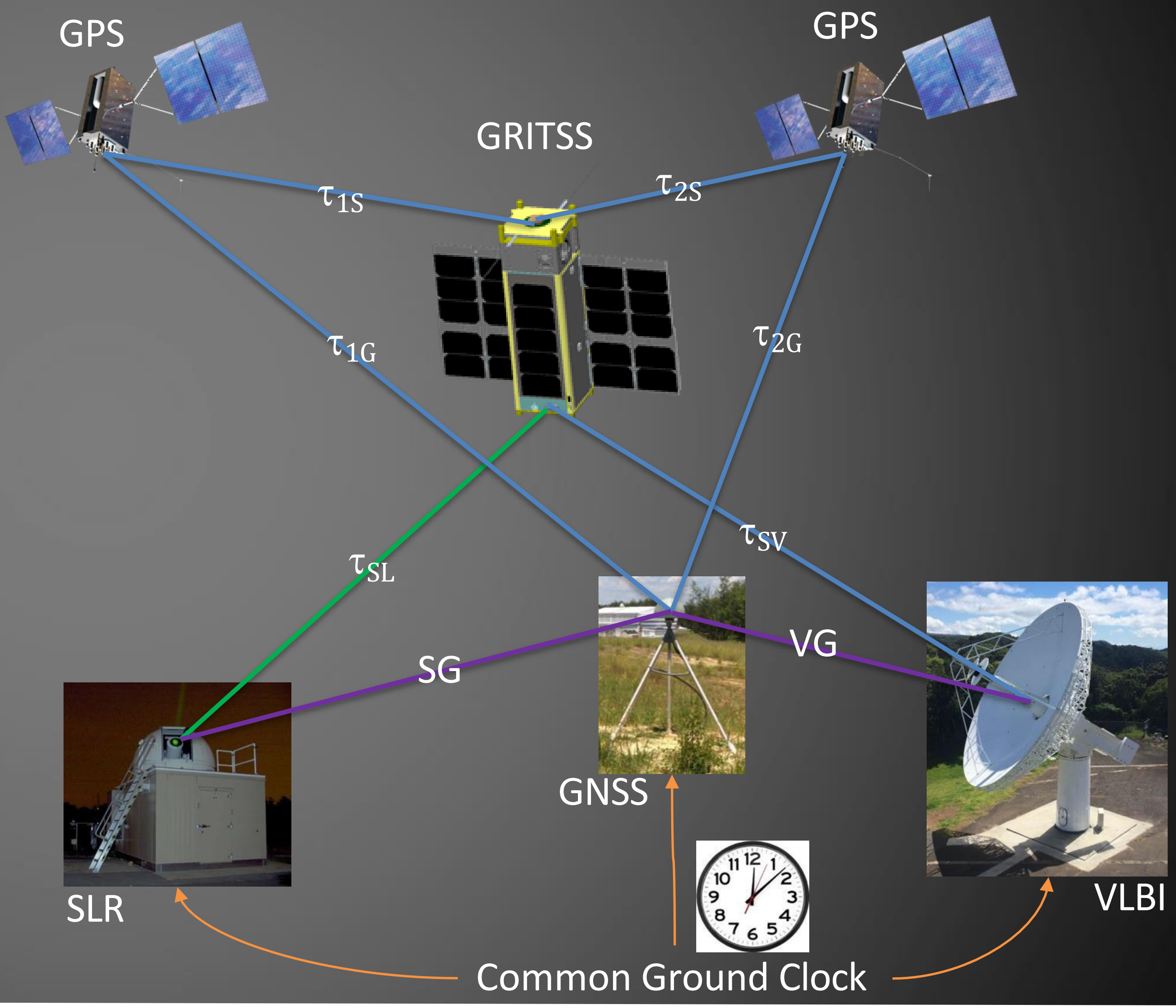
Geodetic Colocation In Space

Observations of a common space-based reference has the potential for reducing the uncertainty in the local-ties to the mm level thus improving the ITRF combination.



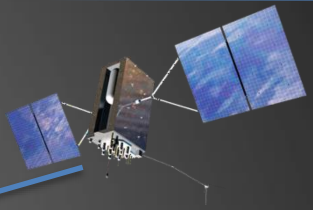
The GRITSS Observables

- τ_{sv} observable is a clock bias term that is obtained through differencing of space/VLBI GPS clock biases
- Differencing allows direct suppression of common clock terms.
- Fitting τ_{sv} to model given CubeSat Precision Orbit Determination yields VLBI position

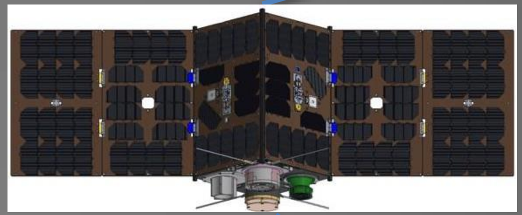


The GRITSS Dog-Leg

GRITSS upconverts and transponds GPS signals and PRN sequence to individual VGOS ground stations.



GPS



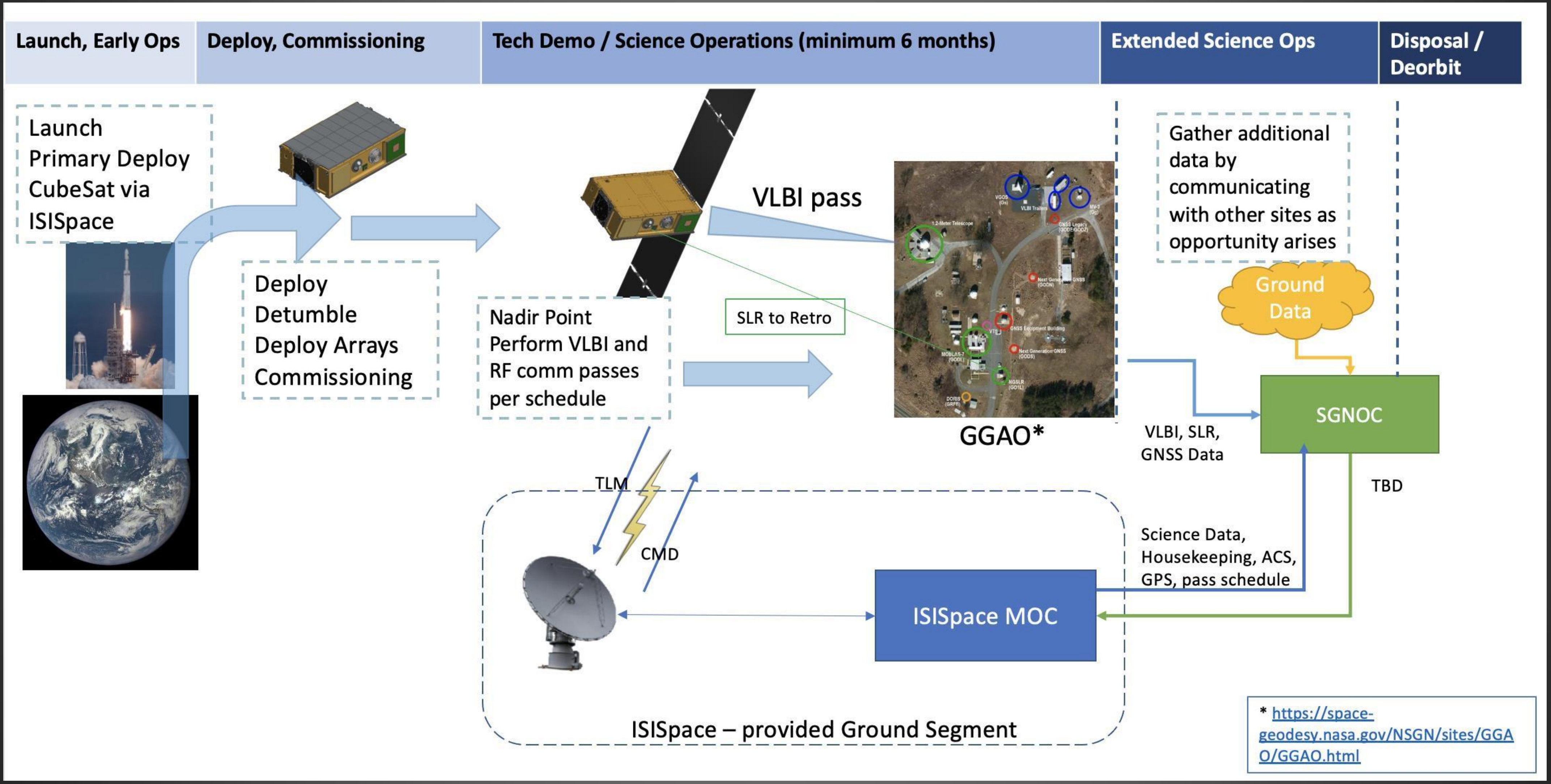
VGOS

The GRITSS Demonstration Mission

- A NASA Earth Science and Technology Office sub-class D technology demonstration mission
- Jointly developed by the University of Massachusetts, Lowell and NASA GSFC
- 12UXL CubeSat, launch, and operations services provided by ISISpace in the Netherlands.
- Nominal operations: 1 year (extendable)
- Orbit: 590km sun synchronous
- Only broadcasts GRITSS signals over VGOS stations as spacecraft power permits
- Spacecraft kept nadir pointing throughout orbit to enable global SLR tracking

Initially targeting US NASA VGOS stations and will invite other VGOS stations to participate after successful first phase

Concept of Operations



Launch, Early Ops | **Deploy, Commissioning** | **Tech Demo / Science Operations (minimum 6 months)** | **Extended Science Ops** | **Disposal / Deorbit**

Launch
Primary Deploy
CubeSat via
ISISpace

Deploy
Detumble
Deploy Arrays
Commissioning

Nadir Point
Perform VLBI and
RF comm passes
per schedule

VLBI pass

SLR to Retro

GGAO*

Gather additional
data by
communicating
with other sites as
opportunity arises

Ground
Data

SGNOC

VLBI, SLR,
GNSS Data

TBD

TLM

CMD

Science Data,
Housekeeping, ACS,
GPS, pass schedule

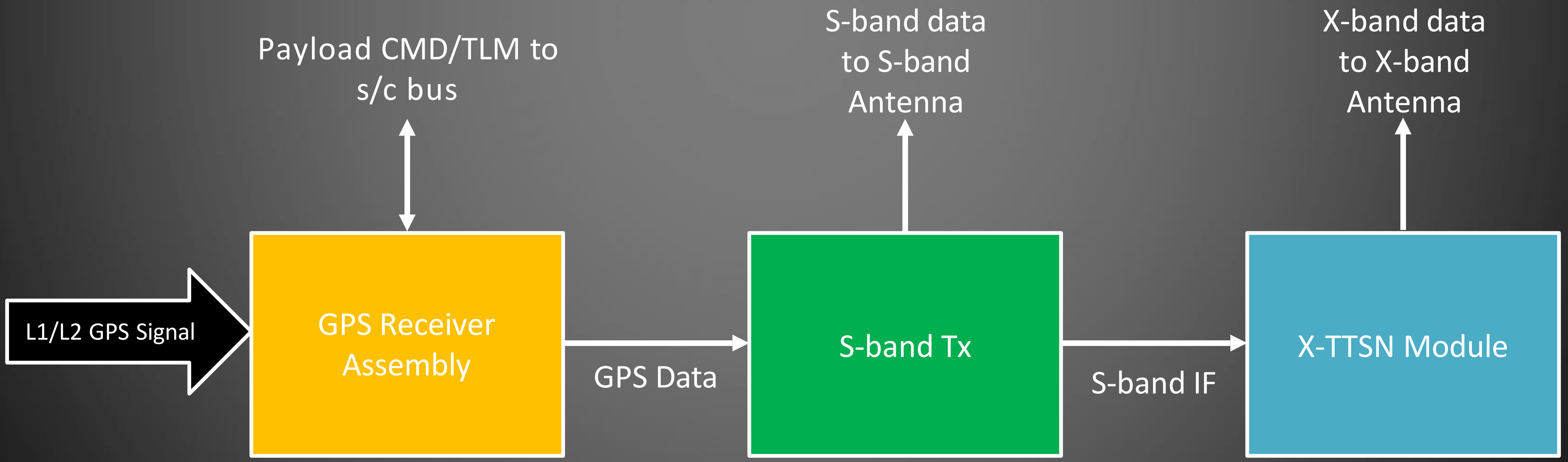
ISISpace MOC

ISISpace – provided Ground Segment

* https://space-geodesy.nasa.gov/NSGN/sites/GGAO/GGAO.html

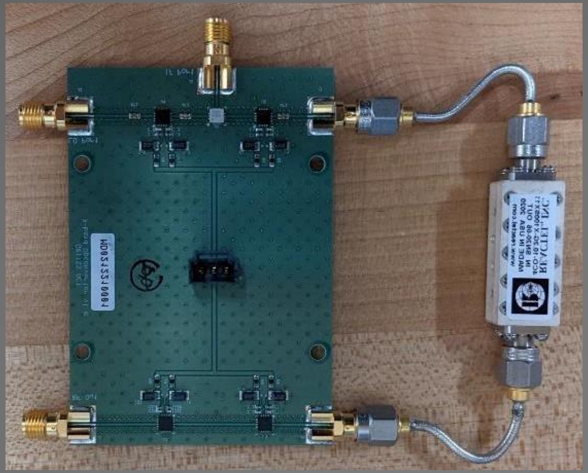
GRITSS Instrument Subsystems

- GPS Receiver Assembly
- Ultra-Stable Oscillator (USO)
- X-band Transmitter and Timing extenSionN (X-TTSN) Module - 10.2 GHz
- S-band Transmitter - 3.2 GHz
- Antennas (L1/L2 GPS, X-band, and S-band)
- Laser Retroreflector



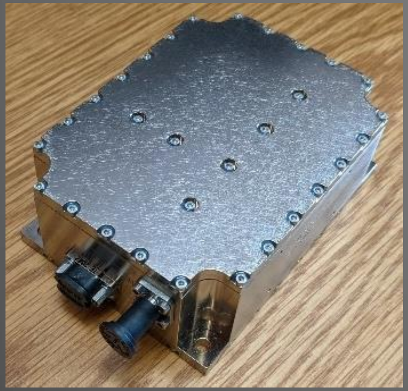
Completed Technology Readiness Level 5 Development

S-band Transmitter



X-band Transmitter

GPS Receiver Assembly

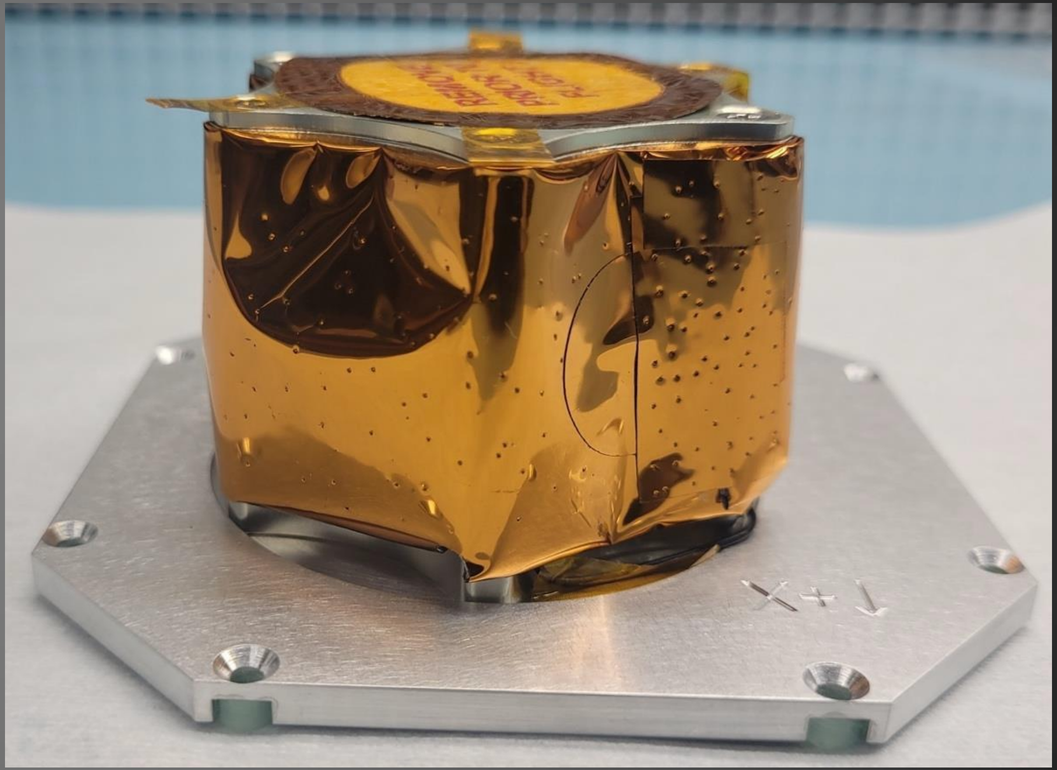


Wenzel USO

Laser Retroreflector

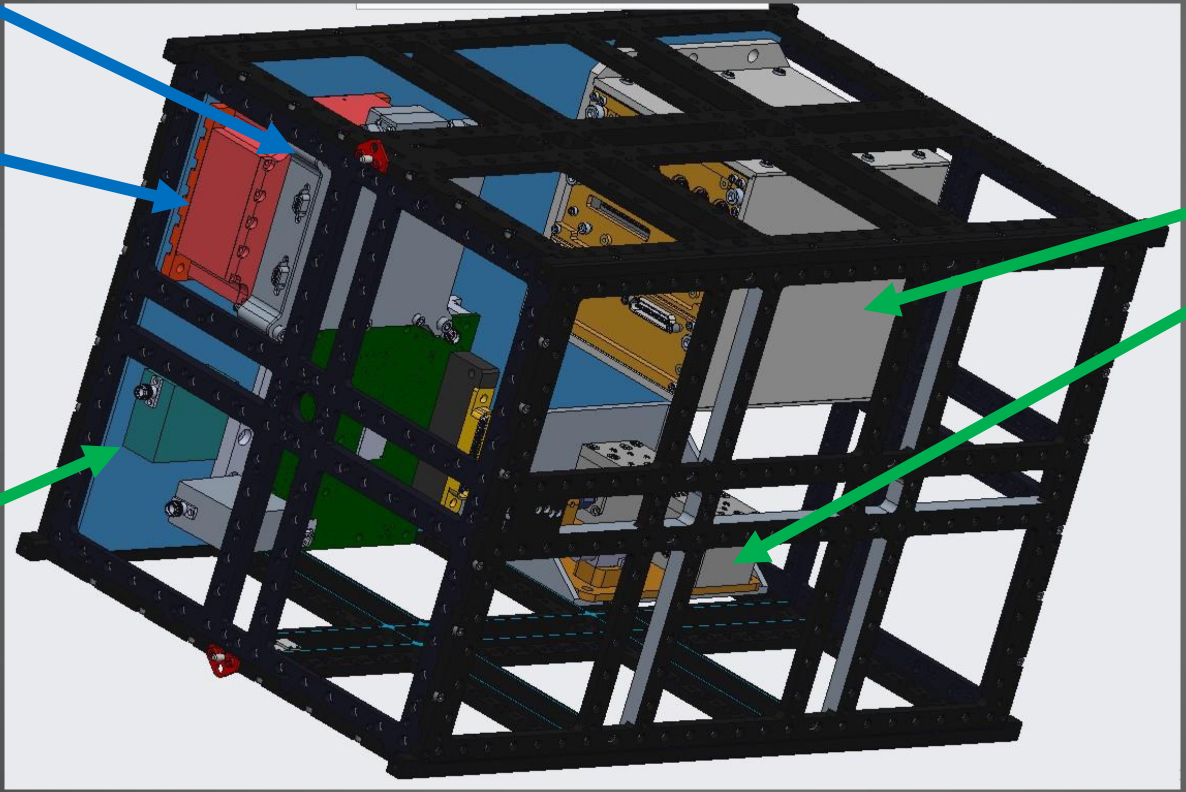
Single 1.6 inch diameter cube corner with measured dihedral angles offsets of 1.7, 1.4, and 1.5 arcsec.

Mounted to the nadir deck that will be kept nadir pointing most of the time.



Designed and built by KBR

GRITSS Instrument Fits Within 6U Volume



X-TTSN Module

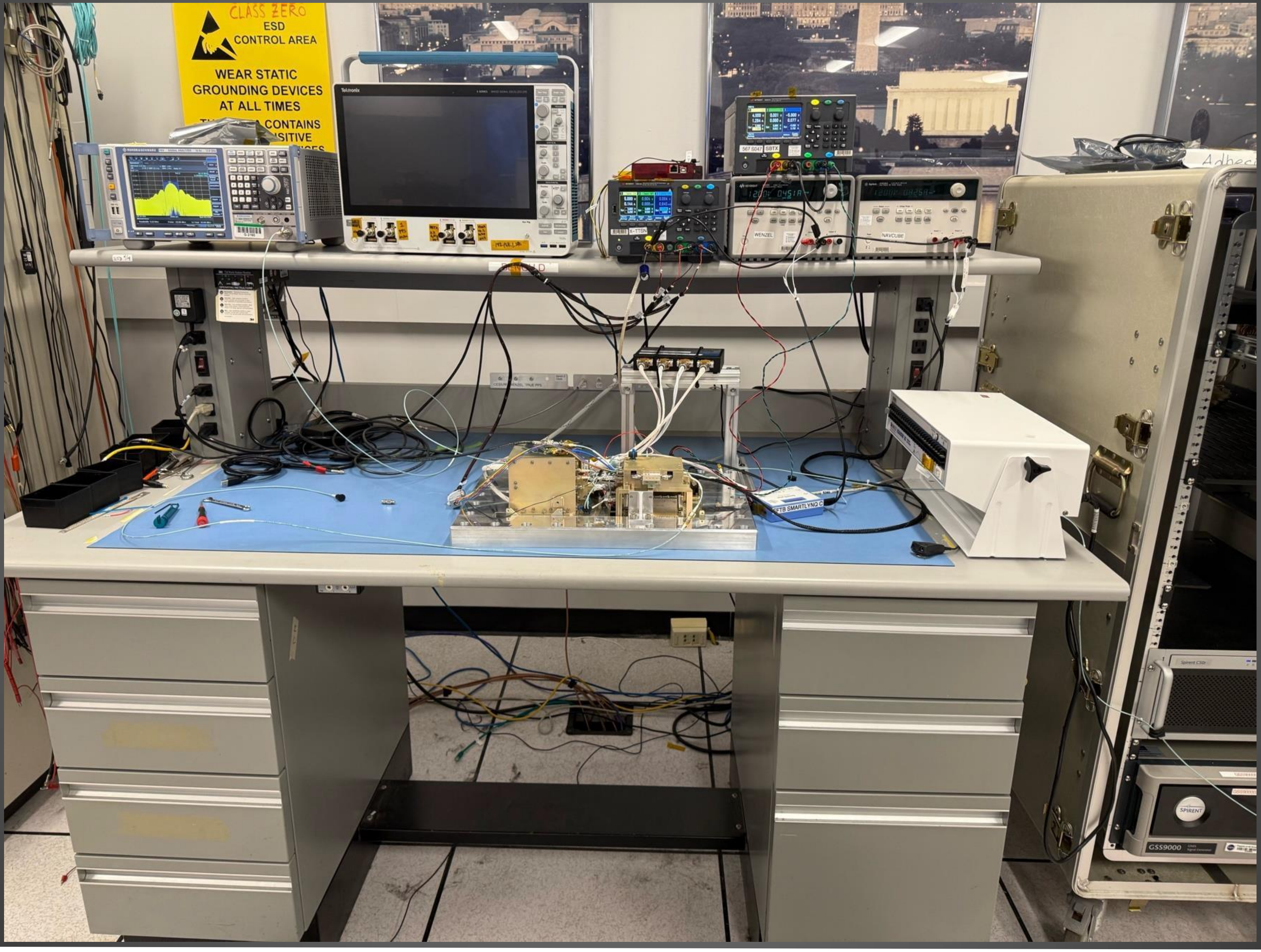
USO

S-band Tx

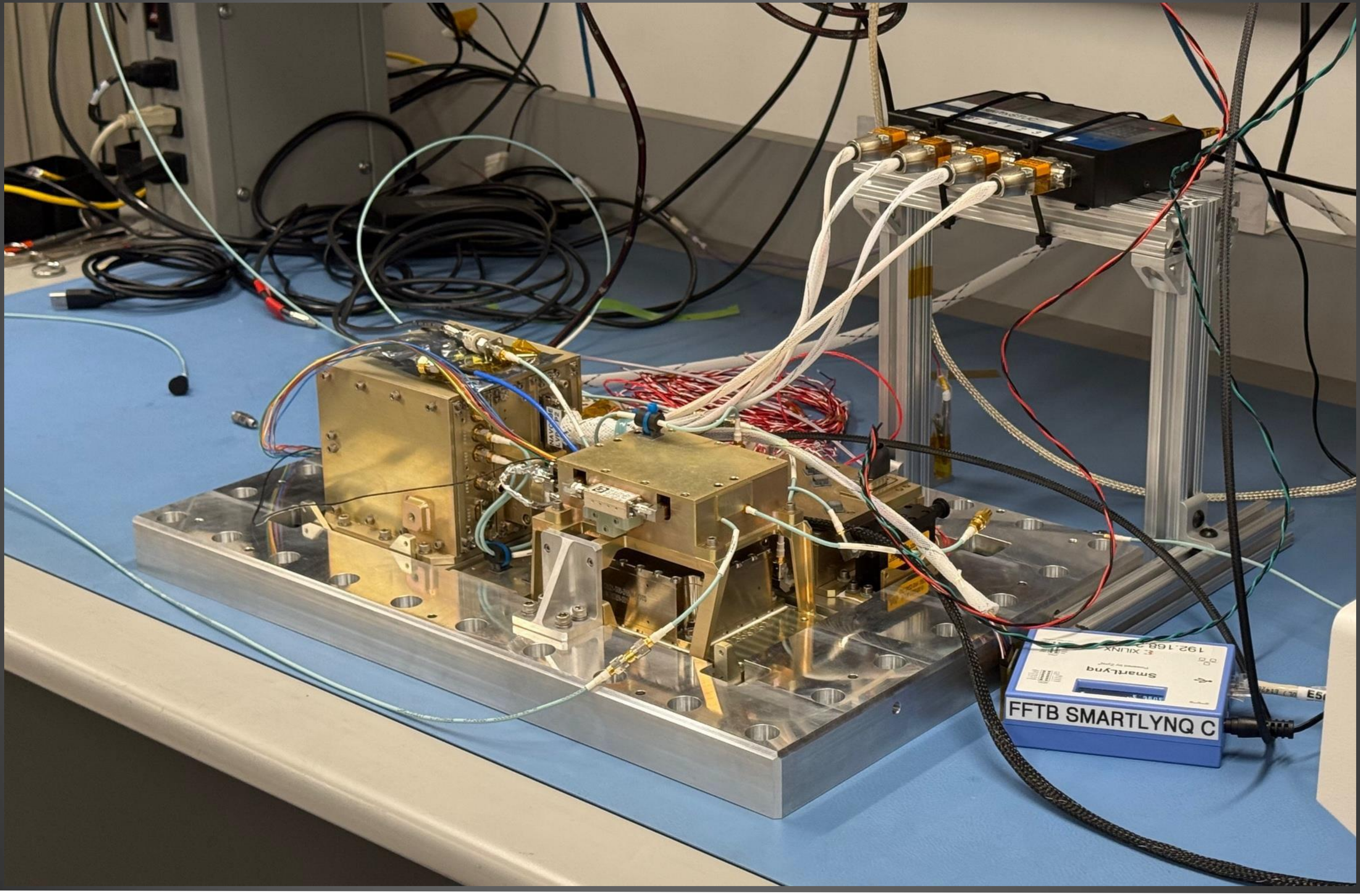
GPS Receiver Assembly
- NavCube3-mini
- Low-Noise Amplifier (LNA)

Instrument Size:
20 cm × 11 cm × 34 cm

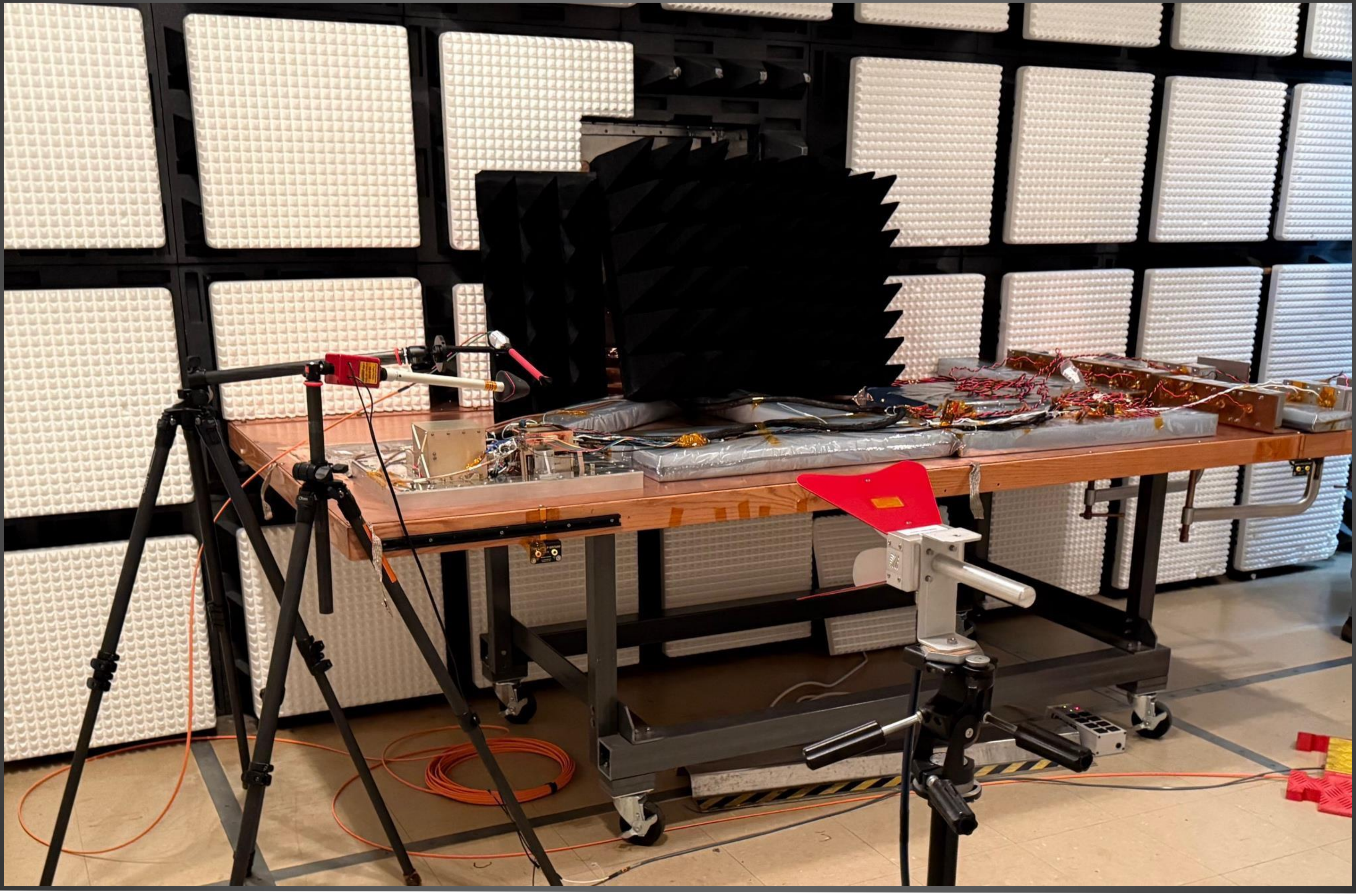
GRITSS Flight Instrument



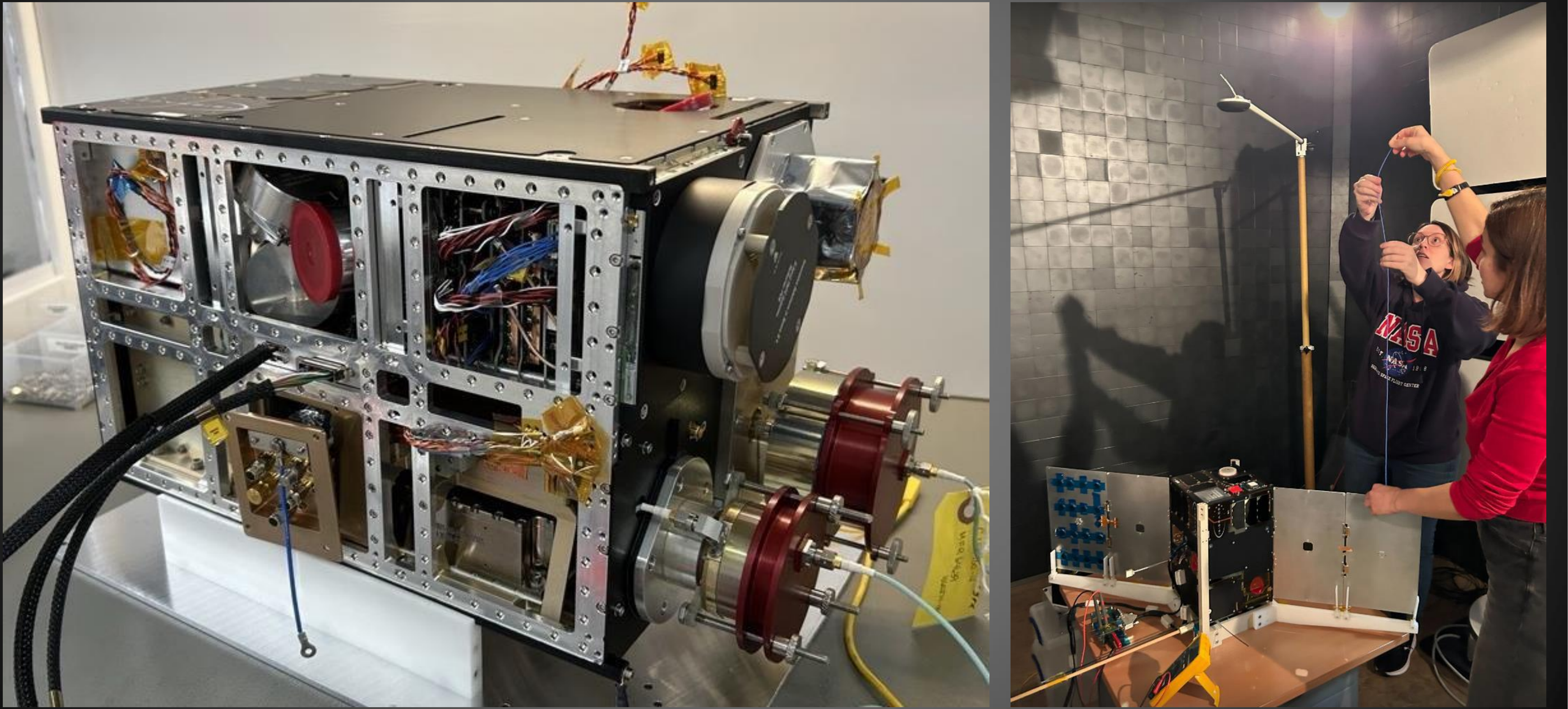
GRITSS Flight Instrument



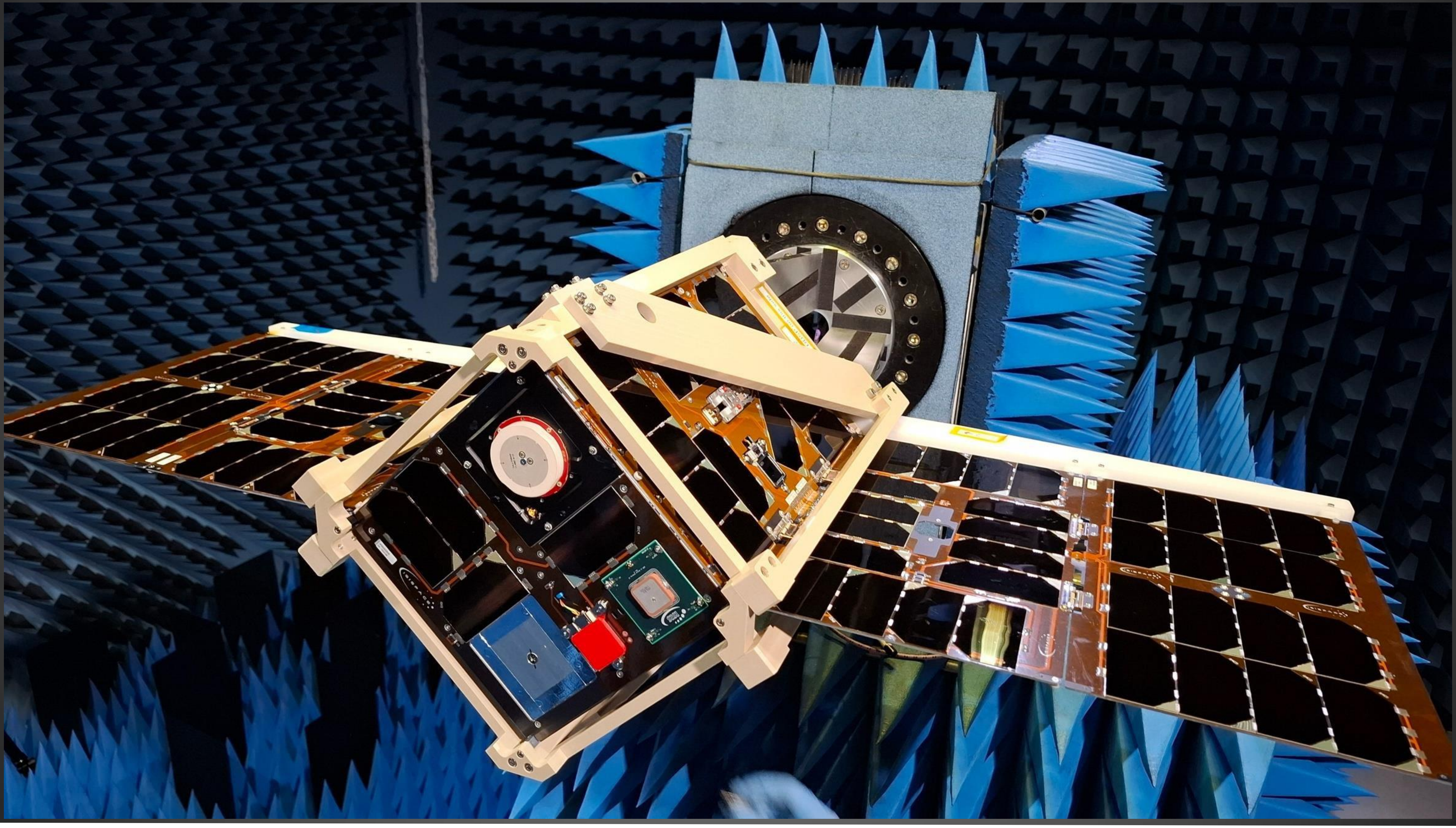
Instrument EMI Testing at GSFC



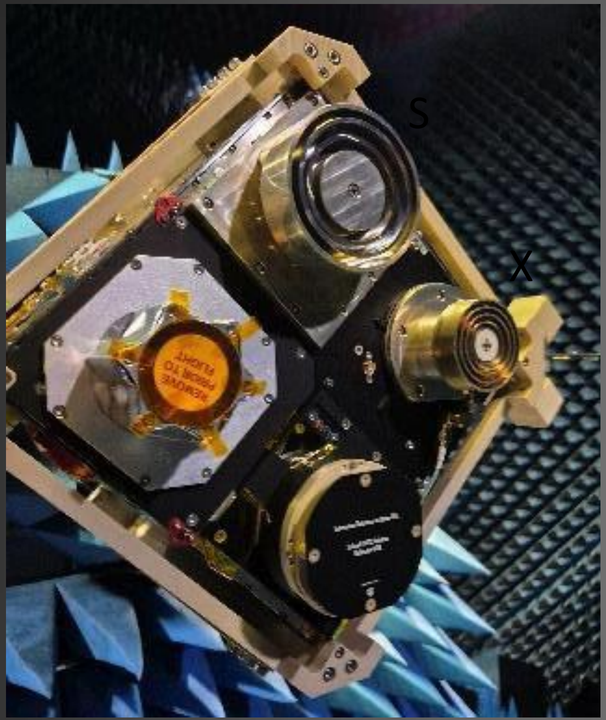
Integration with Spacecraft at ISISpace

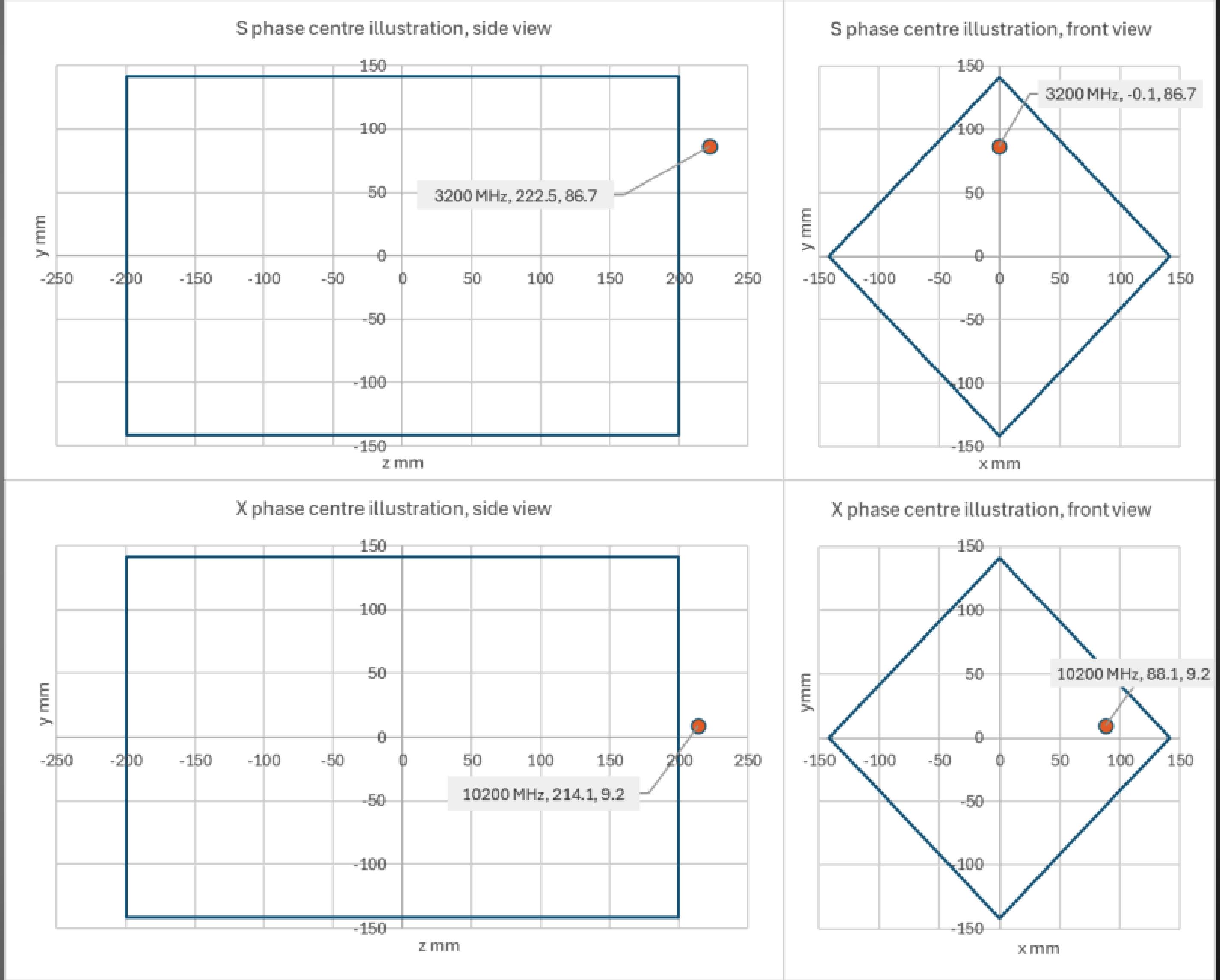


Antenna Characterization at ESTEC



Phase Center Measurements

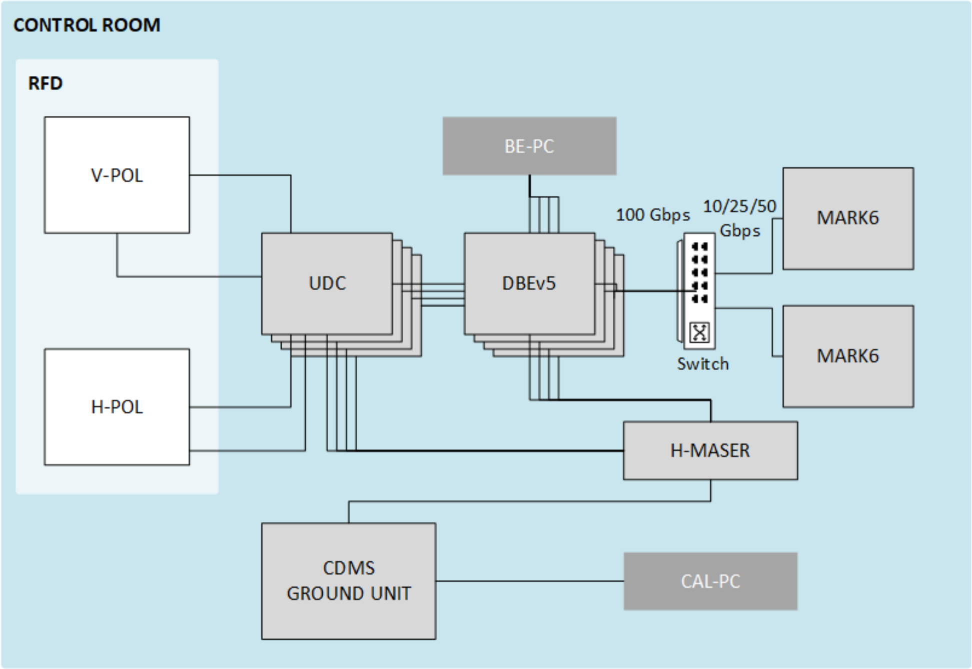




- Other measurements include
  - Full sphere phase patterns,
  - Group delay,
  - Directivity, gain, and losses

VGOS Station Preparations

- Antenna low Earth orbit satellite tracking capabilities.
- Measurements/characterization of VGOS signal-chain electrical delays.
- Upgrade signal chain back end to record GRITSS signals.
- End-to-end testing with simulated GRITSS-like signals.



CONTROL ROOM

RFD

V-POL

H-POL

UDC

BE-PC

DBEv5

100 Gbps

10/25/50 Gbps

Switch

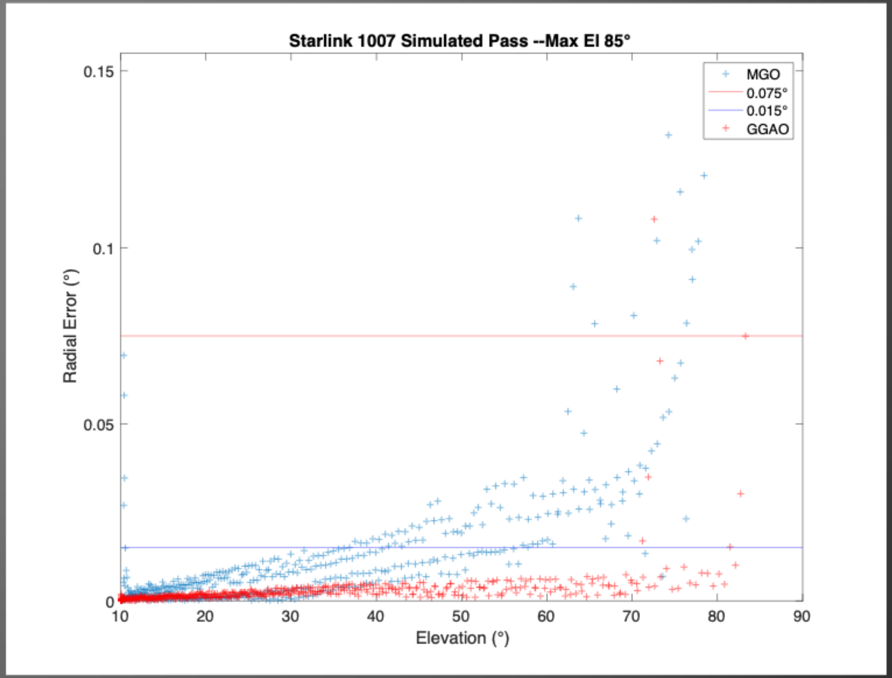
MARK6

MARK6

H-MASER

CDMS GROUND UNIT

CAL-PC



Summary

- GRITSS will demonstrate a space-tie using the novel approach of transponding the GPS signals to a VGOS antenna enabling it to be in Low Earth Orbit with view of only one VGOS station at a time.
- Nearly completed Integration and Test and preparing spacecraft for shipment to SpaceX for launch on Transporter-17 in July 2026.

Foundation CORS

Access to the National Spatial Refence System (NSRS)

Shachak Peeri, Will Freeman, Fran Coloma, John Galetzka, Dan Roman and Steve Breidenbach
NOAA, National Geodetic Survey
April 20 2026
Annual CGSIC Meeting

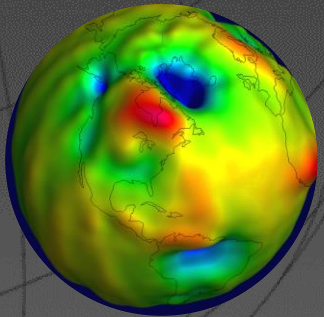
Special Thanks to:

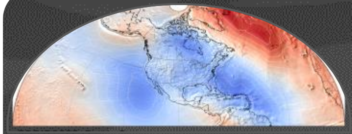
Neil Winn, National Park Service teams, and the USCG/Navigation Center

NSRS Modernization Timeline

June 2025	Initial release of key data sets (Beta site)
Sep 2025	Second release of tools and services (Beta site)
Early 2026	Finalizing tools and service based on comments provided through the Beta site (Beta site)
Late 2026/7	FGDC Approval - Moving all data, tools and services into production **Modernized NSRS Deploys!**

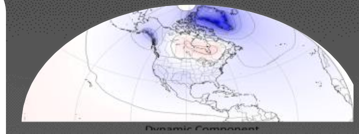
Geopotential modeling (Geoid2022)





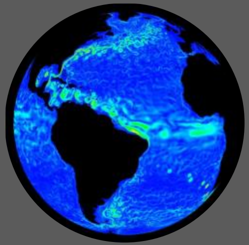
Geoid Undulation (Static)

+

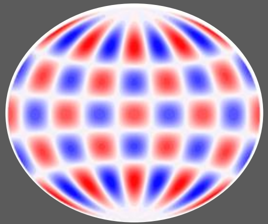


Dynamic component

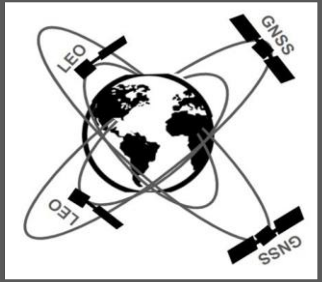
Vertical reference system
⋮
Height relationships
⋮
Tidal datums



Hydrodynamic models



Spherical Harmonics

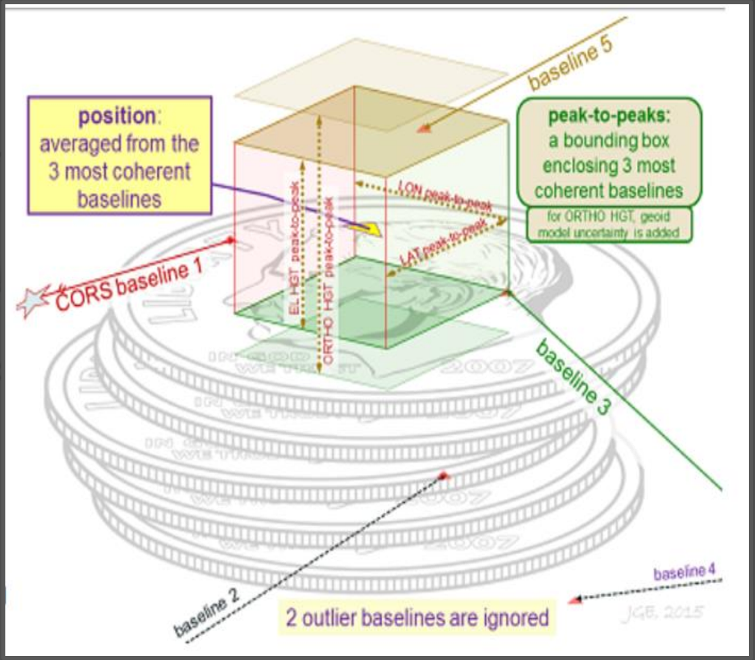


Orbit Determination

How do we access the modernized NSRS?

Answer: Using GNSS, or more specifically -

Online Positioning User Service (OPUS) -https://geodesy.noaa.gov/OPUS/



OPUS Rapid Static (OPUS-RS)

- 15 minutes to 2 hours of GPS data

OPUS Static (OPUS-S)

- same requirements as above
- 2 to 48 hours of GPS data

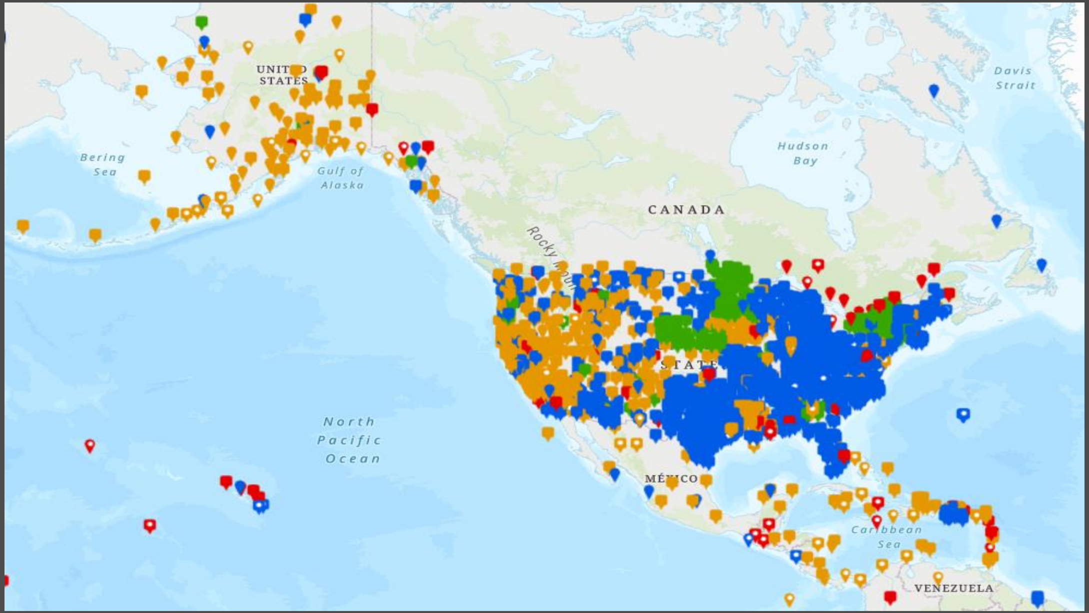
OPUS Projects (OP)

- adds session processing and network adjustment
- training by NGS currently required (~12 hours)

How do we access the modernized NSRS?

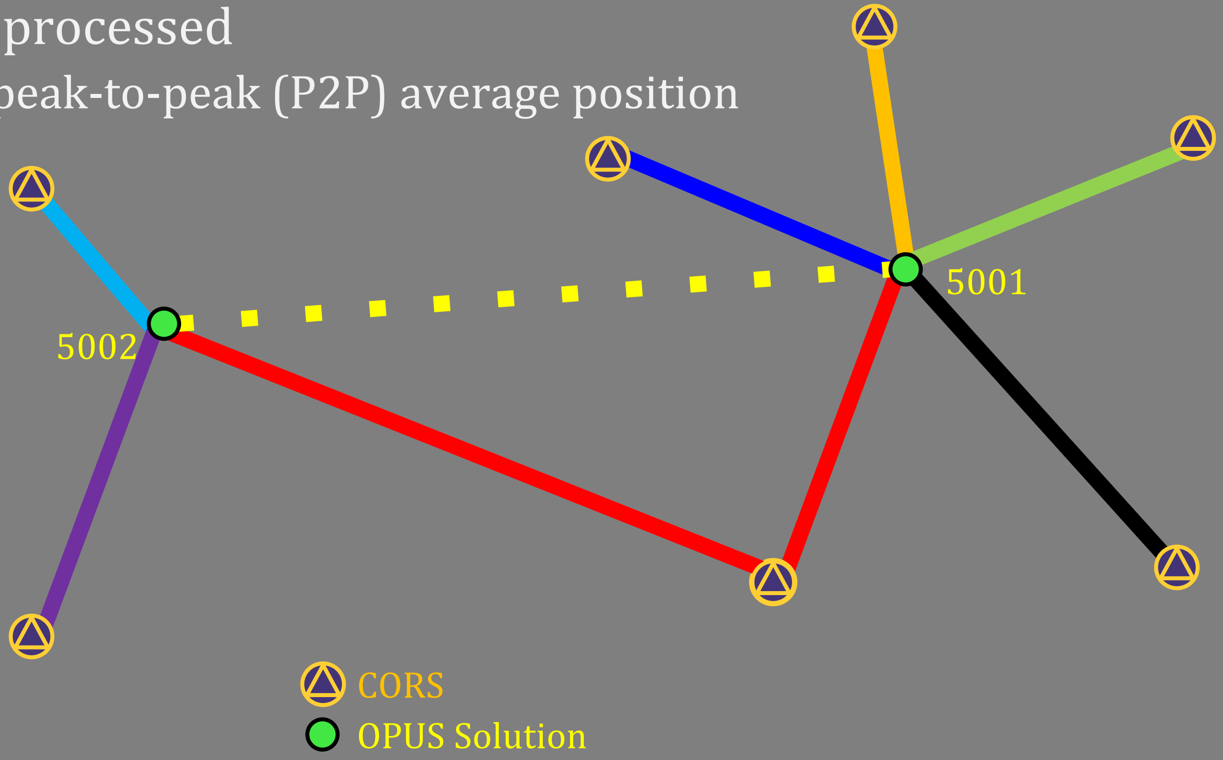
NOAA's **Continuously Operating Reference Station (CORS)** Network (NCN) provides Global Navigation Satellite System (GNSS) data, supporting three dimensional positioning, meteorology, space weather, and geophysical applications throughout the United States.

The NCN is a multi-purpose, multi-agency cooperative endeavor, combining the efforts of hundreds of government, academic, and private organizations. **The stations are independently owned and operated.** Each agency shares their GNSS carrier phase and code range measurements and station metadata with NGS, which are analyzed and distributed free of charge.



OPUS Static (OPUS-S)

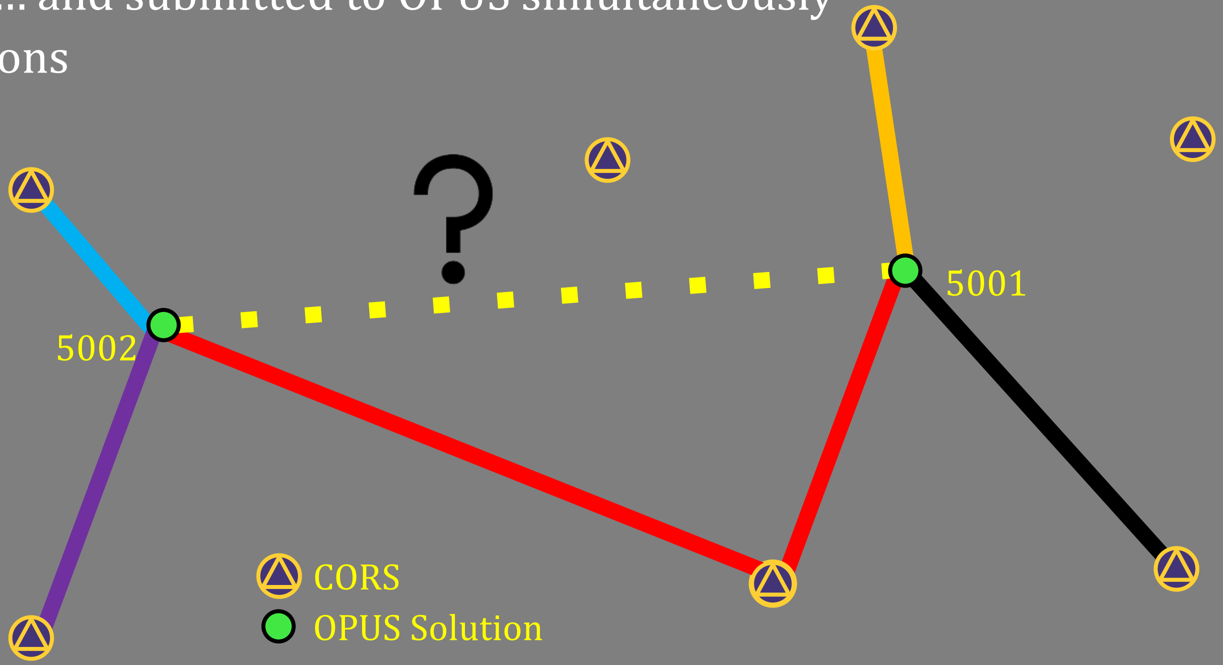
- 2 to 48 hours
- Best 3 of 5 baselines
- Sequentially processed
- Reports your peak-to-peak (P2P) average position



OPUS Static (OPUS-S)

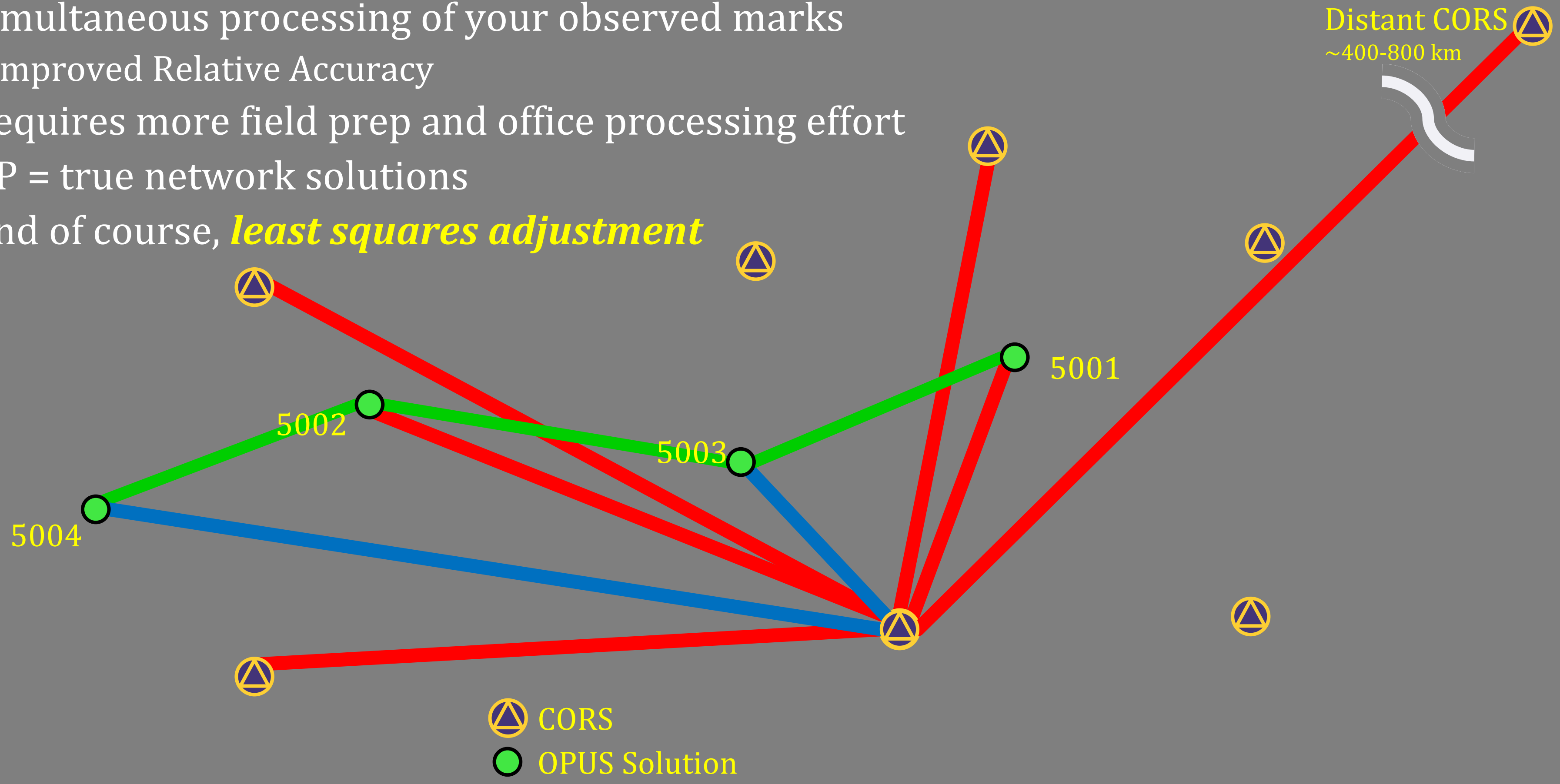
- No correlation between your observed marks
  - Low Relative Accuracy
- Even if … collected simultaneously

  … and submitted to OPUS simultaneously
- OPUS-S = independent solutions



OPUS Projects (OP)

- Simultaneous processing of your observed marks
  - Improved Relative Accuracy
- Requires more field prep and office processing effort
- OP = true network solutions
- And of course, ***least squares adjustment***



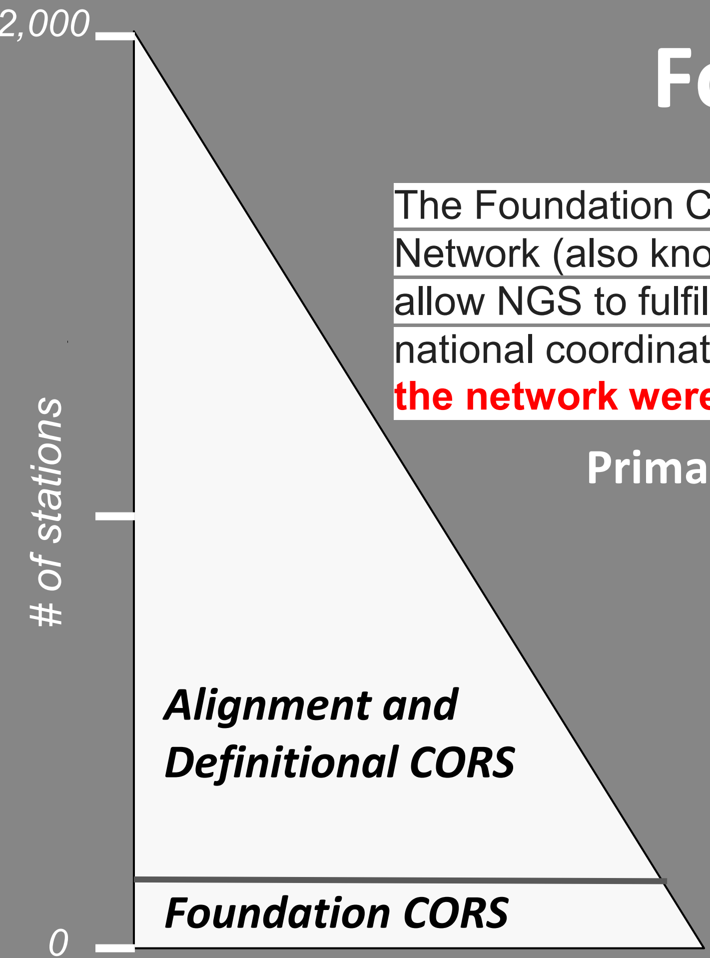
CORS standards in the modernizes NSRS

Standarized format -
Receiver Independent Exchange Format (RINEX) version 3.0 or newer

Naming conventions -
Due to the large number of CORS and other permanent GNSS station available, the station names will be expanded from four-character to nine-character

Resiliency?-
Are all CORS that are used as access services to the NSRS are dependent on publicly-owned volunteer data?

Foundation CORS (FCORS)

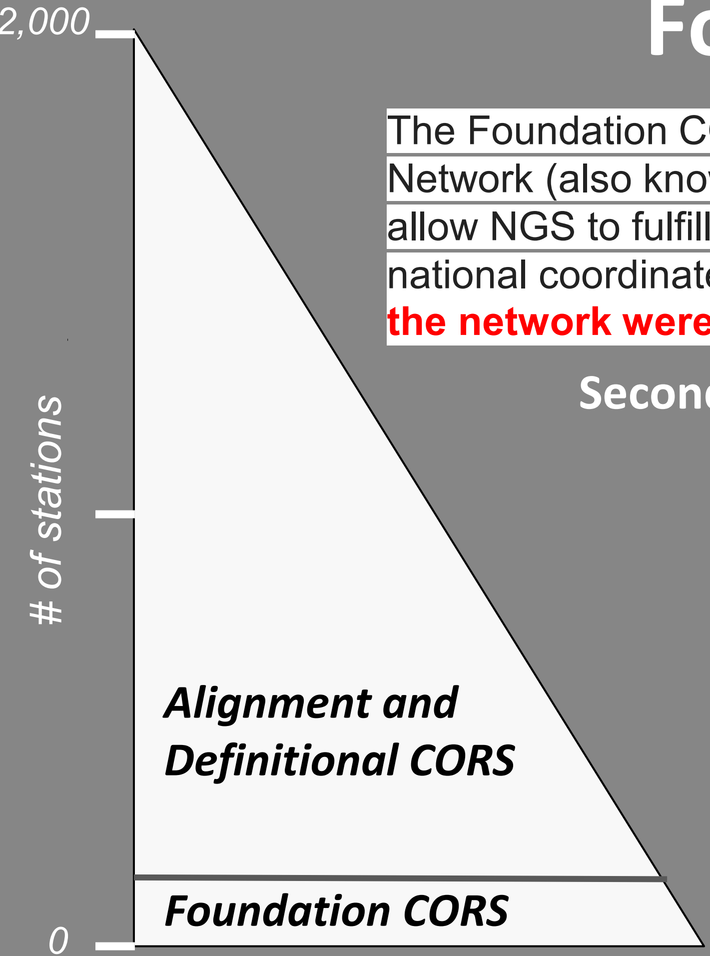


The Foundation CORS (FCORS) are the "backbone" of the NOAA permanent GPS Network (also known as, NOAA CORS Network, NCN). The purpose of FCORS is to allow NGS to fulfill its core mission: to define, maintain, and provide access to the national coordinate system defined by NOAA, **even if every single other station in the network were to cease providing data**

Primary requirements:

- A permanent GPS station that provides stable measurements that allows accurate station position and velocity.
- The location of station should outside of a tectonic fault zone
- The station cannot be down (offline or not functioning) for more than 14 days.
- 800 km to 1,000 km to support OPUS services
- Collect at a 1 second rate in order to support RTN operations

Foundation CORS (FCORS)



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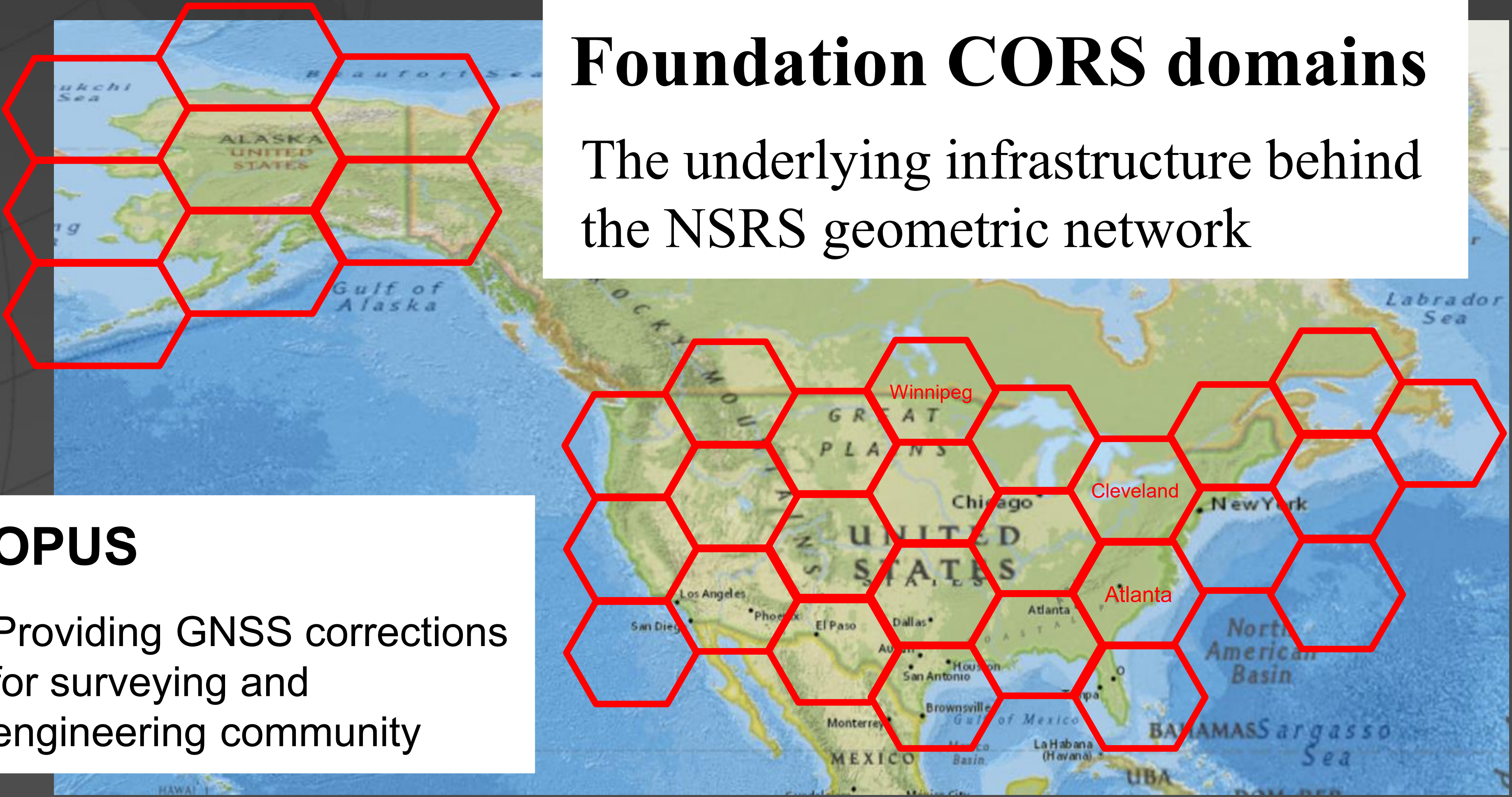
Secondary requirements:

- ○ Ability to acquire other GNSS signals (e.g., Galileo, GLONAAS, and BeiDou).
- ○ Additional locations can be included in areas that are co-located with other space geodetic techniques (SLR, VLBA, DORIS).
- ○ The monumentation of the station is on the ground rather than on top of a roof
- ○ PNT resilient against electronic warfare
- ○ Utilize nearby CORS as backup stations to ensure continuation of operations

Foundation CORS domains

The underlying infrastructure behind the NSRS geometric network



OPUS

Providing GNSS corrections for surveying and engineering community

Federal Partners

DoC/NOAA

NASA

DoD/USACE

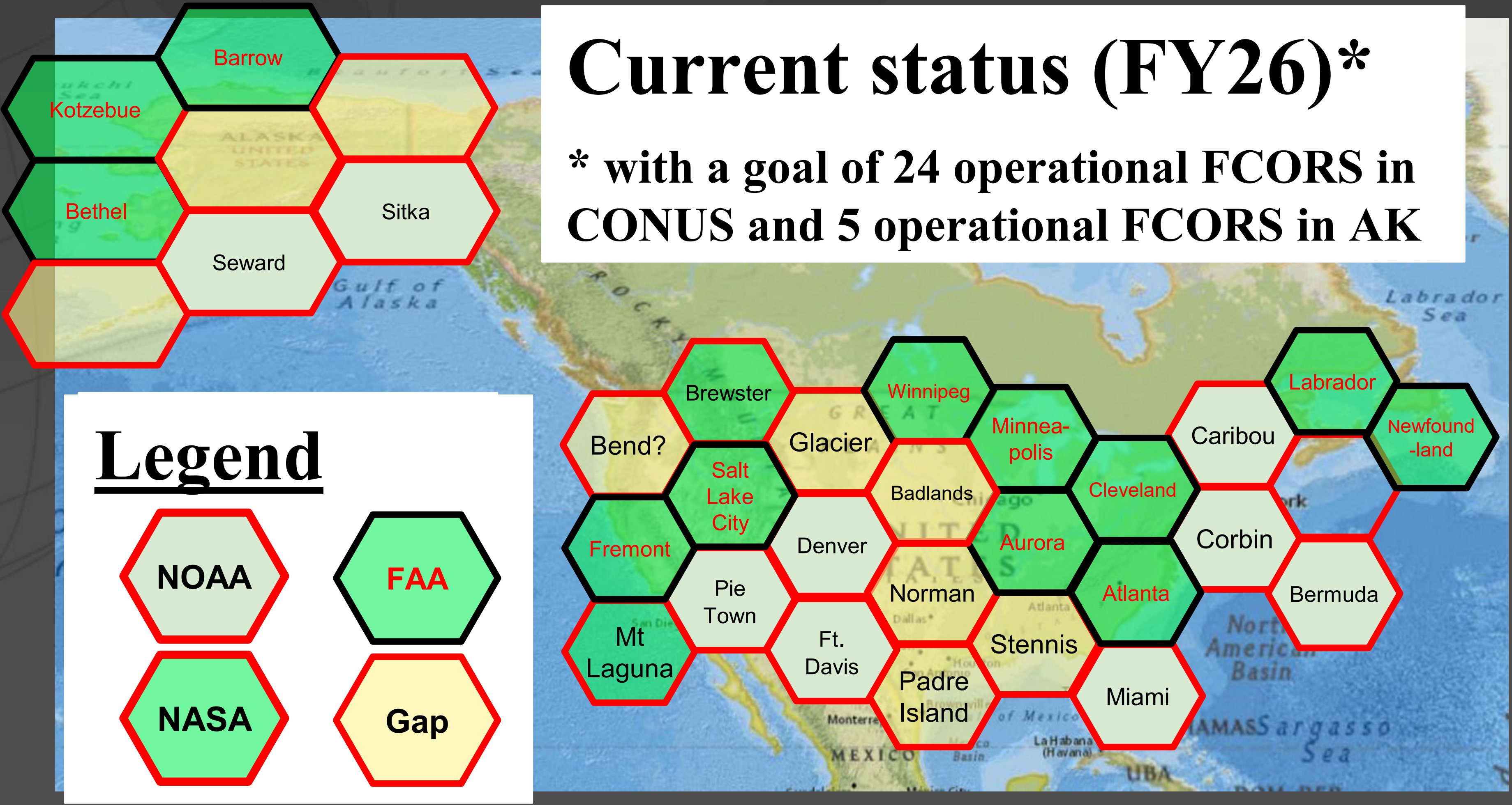
DoI/NPS

DoT/FAA*

* To supplement the coverage FCORS network includes **FAA WAAS** stations as a temporary solution

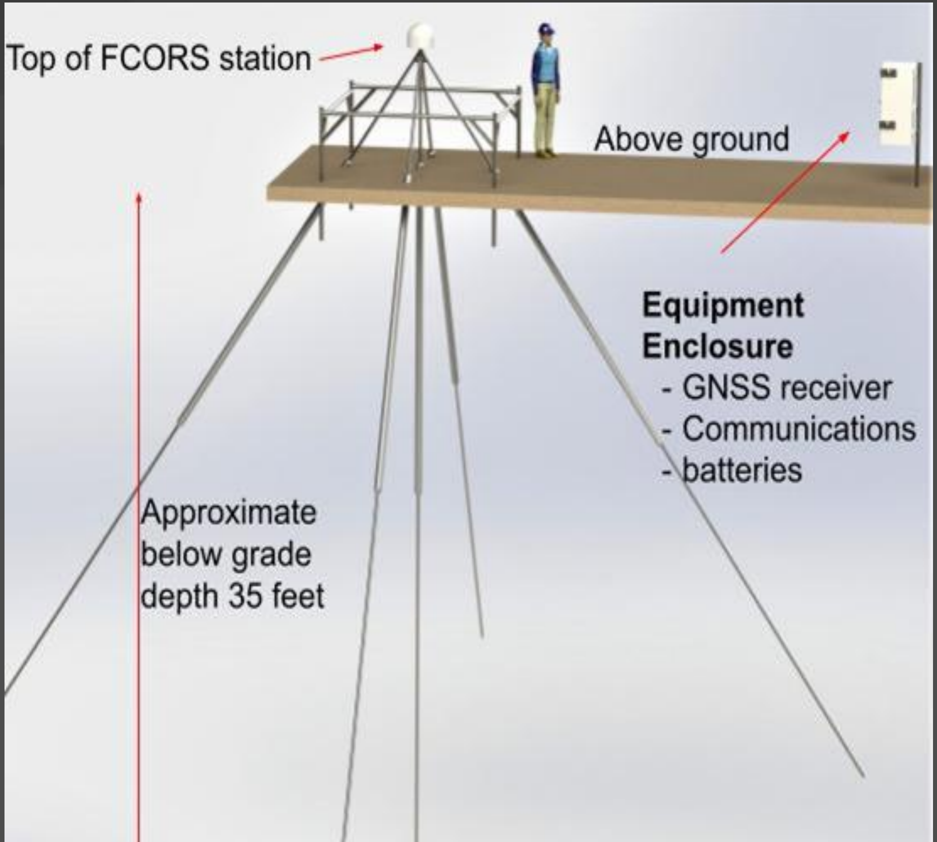
Current status (FY26)*

*** with a goal of 24 operational FCORS in CONUS and 5 operational FCORS in AK**



Foundation CORS Design

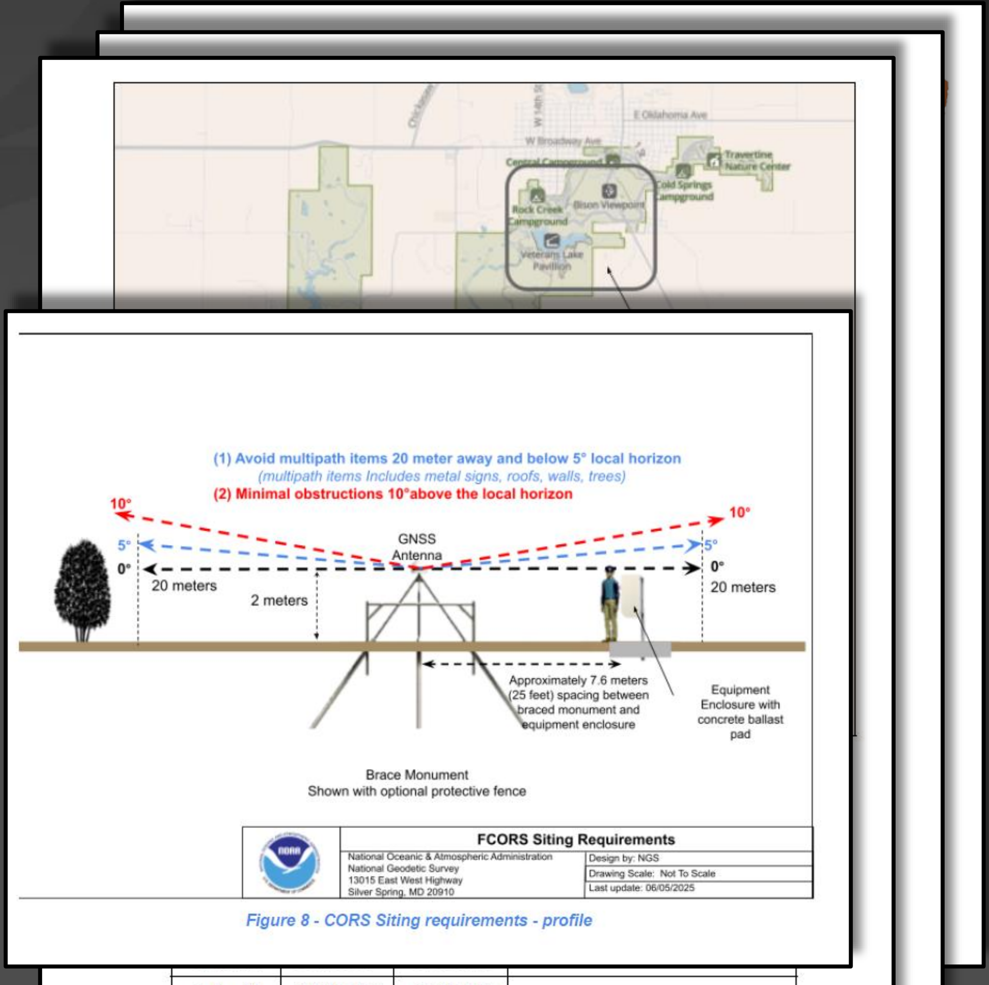
Complete Geodetic monument (antenna at top)



Deep Drilled Braced Monument (DDBM)

Logistics

- ✓ Hardware
- ✓ Contractor on call
- ✓ Field crew
- ■ Permit?



FCORS Siting Requirements

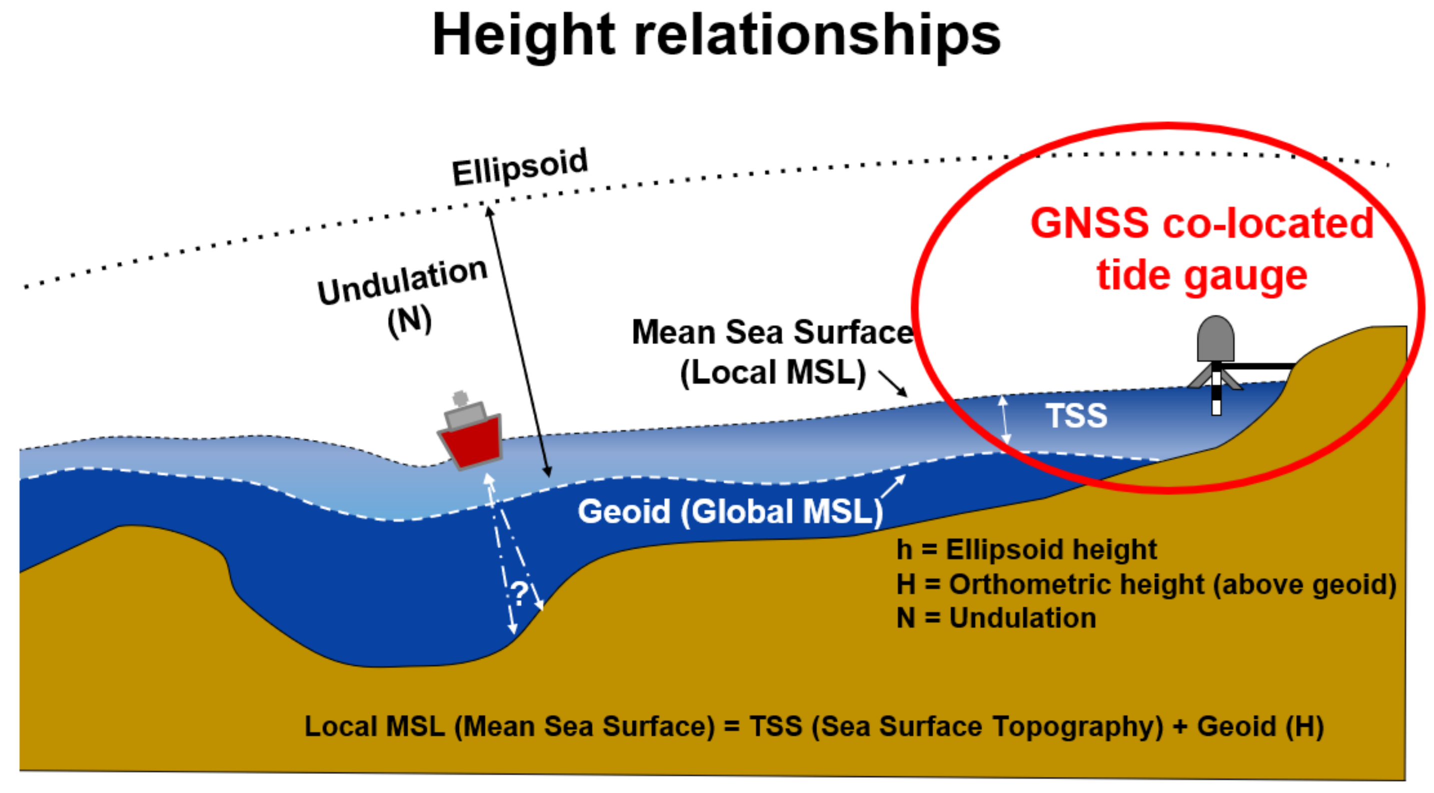
National Oceanic & Atmospheric Administration
National Geodetic Survey
13015 East West Highway
Silver Spring, MD 20910

Design by: NGS
Drawing Scale: Not To Scale
Last update: 06/05/2025

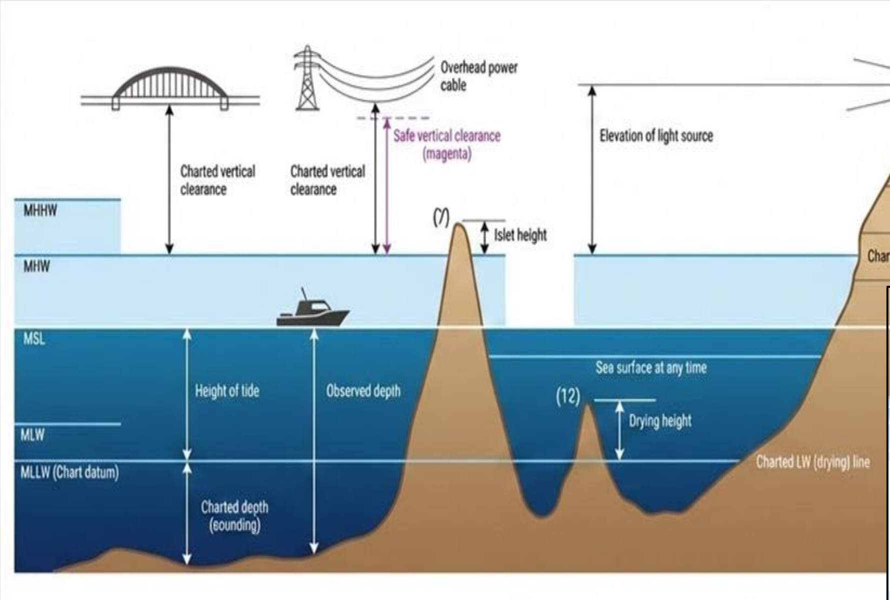
Figure 8 - CORS Siting requirements - profile

Civil applications examples that require access to the NSRS

Connecting the tidal datum to the NSRS



Precision Marine Navigation



Schematic illustration of Hazards to Navigation
and
Aids to Navigation
(NOAA Chart No. 1)

Schematic illustration of S-1XX and S-4XX layers
(IHO.int)

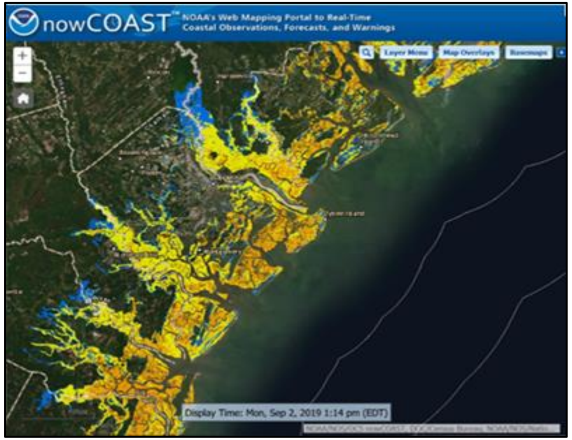
Water Forecasting, Warnings, Emergency Response, and Planning

NOAA that includes federal and academic partners to review NOAA needs and consolidate them into individual modeling systems (i.e., global and regional atmosphere, ocean, land, etc.) using a smaller set of coupled Earth System models that would continue to serve its various stakeholders.

Risk Reduction

Aftermath of Hurricane Michael in Mexico Beach, FL. (AP Photo/Gerald Herbert)

Total Water Level

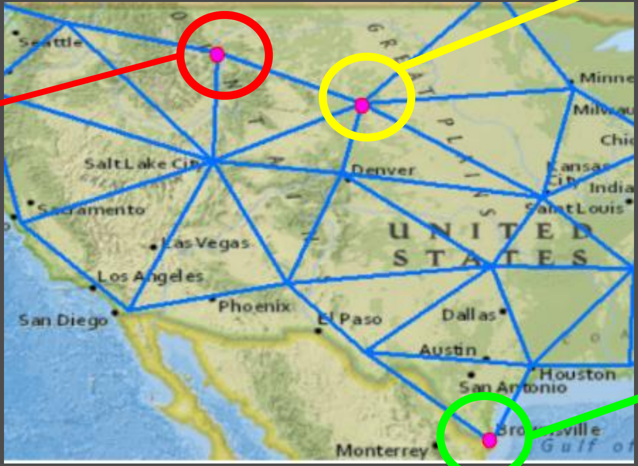


NWS Potential Storm Surge Flooding Map for Hurricane Dorian (NowCOAST - 9/2019)

Control using Complimentary Positioning, Navigation, and Timing (CPNT)

Co-location with eLoran sites (USCG)

Gillette, WY



Havre, MT

Raymondville, TX

Summary

- NOAA is releasing a new modernized National Spatial Reference System (NSRS)
- To align observations, marks and other features in the new NSRS, it is possible to use NOAA's Online Positioning User Service (OPUS) that calculates a GNSS observation with respect to NOAA's CORS network.
- The new Foundation CORS network will support's NOAA's NGS core mission: to define, maintain, and provide access to the national coordinate system defined by NOAA, even if every single other station in the network were to cease providing data

Thanks!

Working with industry, government, and academia to adopt NSRS
(U.S. - Canada Industry Summit, 4/23-24/2025)

AUTODESK
BLUE MARBLE GEOGRAPHICS
Cansel Improving field to finish productivity
Dewberry
esri
FUGRO
HEXAGON
hobu
Leica Geosystems
looq
NV5 GEOSPATIAL
PROJ
SmartNet North America Any Constellation - Any Application - Open to All
TOWILL Surveying, Mapping and GIS Services
sanborn geospatial
Shell
Trimble
WOOLPERT DESIGN | GEOSPATIAL | INFRASTRUCTURE

CSAT

CORS ANALYTIC TOOL

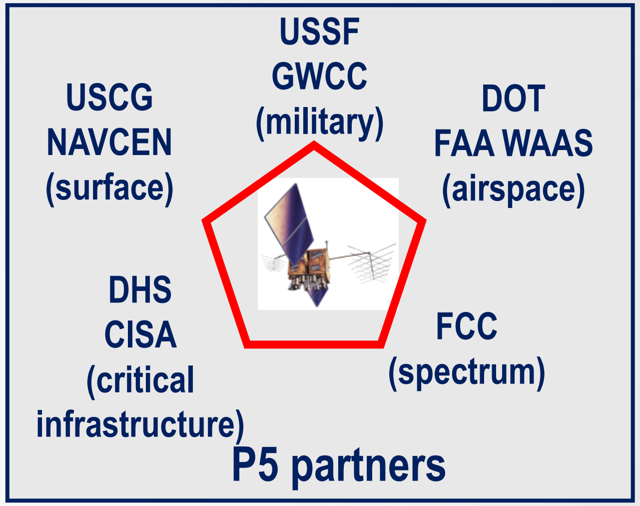
Leveraging National CORS Network for GPS Interference Detection

- Presented by: Dr. Andria Bilich - NGS
- Co-author: Christopher Gauthier
- Chief Operations Specialist
- Supervisor Navigation Information Service (NIS)

U.S. Coast Guard Navigation Center

NAVCEN’s Role in GPS

- The Navigation Center (NAVCEN) is the designated civilian interface to the Global Positioning System (GPS).
- Core responsibilities include disseminating GPS health and status information and, crucially, receiving, analyzing, and documenting public reports of GPS service disruptions.


USSF GWCC (military)

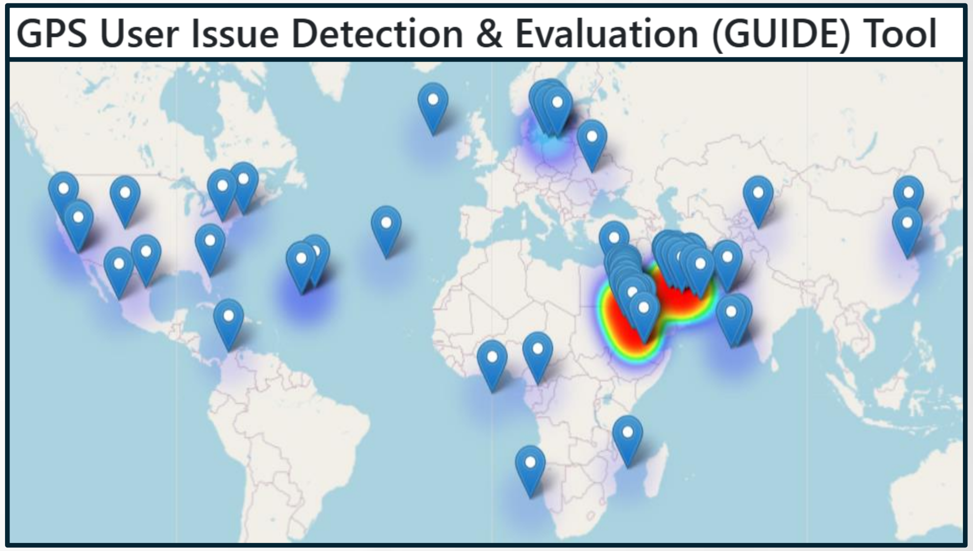
USCG NAVCEN (surface)

DOT FAA WAAS (airspace)

DHS CISA (critical infrastructure)

FCC (spectrum)

P5 partners

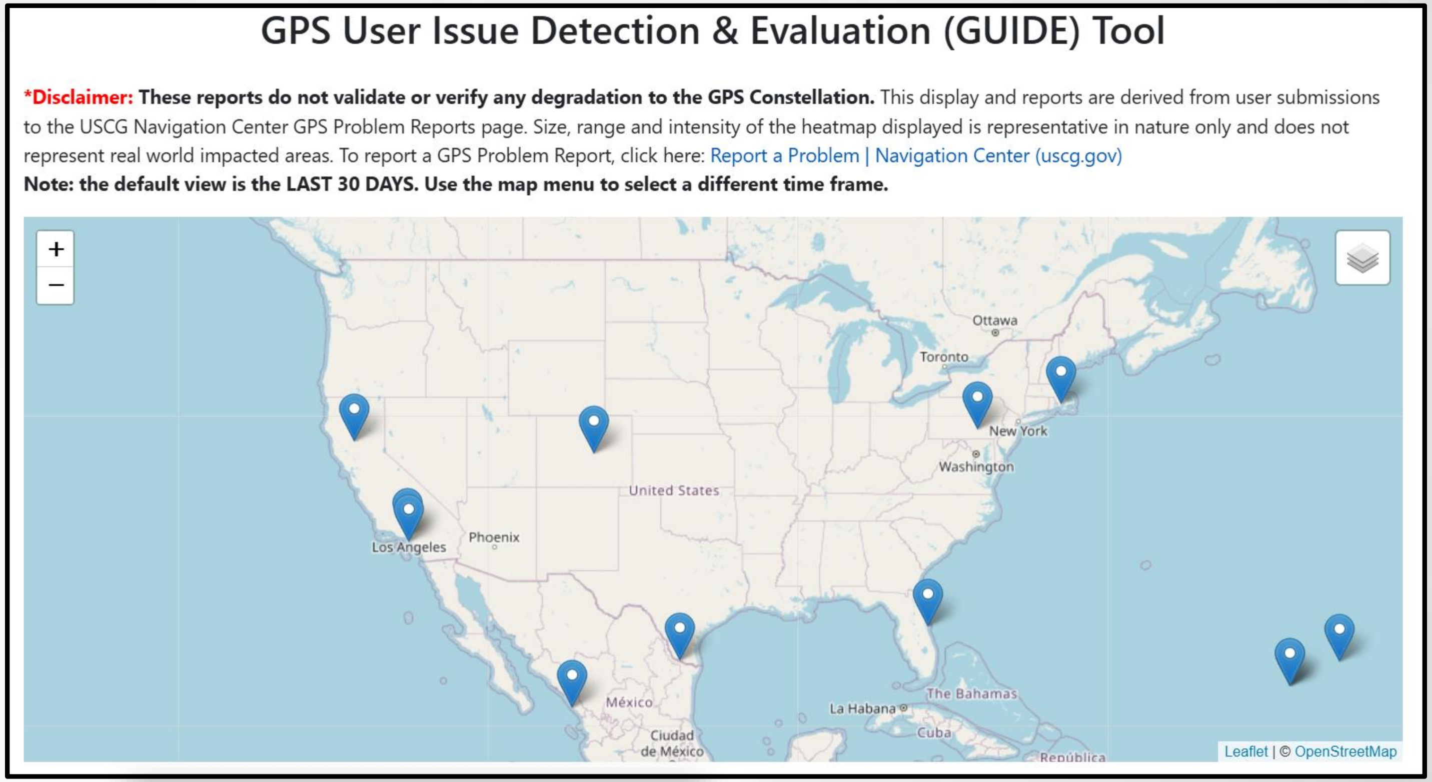

GPS User Issue Detection & Evaluation (GUIDE) Tool

GPS User Issue Detection & Evaluation (GUIDE) Tool | Navigation Center

The Challenge: Validating GPS Interference Reports

The Analytical Gap:

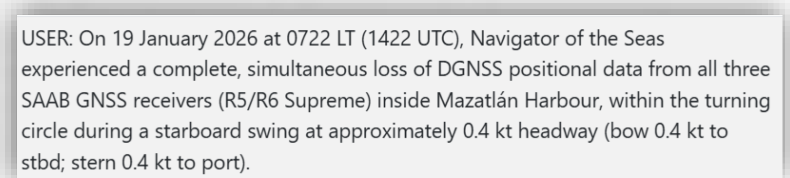
- NAVCEN receives numerous user reports of potential GPS disruptions, ranging from single-user issues to wide-area events.
- Historically, there has been a lack of a robust, data-driven system to rapidly and independently validate these reports.



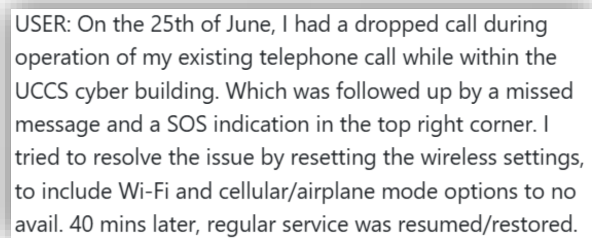
GPS User Issue Detection & Evaluation (GUIDE) Tool

***Disclaimer: These reports do not validate or verify any degradation to the GPS Constellation.** This display and reports are derived from user submissions to the USCG Navigation Center GPS Problem Reports page. Size, range and intensity of the heatmap displayed is representative in nature only and does not represent real world impacted areas. To report a GPS Problem Report, click here: Report a Problem | Navigation Center (uscg.gov)

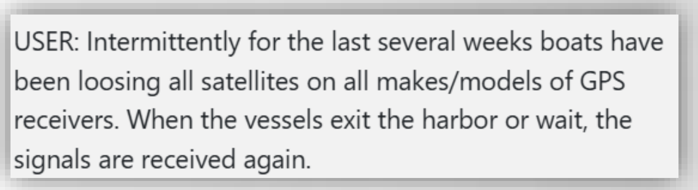
Note: the default view is the LAST 30 DAYS. Use the map menu to select a different time frame.



USER: On 19 January 2026 at 0722 LT (1422 UTC), Navigator of the Seas experienced a complete, simultaneous loss of DGNSS positional data from all three SAAB GNSS receivers (R5/R6 Supreme) inside Mazatlán Harbour, within the turning circle during a starboard swing at approximately 0.4 kt headway (bow 0.4 kt to stbd; stern 0.4 kt to port).



USER: On the 25th of June, I had a dropped call during operation of my existing telephone call while within the UCCS cyber building. Which was followed up by a missed message and a SOS indication in the top right corner. I tried to resolve the issue by resetting the wireless settings, to include Wi-Fi and cellular/airplane mode options to no avail. 40 mins later, regular service was resumed/restored.



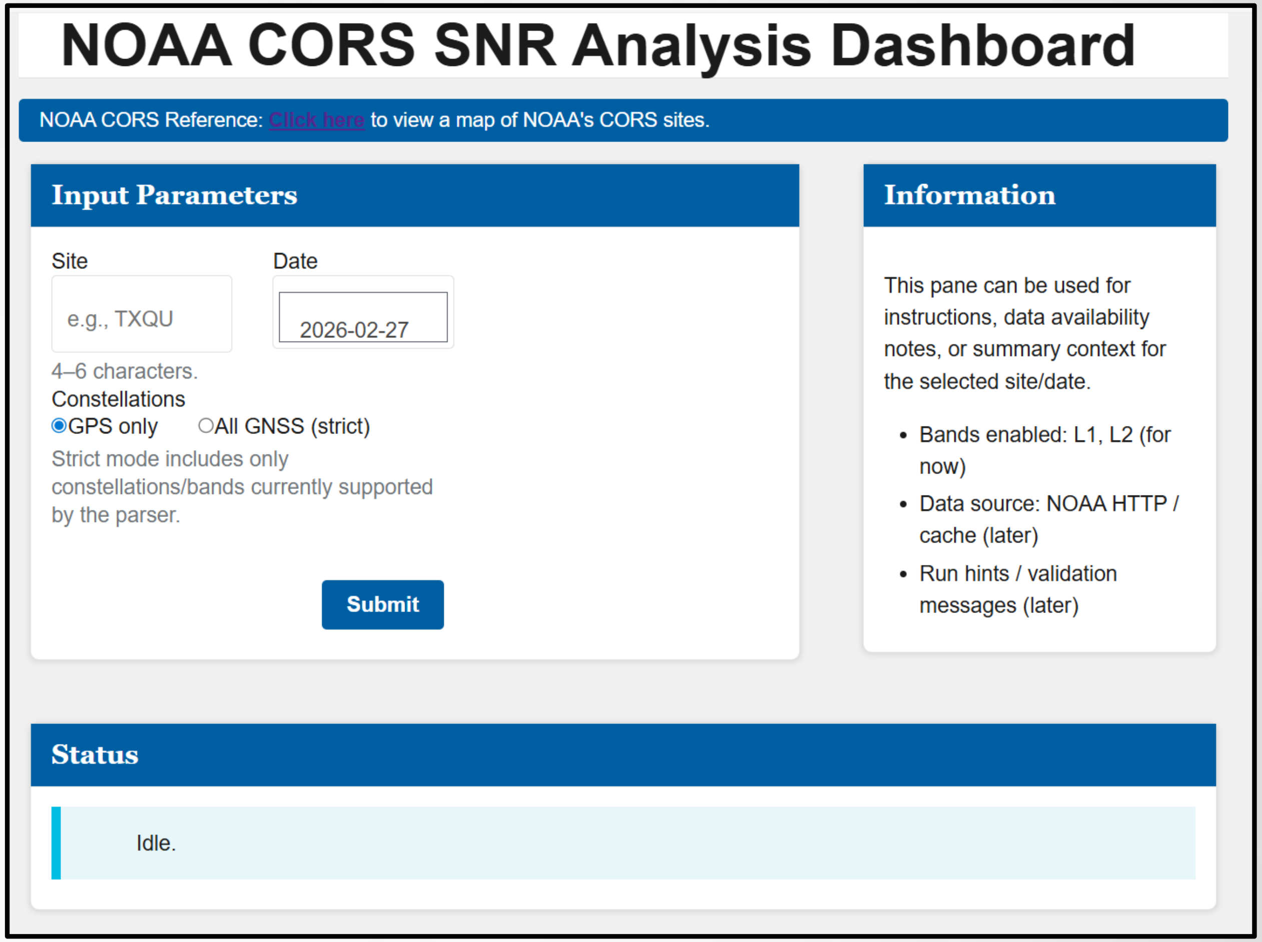
USER: Intermittently for the last several weeks boats have been loosing all satellites on all makes/models of GPS receivers. When the vessels exit the harbor or wait, the signals are received again.

Problem: How can NAVCEN reliably differentiate between a user's equipment malfunction and a genuine, localized GPS interference event without immediately deploying costly physical assets?

Solution: CORS Analytic Tool (CSAT)

CSAT is a novel tool developed in-house designed to provide objective, quantifiable evidence of GPS signal degradation.

- CSAT ingests data from the NOAA Continuously Operating Reference Station (CORS) network.
- By utilizing this existing, high-fidelity data source (RINEX files), CSAT provides a low-cost government solution for GPS interference detection.



NOAA CORS SNR Analysis Dashboard

NOAA CORS Reference: Click here to view a map of NOAA's CORS sites.

Input Parameters

Site: e.g., TXQU

4–6 characters.

Date: 2026-02-27

Constellations

● GPS only ○ All GNSS (strict)

Strict mode includes only constellations/bands currently supported by the parser.

Information

This pane can be used for instructions, data availability notes, or summary context for the selected site/date.

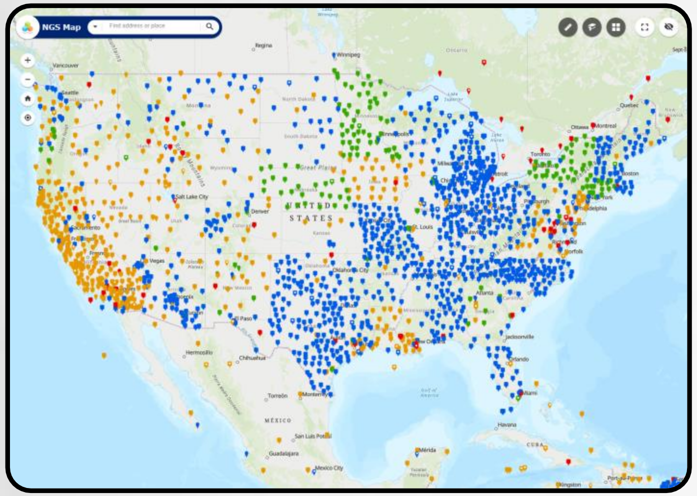
- Bands enabled: L1, L2 (for now)
- Data source: NOAA HTTP / cache (later)
- Run hints / validation messages (later)

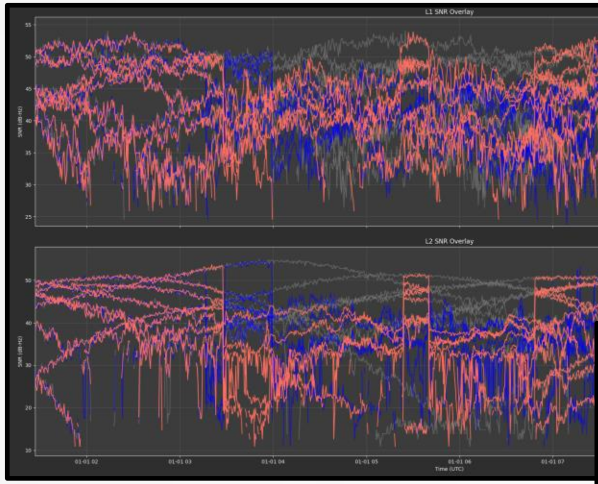
Status

Idle.

CORS Analytic Tool (CSAT)

CSAT leverages the 1800+ CORS sites to retrieve and process observational data into clear and insightful plots. Clean and simplified plots allows non-technical users to clearly identify and corroborate GPS Disruption Reports.





Raw SNR data

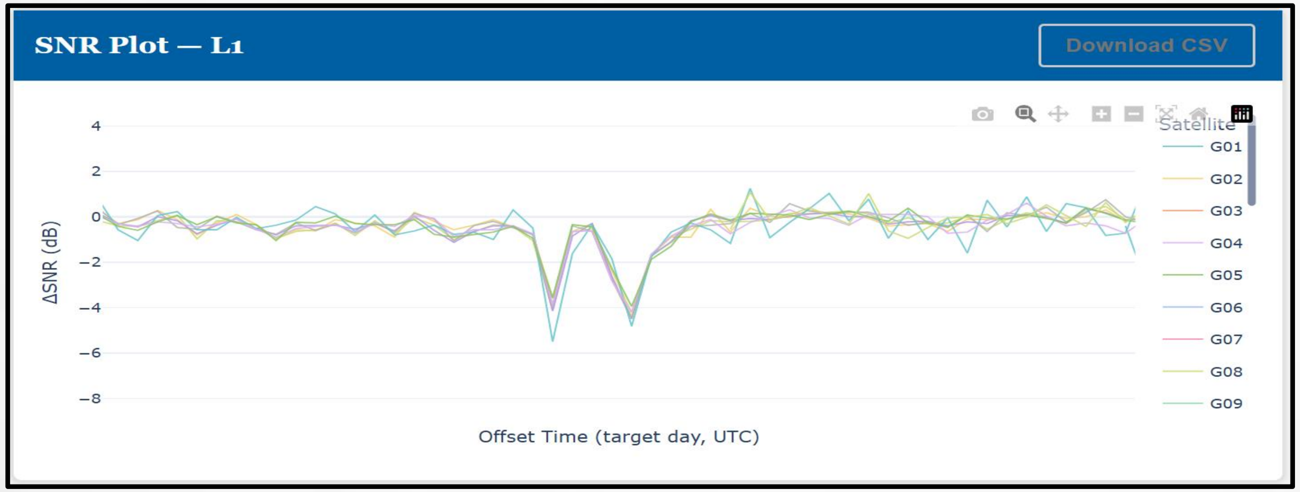
The Core Metric: Signal–To–Noise Ratio (SNR)

Why SNR is a Key Indicator of Interference:

- SNR is routinely recorded by GNSS receivers operating at CORS. SNR recorded for a single satellite will repeat every day, unless environmental conditions change.

- CSAT is engineered to detect this anomalous drop, by measuring assumed “normal” observation days against a suspected interference day.

- CSAT is built to process each satellite observation individually, and flags anomalies only when all satellites observe the same anomaly.



By maintaining each SV’s observations, we can easily identify effects of localized EMI across all satellites.

CSAT Analytical Method

Data Retrieval

- The tool retrieves RINEX observation data from a user-specified CORS site for the target "Day of Interest" (DOI) and the two preceding "control" days.

Sidereal Offset

- The control days' data is time-shifted by approximately 3 minutes and 56 seconds per day to ensure satellites are on the same sky track.

Data Aggregation (Binning)

- Observation epochs are pooled into 60-second intervals to smooth high-frequency noise and create a statistically stable time series

Anomaly Detection (ΔSNR Calculation)

- A "quiet" baseline is established by averaging the SNR values from the two control days for each bin.

Visualization

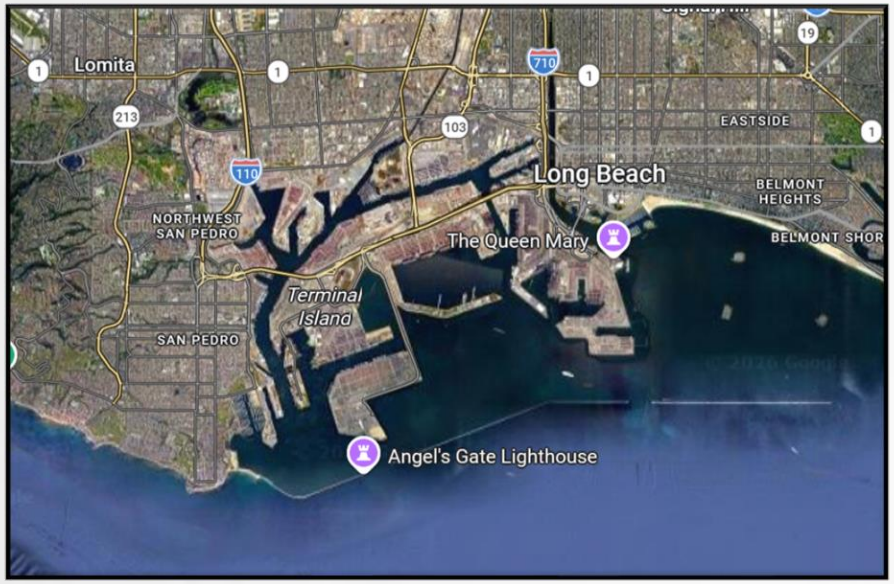
- CSAT calculates the delta (ΔSNR) then plotted as a time series for each satellite in view.

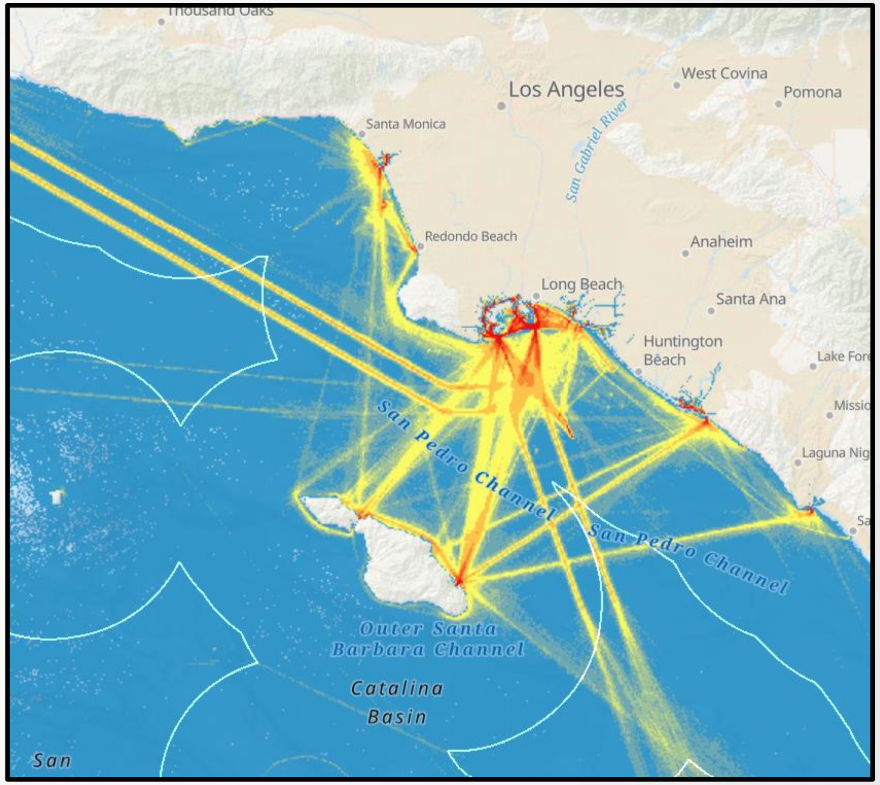
Case Study

CSAT Performance against a known GPS Interference event

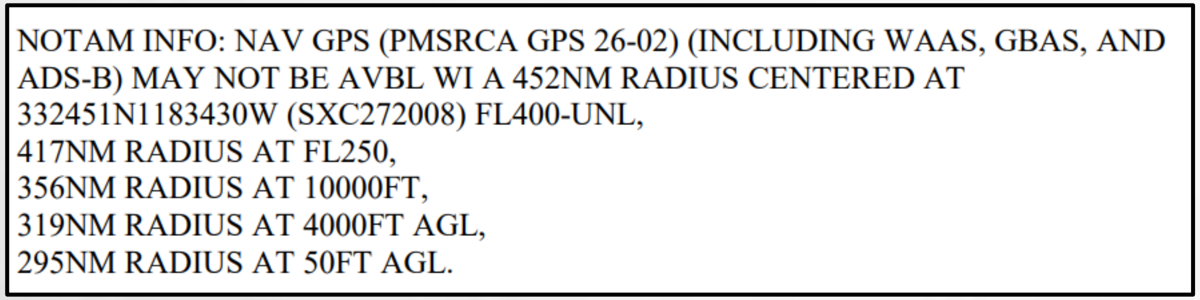
Point Mugu Sea Range, CA (30 Jan 2026)

Summary: USCG Vessel Traffic Service Los Angeles / Long Beach received nearly 20 reports of vessels experiencing a total loss of GPS within or near the Port of LA in a 1 hour timeframe between 0700z – 0800z.



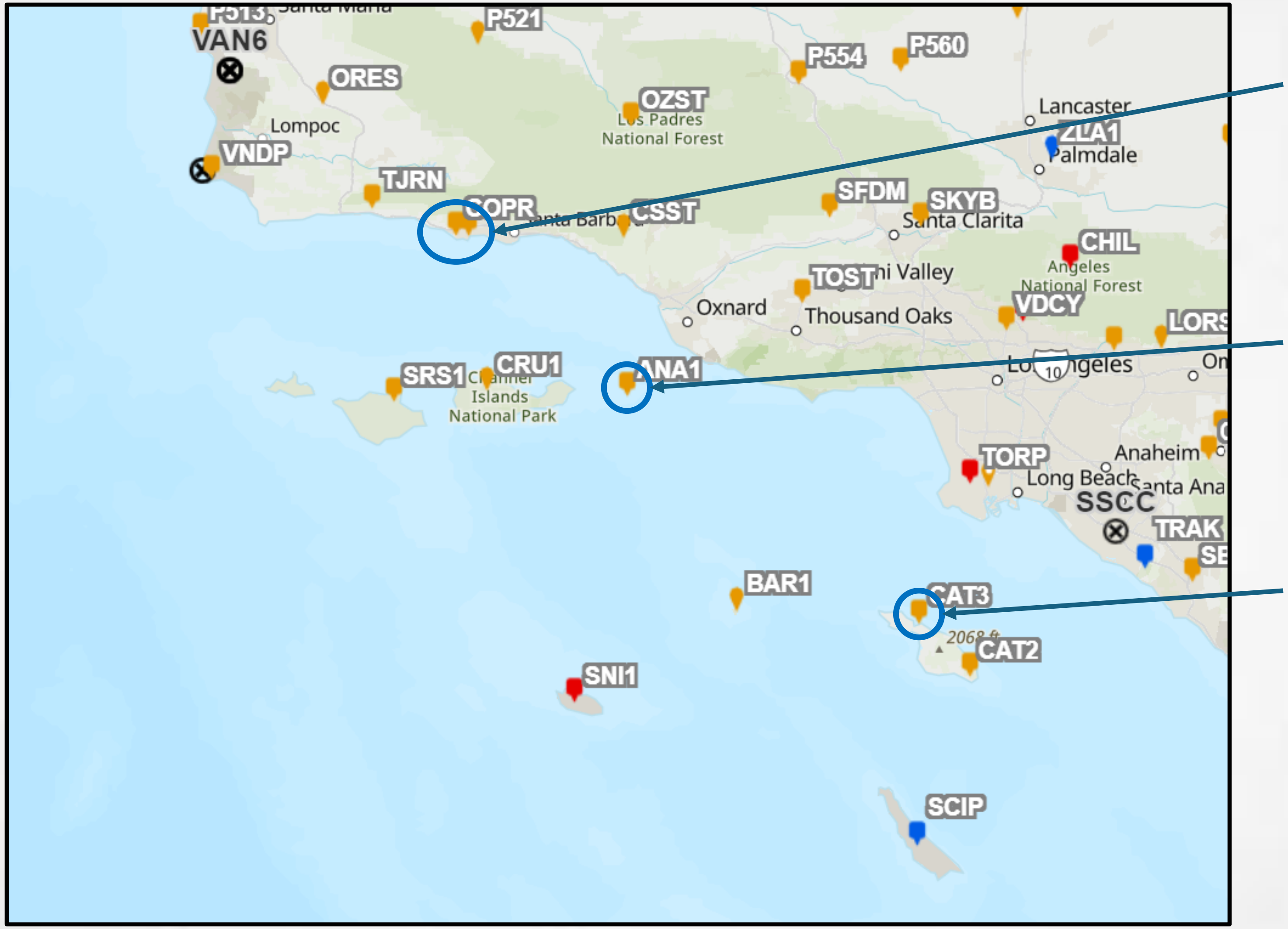


Source: Marine Cadastre National Viewer



NOTAM INFO: NAV GPS (PMSRCA GPS 26-02) (INCLUDING WAAS, GBAS, AND ADS-B) MAY NOT BE AVBL WI A 452NM RADIUS CENTERED AT 332451N1183430W (SXC272008) FL400-UNL,
417NM RADIUS AT FL250,
356NM RADIUS AT 10000FT,
319NM RADIUS AT 4000FT AGL,
295NM RADIUS AT 50FT AGL.

AOI - Sampled 3 Sites: CASN, ANA1, CAT3

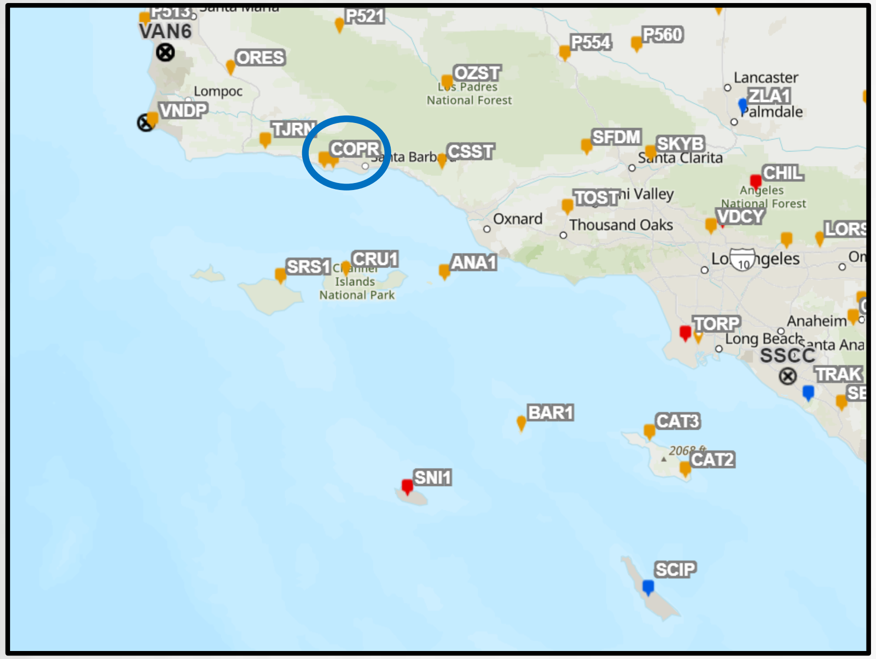


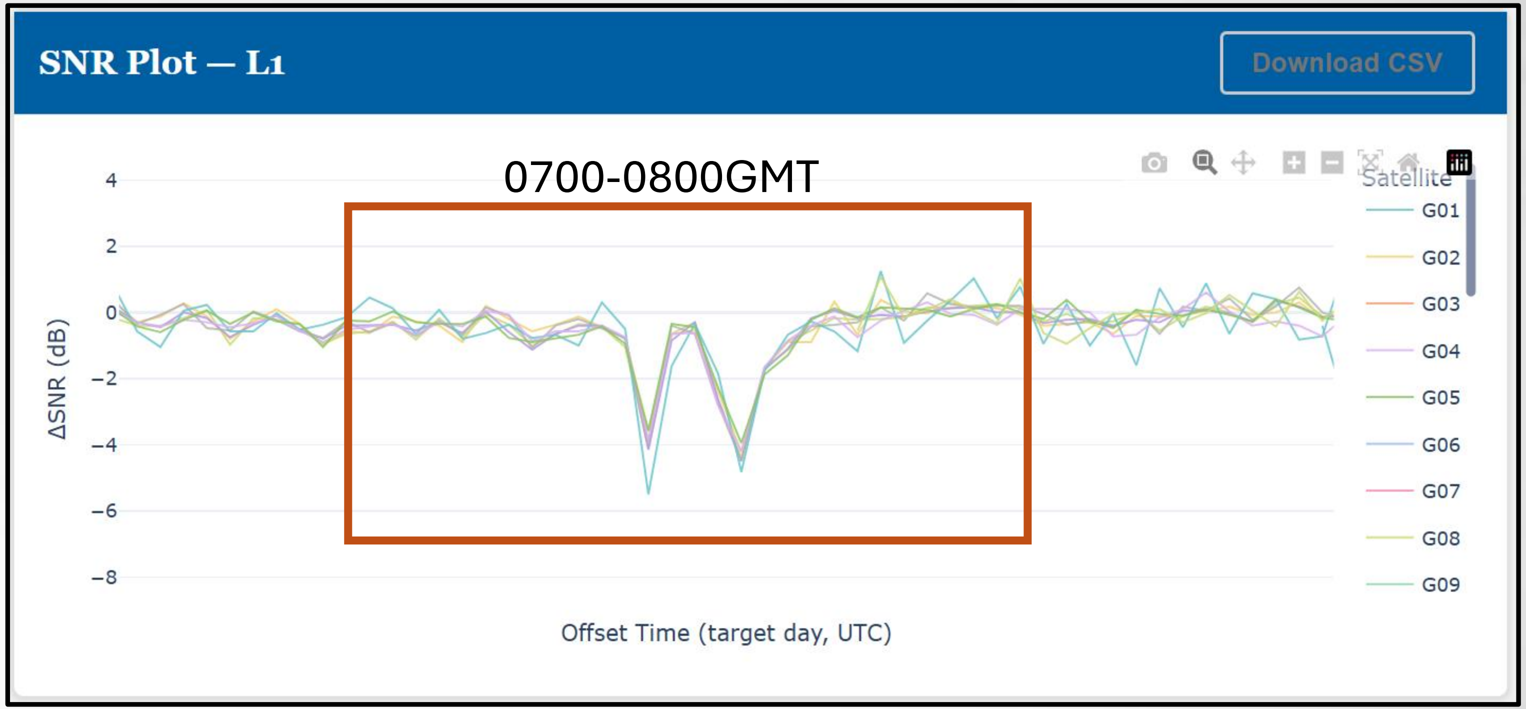
CASN

ANA1

CAT3

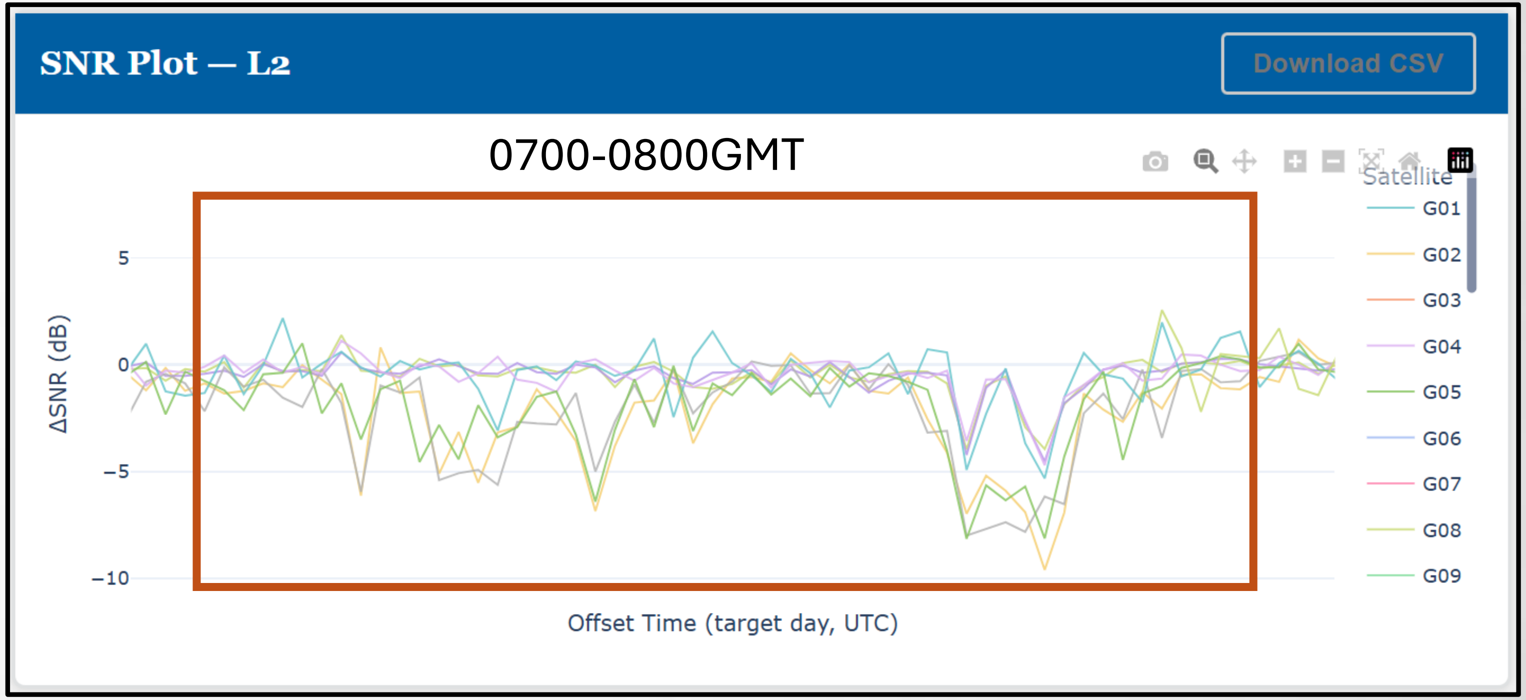
CASN – PMSR – 30Jan





SNR Plot — L1

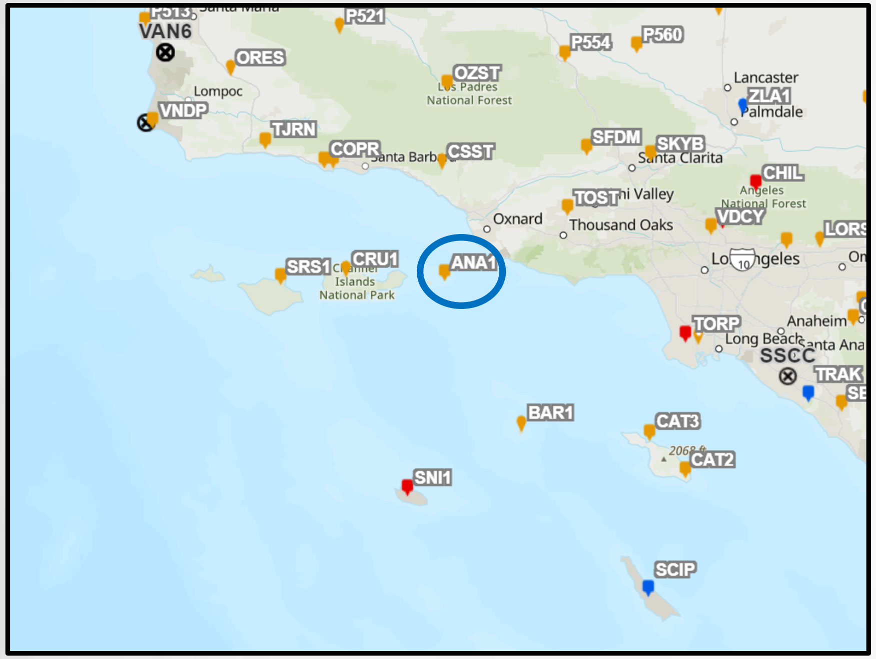
0700-0800GMT

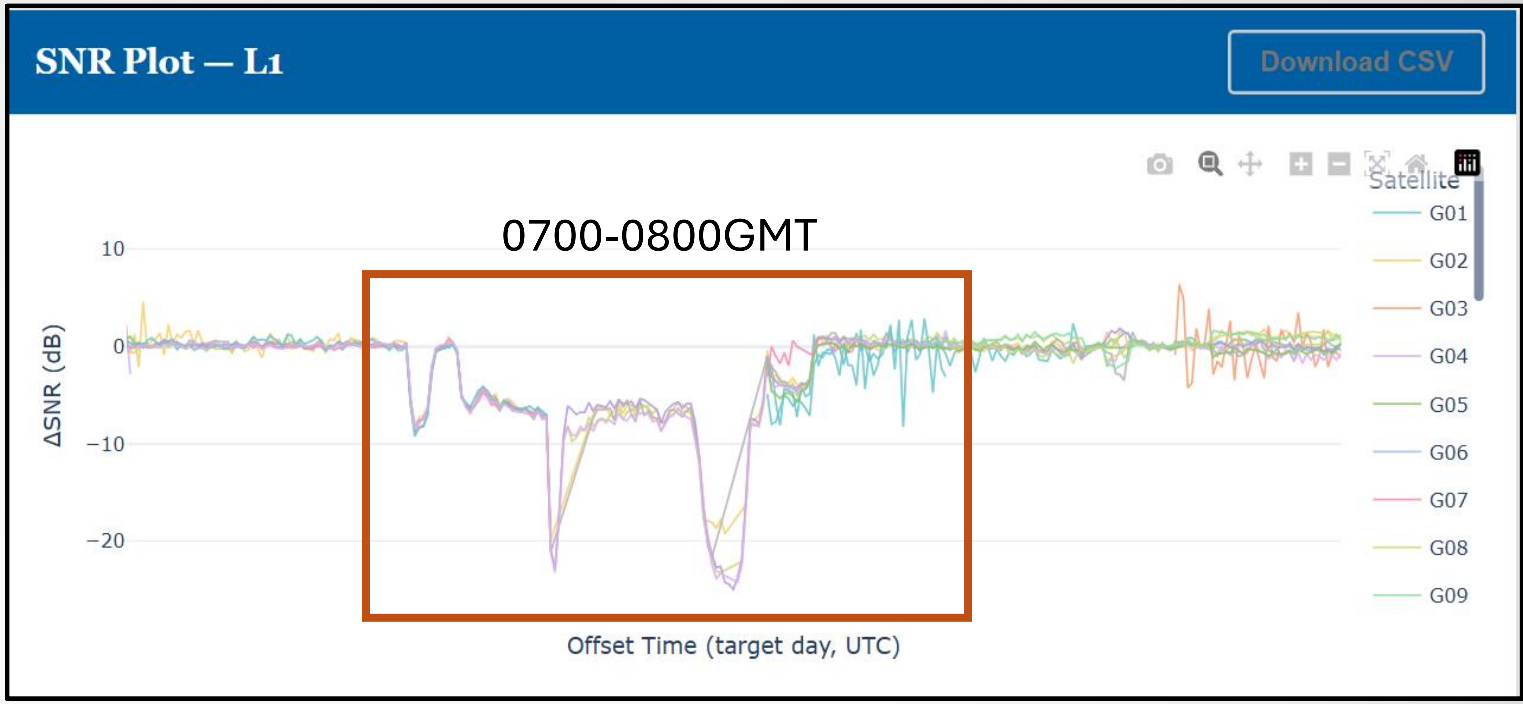


SNR Plot — L2

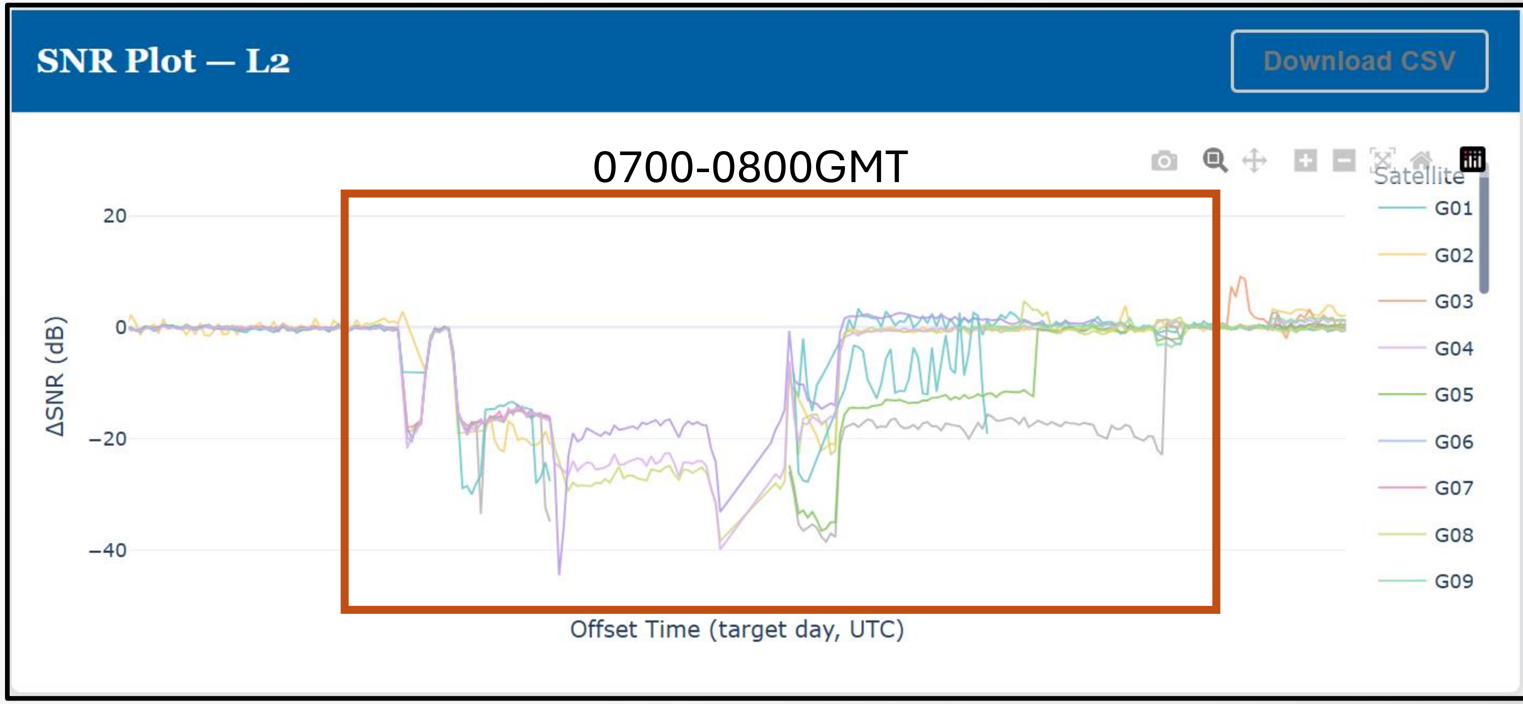
0700-0800GMT

ANA1 – PMSR – 30Jan



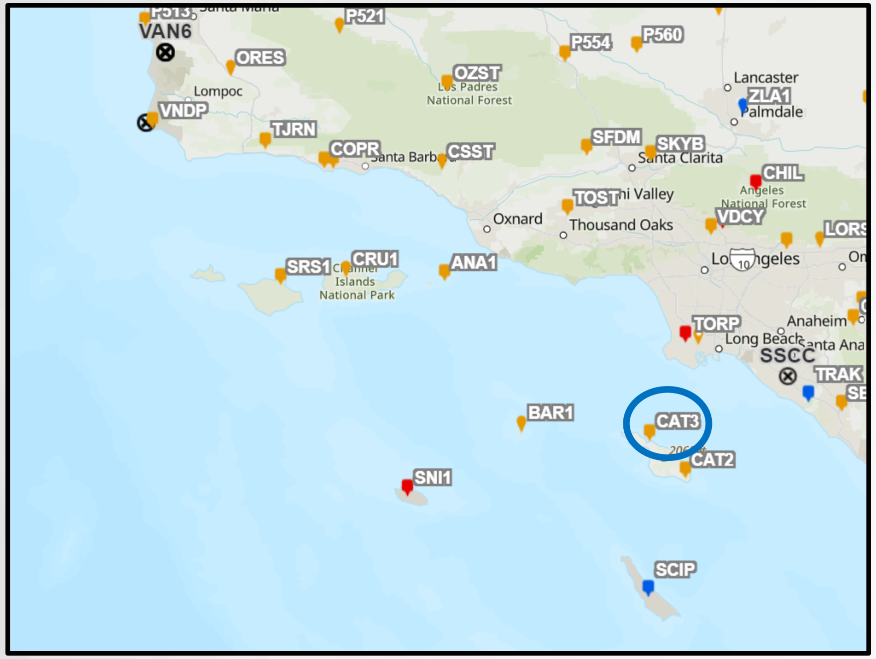


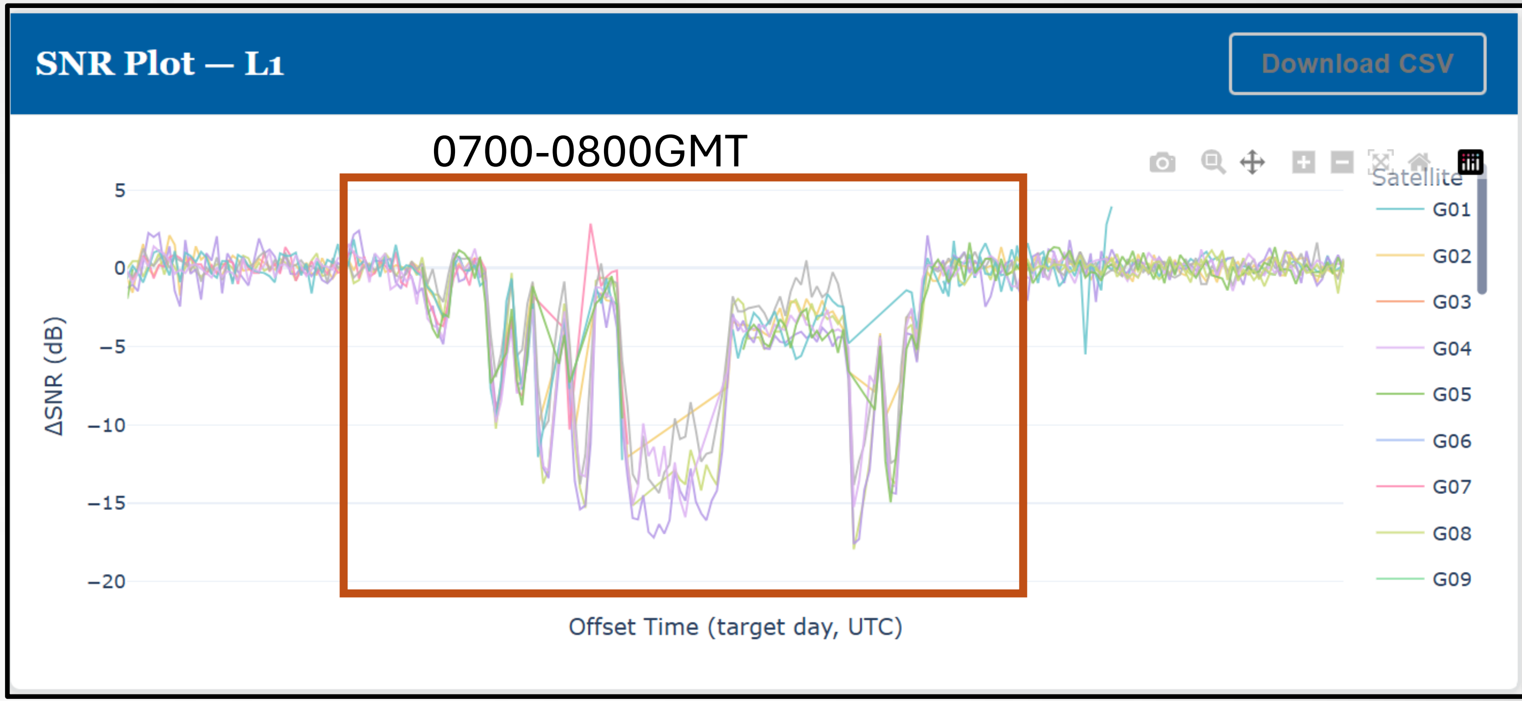
0700-0800GMT



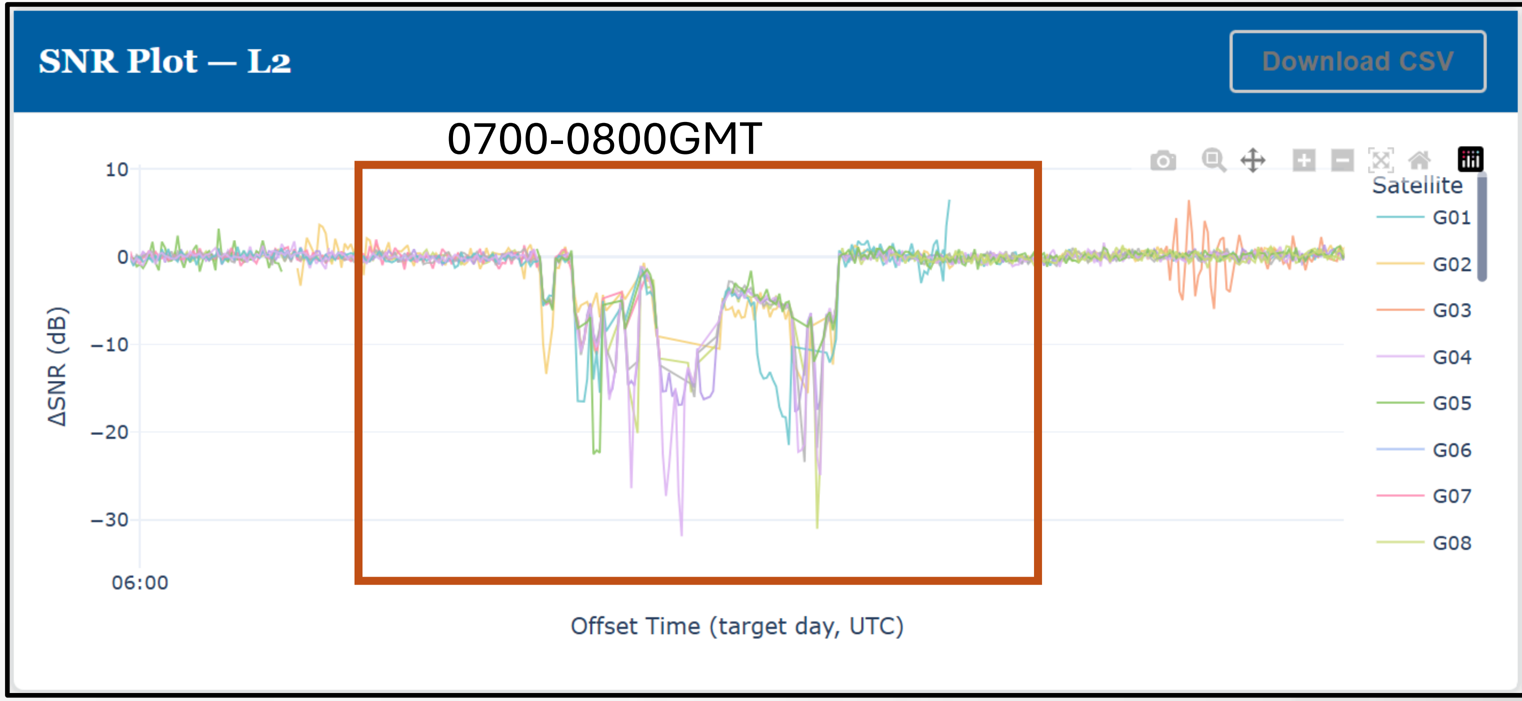
0700-0800GMT

CAT3 – PMSR – 30Jan





0700-0800GMT



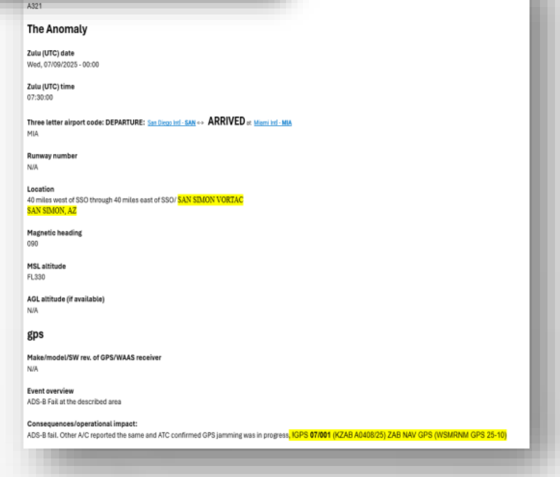
0700-0800GMT

Implication and Use

- Provides a US Government solution for validation of user reports.
- Requires minimal training to use and understand outputs.
- Increases confidence before expending limited resources.
- Leverages existing infrastructure (CORS) and well supported data format (RINEX), allowing easy expansion into other international ground based observational data.

[Non-DoD Source] 2026-14 - Your GPS Disruption Report

NW NAVCEN Website <no-reply@navcen.uscg.gov>
To ⊞**NAVCEN-Web-GPS-Disruption-Report**; ○TIS-SMB-NAVCEN-WebTeam
Cc ⊞**NAVCEN-Web-CC-GPS-Disruption-Report**
Retention Policy Non-Capstone (10 years) Expires 2/26/2036



A321

The Anomaly

Zulu (UTC) date
Wed, 07/09/2025 - 00:00

Zulu (UTC) time
07:30:00

Three letter airport code: DEPARTURE: San Diego Intl - SAN <-> **ARRIVED** at Miami Intl - MIA
MIA

Runway number
N/A

Location
40 miles west of SSO through 40 miles east of SSO/ SAN SIMON VORTAC
SAN SIMON, AZ

Magnetic heading
090

MSL altitude
FL330

AGL altitude (if available)
N/A

gps

Make/model/SW rev. of GPS/WAAS receiver
N/A

Event overview
ADS-B Fail at the described area

Consequences/operational impact:
ADS-B fail. Other A/C reported the same and ATC confirmed GPS jamming was in progress, !GPS **07/001** (KZAB A0408/25) ZAB NAV GPS (WSMRNM GPS 25-10)

Conclusion

Way Forward:

- Incorporate more GNSS constellations and bands.
- Add international ground-based reference stations data.
- Continue building partnerships with experts to validate data and use.

Key Takeaway: CSAT demonstrates how we can leverage existing national infrastructure to counter emerging threats. This model of agile innovation and cross-agency collaboration is essential for addressing future challenges in the PNT environment.

Reducing the “Geodesy Crisis” with a new Geodesy Master’s Program and Undergraduate Internship Program

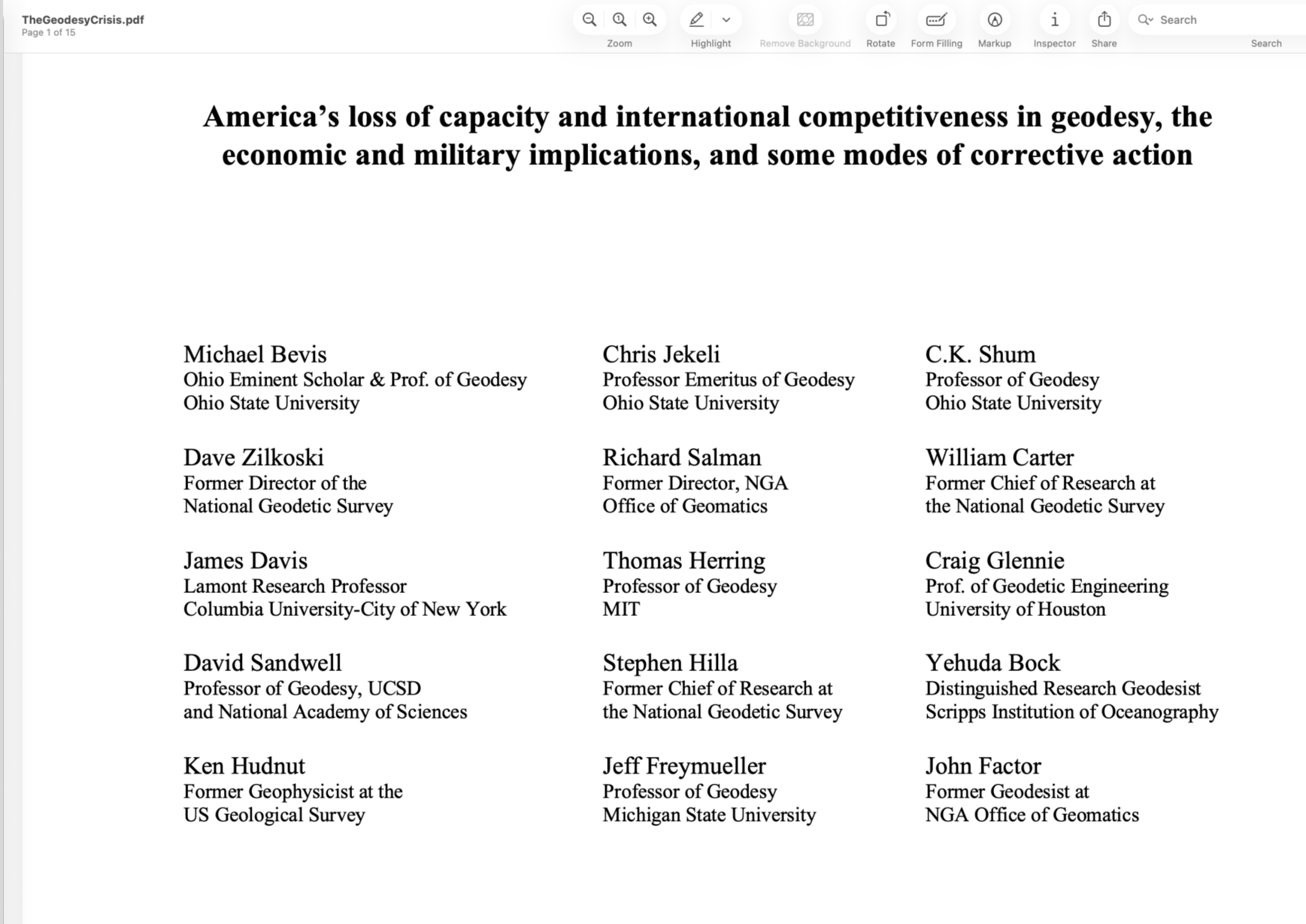
Dr. Jeffrey T. Freymueller

Dr. Julie L. Elliott

Department of Earth and Environmental Sciences

MICHIGAN STATE UNIVERSITY

The Geodesy Crisis



America's loss of capacity and international competitiveness in geodesy, the economic and military implications, and some modes of corrective action

Michael Bevis
Ohio Eminent Scholar & Prof. of Geodesy
Ohio State University

Chris Jekeli
Professor Emeritus of Geodesy
Ohio State University

C.K. Shum
Professor of Geodesy
Ohio State University

Dave Zilkoski
Former Director of the
National Geodetic Survey

Richard Salman
Former Director, NGA
Office of Geomatics

William Carter
Former Chief of Research at
the National Geodetic Survey

James Davis
Lamont Research Professor
Columbia University-City of New York

Thomas Herring
Professor of Geodesy
MIT

Craig Glennie
Prof. of Geodetic Engineering
University of Houston

David Sandwell
Professor of Geodesy, UCSD
and National Academy of Sciences

Stephen Hilla
Former Chief of Research at
the National Geodetic Survey

Yehuda Bock
Distinguished Research Geodesist
Scripps Institution of Oceanography

Ken Hudnut
Former Geophysicist at the
US Geological Survey

Jeff Freymueller
Professor of Geodesy
Michigan State University

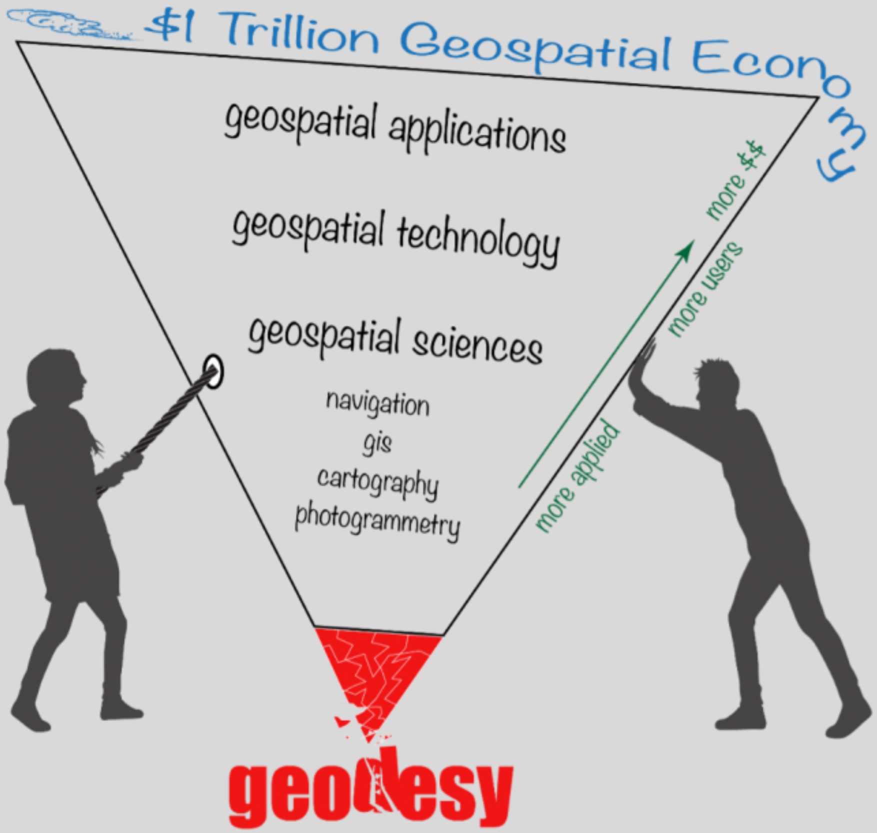
John Factor
Former Geodesist at
NGA Office of Geomatics

The Geodesy Crisis

- Geodesy is the foundation of the geospatial economy, but the US is not educating enough geodesists

- *“The U.S. is on the verge of being permanently eclipsed in geodesy and in the downstream geospatial technologies. This threatens our national security and poses major risks to an economy that is strongly tied to the geospatial revolution, on Earth and, eventually, in space.”*

The inverted geospatial pyramid



The entire geospatial economy is supported by geodesy!

Image: Dana Caccamise, NGS

Addressing the Geodesy Crisis

- National Academies' "Meeting of Experts" Dec 2024
- Certain US government agencies need people with geodetic expertise, and are having a hard time finding US citizens/permanent residents to hire
    - National Geodetic Survey, National Geospatial Intelligence Agency, etc
    - Another example: the Census Bureau's new geospatial database relies on precise positions
- Private sector usually doesn't need Ph.D. level geodesists, but values graduate education
- They recognize a need to educate more geodesists
- All of this is now worse than it was a year ago…

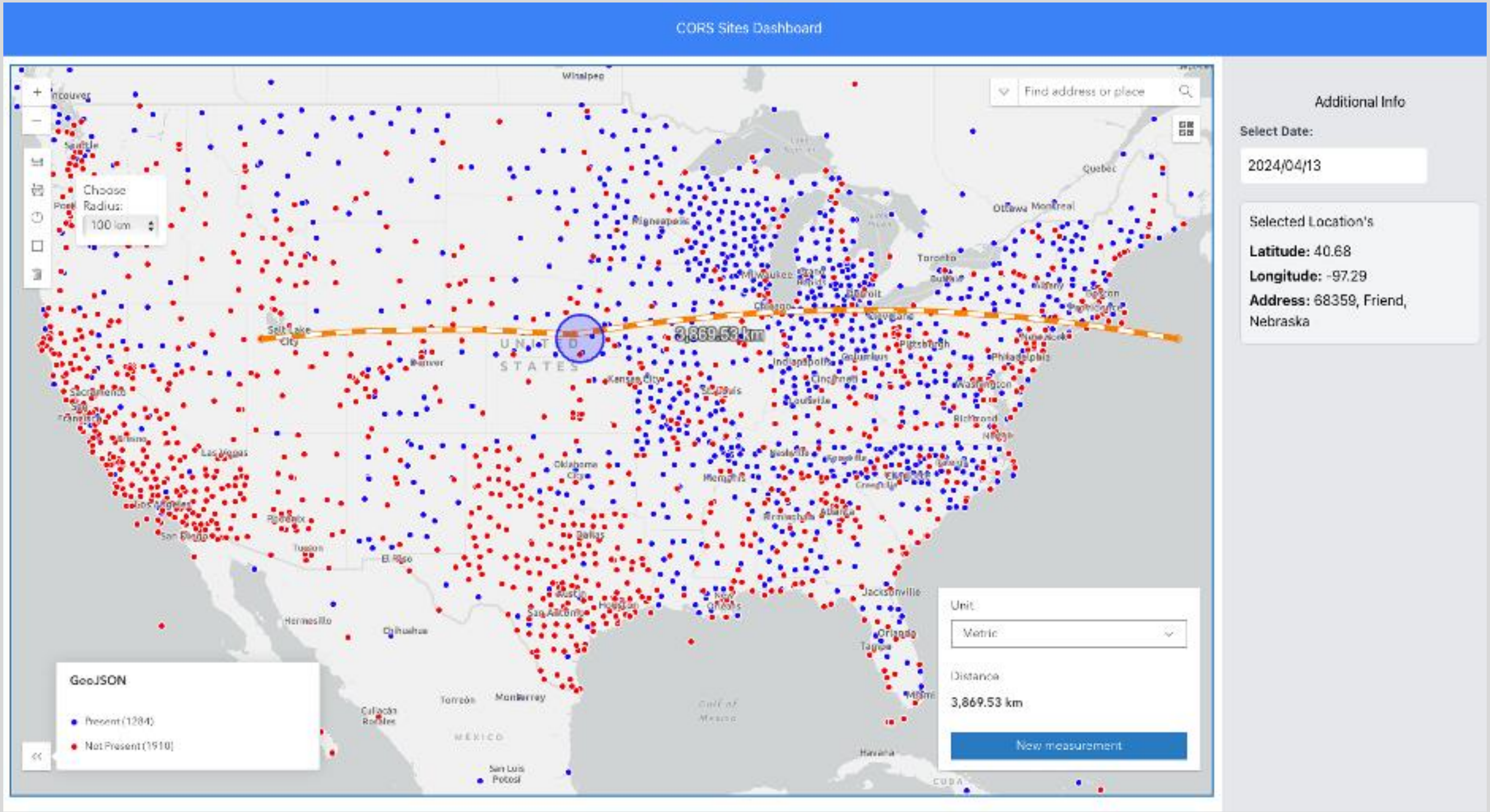
National Geodetic Survey Geospatial Modeling Grant

- NGS put out a solicitation about 2 years ago to fund efforts that would meet some of their needs and educate more students
- Four universities were selected: MSU, Ohio State, Oregon State, UC San Diego
- Each University had its own distinct projects and some elements of geodesy education.

Two Funded Components at MSU

- CORS Dashboard: Tool for monitoring the CORS network
  - Designed to help assess BOTH data and assumed models for motion of sites
  - Struggling through some last IT hurdles to get the first version live
- Geodesy Master’s Program and Internship Program

CORS Dashboard: Enhanced Monitoring of a CORS Network



CORS Sites Dashboard

Additional Info

Select Date: 2024/04/13

Selected Location's

Latitude: 40.68

Longitude: -97.29

Address: 68359, Friend, Nebraska

Choose Radius: 100 km

GeoJSON

- ● Present (1284)
- ● Not Present (1910)

Unit: Metric

Distance: 3,869.53 km

New measurement

What is the Error in Your Position?

$$\sigma_{total} = (\sigma^2_{yours} + \sigma^2_{ref})^{0.5}$$

Users
control

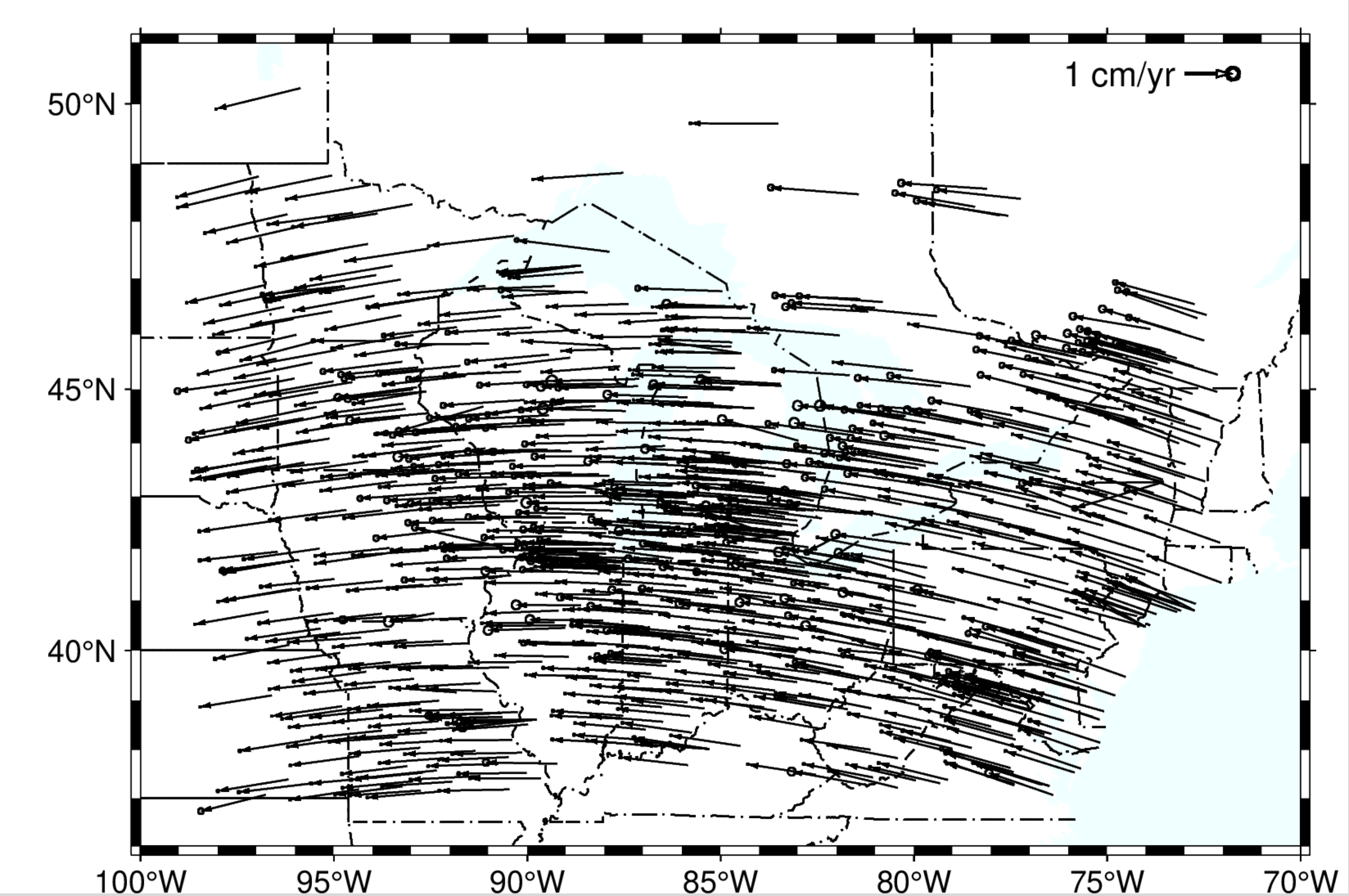
Users
expect this
to be small

- Keeping the error in the spatial reference system small is hard work on a moving, actively deforming Earth!

Enhanced Monitoring of CORS Network

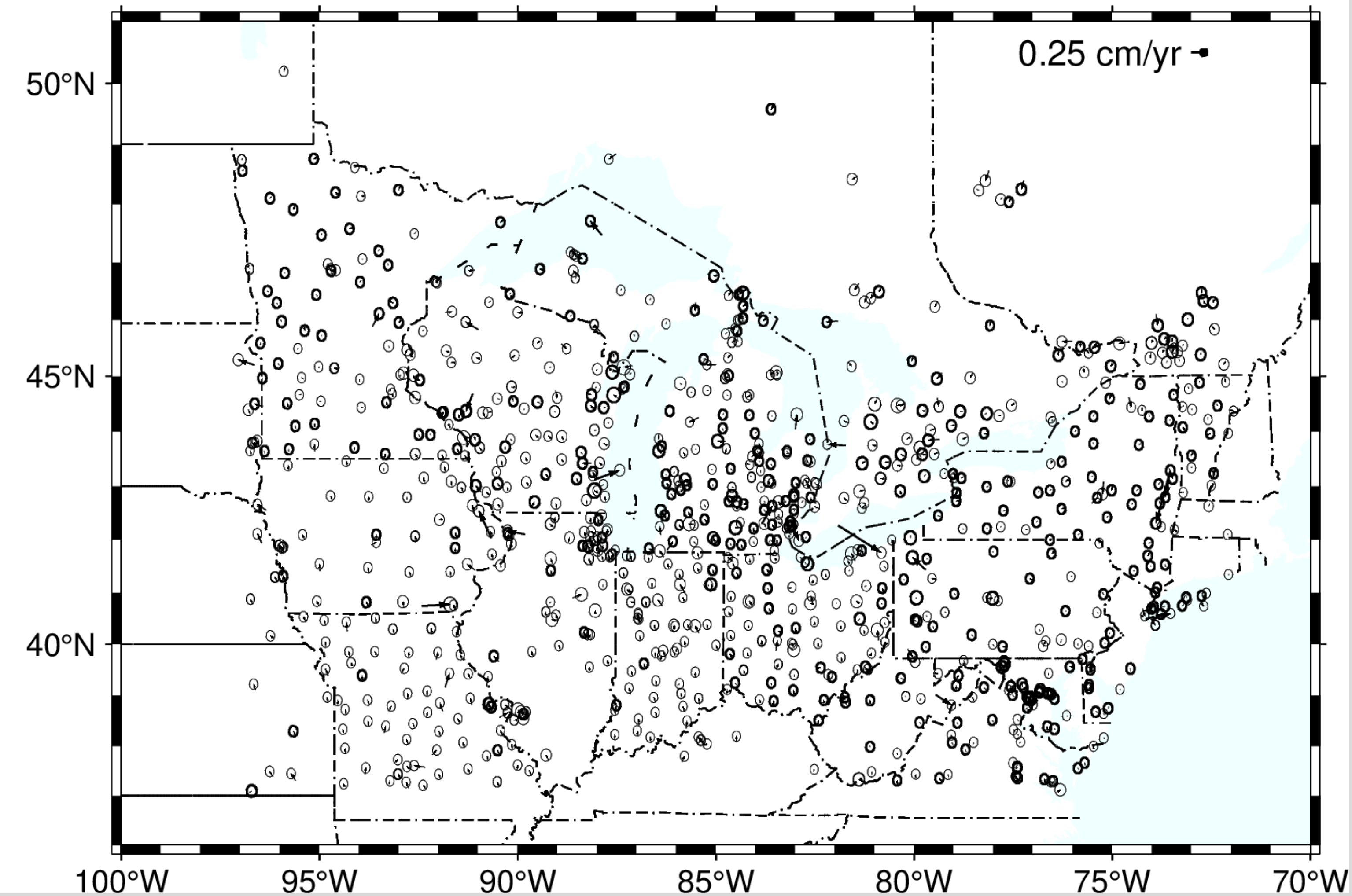
- Are the CORS stations in the locations we think they are?
- If so, hooray!
- If not, can we identify the cause and repair the coordinates?
- Common causes:
    - Earthquakes and other transient tectonic events
    - Equipment changes
    - Inaccurate velocity models
    - Time-varying deformation such as hydrology

Site Velocities Relative to ITRF



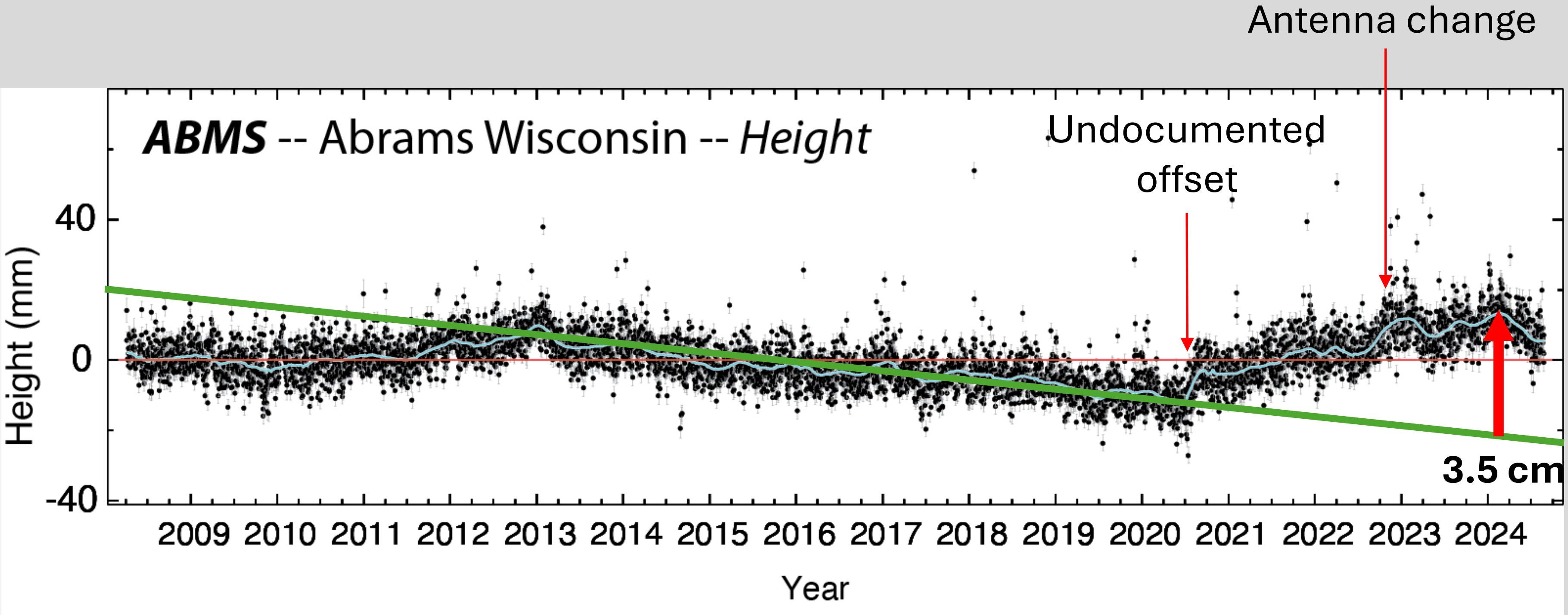
ITRF = International Terrestrial Reference Frame

Relative to North America



NATRF22 is North America-fixed

In the Great Lakes, Coordinate Changes are in the Vertical



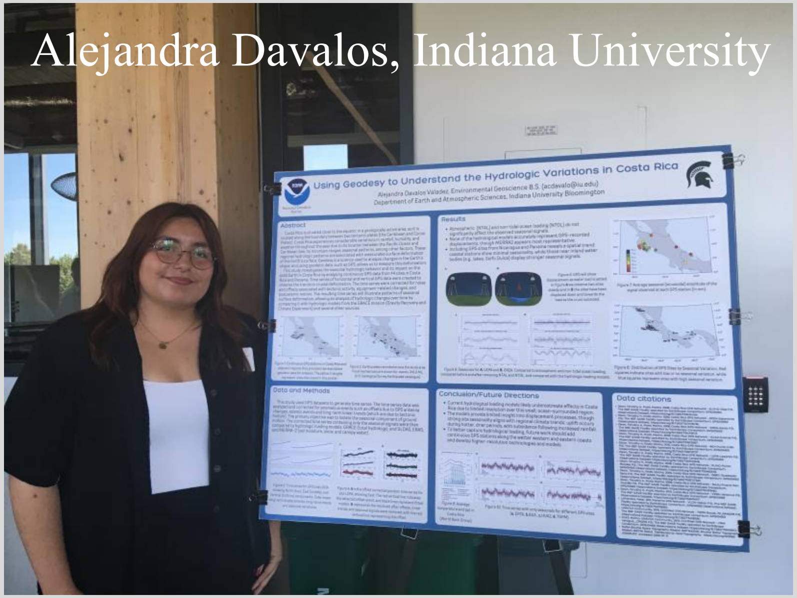
Why is this?

- *Elastic deformation of the solid Earth due to the changing load (weight) of water in the Great Lakes (plus other surface water and groundwater)*

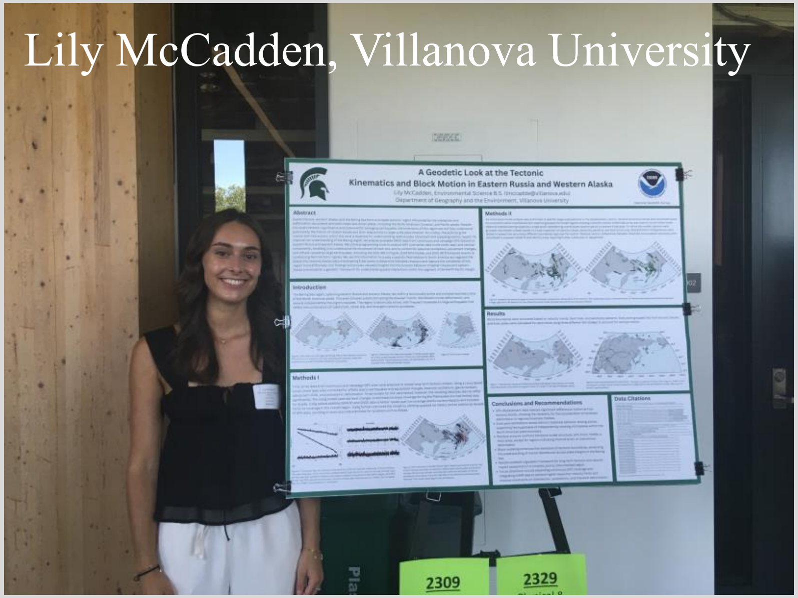
NGS Funded
MSU Educational Activities

- Consortium Geodesy Master’s Program
- Summer Undergraduate Internship Program
- Introduce people to geodesy and geodesy careers during earlier stages of education, especially in adjacent fields (geoscience, physics, math, engineering)
- Make geodesy education more accessible
  - On-ramps and alternative paths to geodesy
  - Online formats

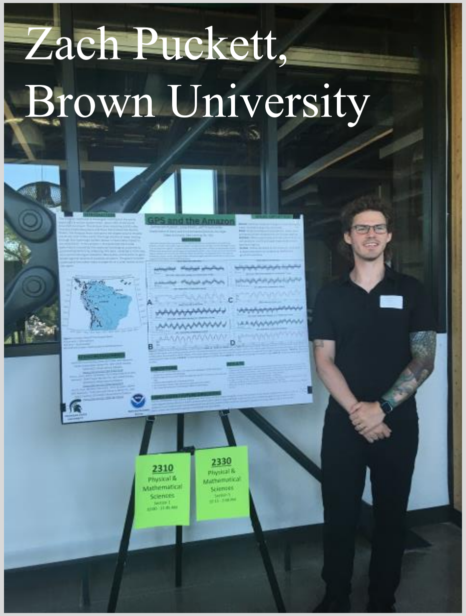
Intern Projects



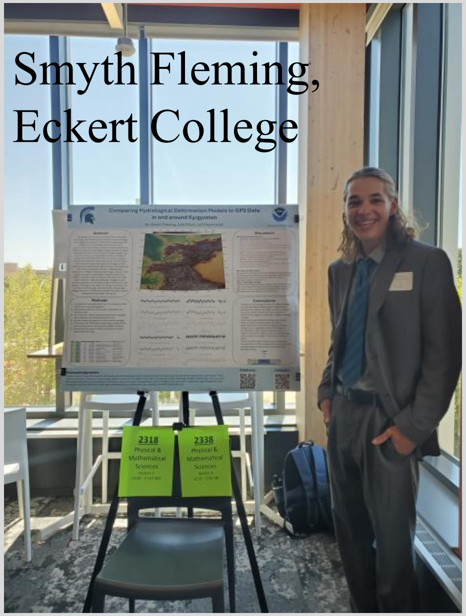
Alejandra Davalos, Indiana University



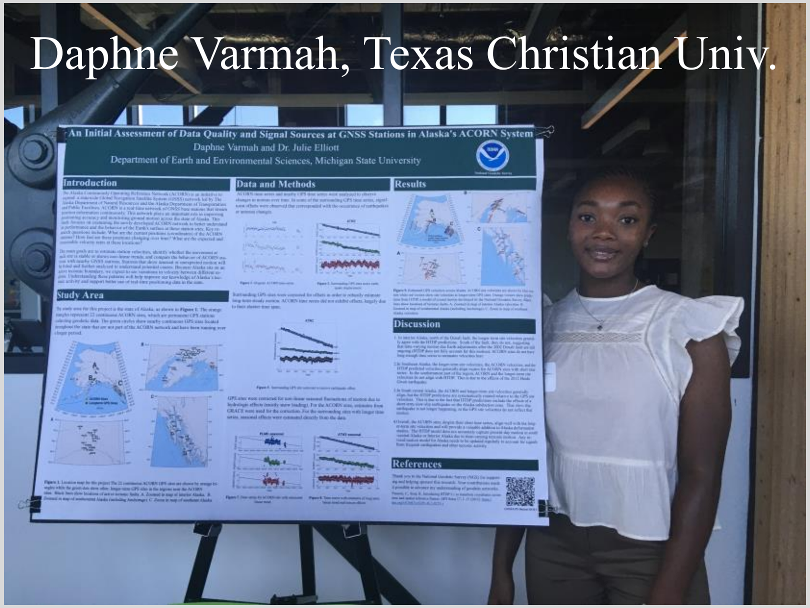
Lily McCadden, Villanova University



Zach Puckett, Brown University



Smyth Fleming, Eckert College



Daphne Varmah, Texas Christian Univ.

MSU Undergraduate Geodesy Internship Program

- Designed for students with little or no previous experience in geodesy
- Eight-week internship, in person at MSU
- Summer 2025 first round of interns
- Interns received stipend, on-campus housing, meal plan, and transportation
- 49 applicants, 5 students selected
- Involved lectures, lab-style activities, discussion of geodesy related careers, and a research project

MSU Undergraduate Geodesy Internship Program

- Skills Acquired:
  - Setting up tripod campaign GNSS sites
  - Unix/Linux operating system
  - Basic MATLAB and Python programming
  - GMT mapping software
  - Time series analysis

- Lecture Topics:
  - Linear Algebra basics
  - Overview of geodetic data types and geodesy applications
  - GNSS positioning basics and GNSS error/noise
  - Coordinate systems and reference frames
  - How to assess and interpret geodetic data
  - Plate tectonic motion and earthquakes
  - Loading deformation

Geodesy Master's Program

- Consortium Model

UAF
UNIVERSITY OF ALASKA FAIRBANKS

MICHIGAN STATE UNIVERSITY

1885
Michigan Technological University

- Online
- Coursework-based (no thesis), 2-year program
- Students will take mix of courses from the consortium institutions to total 30 credits
- Courses are going through approvals

Planned Curriculum

Foundations of Geodesy

Provides background in mapping, projections, datums, reference frames, and transformations

Mathematical and Computational Concepts

Provides foundation in programming and mathematical techniques (including inversion theory and linear regression) essential for geodesy

Fundamentals of Geodesy and Geophysics

Provides background in geodetic theory, measurement and interpretation of steady state and time variable motions within the solid Earth, cryosphere, and hydrosphere, data processing, and geophysical modeling.

Geodetic Methods and Applications

Extends knowledge into additional land- and satellite geodetic techniques, network design, and geophysical applications

Extra Slides

Planned Curriculum

Foundations of Geodesy

Two courses are required:

- *Coordinate Systems, Map Projections, and Reference Frames (MSU)*
- Geodetic Models (MTU)

Fundamentals of Geodesy and Geophysics

At least two of the following are required:

- Modern Geodesy and Applications (MSU) *or* Geodetic Methods and Applications (UAF)
- *Geodetic Data Processing and Analysis (MSU)*
- Foundations of Geophysics (UAF)
- Positioning with GNSS (MTU)

Planned Curriculum

Mathematical and Computational Concepts

At least two of the following are required:

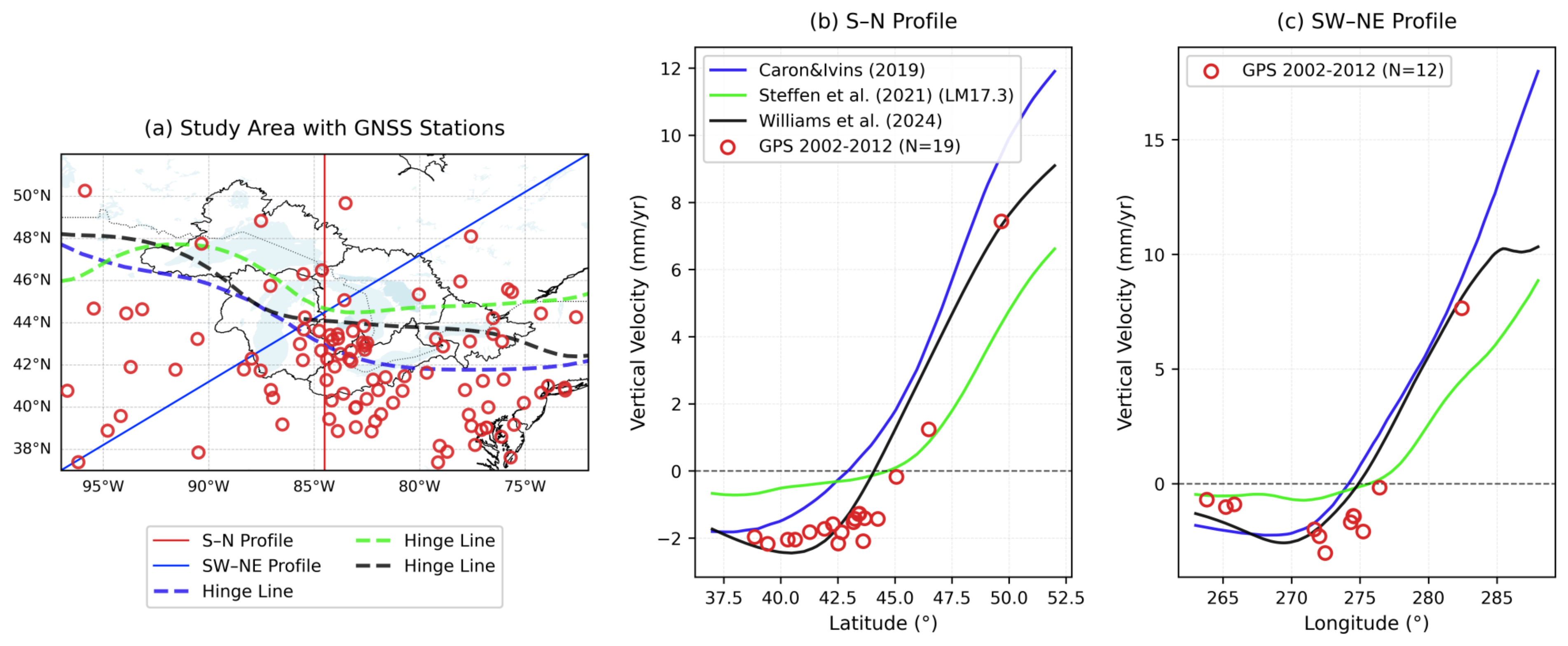
- Programming and Automation for Geoscientists (UAF)
- Data Analysis and Adjustments (MTU)
- Inverse Problems and Parameter Estimation (UAF)
- Numerical Analysis (UAF)

Geodetic Methods and Applications

At least one of the following are required:

- 3D Surveying and Modeling with Laser Scanning Data (MTU)
- Advanced Photogrammetry – Satellite Photogrammetry (MTU)
- Microwave Remote Sensing (UAF)
- Digital Image Processing in the Geosciences (UAF)
- *Design of Geodetic Sites and Networks (MSU)*
- InSAR and Its Applications (UAF)
- MSU Geography courses

Physical Models of GIA Produce Systematic Misfits



(a) Study Area with GNSS Stations

(b) S–N Profile

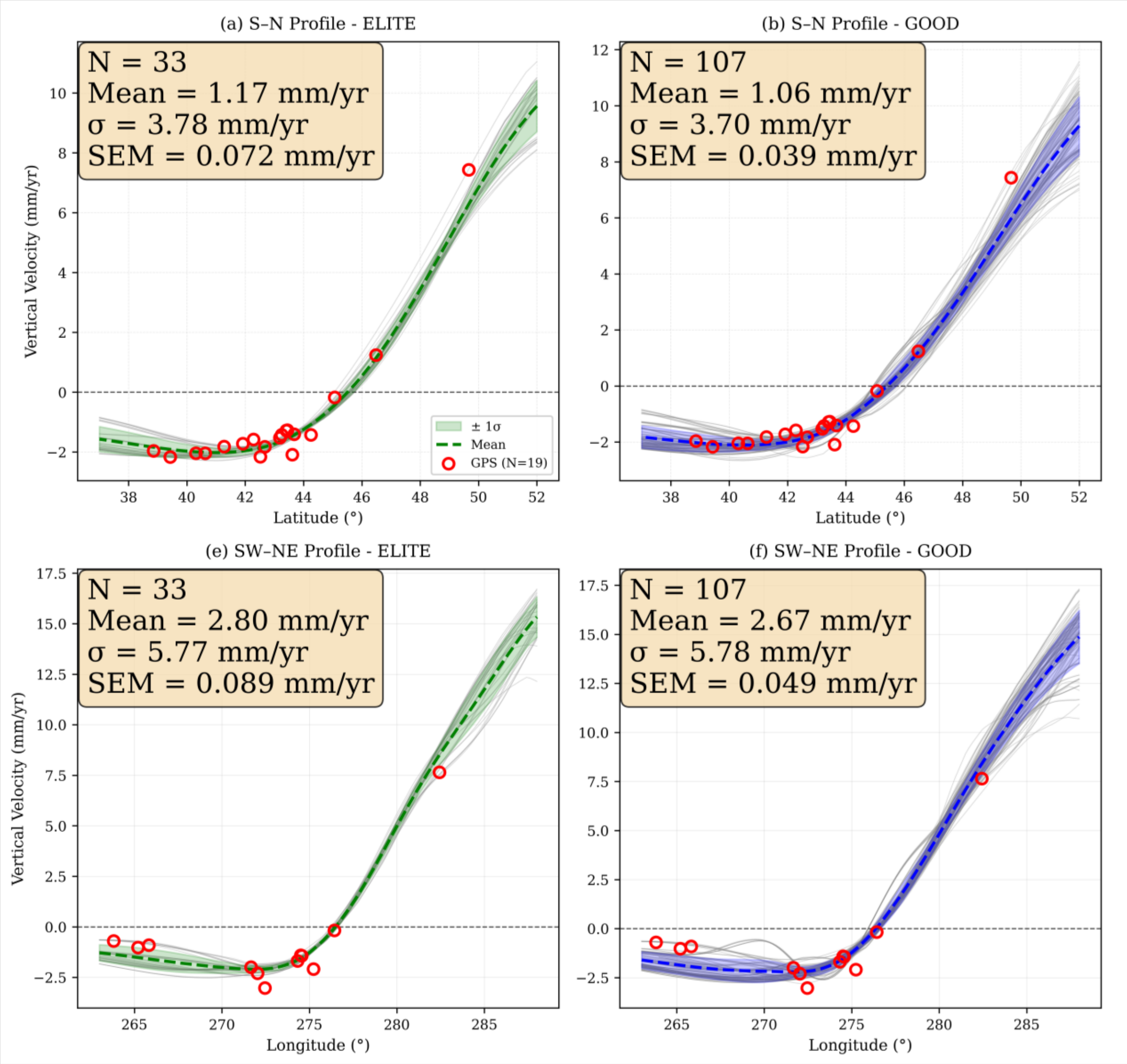
(c) SW–NE Profile

All GIA models place the hinge line **too far south** relative to the GNSS observations.

But many GIA model predictions look a lot like a shifted version of the data. What happens if we empirically shift the model predictions to best match the data?

Ensemble of Shifted Models

We rank all 576 optimized realizations by their RMS values and group them into hierarchical ensembles by misfit in mm/yr: ELITE (RMS ~ 0.40-0.49), GOOD (0.49-0.60).



The *shapes* of predicted profiles match the observations extremely well: **0.4-0.6 mm/yr** for the two best ensembles.

This is comparable to the nominal velocity uncertainty.

The need to shift the GIA models probably results from errors in the assumed distribution of ice at the Last Glacial Maximum

Research Wrap-up

- We can explain the time-varying vertical displacements of CORS sites as the sum of two physical processes
  - Glacial isostatic adjustment (GIA) due to the ongoing response to the former ice sheet
  - Present-day water level changes in the Great Lakes and other surface water/groundwater
- We can describe the observed coordinate variation in terms of physical models
  - Needed to monitor and project coordinates forward in time, and maintain accuracy of reference system

Oregon State University

COLLEGE OF ENGINEERING | School of Civil and Construction Engineering

65th CGSIC Meeting

GNSS and Geomatics research at Oregon State University

Jihye Park

Oregon State University

Overview

- Geomatics Program at Oregon State University (OrSU)
- Geospatial Center for the Arctic and Pacific (GCAP) at OrSU
- GNSS as a versatile tool for monitoring the Earth environment
  - Hazard monitoring using GNSS
  - GNSS as a tide gauge

Geomatics at Oregon State University (OrSU)

Oregon State University

- Graduate Program
  - Current enrollment (WI 2026): 10 PhD, 7 MSc, 1 Post docs
  - Graduates (since 2011): 23 PhD, 51 MSc, 3 Meng, 6 Post Docs
- Minor in Geomatics Engineering
  - 26 required + 7 elective credits: 33 credits required
  - Currently 55 students enrolled and 20 are expected to graduate in June 2026
- ***Undergrad Geomatics degree*** proposed

OSU Geomatics

Pursuit of a BSc in Geodesy, Geomatics, and Geospatial Engineering (3xGE)

Oregon State University

Goal:

Expand success of OSU's graduate program in geomatics to undergraduate level to help alleviate short-fall of geospatial professionals and geodesist in the US.

Core Curriculum to include:

- Programming
- Reference Frames
- Map Projections
- Gravity
- Geodynamics
- GNSS
- Uncertainty Analysis
- Least Squares Adjustments
- Inertial Navigation and Timing

Geodesy (Reference Frames, Map Projections, Gravity, Geodynamics, GNSS)

Additional Courses in:

- Cadastral Surveying
- Photogrammetry
- 3D Laser Scanning / Reality Capture
- Geodetic Surveying Methods
- Hydrographic Surveying
- GIS
- Electrical & Computer Engineering
- Computer Science

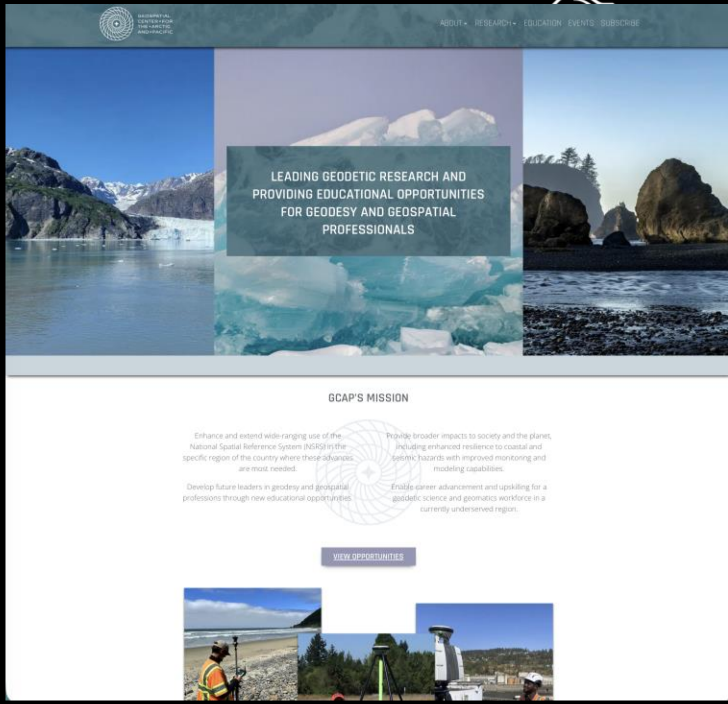
Geospatial Center for the Arctic and Pacific (GCAP)

- NGS Geospatial Modeling Grant Project (Award Number: NOAA-NOS-NGS-2023-2007815)

- Oregon State University, University of Alaska Anchorage, the Columbia River Intertribal Fish Commission (CRITFC), and the Yurok Tribe
- Enhance and extend wide-ranging use of the National Spatial Reference System (NSRS) in the specific region of the country where these advances are most needed—PNW and AK
- Develop future leaders in geodesy and geospatial professions through new educational opportunities

GCAP Activities

- GNSS and Geodetic Research
  - GNSS algorithm (PPP, RTK) development and testing
  - PPP and RTK integration into the NSRS
  - Support the success transition to and use of the modernized NSRS
- Education and Workforce development
  - Proposed new undergrad degree program in Geodesy, Geomatics, and Geospatial Engineering at Oregon State University
  - GCAP Workshop Series (GNSS & Geodesy)
  - Hosted ASCE UESI Surveying & Geomatics Conference at OSU
  - Participated in AAGS Geodesy YouTube Series



LEADING GEODETIC RESEARCH AND PROVIDING EDUCATIONAL OPPORTUNITIES FOR GEODESY AND GEOSPATIAL PROFESSIONALS

GCAP'S MISSION

Enhance and extend wide-ranging use of the National Spatial Reference System (NSRS) in the specific region of the country where these advances are most needed.

Develop future leaders in geodesy and geospatial professions through new educational opportunities.

Provide broader impacts to society and the planet, including enhanced resilience to coastal and seismic hazards with improved monitoring and modeling capabilities.

Enable career advancement and upskilling for a geodetic science and geomatics workforce in a currently underserved region.


2024 Geodesy & GNSS Workshop

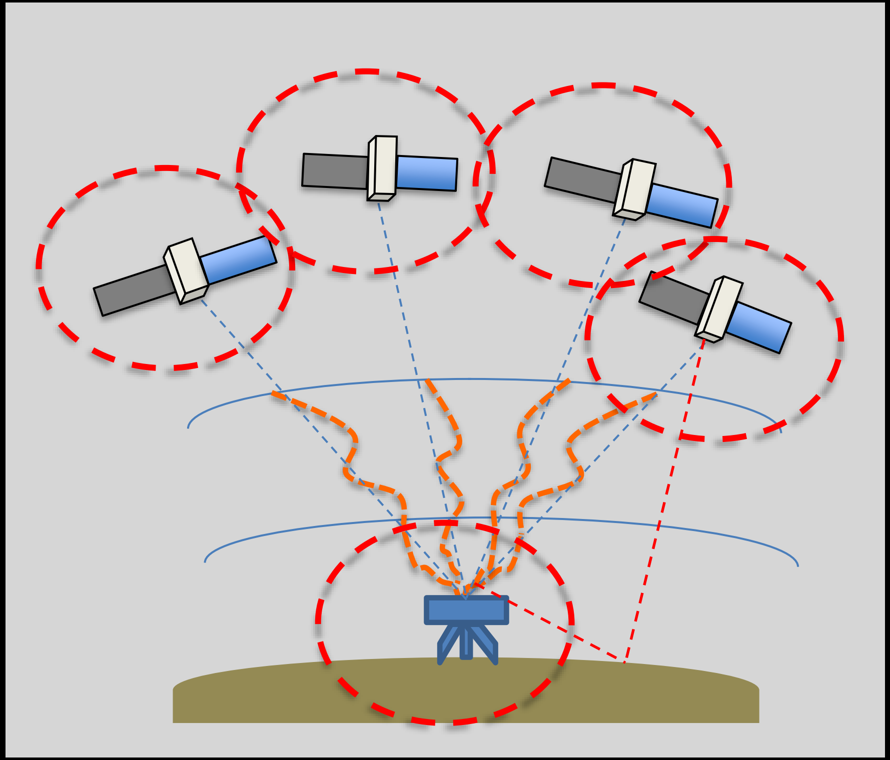

DoV observations

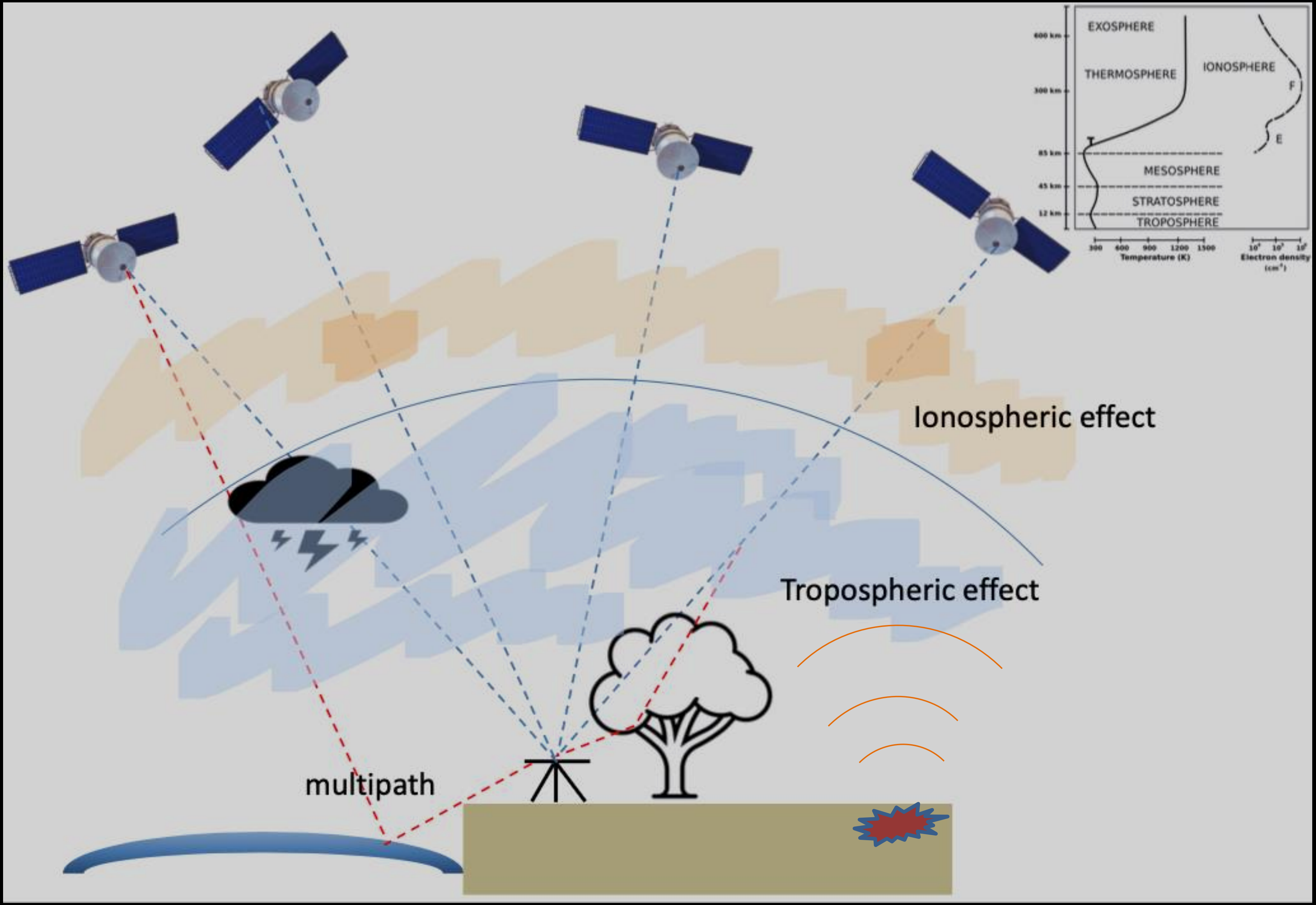
How to treat the propagation errors

- Positioning/Navigation
  - Atmospheric effect? → Atmospheric delay or ERROR
    - Ionospheric delay
    - Tropospheric delay
  - Multipath → multipath error

- GNSS Remote sensing
  - Ionospheric observation
  - Weather forecasts

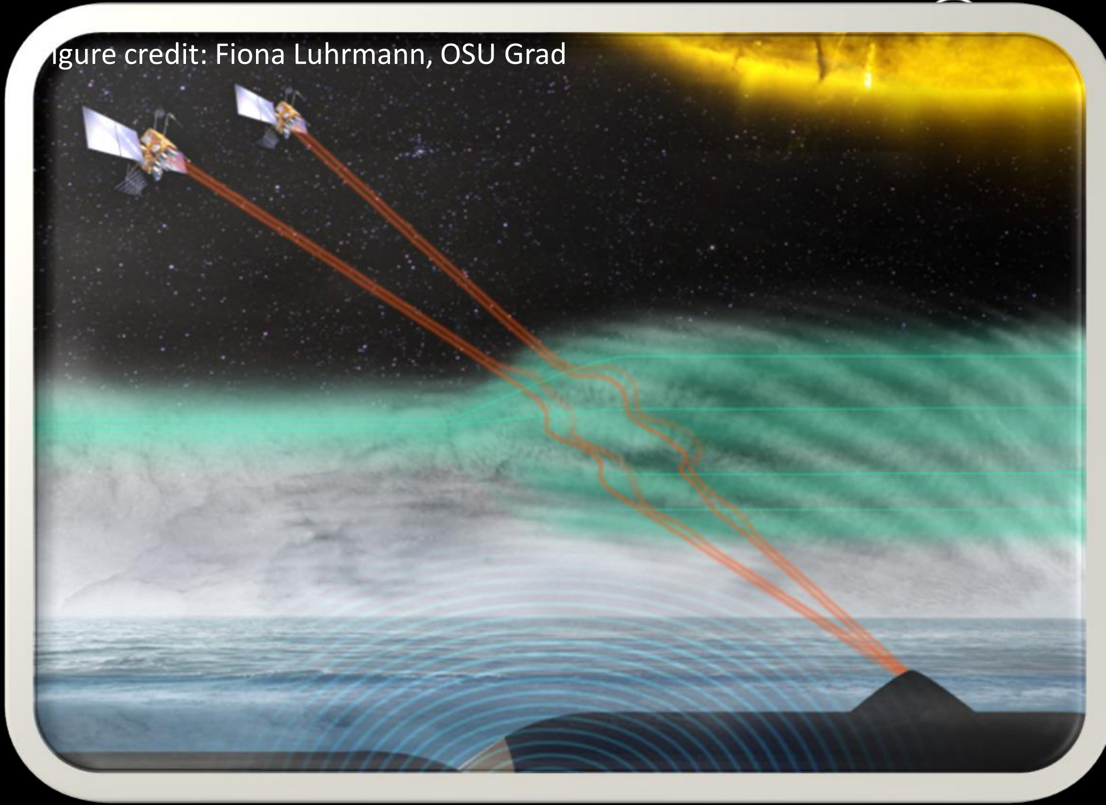
- GNSS-Reflectometry
  - Near ground/surface monitoring tools



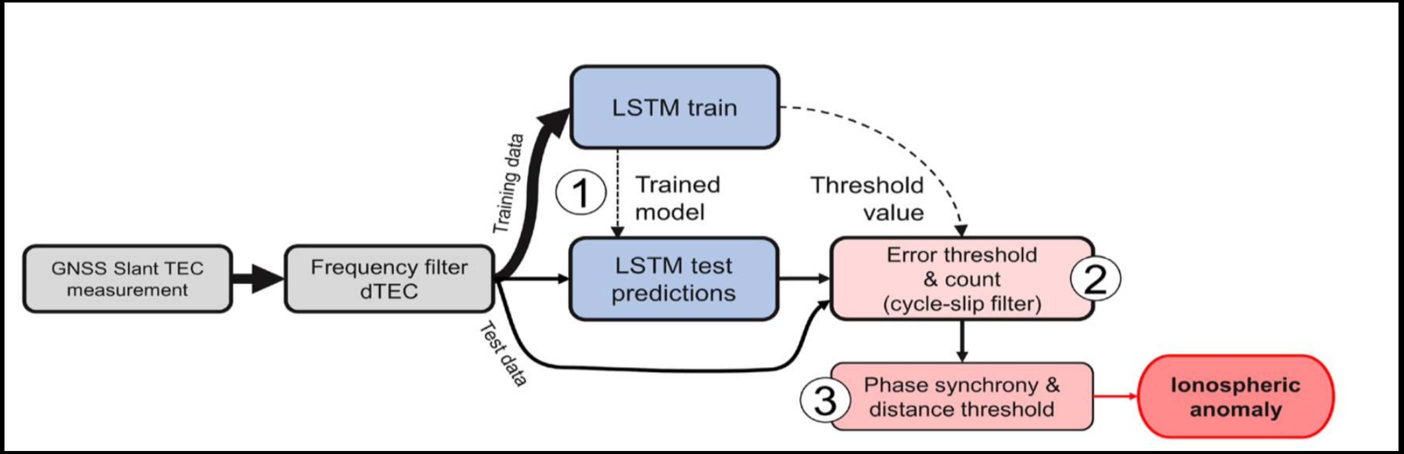

EXOSPHERE
THERMOSPHERE
IONOSPHERE
F
E
MESOSPHERE
STRATOSPHERE
TROPOSPHERE
600 km
300 km
85 km
45 km
12 km
300
600
900
1200
1500
Temperature (K)
Electron density (cm^{-3})
Ionospheric effect
Tropospheric effect
multipath

Hazard monitoring using GNSS

- Various geophysical events, such as geomagnetic storms, earthquakes, tsunamis, volcanic eruptions, tropical storms, surface/underground explosions, generate Ionospheric disturbances
- Traveling Ionospheric Disturbances (TIDs) will change the ionospheric electron density
- By investigating TIDs detected in GNSS signals, the source of the TID may be revealed
- Various methods have been explored to identify the TIDs; recent development involves AI techniques



igure credit: Fiona Luhrmann, OSU Grad



GNSS Slant TEC measurement

Frequency filter dTEC

Training data

Test data

LSTM train

① Trained model

LSTM test predictions

Threshold value

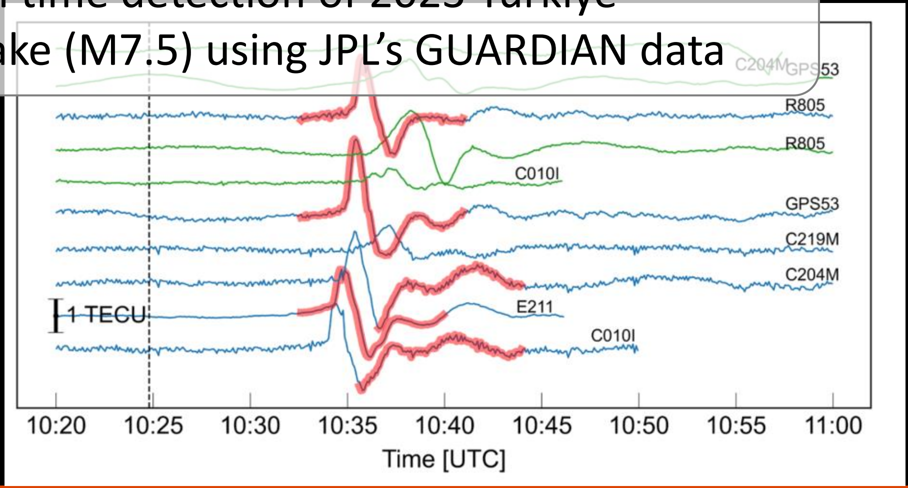
Error threshold & count (cycle-slip filter) ②

③ Phase synchrony & distance threshold

Ionospheric anomaly

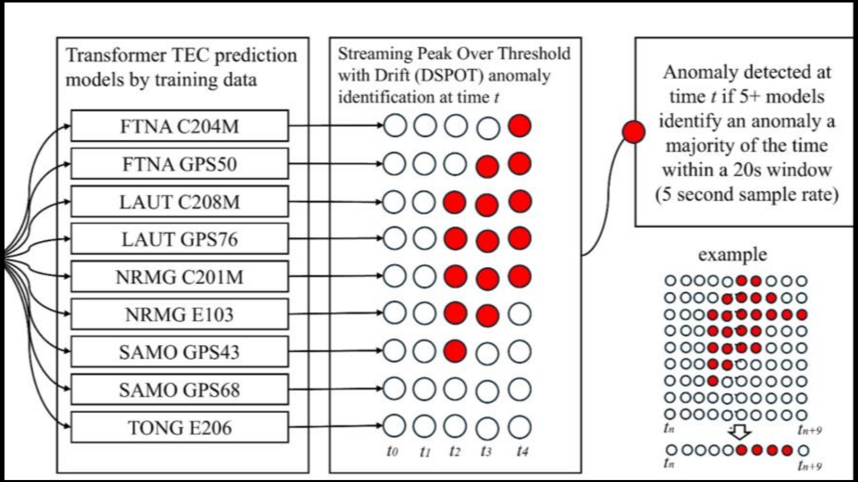
Anomaly detection using LSTM (Luhrmann et al., 2025)

Near real time detection of 2023 Turkiye earthquake (M7.5) using JPL's GUARDIAN data



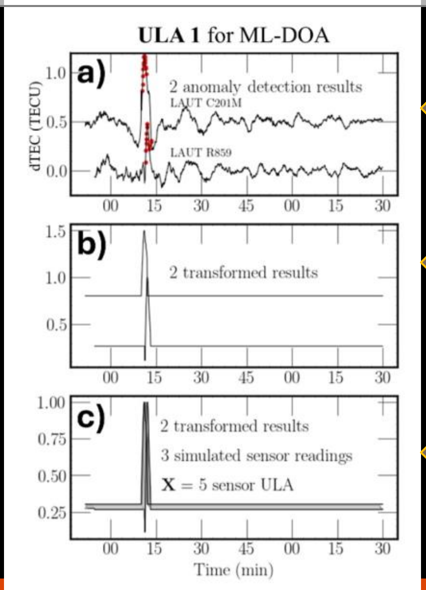
Ionospheric detection and source geolocation

Detection
Majority of receivers identify anomaly over majority of 20s window



Anomaly detected at time t if 5+ models identify an anomaly a majority of the time within a 20s window (5 second sample rate)

Geolocation
Interpolate ULA and back out location with velocity values

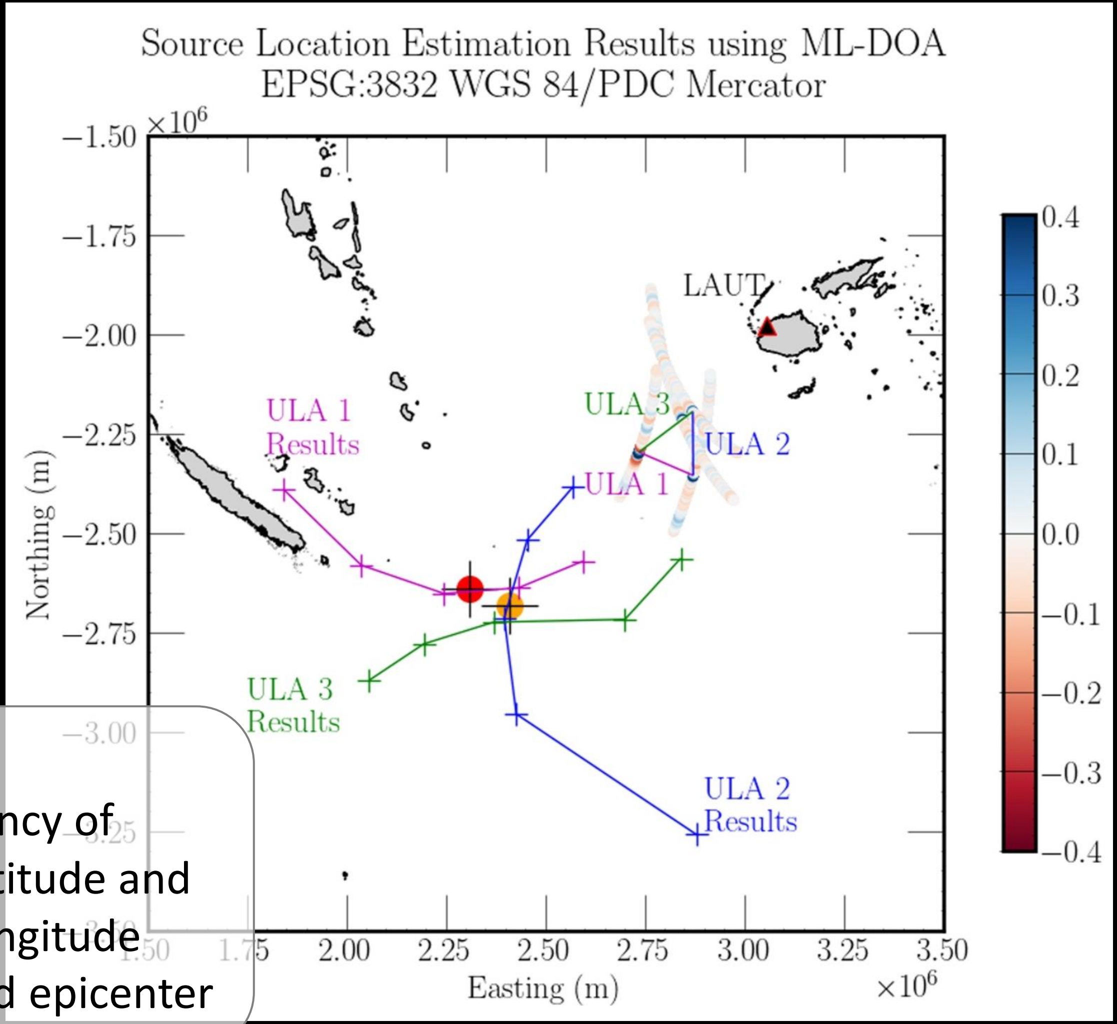


2 anomaly signals

Isolate 2 anomalies in time series

Interpolate ULA between 2 anomaly signals

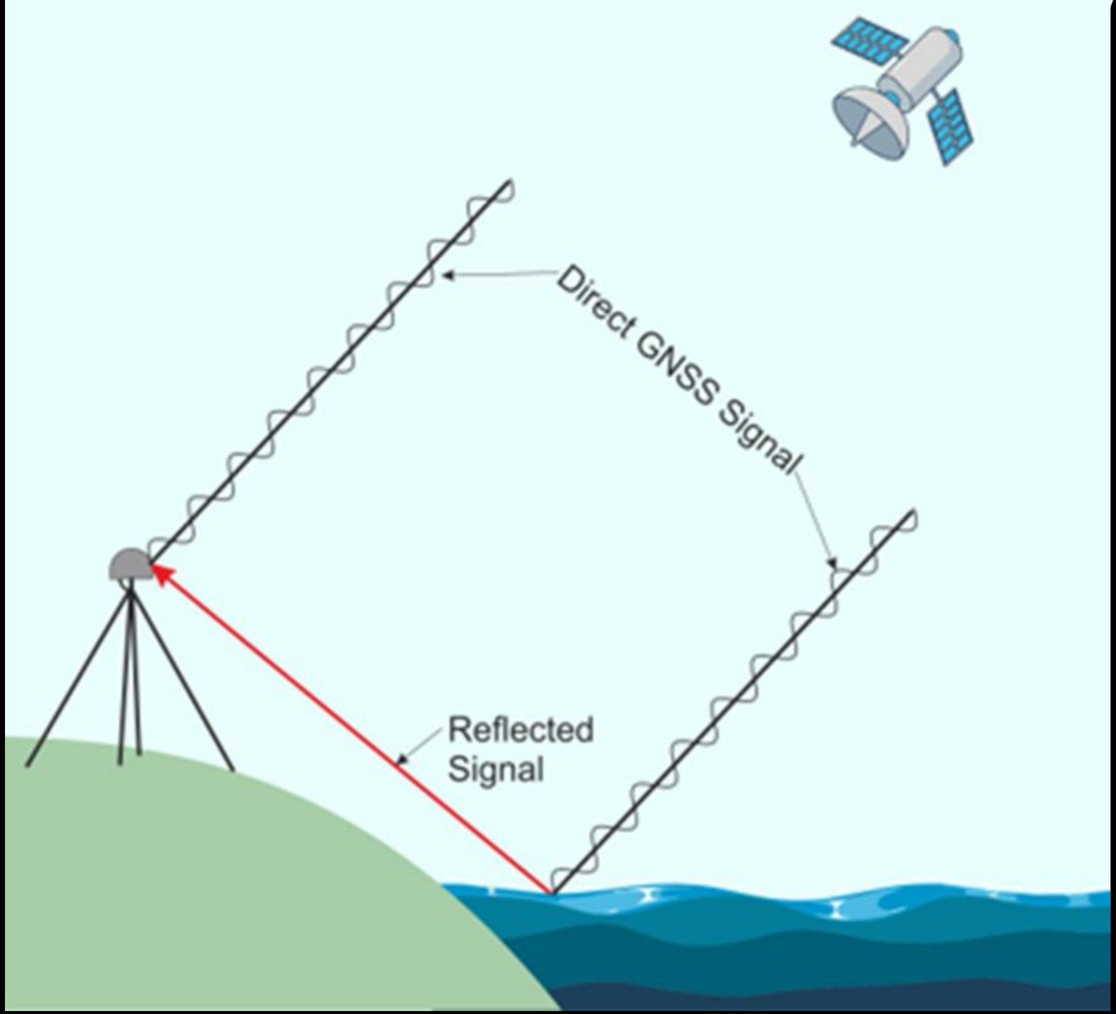
Result
A discrepancy of 0.34° in latitude and 0.90° in longitude to reported epicenter



Monitoring the earth surface using GNSS-IR

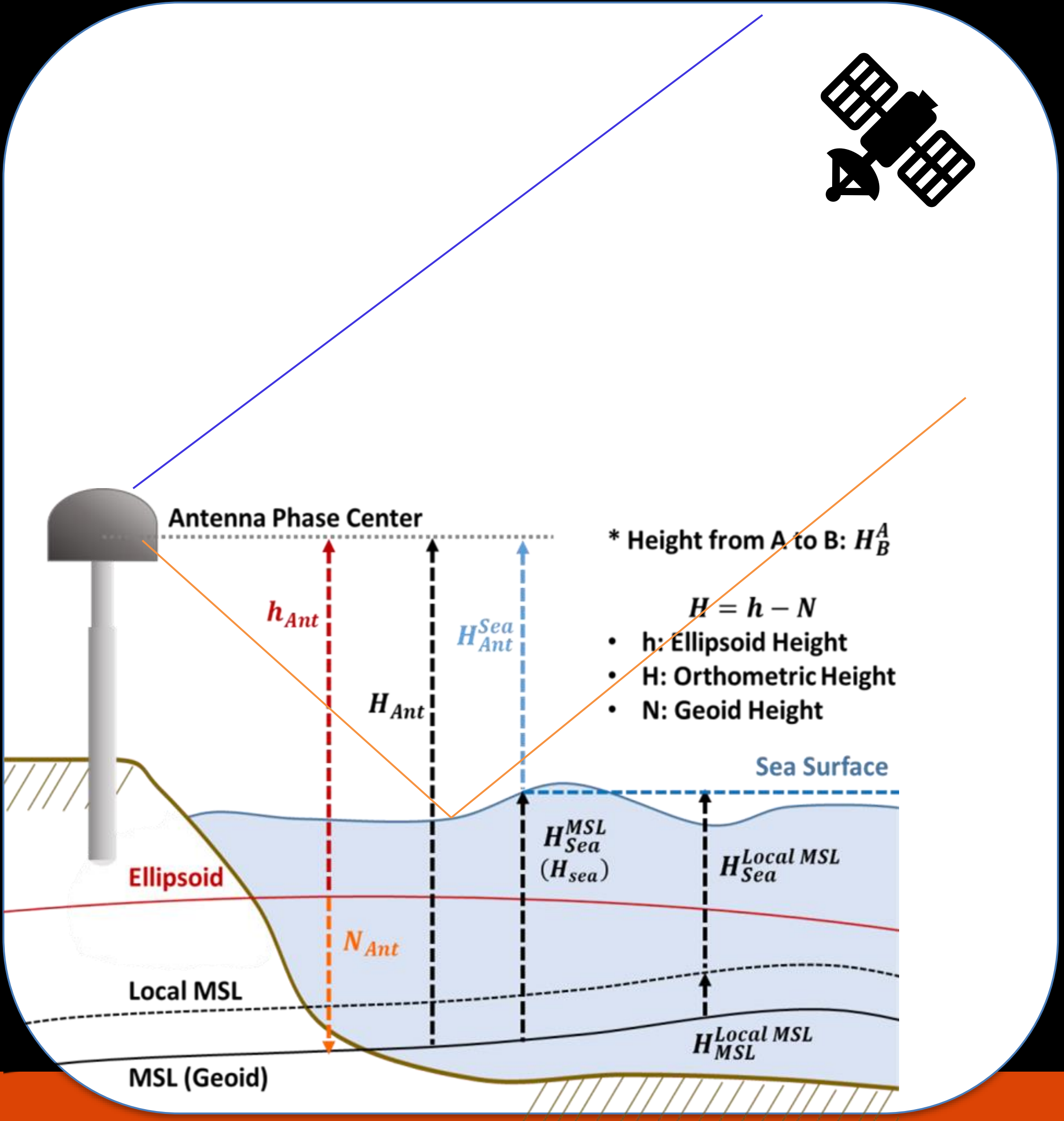
Oregon State University

- Receiver records direct and reflected signals
- Extract reflected signal
- Calculate antenna height above reflecting surface
- Applications:
  - Water level monitoring
  - Ocean wind estimation
  - Soil moisture measurement
  - Vegetation/biomass monitoring
  - Snow/ice monitoring



GNSS based Water-level Observing System (GWOS)

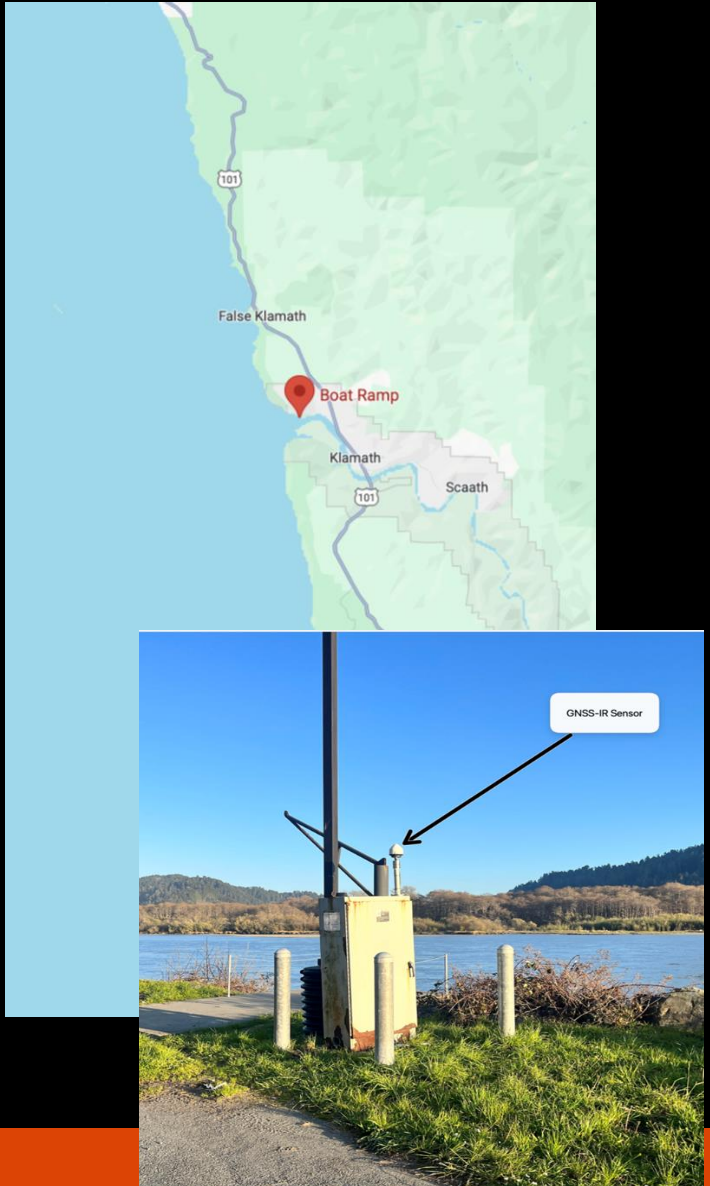
Adapting GNSS-Reflectometry (GNSS-R) as an operational framework for coastal monitoring funded by NOAA Integrated Ocean Observing System (IOOS) – Award Number: NA21NOS0120144



* Height from A to B: H_B^A

$$H = h - N$$

- h: Ellipsoid Height
- H: Orthometric Height
- N: Geoid Height



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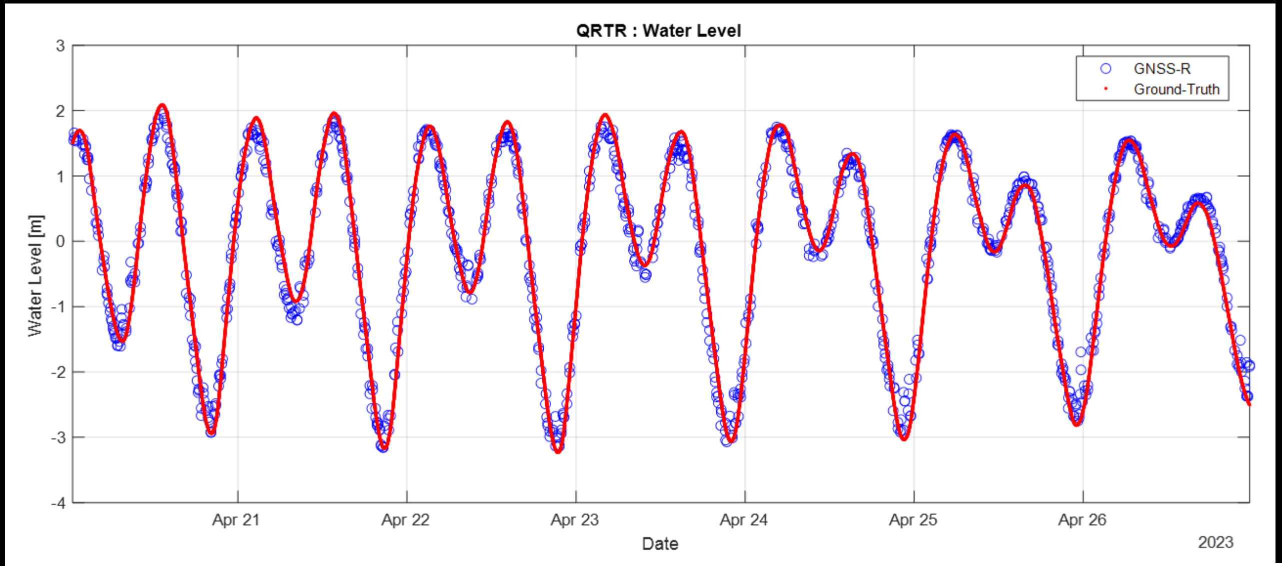
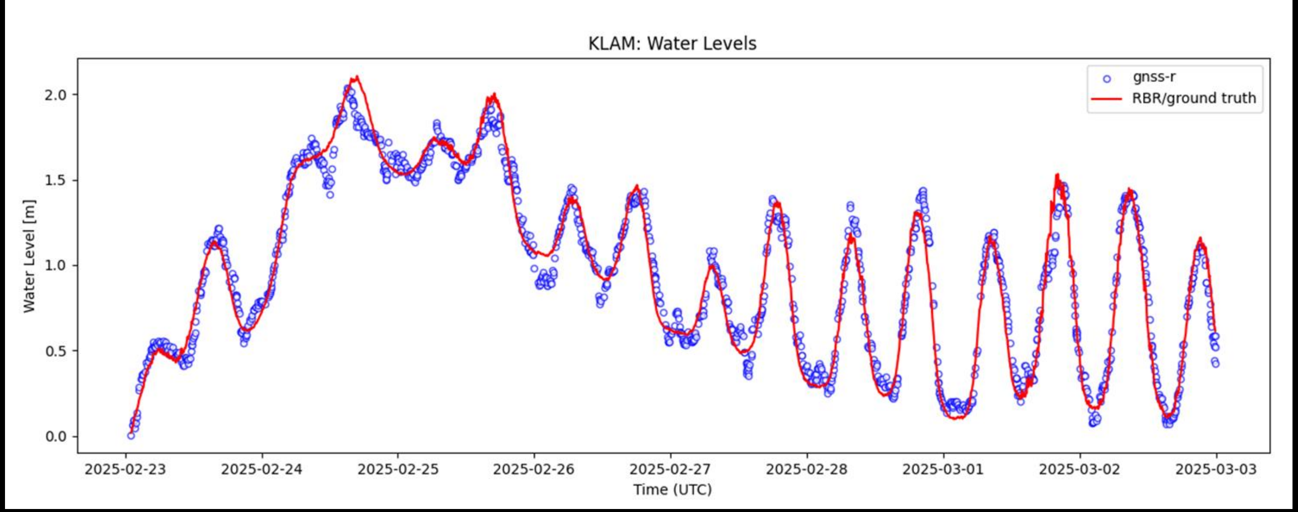
Oregon State University



- Tide range of 5m: from -3m to 2m
- ME is about 5.2 cm (about 1% of the tide range
- Std. of discrepancy is 10.31cm

Srisutha and Park (2025)



- Tide range of 2 m: from 0m to 2m
- ME is about 6.7 cm
- Std. of discrepancy is 5.4 cm

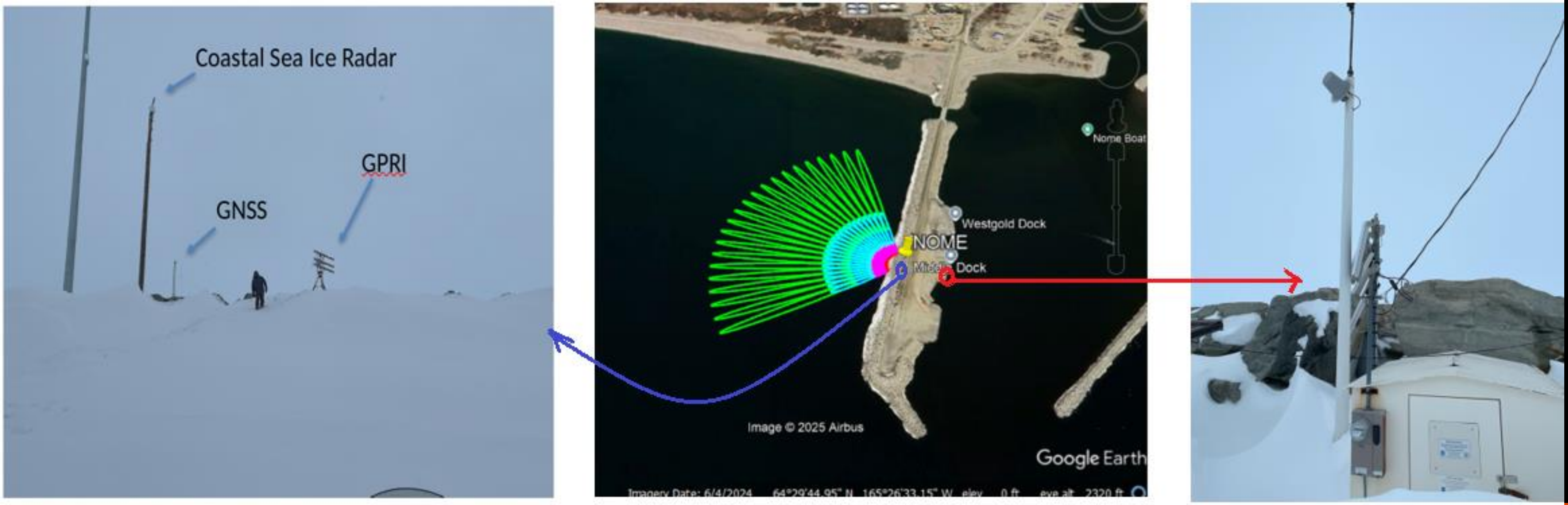
$$ME = \sum_{i=1}^{n} \frac{\left|WL_{GNSS} - GT\right|}{n}$$

Water Level and Sea Ice monitoring in the Arctic

Monitoring Nearshore Ice and Closing the Arctic tide-gauge gap with GNSS-Reflectometry (MONICA)
(NSF Award number: 2321313)

- Objectives
  - Determine motion of landfast ice using GNSS-IR
  - Isolate tidal motion by removing snow and ice effects

Nome, AK (lat : 64.4957°, long: -165.4389°)

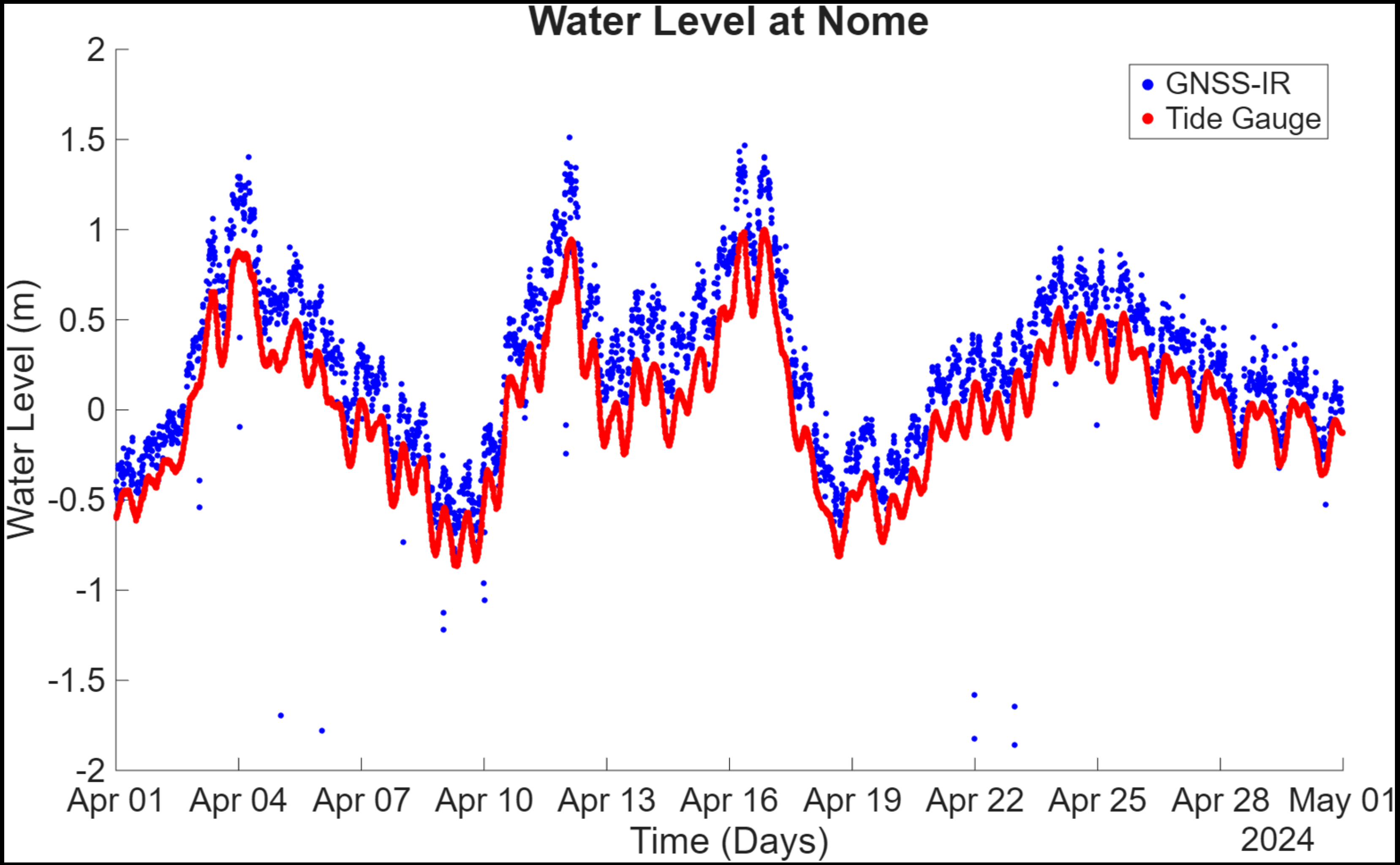


April 2024 Data

Bohn et al. 2026

Oregon State University

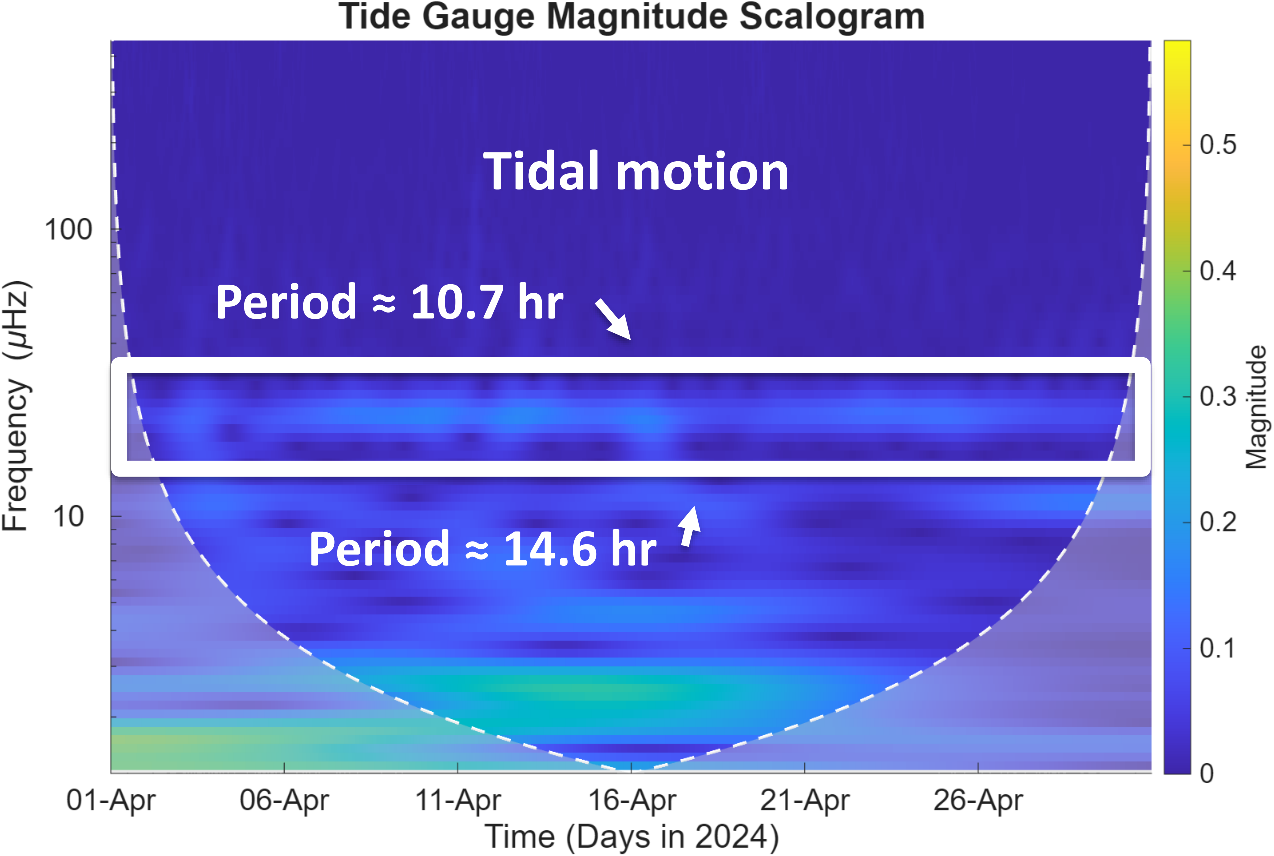
- Landfast ice and snow present
- Expect GNSS-IR signal to follow tides
- Snow accumulation alters reflecting surface



Continuous Wavelet Transform (CWT)

Bohn et al. 2026

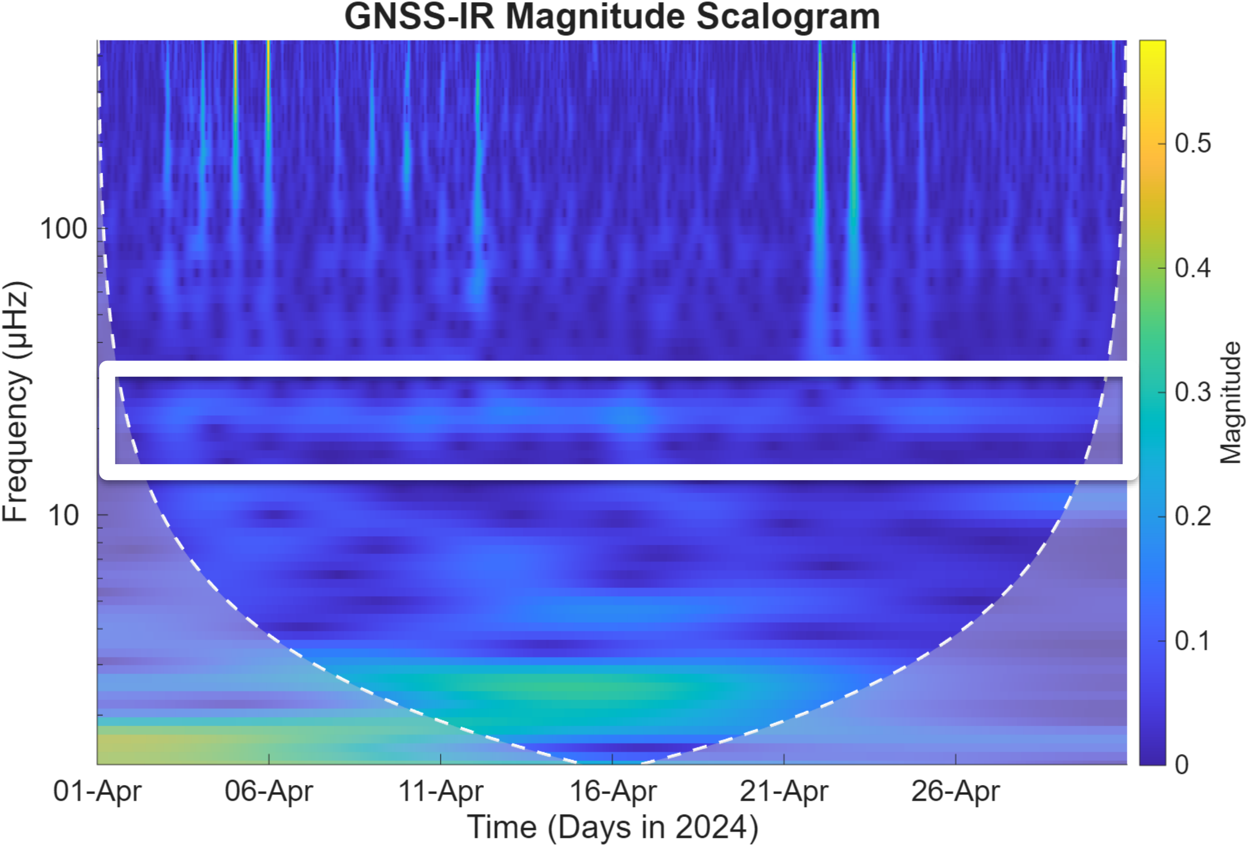
- Frequency, amplitude, and time information
- Expect semidiurnal tides at high-amplitude, low frequency


Tide Gauge Magnitude Scalogram

Tidal motion

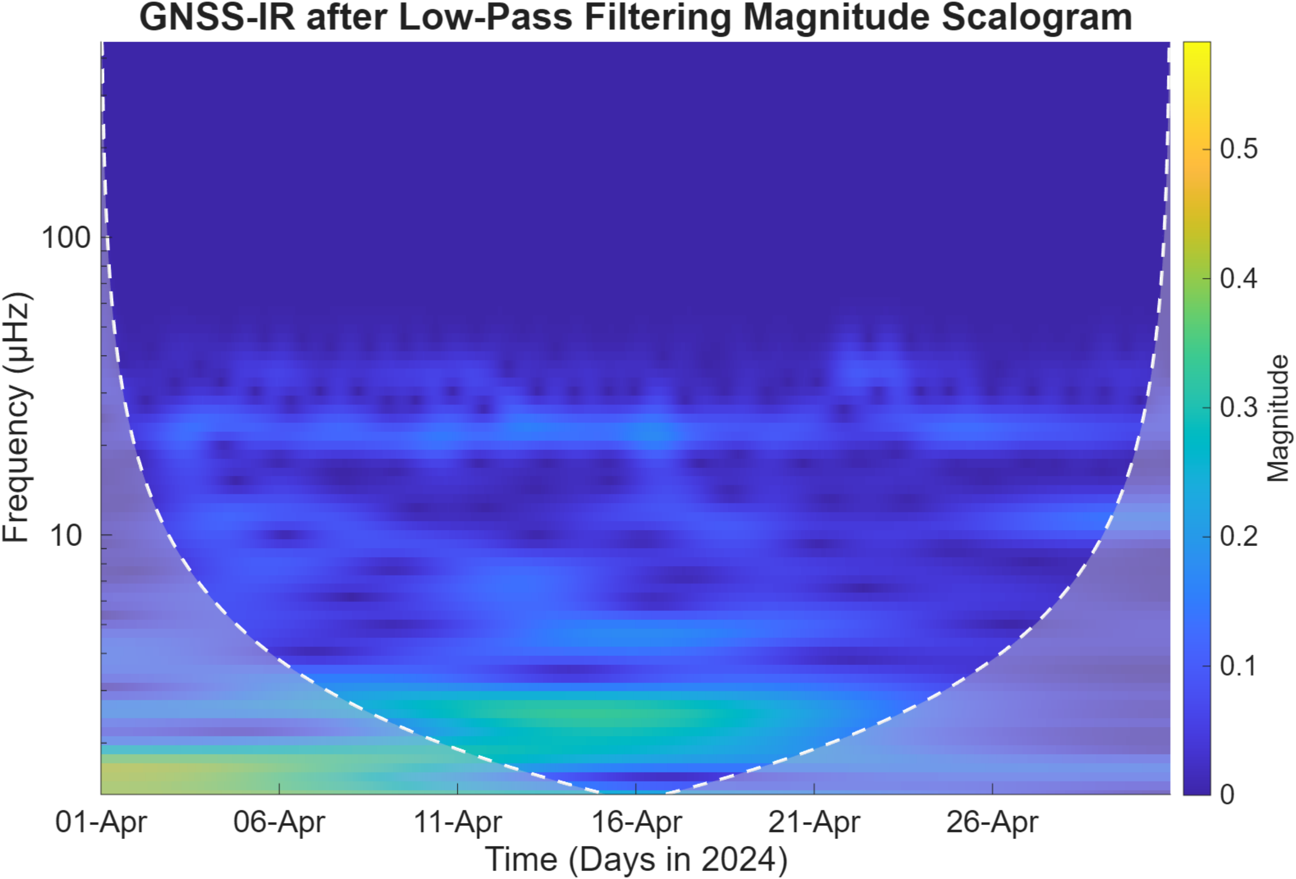
Period ≈ 10.7 hr

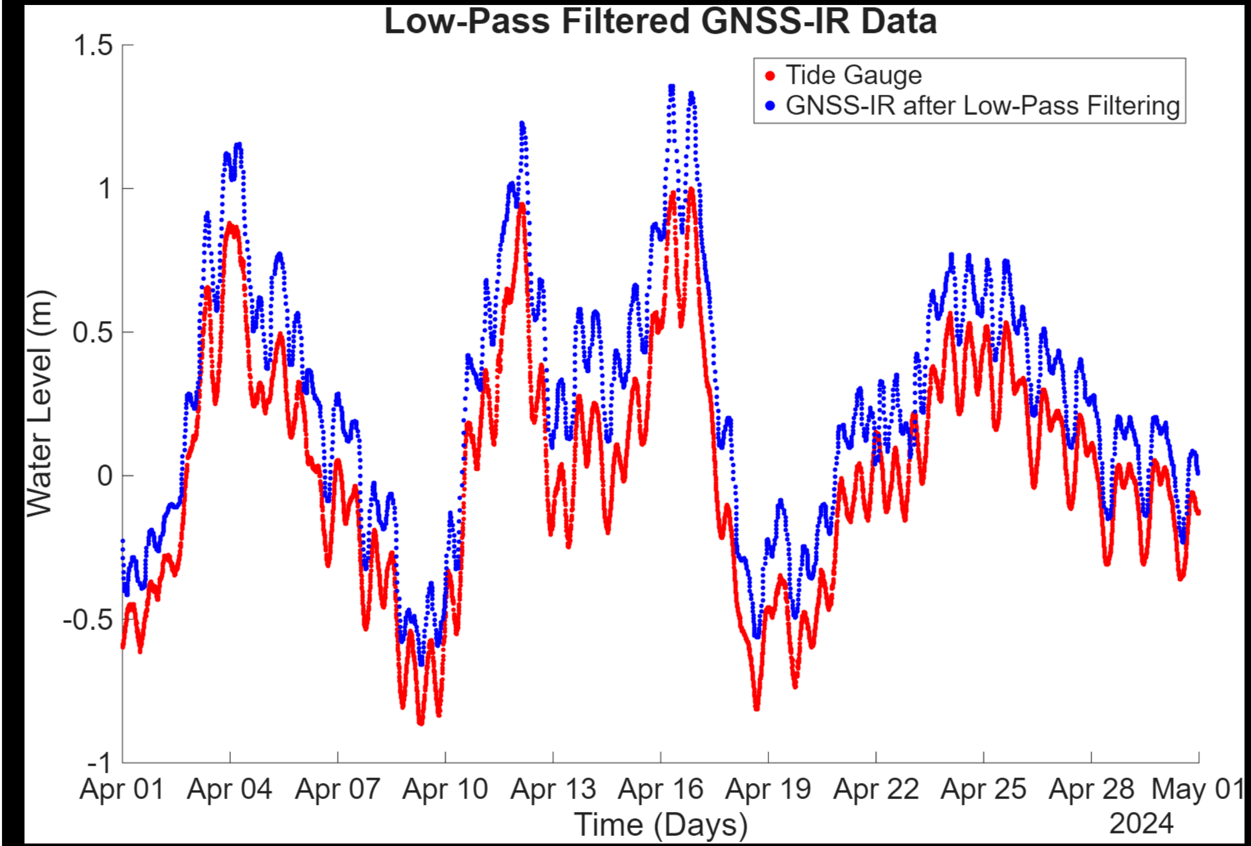
Period ≈ 14.6 hr


GNSS-IR Magnitude Scalogram

Low-Pass Filtering

- Extract tidal motion
- Filtered at 2.6×10^{-5} Hz or T = 10.7 hr

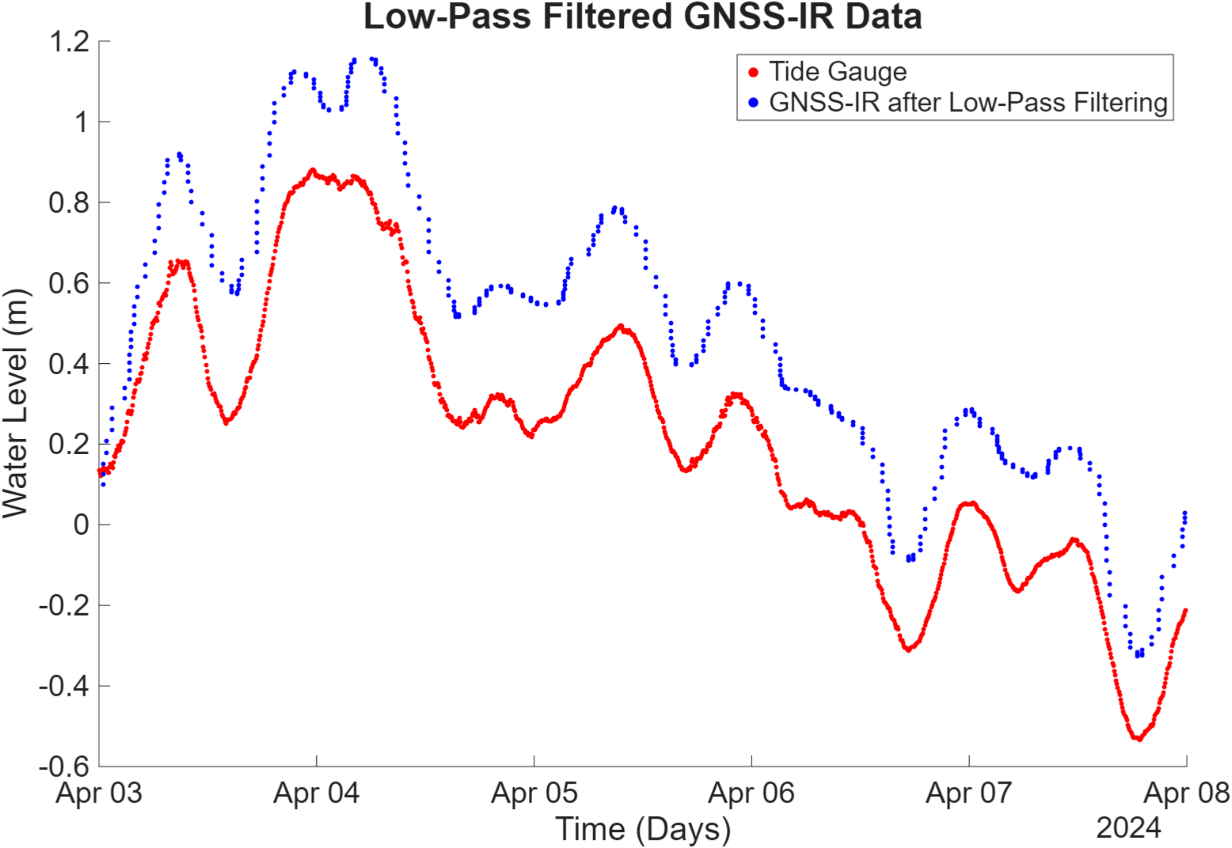


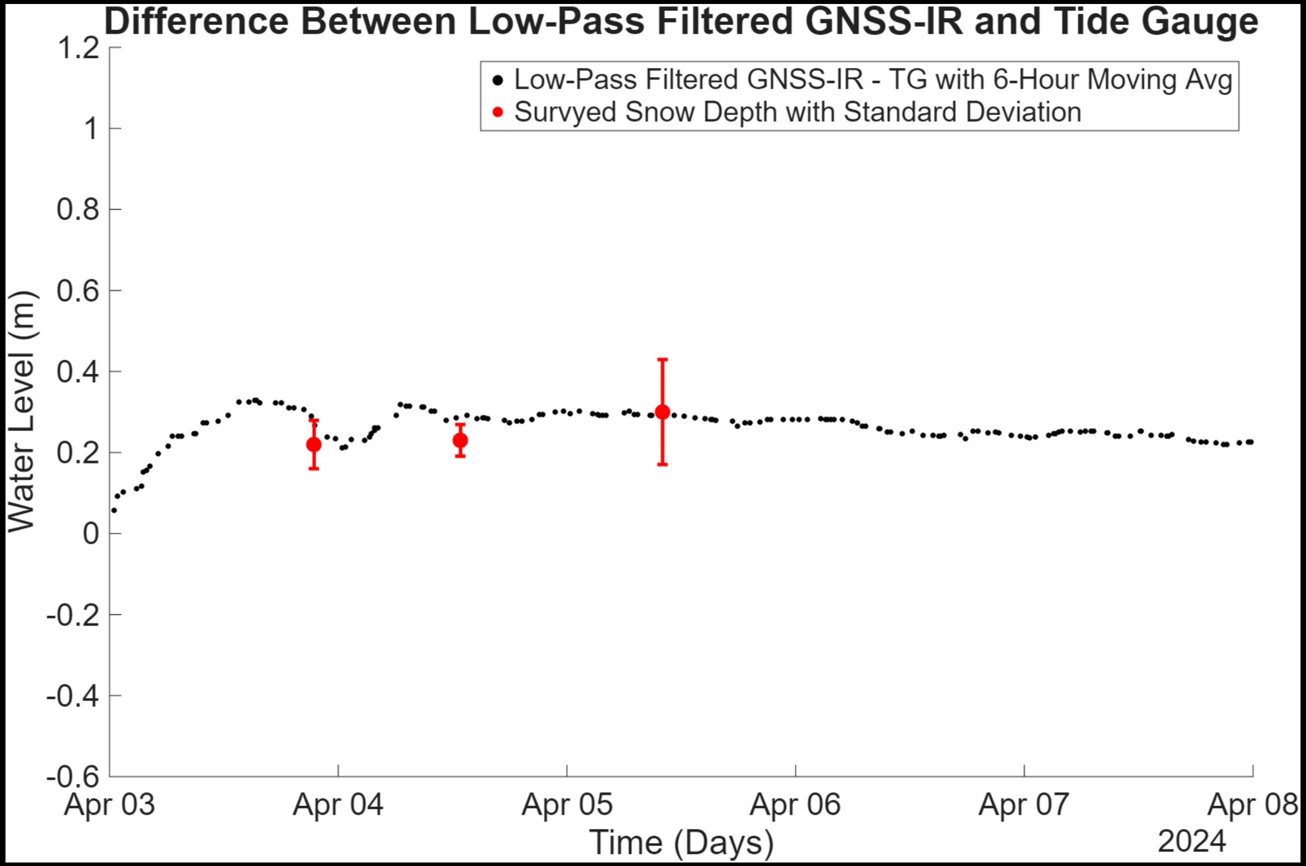


Snow Depth

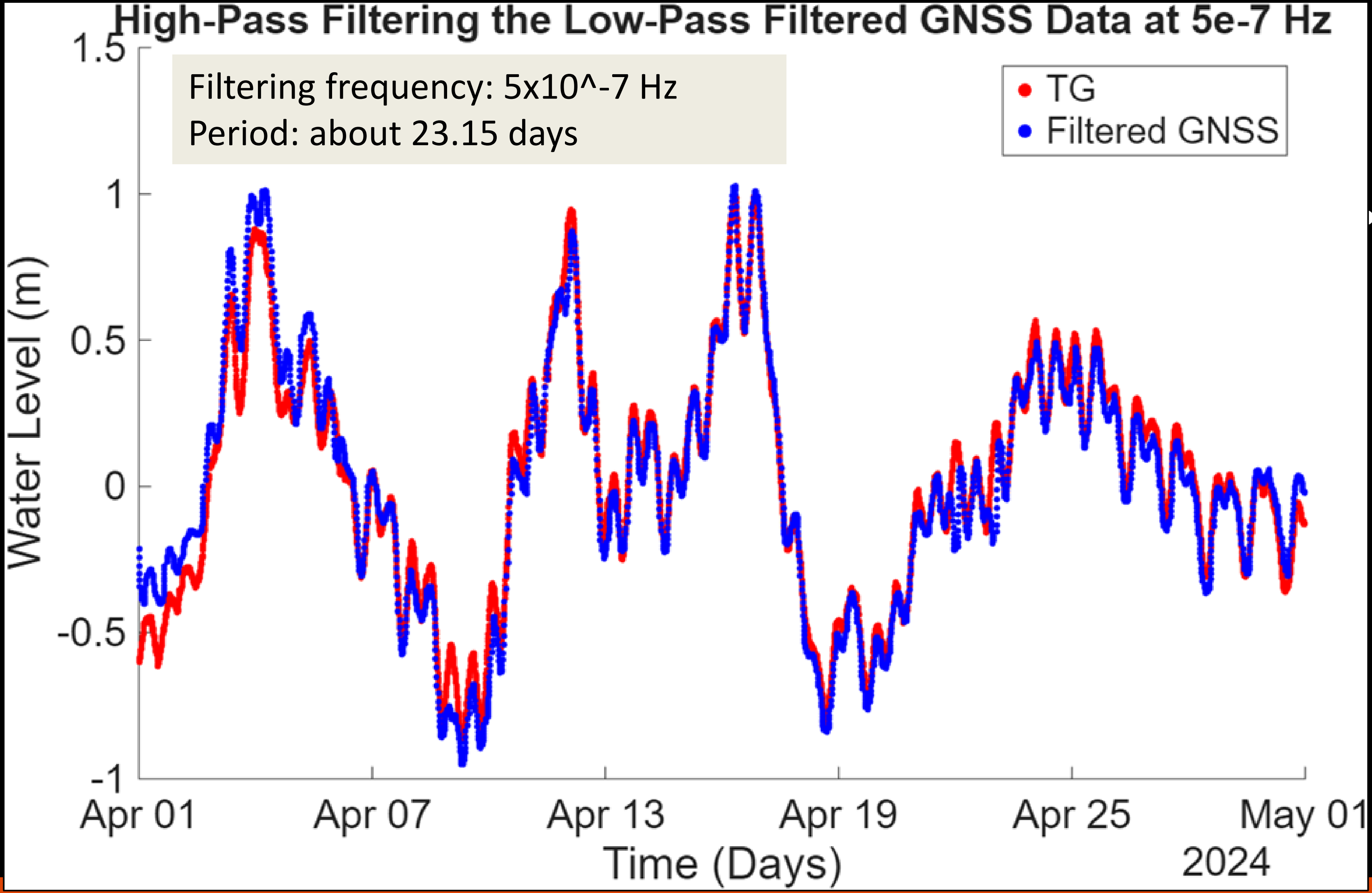
Oregon State University

- Fieldwork April 3 – 7, 2024
- Difference in data sets likely due to snow





- Temp and precipitation data from Nome airport



- On-going Research work
  - Exclude the snow effect
  - Determine vertical displacement of sea ice
  - Estimate horizontal motion of sea ice

Summary

- Geomatics at Oregon State University continuously put efforts on *training and workforce development* through running high level graduate program, Geomatic Minor for undergraduate, as well as developing a geomatics degree program

- Through the GCAP, OrSU and GCAP partners actively contributes to GNSS research by developing and testing GNSS algorithms, contributing to NSRS transitions, and training and educating for future leaders in geodesy and geospatial professions

- Various GNSS research activities have been performing not only for the PNT but also sensing the earth environment

- **Publications**
  - **Luhrmann, F.**, Park, J., & Wong, W.-K.(2026). Ionospheric anomaly detection and source geolocation over open ocean with GNSS remote sensing. Journal of Geophysical Research: Space Physics, 131, e2025JA034460. https://doi.org/10.1029/2025JA034460.
  - **Bohn, J.J.**, J. Park, A. Mahoney, E. Fedders (2026), Monitoring the Dynamic Motion of Landfast Ice in Alaska Using GNSS-Interferometric Reflectometry (GNSS-IR), Proceedings of the 2025 International Technical Meeting of The Institute of Navigation, Anaheim, California, January, 2026.
  - **Srisutha, K.** and J. Park (2025), GNSS Interferometric Reflectometry as An Operational Framework for Real-Time Tide Estimation, *Journal of Surveying Engineering*, Vol 151, Issue 2, https://doi.org/10.1061/JSUED2.SUENG-1545
  - **Luhrmann, F.**, Park, J., Wong, WK. et al. (2025), Detection of ionospheric disturbances with a sparse GNSS network in simulated near-real time Mw 7.8 and Mw 7.5 Kahramanmaraş earthquake sequence. GPS Solut 29, 54. https://doi.org/10.1007/s10291-024-01808-2
- **GCAP Website**: https://gcapgeospatial.org

A Full Kinematic, Backwards-Compatible Reference Frame for the Continental United States of America and Canada

Demián D. Gómez, Chong-You Wang, Michael G. Bevis, and Joachim Moortgat

Presentation outline

- Project goals
- National-level Kinematic Reference Frame
- Visual interactive processing line (GeoDE)
- Intraframe deformation
- Contributions to solve the Geodesy crisis

Project goals

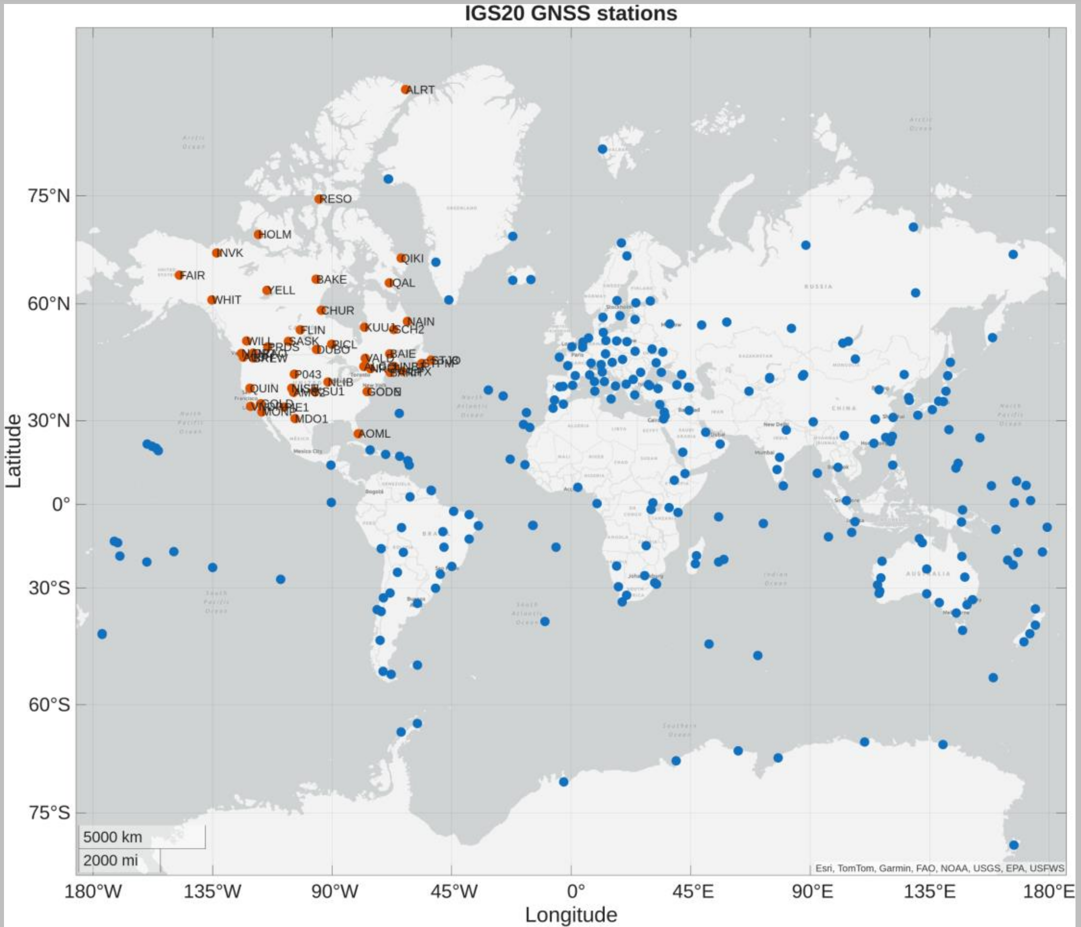
- **Develop a workflow** involving data curation, processing, and analysis to create an operational (*sandbox*) kinematic reference frame.

- We call this workflow the ***Geometric Geodesy Processing Line* (GGPL)**

- Features of the GGPL include:
  - A **relational database** (PostgreSQL) to store **all** the data and products, including the frame itself
  - **Integration** between **GNSS solutions**, station **trajectory models**, and other observations such as **InSAR**
  - **Artificial intelligence** techniques to **improve** trajectory models and model deformation constraints using InSAR observations
  - A software package that **streamlines creation of models and frame access**

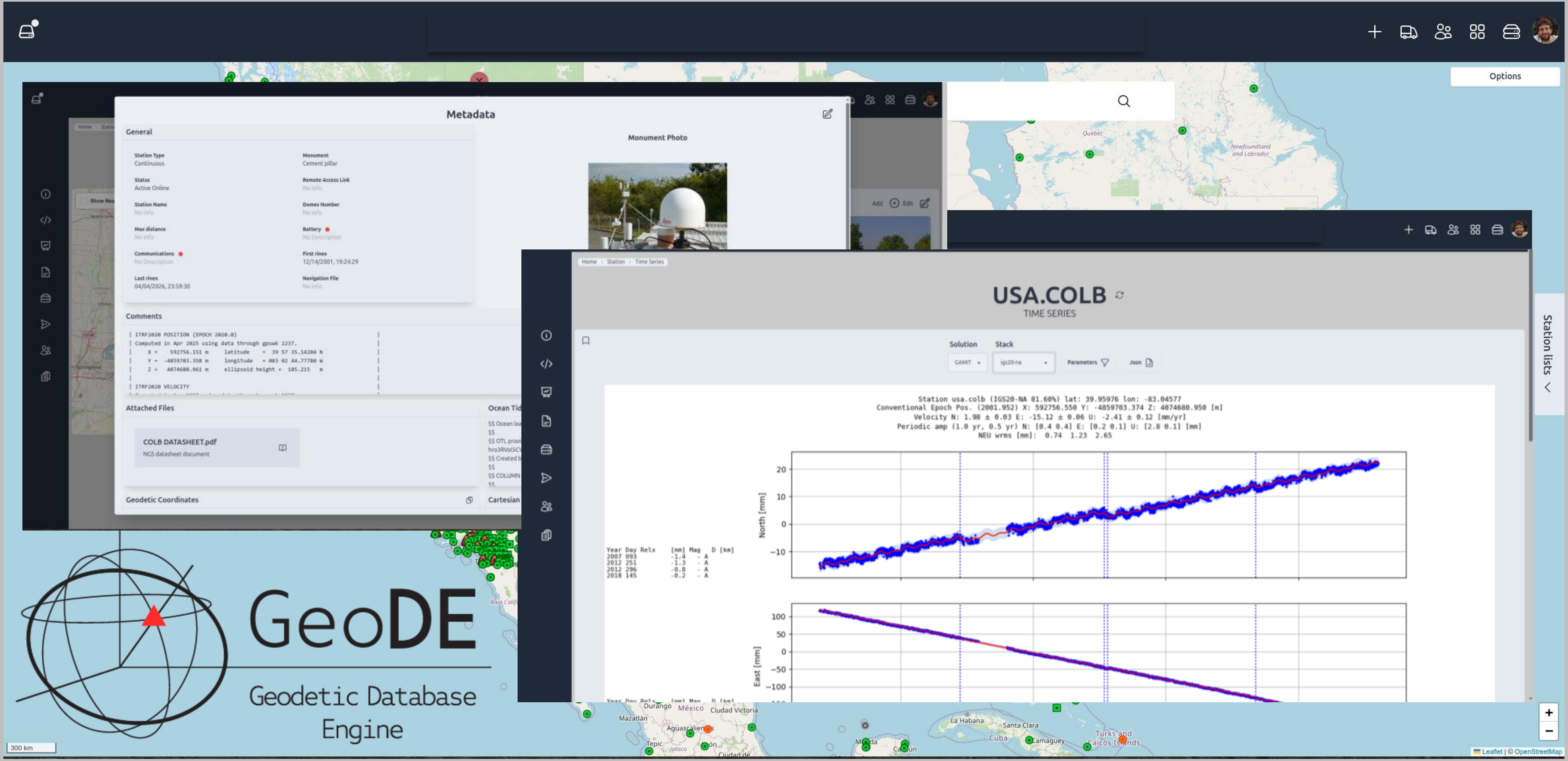
NGS CORS for a National-level KRF

- Using ~1,800 NGS CORS, we realized a kinematic reference frame (KRF) for CONUS and Canada
- Definition: the coordinates and model parameters defining the reference frame are time-dependent
- **Single or multiple conventional epochs**, accessible to all users anytime and anywhere to guarantee topologic homogeneity.
- Models to access the conventional epoch are mandatory, even after an earthquake
- **CORS data is essential to meet this goal**



THE OHIO STATE UNIVERSITY

Geodetic Database Engine (GeoDE)



Metadata

General

Station Type
Continuous

Status
Active Online

Station Name
No info

Max distance
No info

Communications ●
No Description

Last rinex
04/04/2026, 23:59:30

Monument
Cement pillar

Remote Access Link
No info

Domes Number
No info

Battery ●
No Description

First rinex
12/14/2001, 19:24:29

Navigation File
No info

Comments

```
| ITRF2020 POSITION (EPOCH 2020.0)                                  |
| Computed in Apr 2025 using data through gpswk 2237.              |
|     X =    592756.151 m     latitude    =  39 57 35.14204 N      |
|     Y =  -4859703.358 m     longitude   = 083 02 44.77780 W      |
|     Z =   4074680.961 m     ellipsoid height =  185.215   m      |
|                                                                   |
| ITRF2020 VELOCITY                                                 |
```

Attached Files

COLB DATASHEET.pdf
NGS datasheet document

Geodetic Coordinates

USA.COLB

TIME SERIES

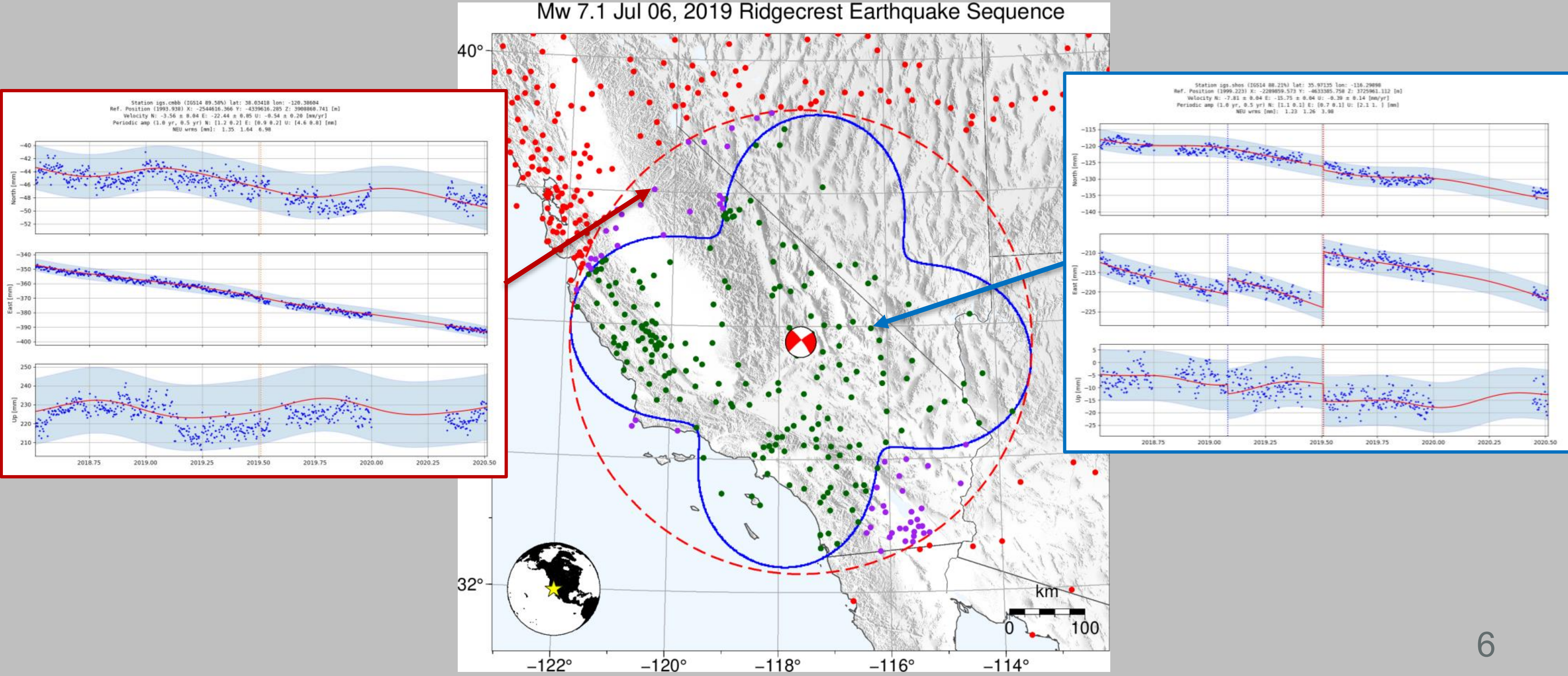
Solution: GAMIT
Stack: igs20-na
Parameters
Json

```
Station usa.colb (IGS20-NA 81.60%) lat: 39.95976 lon: -83.04577
Conventional Epoch Pos. (2001.952) X: 592756.550 Y: -4859703.374 Z: 4074680.950 [m]
Velocity N: 1.98 ± 0.03 E: -15.12 ± 0.06 U: -2.41 ± 0.12 [mm/yr]
Periodic amp (1.0 yr, 0.5 yr) N: [0.4 0.4] E: [0.2 0.1] U: [2.8 0.1] [mm]
NEU wrms [mm]:  0.74  1.23  2.65
```

```
Year Day Relx      [mm] Mag   D [km]
2007 093           -1.4   -  A
2012 251           -1.3   -  A
2012 296           -0.8   -  A
2018 145           -0.2   -  A
```

Automation within the GeoDE

Earthquake detection → significant improvement over current methods → better time series

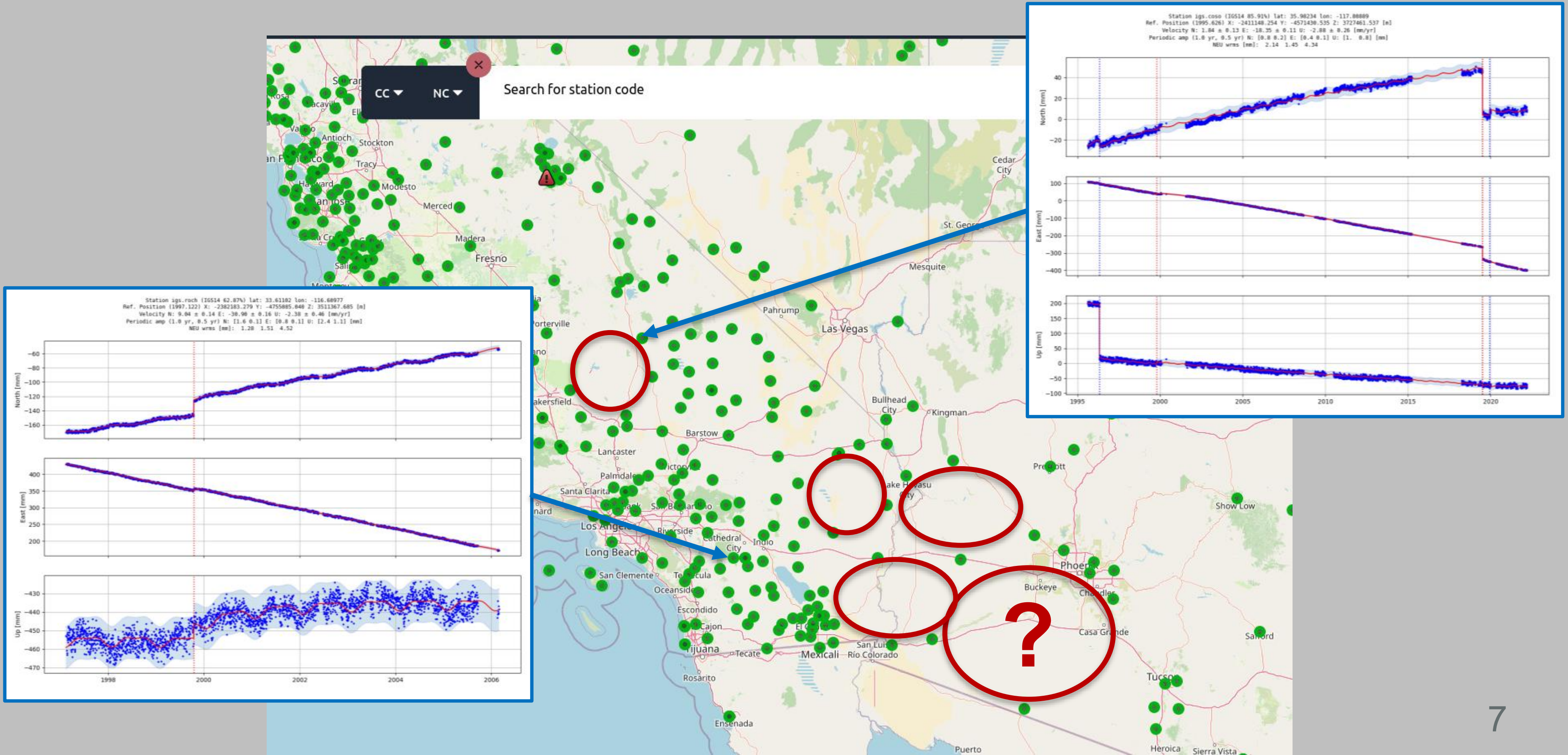


Mw 7.1 Jul 06, 2019 Ridgecrest Earthquake Sequence

Station igs.cmbb (IGS14 89.58%) lat: 38.03418 lon: -120.38604
Ref. Position (1993.938) X: -2544616.366 Y: -4339616.285 Z: 3908868.741 [m]
Velocity N: -3.56 ± 0.04 E: -22.44 ± 0.05 U: -0.54 ± 0.20 [mm/yr]
Periodic amp (1.0 yr, 0.5 yr) N: [1.2 0.2] E: [0.9 0.2] U: [4.6 0.8] [mm]
NEU wrms [mm]: 1.35 1.64 6.98

Station igs.shos (IGS14 88.21%) lat: 35.97135 lon: -116.29098
Ref. Position (1999.223) X: -2289859.573 Y: -4633385.758 Z: 3725961.112 [m]
Velocity N: -7.81 ± 0.04 E: -15.75 ± 0.04 U: -0.39 ± 0.14 [mm/yr]
Periodic amp (1.0 yr, 0.5 yr) N: [1.1 0.1] E: [0.7 0.1] U: [2.1 1.] [mm]
NEU wrms [mm]: 1.23 1.26 3.98

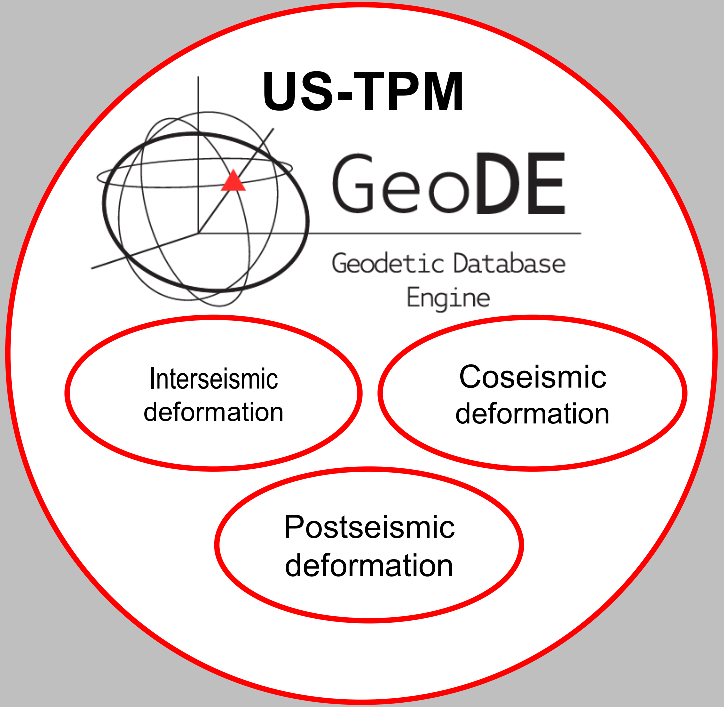
Intraframe Deformation



GGPL in Practice: Intraframe Deformation

Trajectory Prediction Models (TPM)

- A **TPM, continuous in space and time,** that allows us to predict the behavior of passive benchmarks.
- This model ensures the access to a geodetic reference frame after large magnitude earthquakes using postseismic coordinates.
- These models allow the frame users to obtain accurate predictions of position and uncertainty in the target frame.



US-TPM

Interseismic deformation

Coseismic deformation

Postseismic deformation

Intraframe Deformation

GNSS vs InSAR: complementary observations

- GNSS daily solutions

  Mostly in **ITRF/IGS** or regional densifications of it

  Have random errors. Spatially correlated errors are largely reduced/estimated

- InSAR:

  In a **relative reference frame**

  In addition to **random errors**, under-corrected spatially correlated errors usually exist. **Atmospheric errors are (in general) still present in final products**

To achieve integration, we must unify the reference frames and deal with uncertainties

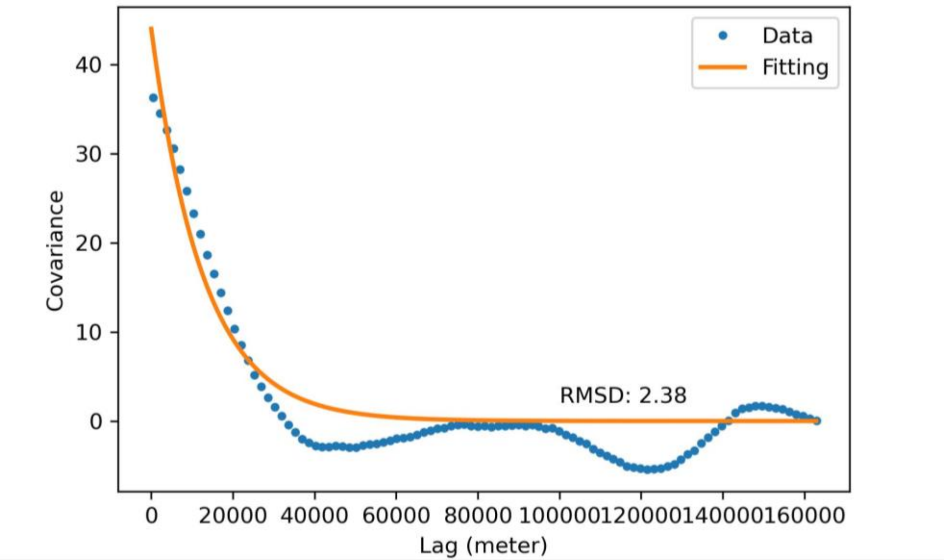
Intraframe Deformation

Integration: Least-squares Collocation InSAR (CoInSAR)

- We model the turbulent errors and mitigate them.

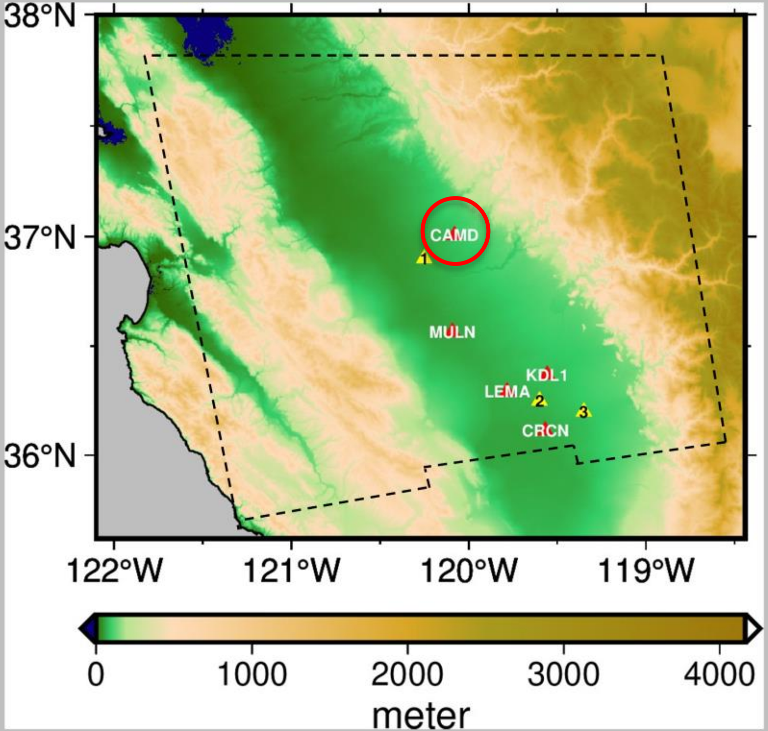
- Using all available GNSS stations around an area of interest, we find the reference frame transformation parameters while accounting for turbulent and random errors.

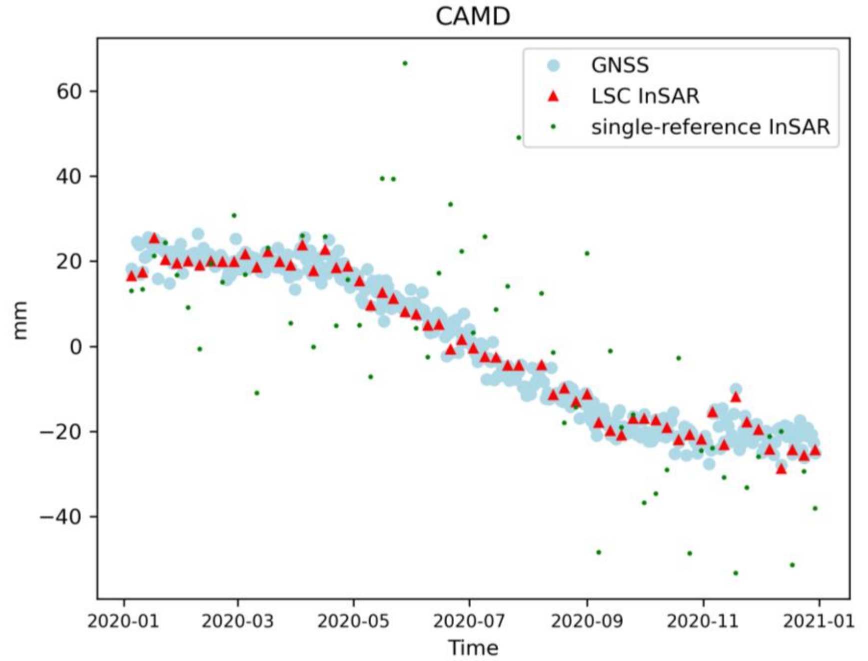
- We apply the transformation to InSAR displacements to achieve integration



Intraframe Deformation

Some results in San Joaquin Valley

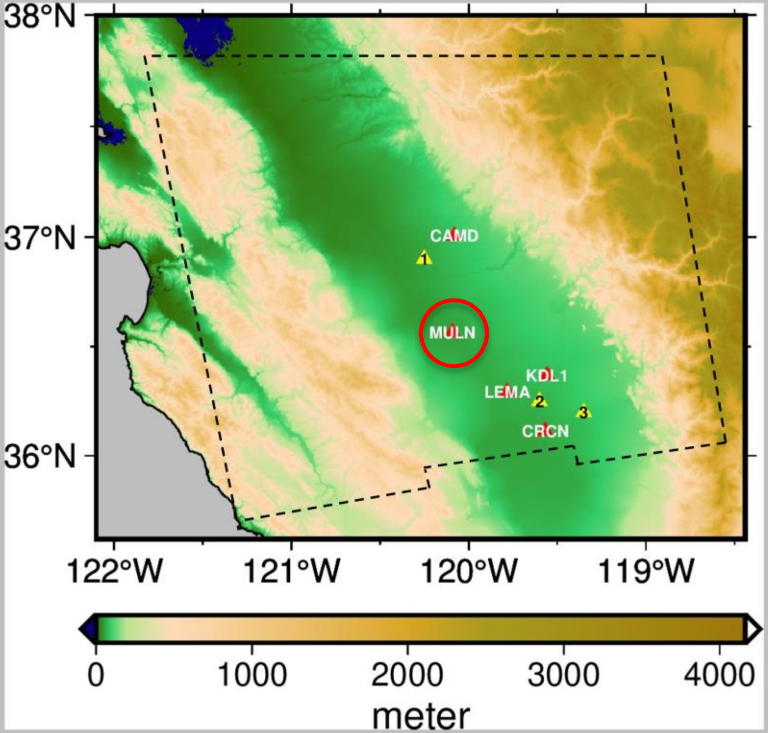


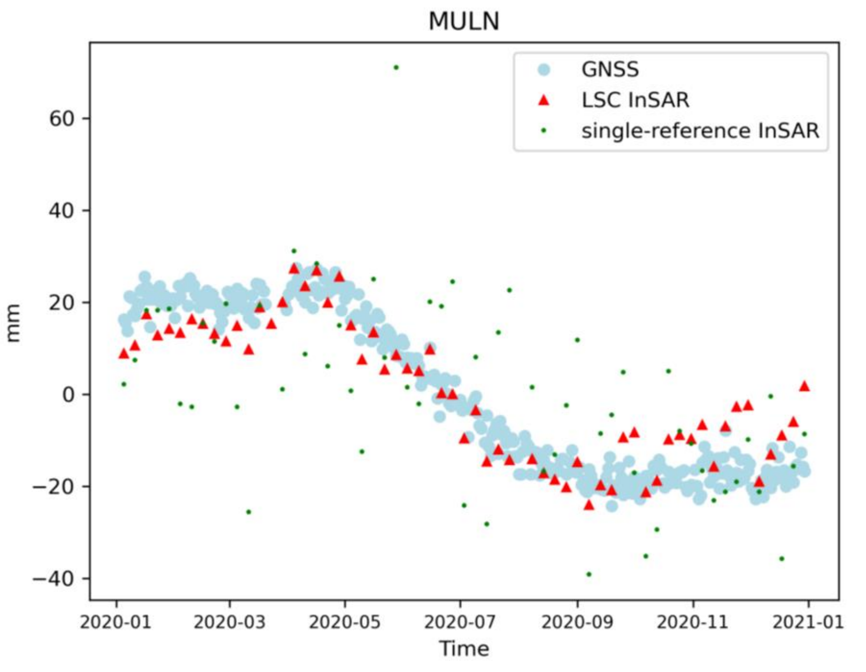


LSC InSAR RMSD: 7.45 mm
Single-reference RMSD: 20.74 mm

Intraframe Deformation

Some results in San Joaquin Valley

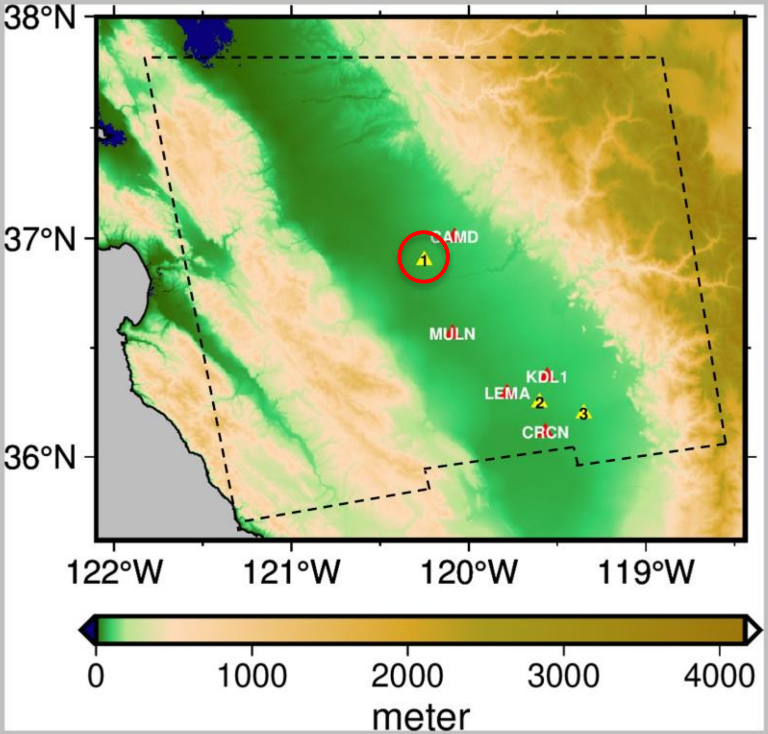


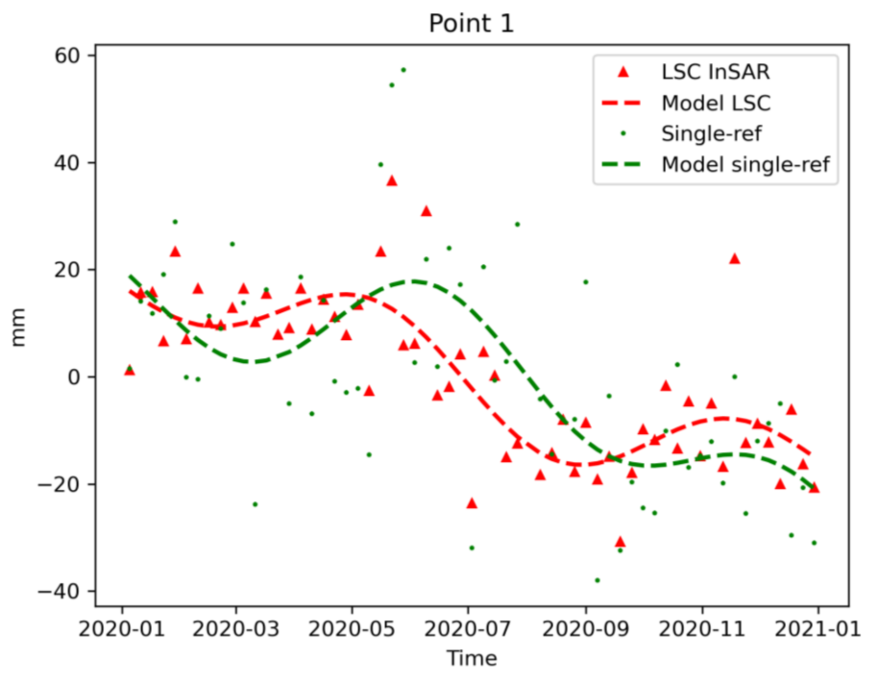


LSC InSAR RMSD: 6.78 mm
Single-reference RMSD: 18.20 mm

Intraframe Deformation

Some results in San Joaquin Valley





LSC InSAR RMSD: 9.40 mm
Single-reference RMSD: 16.53 mm

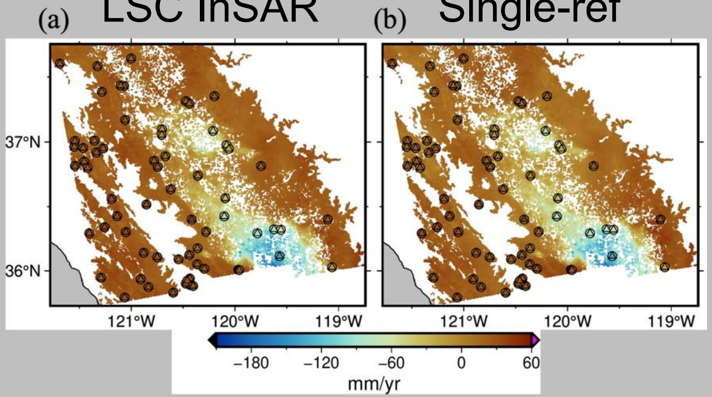
Intraframe Deformation

Derived linear velocity

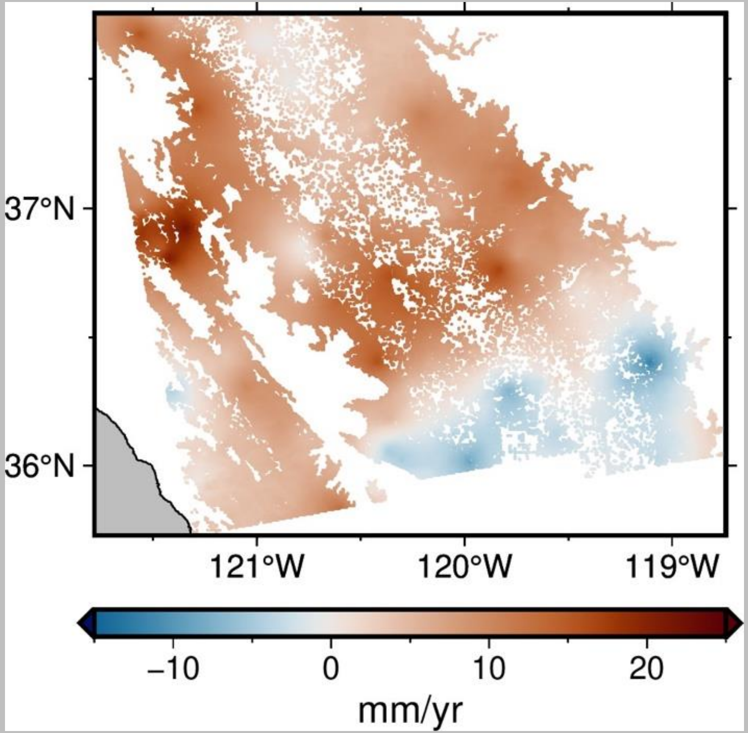
LSC InSAR

Single-ref

Velocity



Velocity difference



- Direct integration with our trajectory prediction models (intraframe deformation)
- Possibility of assimilating JPL’s OPERA products
- **Direct impact on NGS’ user community:** better models to work on high deformation regions

Solving the Geodesy Crisis

Contributions to solve the Geodesy crisis

Workforce Development

- Training the next generation of geodesists: three fully-funded PhD students and one postdoctoral position (to be filled in coming months) directly addressing the national geodesy workforce shortage
- Students contribute to open-source geodetic software, ensuring skills transfer beyond the grant period

Integration of Space Geodetic Observations (CoInSAR)

- Fusion of InSAR and GNSS observations via least-squares collocation to densify the spatial sampling of the geometric reference frame, particularly in regions with sparse continuous GNSS coverage

Kinematic Reference Frame Realization

- Research directly supports NGS’ efforts toward a time-dependent realization of the National Spatial Reference System (NSRS), accounting for ongoing crustal motion, postseismic deformation, and glacial isostatic adjustment
- Prototype (“sandbox”) reference frame environment and associated tools designed for direct technology transfer to NGS operational workflows

Team members

Principal- and co-investigators

Research Scientists

Graduate Students

Franco Sobrero

Kevin Wang

Bennett Kellmayer

Fiona Bishop
(Starting Fall 2026)

THE OHIO STATE UNIVERSITY

gomez.124@osu.edu

Questions?

¿Preguntas?

Thank you for your attention!

¡Muchas gracias por la atención!

GDGPS High Accuracy Products for Real-Time Applications: Supporting Public and Scientific Communities

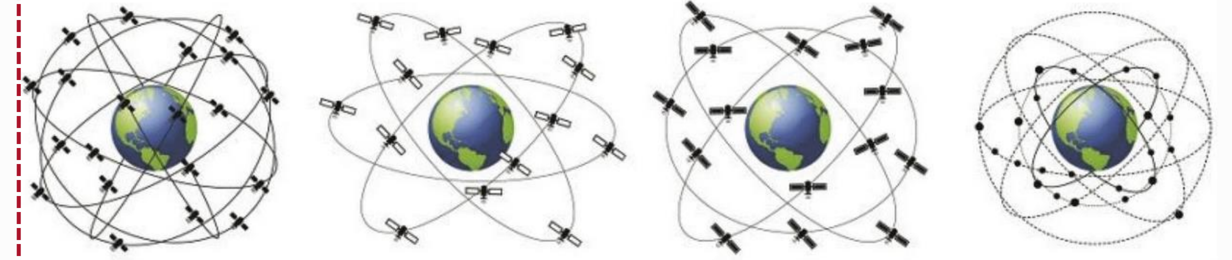
Attila Komjathy, Group Supervisor

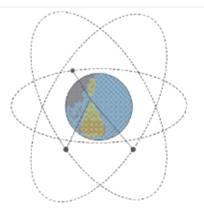
Outline

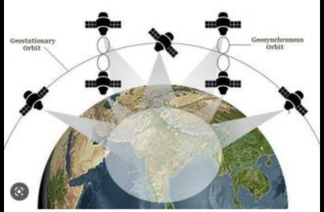
- GDGPS status and JPL activities
  - GDGPS Operations Centers (GOCs) transition
  - Real-time public products for distribution
- GDGPS public products performance
  - User Range Error (URE) comparisons
- Standalone JPL prototype client
- Other GDGPS-based science products to detect natural hazards
- Summary
- Acknowledgements

*CODE – Center of Orbit Determination of Europe

The Real-Time GDGPS System







GPS

Galileo

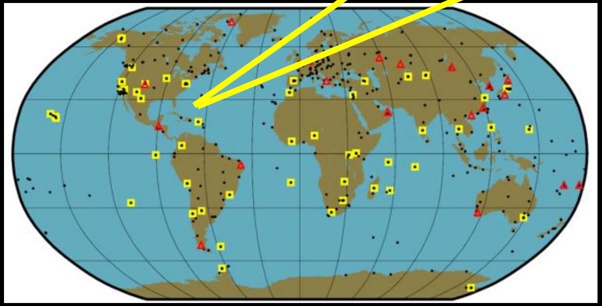
GLONASS

BeiDou

QZSS

NavIC

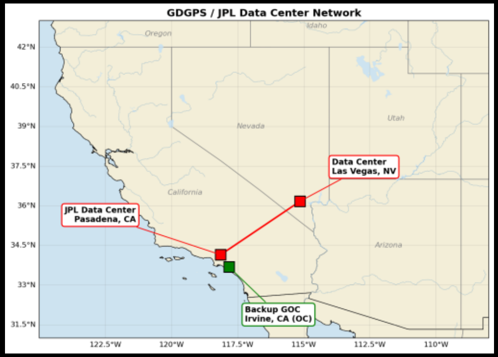
GDGPS



Reference Network
(Core is NASA's GGN)

GipsyX / RTGx

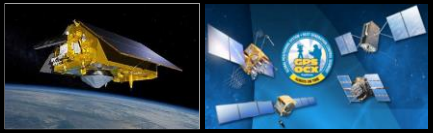
GDGPS Software



Multiple Redundant Operation Centers

Products, Services

Precise Positioning and GNSS Signal Monitoring



Time-Critical Environmental Monitoring and Science Products

GUARDIAN

GNSS-based Upper Atmospheric Realtime Disaster Information and Alert Network

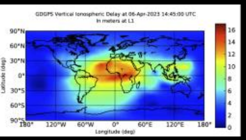
How to Navigate

Legend

GPS GLONASS GALILEO BEIDOU

Earthquake USGS Tsunami Watch GDGPS Station

Crustal Dynamics Data Information System

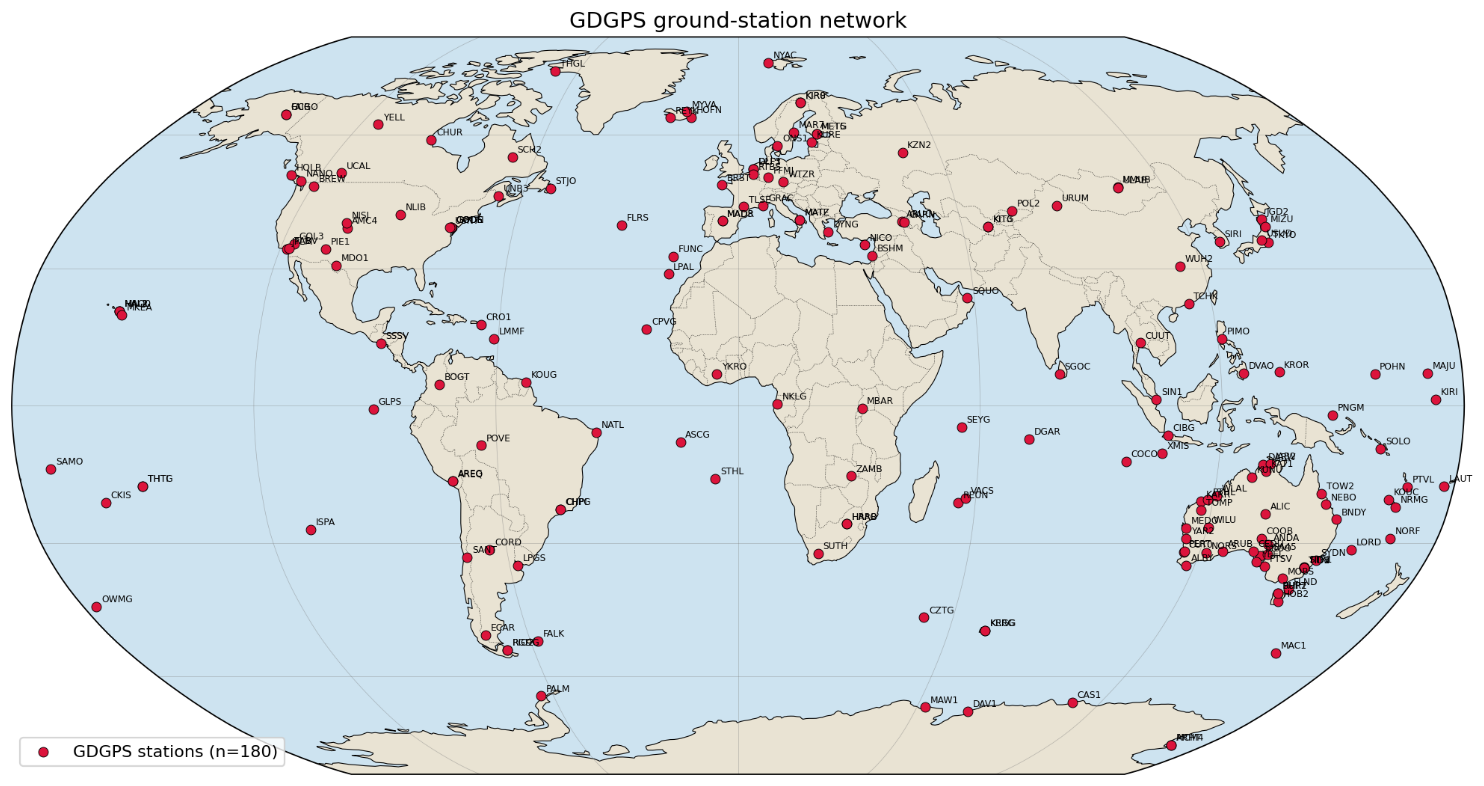


GDGPS enables 5-10 cm real-time accuracy, and provides other unique products

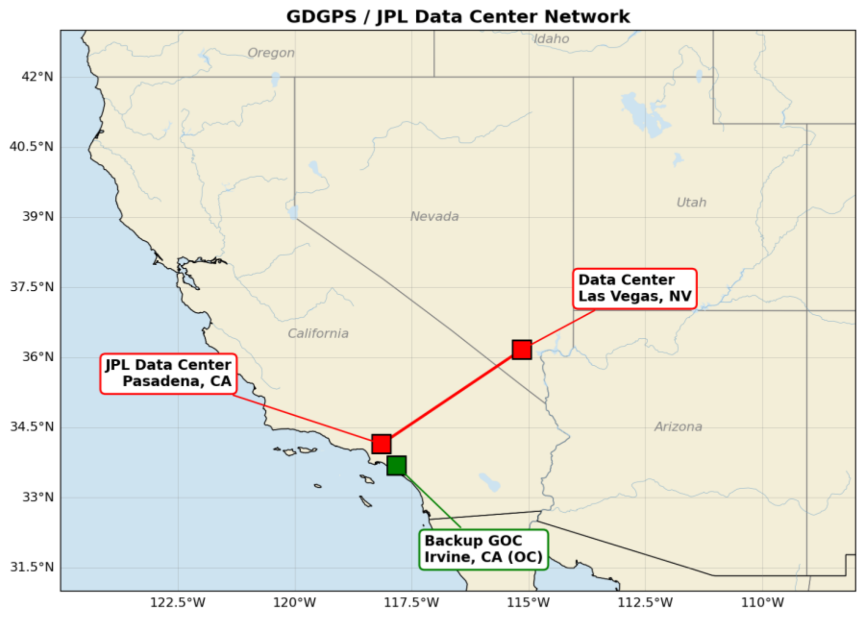
Network of GDGPS-Processed GNSS Receivers

- GDGPS uses and supports NASA-owned JPL-operated GNSS receivers (GGN)
- Network augmented by a smaller set of GDGPS-operated sites
- Publicly available IGS streaming data supplements the global network

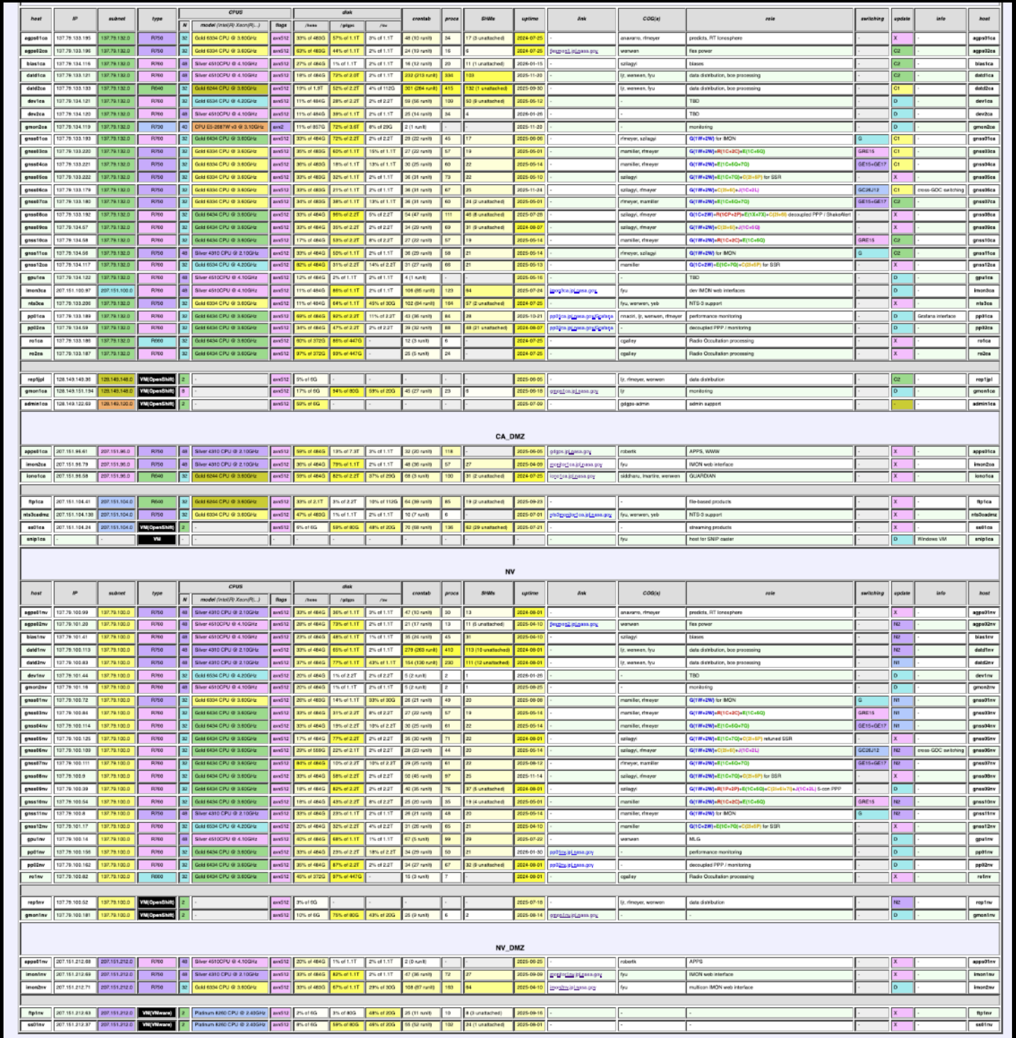
The available global tracking network undergoes continual review and upgrading



Completion of GOCs Transition to JPL Data Centers



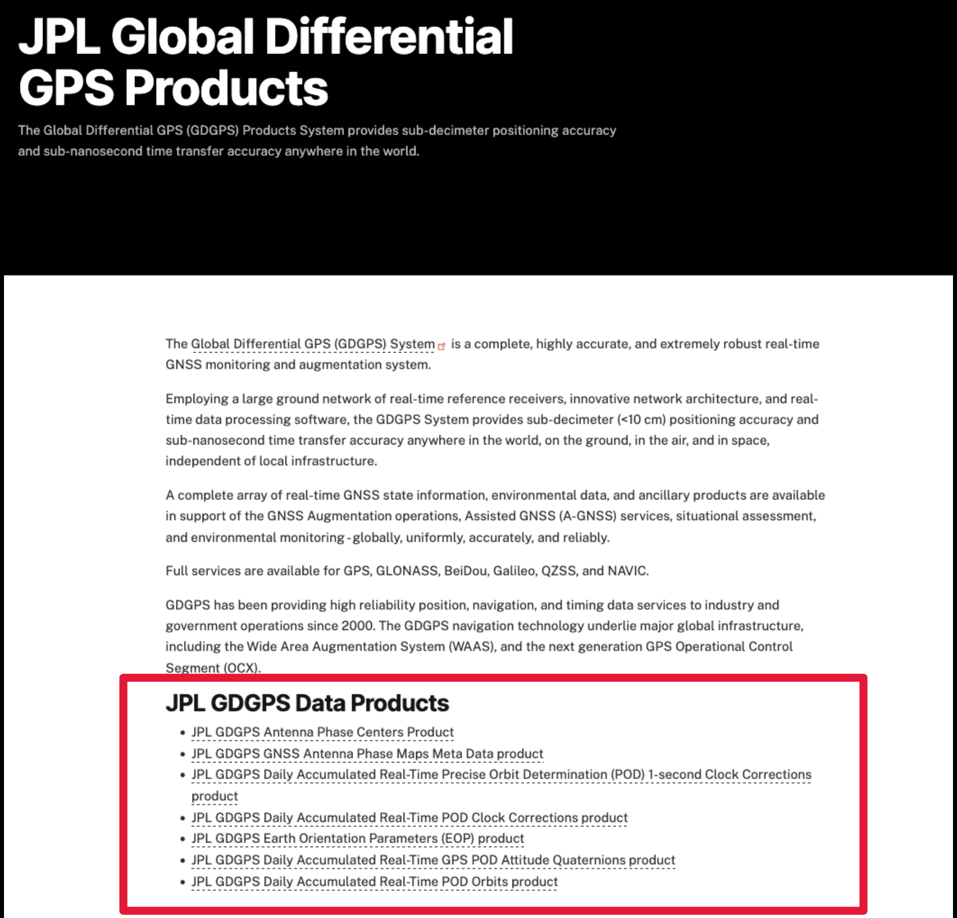
- Operational data processing is carried out in multiple independent GDGPS Operations Centers (GOCs)
- Completed of transition of two **JPL Data Centers** located at JPL and Las Vegas to comply with **NASA data security requirements** (FISMA)



50+ servers are JPL and Las Vegas Data Centers

GDGPS Public Products at NASA EarthData Now

Jet Propulsion Laboratory
California Institute of Technology



JPL Global Differential GPS Products

The Global Differential GPS (GDGPS) Products System provides sub-decimeter positioning accuracy and sub-nanosecond time transfer accuracy anywhere in the world.

The Global Differential GPS (GDGPS) System is a complete, highly accurate, and extremely robust real-time GNSS monitoring and augmentation system.

Employing a large ground network of real-time reference receivers, innovative network architecture, and real-time data processing software, the GDGPS System provides sub-decimeter (<10 cm) positioning accuracy and sub-nanosecond time transfer accuracy anywhere in the world, on the ground, in the air, and in space, independent of local infrastructure.

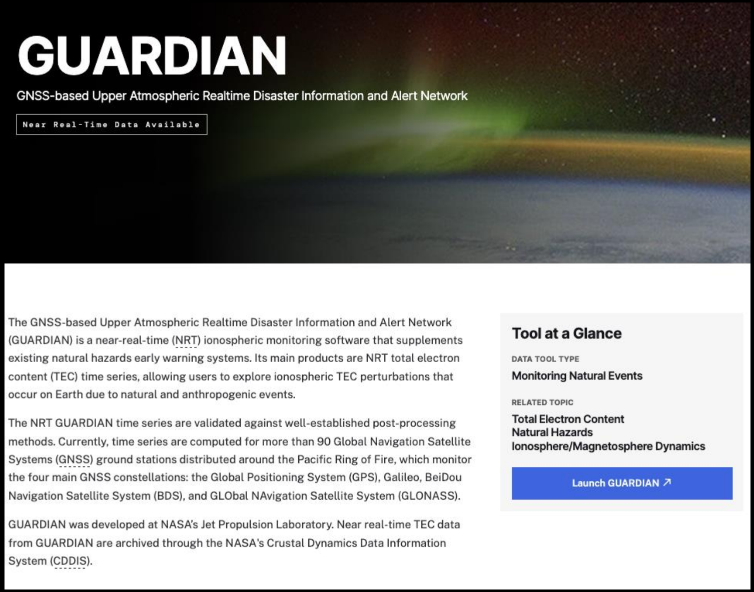
A complete array of real-time GNSS state information, environmental data, and ancillary products are available in support of the GNSS Augmentation operations, Assisted GNSS (A-GNSS) services, situational assessment, and environmental monitoring - globally, uniformly, accurately, and reliably.

Full services are available for GPS, GLONASS, BeiDou, Galileo, QZSS, and NAVIC.

GDGPS has been providing high reliability position, navigation, and timing data services to industry and government operations since 2000. The GDGPS navigation technology underlie major global infrastructure, including the Wide Area Augmentation System (WAAS), and the next generation GPS Operational Control Segment (OCX).

JPL GDGPS Data Products

- JPL GDGPS Antenna Phase Centers Product
- JPL GDGPS GNSS Antenna Phase Maps Meta Data product
- JPL GDGPS Daily Accumulated Real-Time Precise Orbit Determination (POD) 1-second Clock Corrections product
- JPL GDGPS Daily Accumulated Real-Time POD Clock Corrections product
- JPL GDGPS Earth Orientation Parameters (EOP) product
- JPL GDGPS Daily Accumulated Real-Time GPS POD Attitude Quaternions product
- JPL GDGPS Daily Accumulated Real-Time POD Orbits product



GUARDIAN

GNSS-based Upper Atmospheric Realtime Disaster Information and Alert Network

Near Real-Time Data Available

The GNSS-based Upper Atmospheric Realtime Disaster Information and Alert Network (GUARDIAN) is a near-real-time (NRT) ionospheric monitoring software that supplements existing natural hazards early warning systems. Its main products are NRT total electron content (TEC) time series, allowing users to explore ionospheric TEC perturbations that occur on Earth due to natural and anthropogenic events.

The NRT GUARDIAN time series are validated against well-established post-processing methods. Currently, time series are computed for more than 90 Global Navigation Satellite Systems (GNSS) ground stations distributed around the Pacific Ring of Fire, which monitor the four main GNSS constellations: the Global Positioning System (GPS), Galileo, BeiDou Navigation Satellite System (BDS), and GLObal NAvigation Satellite System (GLONASS).

GUARDIAN was developed at NASA's Jet Propulsion Laboratory. Near real-time TEC data from GUARDIAN are archived through the NASA's Crustal Dynamics Data Information System (CDDIS).

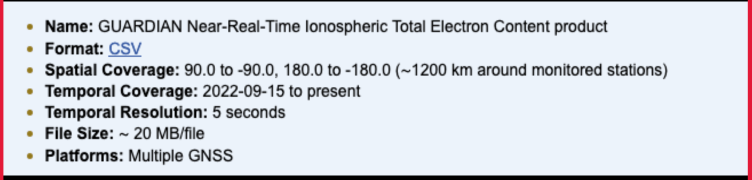
Tool at a Glance

DATA TOOL TYPE
Monitoring Natural Events

RELATED TOPIC
Total Electron Content
Natural Hazards
Ionosphere/Magnetosphere Dynamics

Launch GUARDIAN ↗

TEC Product at EarthData

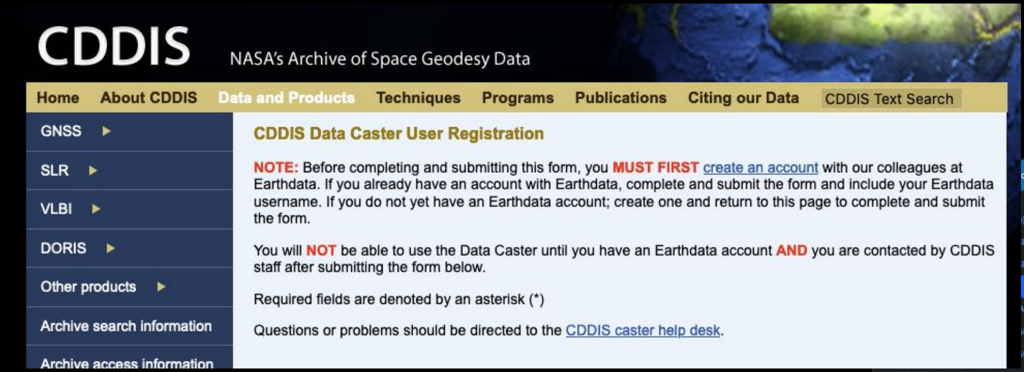


- **Name:** GUARDIAN Near-Real-Time Ionospheric Total Electron Content product
- **Format:** CSV
- **Spatial Coverage:** 90.0 to -90.0, 180.0 to -180.0 (~1200 km around monitored stations)
- **Temporal Coverage:** 2022-09-15 to present
- **Temporal Resolution:** 5 seconds
- **File Size:** ~ 20 MB/file
- **Platforms:** Multiple GNSS

GDGPS-based file products available via NASA's Earthdata.nasa.gov

GDGPS SSR Streams Available via CDDIS and IGS

Jet Propulsion Laboratory
California Institute of Technology



CDDIS Data Caster User Registration

NOTE: Before completing and submitting this form, you **MUST FIRST** create an account with our colleagues at Earthdata. If you already have an account with Earthdata, complete and submit the form and include your Earthdata username. If you do not yet have an Earthdata account; create one and return to this page to complete and submit the form.

You will **NOT** be able to use the Data Caster until you have an Earthdata account **AND** you are contacted by CDDIS staff after submitting the form below.

Required fields are denoted by an asterisk (*)

Questions or problems should be directed to the CDDIS caster help desk.

NASA Streams at CDDIS

NASA Streams at BKG, Germany

IGS RTS AC JPL solution SSRA11JPL0

- PPP client software: BKG Ntrip Client (BNC)
- Location: IGS reference station FFMJ00DEU, Frankfurt
- Observations: 1Hz, dual frequency, GPS+GAL
- Real-Time GNSS analysis software: GIPSY
- Orbits: ??Internal?? Ultra Rapid product
- SSR parameter stream: SSRA11JPL0 by JPL on products.igs-ip.net
- SSR parameter encoding: ??
- Broadcast ephemeris stream: BCEP00BKG0 by BKG on products.igs-ip.net

IGS RTS AC JPL solution SSRA22JPL0

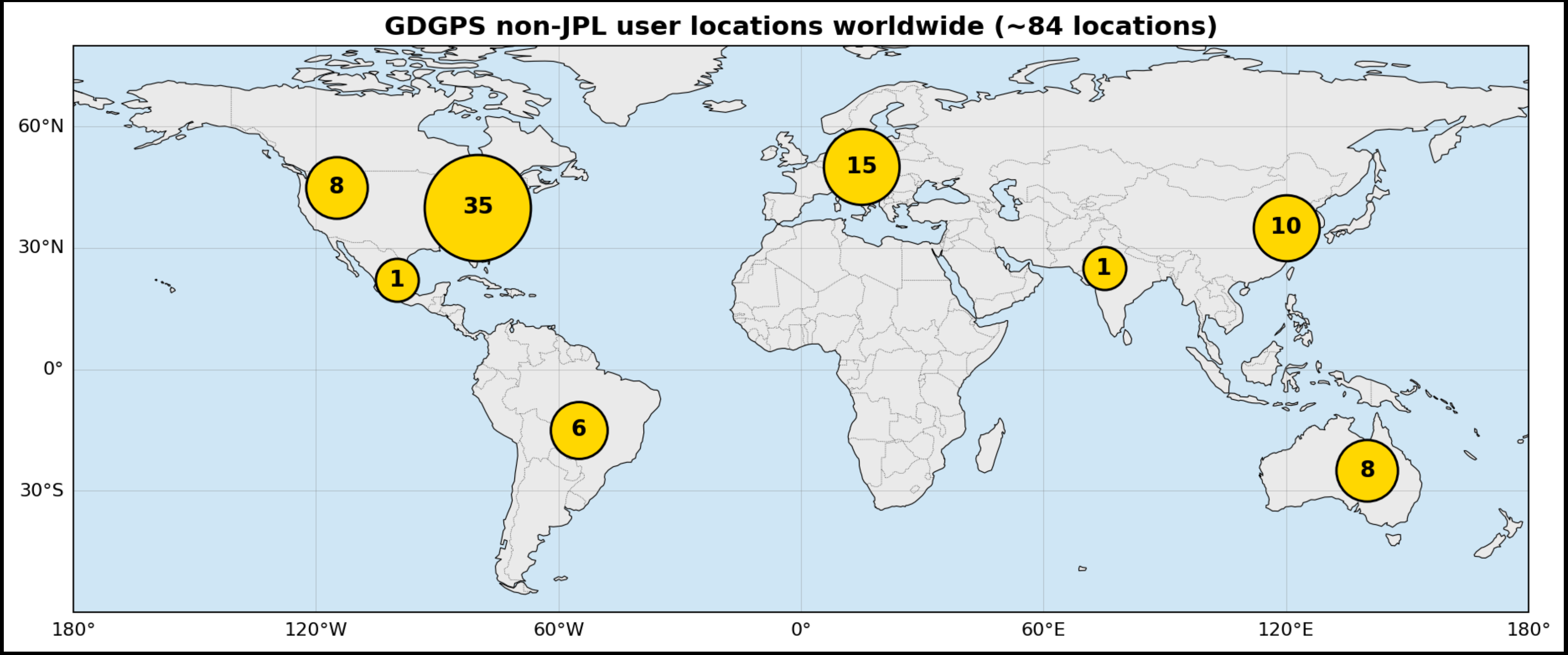
- PPP client software: BKG Ntrip Client (BNC)
- Location: IGS reference station FFMJ00DEU, Frankfurt
- Observations: 1Hz, dual frequency, GPS+GLO
- Real-Time GNSS analysis software: GIPSY
- Orbits: ??Internal?? Ultra Rapid product
- SSR parameter stream: SSRA22JPL0 by JPL on products.igs-ip.net
- SSR parameter encoding: ??
- Broadcast ephemeris stream: BCEP00BKG0 by BKG on products.igs-ip.net

Stream	Former name	Systems	Primary signals	Content
SSRA11JPL0	JPL32T2	GPS + GAL	GPS: 1W/2W GAL: 1C/7Q	Satellite orbits, clocks, and code biases (code and phase biases in beta)
SSRA12JPL0	JPL42T2			
SSRA21JPL0	JPL32T	GPS + GLO	GPS: 1W/2W GLO: 1P/2P	Satellite orbits and clocks
SSRA22JPL0	JPL42T			
BCEP01JPL0	JPLEPH31	GPS + GAL + GLO		Navigation messages
BCEP02JPL0	JPLEPH41			

GDGPS-based streaming products available via NASA's CDDIS and IGS

GDGPS Public Product Users as of March 2026

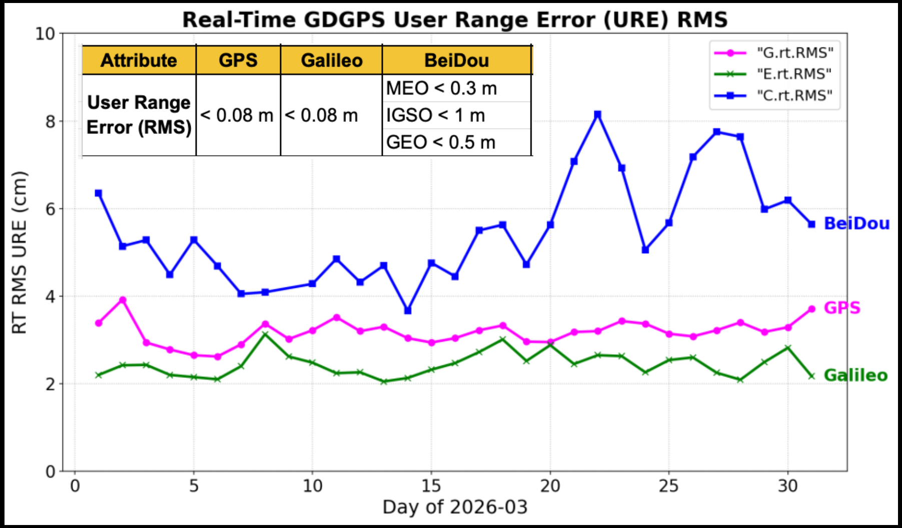
Jet Propulsion Laboratory
California Institute of Technology



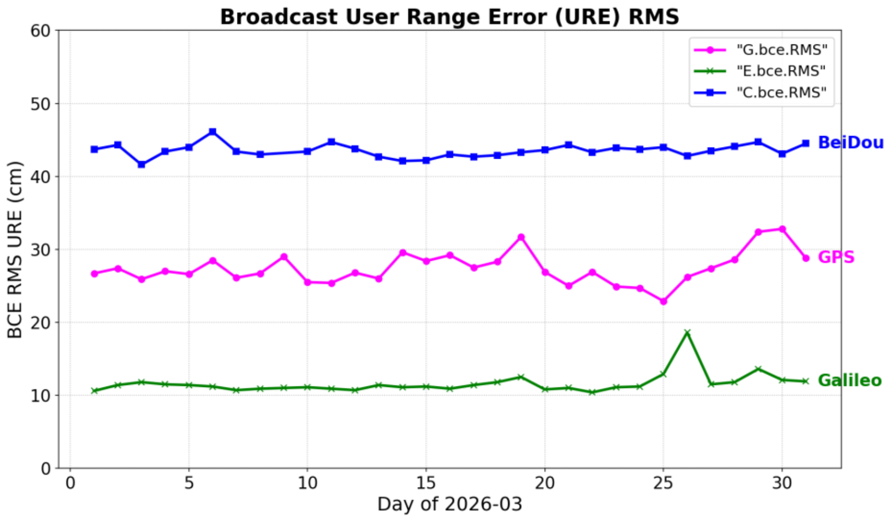
~84 non-JPL users worldwide

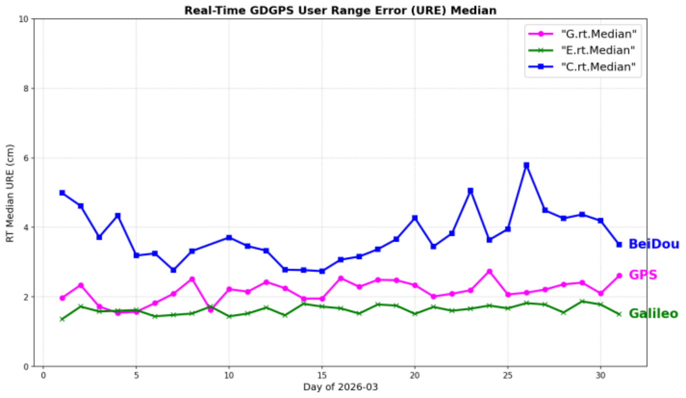
GDGPS Public Products URE RMS Comparison with Final JPL Results for March 2026

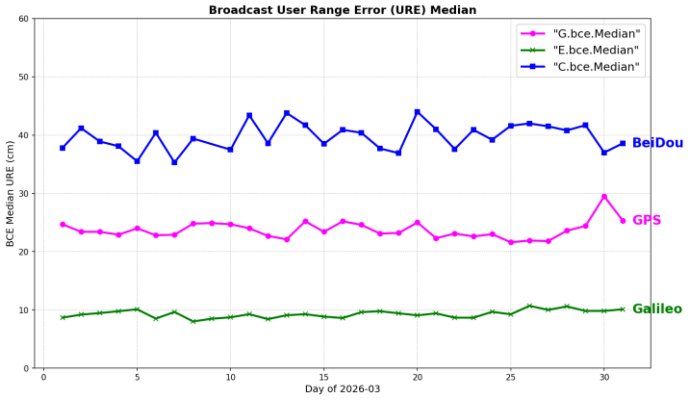
Jet Propulsion Laboratory
California Institute of Technology



Attribute	GPS	Galileo	BeiDou
User Range Error (RMS)	< 0.08 m	< 0.08 m	MEO < 0.3 m IGSO < 1 m GEO < 0.5 m







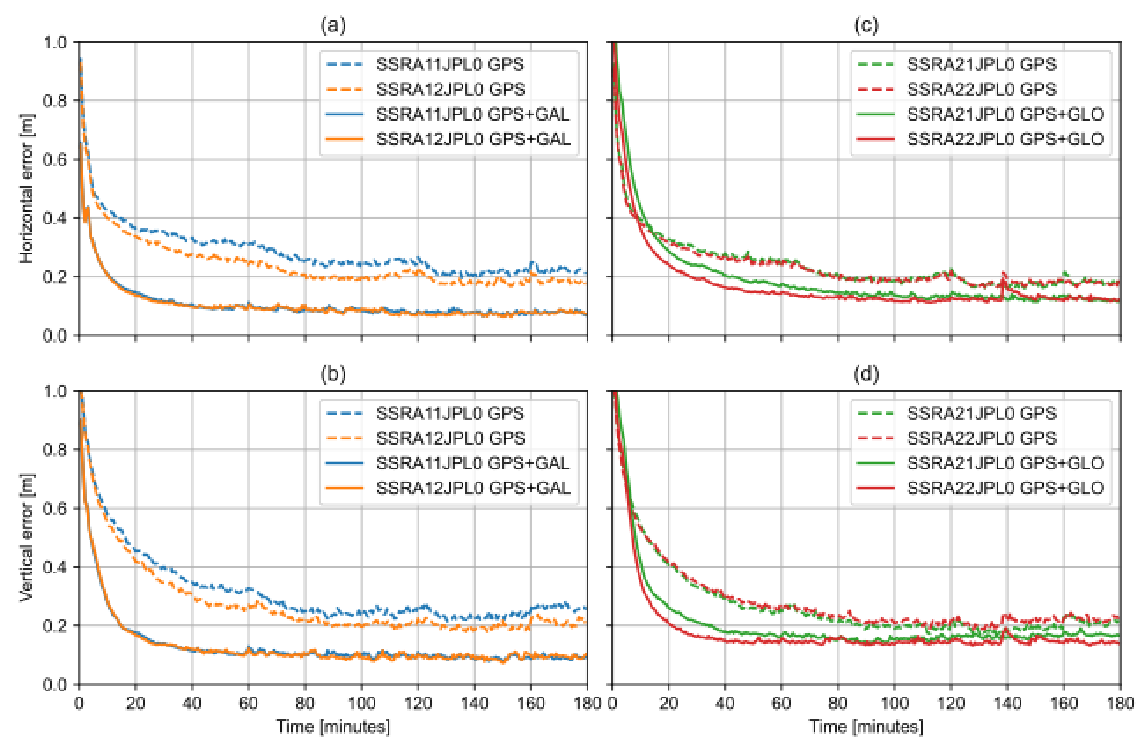
- Low cadence orbit filter **at every 60 sec;** High cadence clock filter **at every second** Comparison to GipsyX final (G,E) and multi-constellation (C) rapid products

GDGPS HAS: Summary of Results

- Dashed lines: single-constellation
- Solid lines: dual-constellation
- Each time series is, for each epoch, the rms of all horizontal / vertical errors after removal of errors > 2 m

- Pairs of streams comparable in performance
- Improvements from dual-constellation over single-constellation

  GPS+GAL results outperform that of GPS+GLO

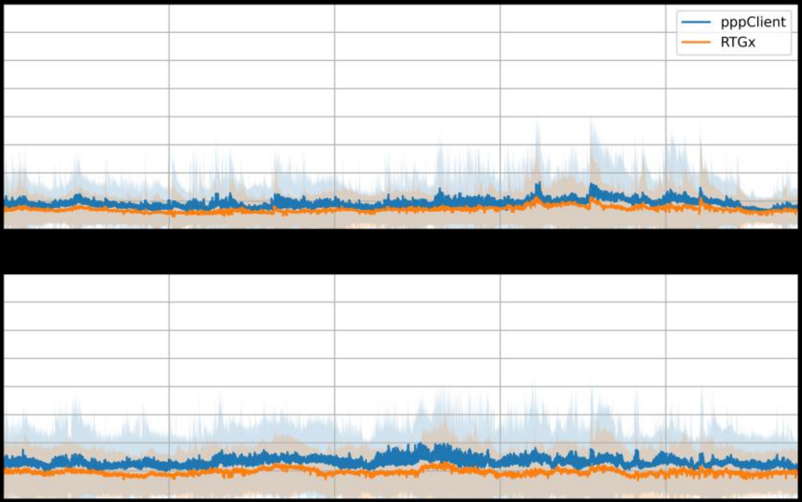


Stream	Multi-GNSS horizontal rms between hours 1 and 3
SSRA11JPL0	12.1 cm
SSRA12JPL0	12.1 cm
SSRA21JPL0	23.4 cm
SSRA22JPL0	20.4 cm

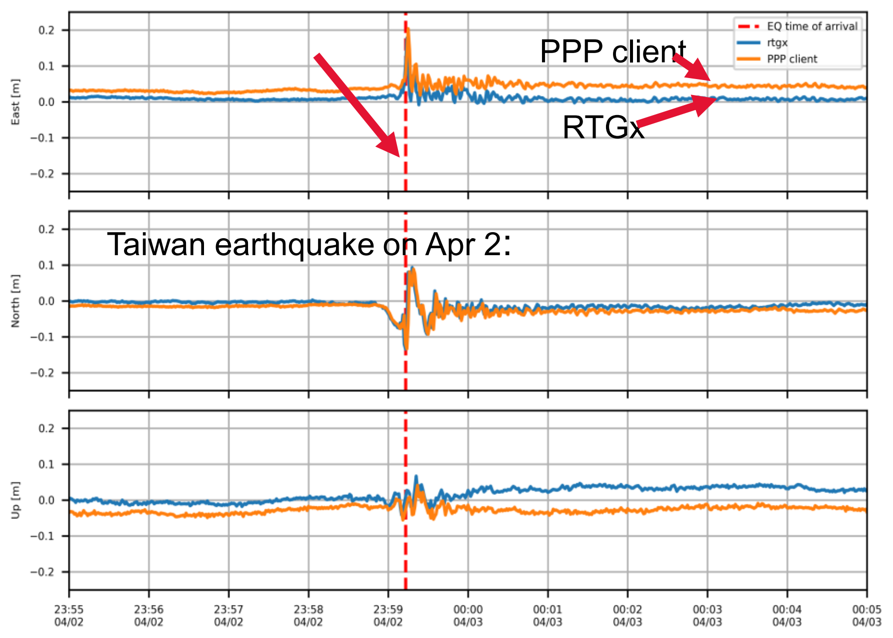
Standalone JPL Client Prototype Development

Current capabilities

- File-based and real-time processing
    - GPS + Galileo support
    - Uncombined (single-frequency) and combined, multi-frequency processing with float solutions



- Full week worth of data from ~30 stations
- The solid lines are average position errors, and the background are standard deviations


PPP client

RTGx

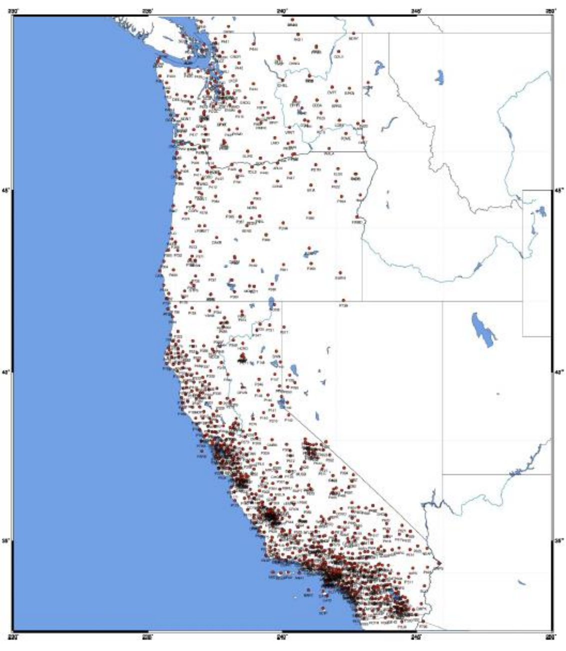
Taiwan earthquake on Apr 2:

- M 7.4 Earthquake near Hualien City, Taiwan 23:58:12 (UTC) on Apr 2, 2024
- 1 Hz GPS+GAL PPP solution at station NCUT

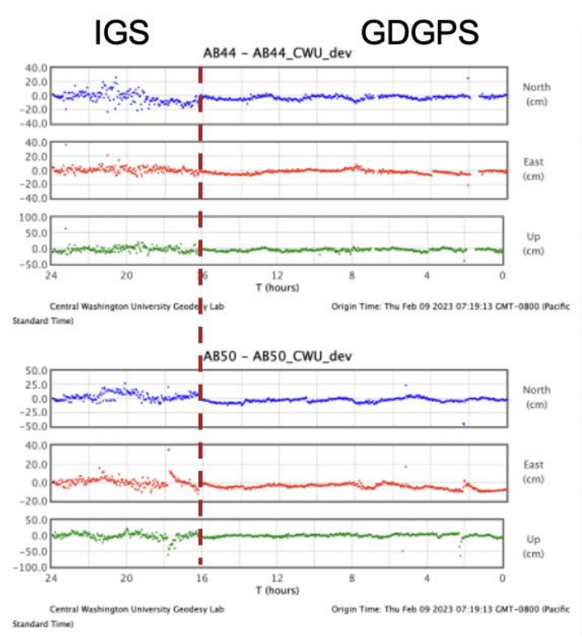
JPL standalone prototype client agrees well with RTGx – EarthScope and USGS are currently in testing mode

GDGPS's Contributions to Earthquake Early Warning

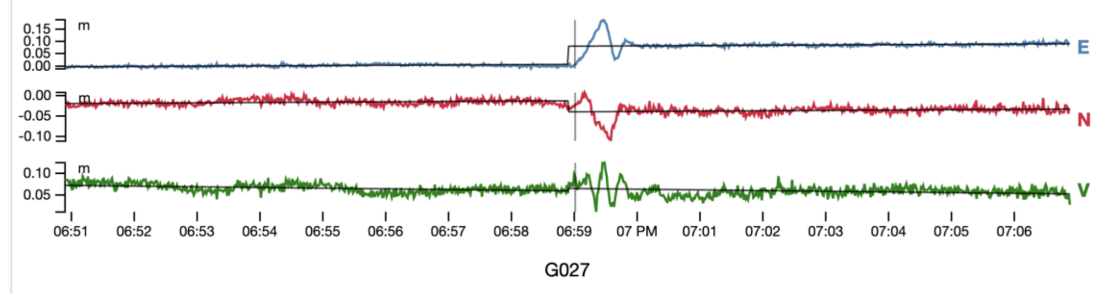
- ShakeAlert is a USGS earthquake early warning system with NASA funding
- NASA requested JPL GDGPS to provide contributions to ShakeAlert
- Novelty here is providing real-time positioning of each station separately using GDGPS
- GDGPS constitutes enabling data for accurate earthquake detection to protect populated areas



~1000 real-time GNSS sites used for ShakeAlert



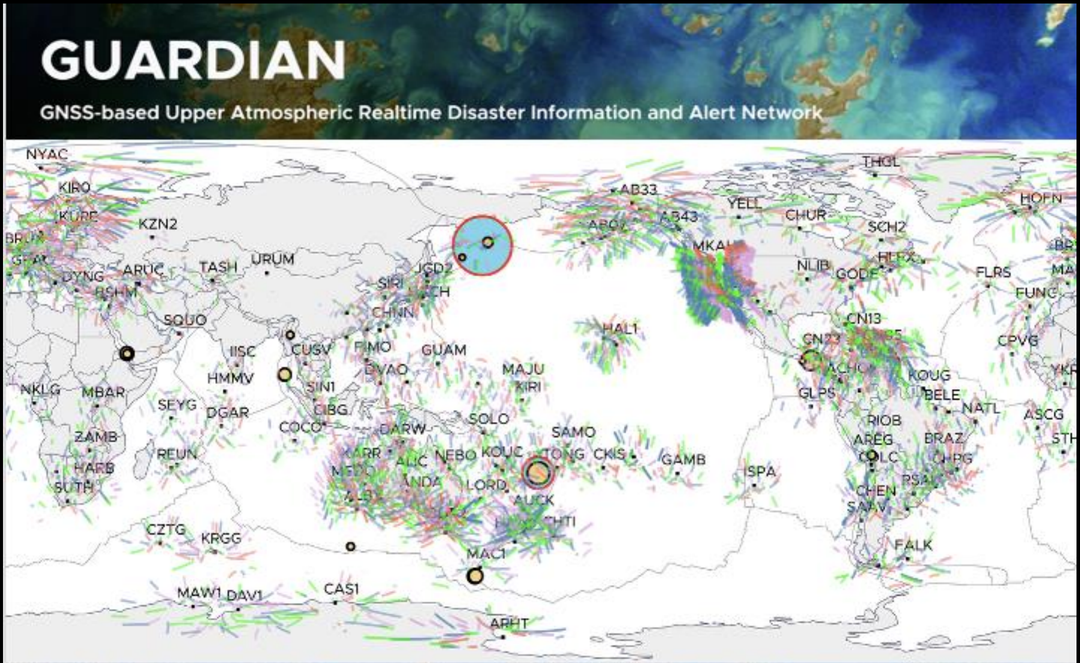
JPL's corrections are used for operational ShakeAlert solutions



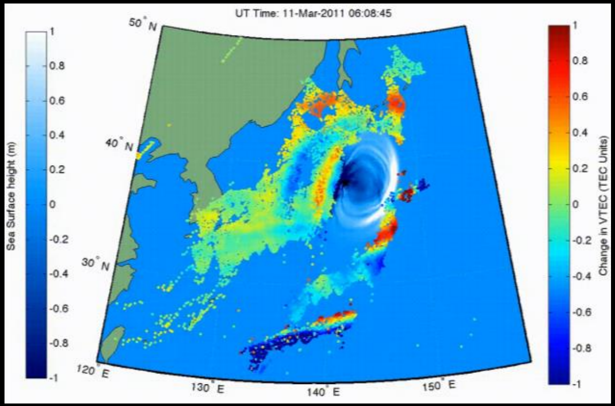
GDGPS real-time measured Kamchatka-generated displacements in July 2025

GDGPS Monitoring Ionospheric Perturbations Induced by Natural Hazards

Jet Propulsion Laboratory
California Institute of Technology



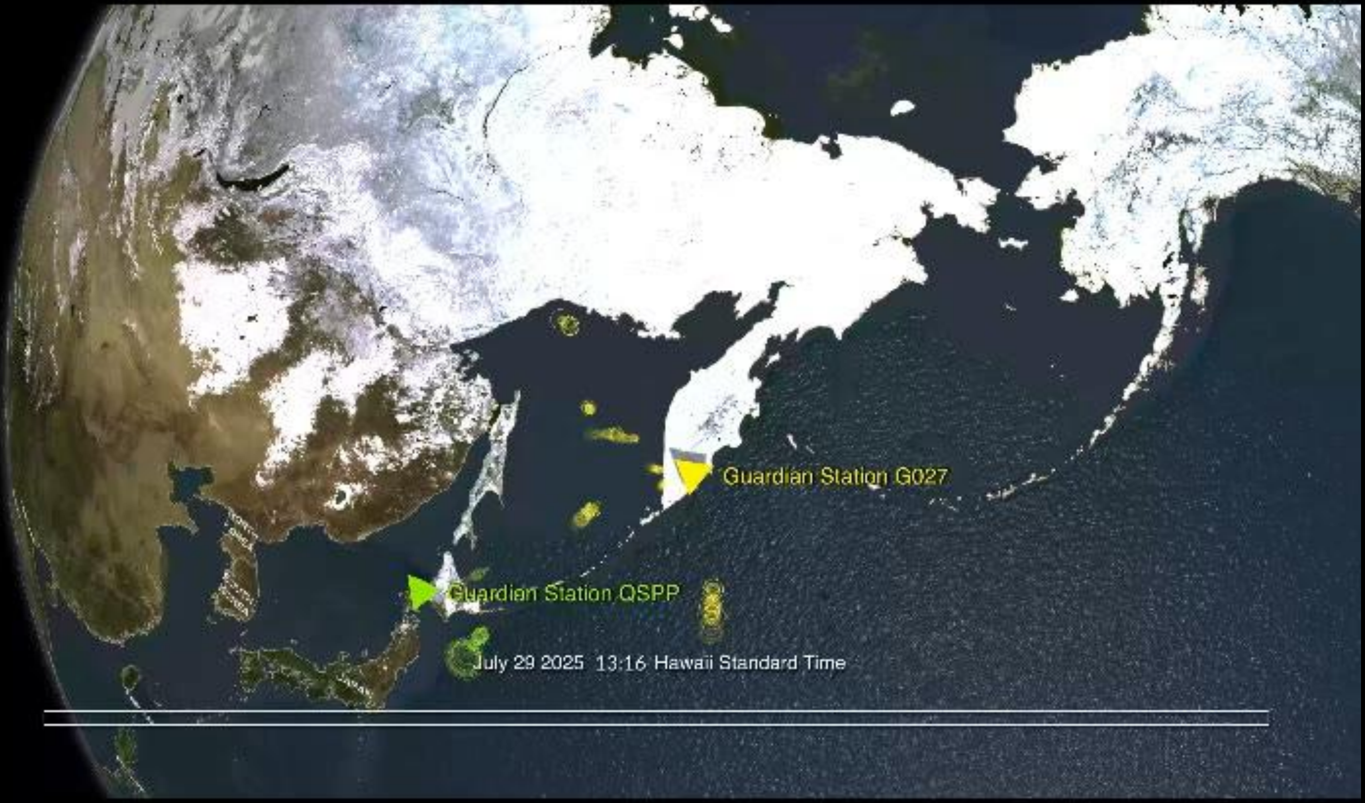
Real-time monitoring of hazards using GDGS measurements



5 MIN READ

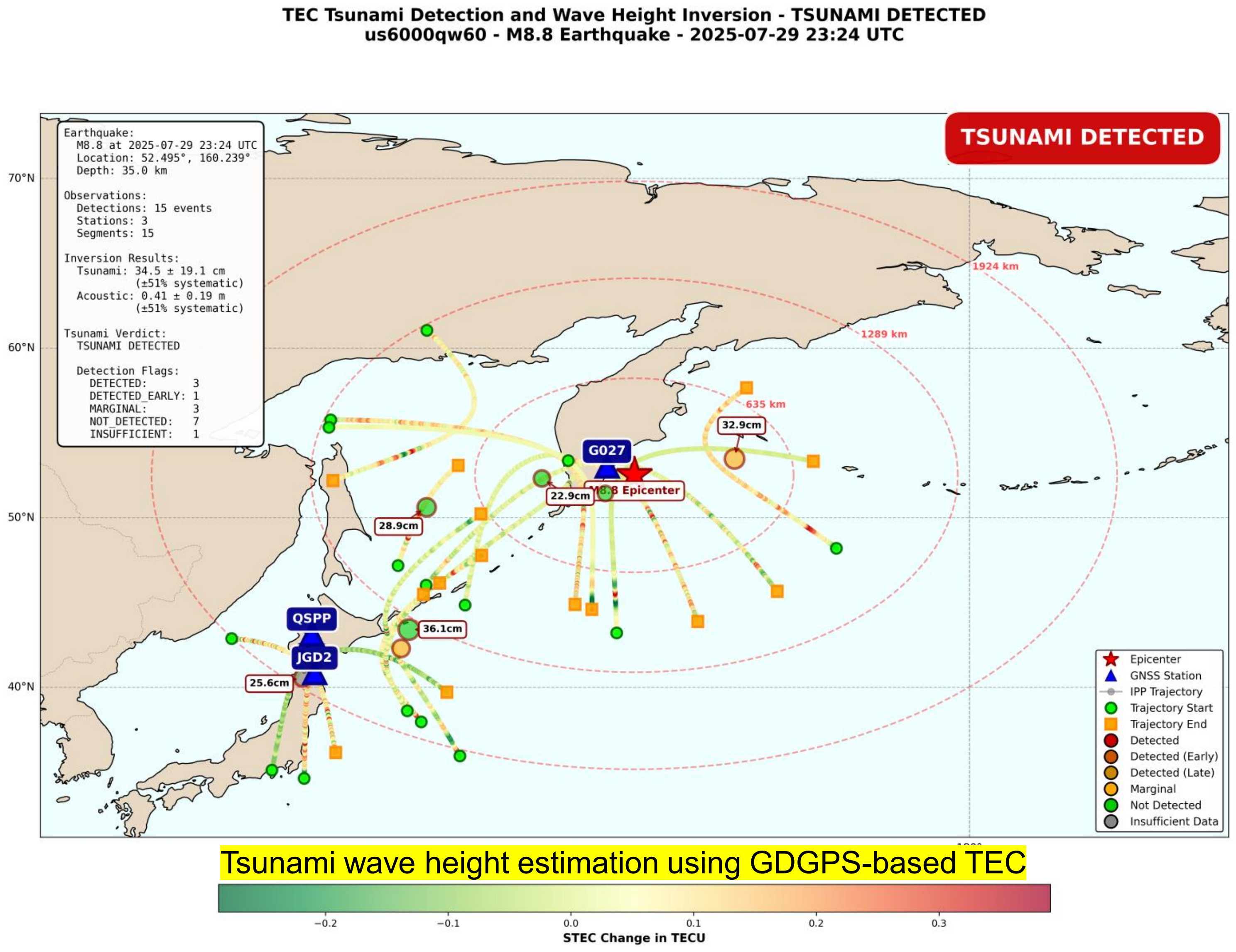
NASA's GUARDIAN Tsunami Detection Tech Catches Wave in Real Time

Kamchatka M8.8 Event Visualization Using GDGPS



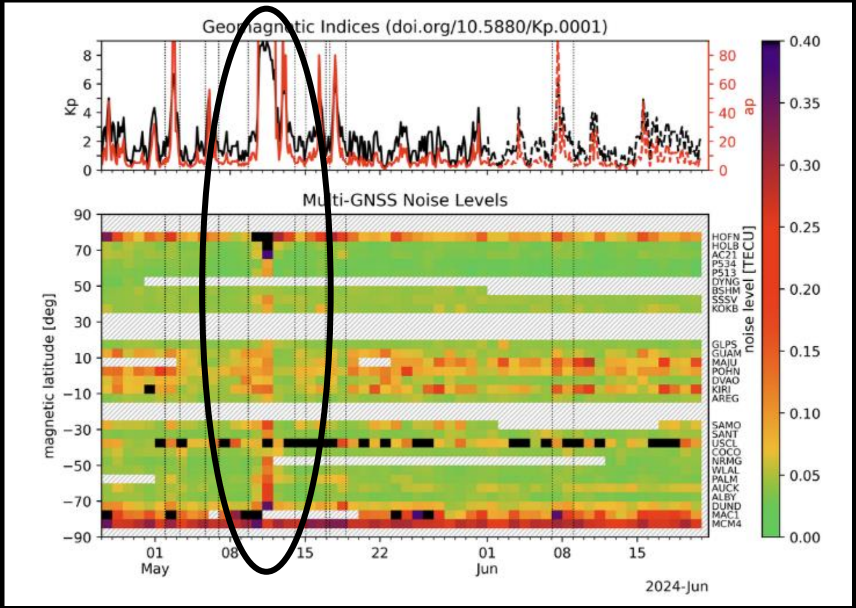
Movie to play

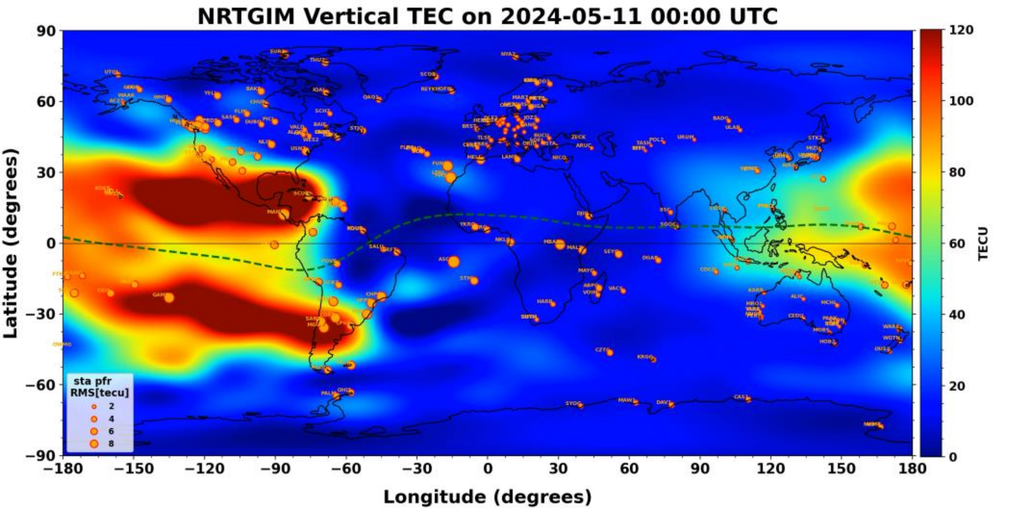
GDGPS/GUARDIAN/Scout Estimating Source: Currently in Testing

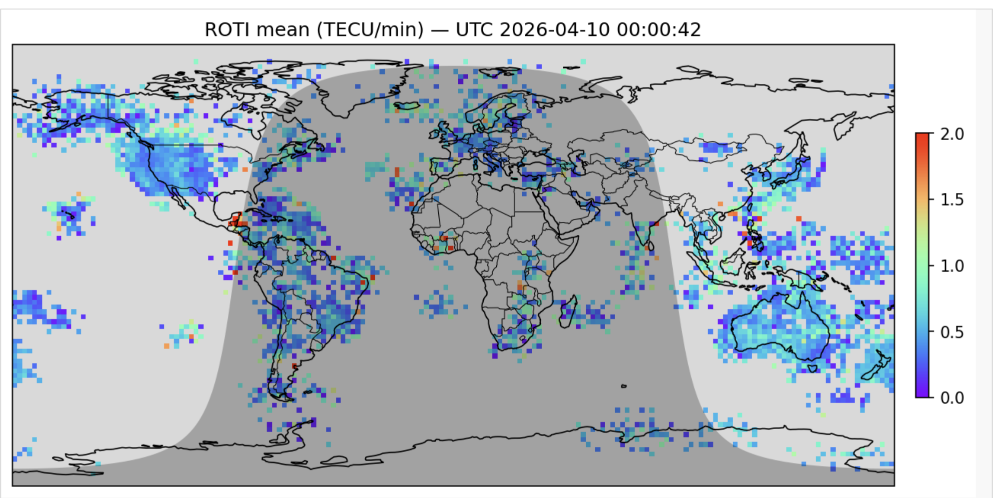


Tsunami wave height estimation using GDGPS-based TEC

NRT Monitoring of Ionospheric Disturbances Using GDGPS





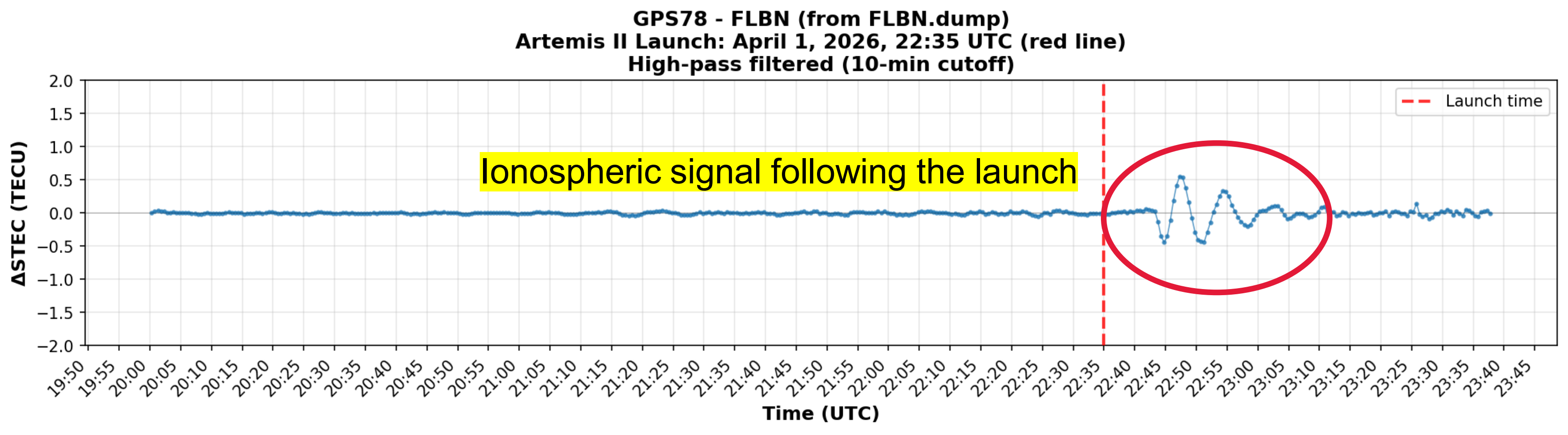


- Near-Real-Time (NRT) monitoring of ionospheric disturbances including geomagnetic and solar disturbances
- GDGPS features additional science capabilities

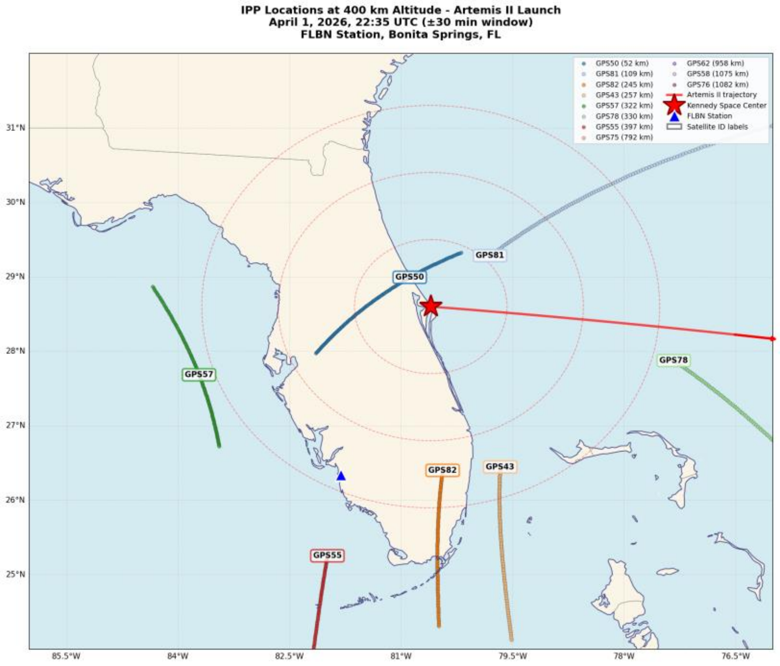
https://sideshow.jpl.nasa.gov/pub/usrs/rfm/nrtgim/

Artemis II Ionospheric Signature Observed by GDGPS on Apr 1 and Apr 10

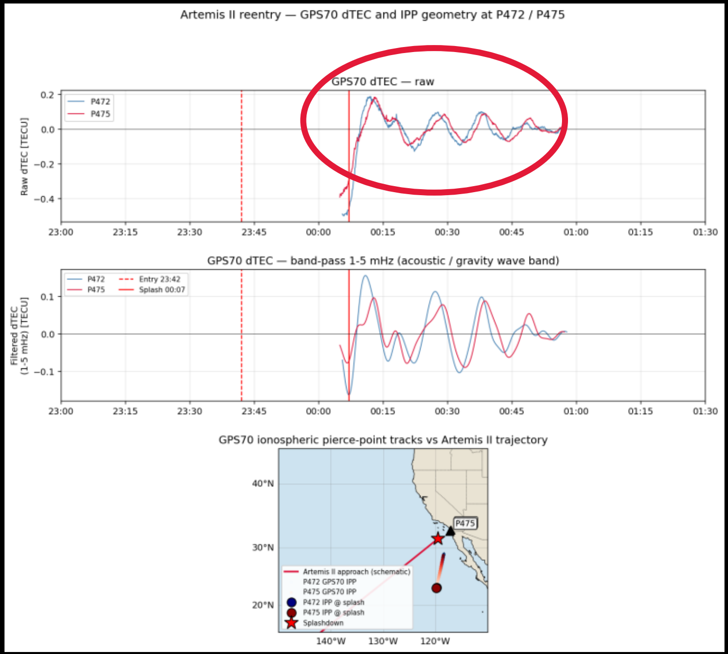
Jet Propulsion Laboratory
California Institute of Technology



Ionospheric signal following the launch



Suspected ionospheric signal upon capsule reentry



Summary

- Public JPL SSR streaming of 1-Hz products as high accuracy corrections and TEC data are distributed via NASA's Earthdata (https://earthdata.nasa.gov) for scientific use
- Prototype real-time JPL PPP client is completed and being tested for users (Earthscope and USGS) to run remotely, providing real-time positioning capability for any site
    - Client software combines GNSS measurements with GDGPS positioning services to provide a real-time PPP solution
- Real-time monitoring of global ionospheric disturbances generated by space weather events and natural hazards available via GUARDIAN at https://guardian.jpl.nasa.gov
- For any inquiries, please contact me at: gdgps-rt@jpl.nasa.gov or Attila.Komjathy@jpl.nasa.gov

Acknowledgements

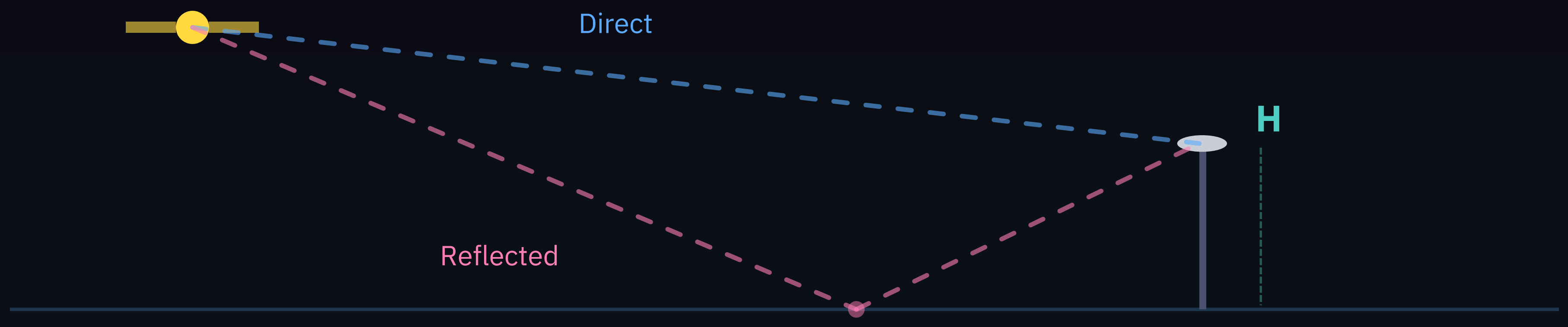
- Contributions were made possible by research carried out with support from **NASA Space Geodesy Program**, GDGPS funds at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration
- Special thanks to **Leo Martire** and **Siddharth Krishnamoorthy** of the Ionospheric and Atmospheric Remote Sensing Group of JPL for key material presented herein
- Special thanks to **Larry Romans** and **Robert Meyer.** All members of the Near Earth Tracking Systems Group (362G) are gratefully acknowledged

Multipath as a Feature: What Can Archived GNSS Noise Tell Us About the Surrounding Environment?

Joel Johnson, Dr. Kristy Tiampo
Cooperative Institute for Research In Environmental Sciences, University of Colorado at Boulder

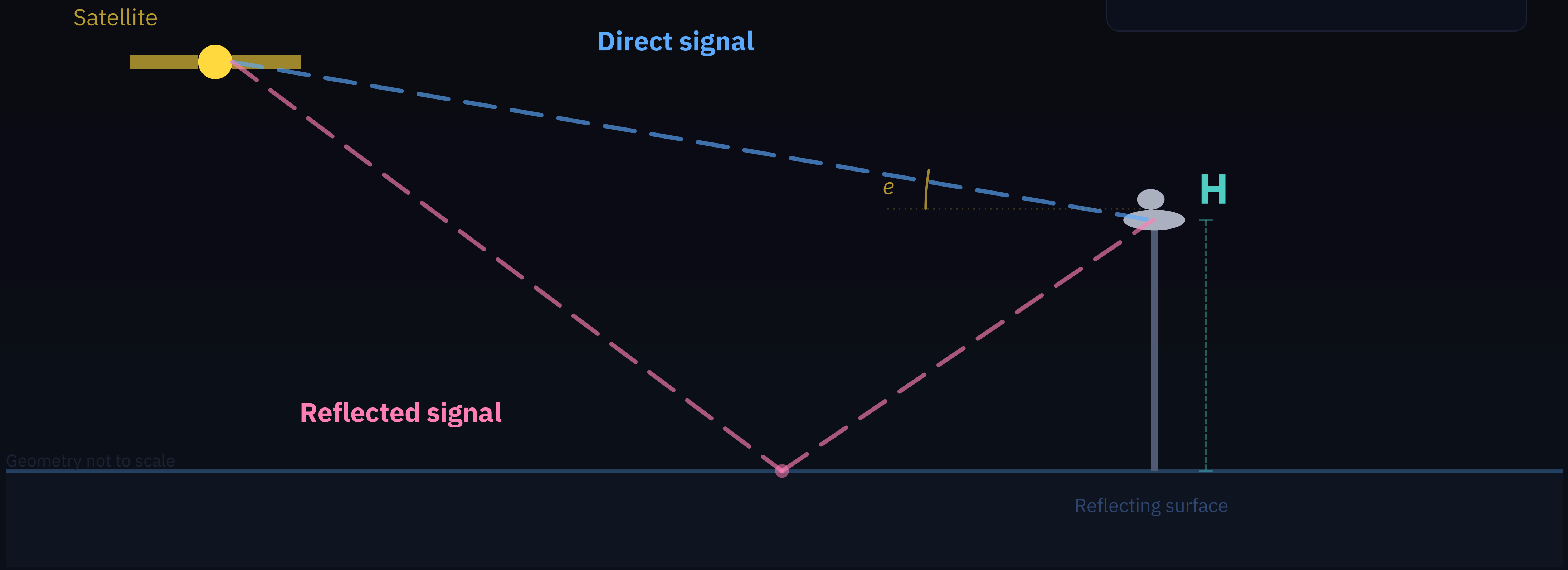
CGSIC 2026

"Multipath is traditionally noise. Here's how we're using it as a measurement."



GNSS-IR treats the constellation as a bistatic radar — the satellite transmits, the surface reflects, the receiver measures both.
The NPS asked us at CU Boulder to set this up across their station network. Here's how it works in one idealized satellite pass

The Setup Geometry

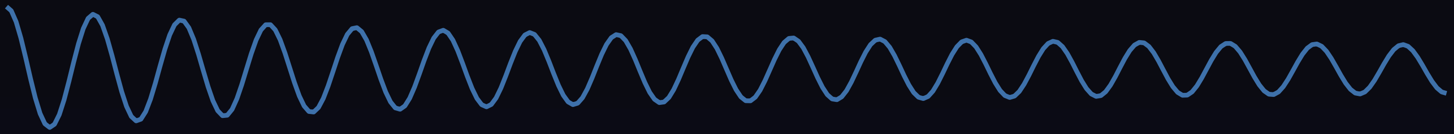


Same signal, two paths to the receiver · The reflected path is longer — the extra distance depends on **H** and **elevation angle**

From Signal to Measurement - GNSSIR

GNSS expects **blue**.
The receiver instead gets **teal**.

The expected signal — **direct only**

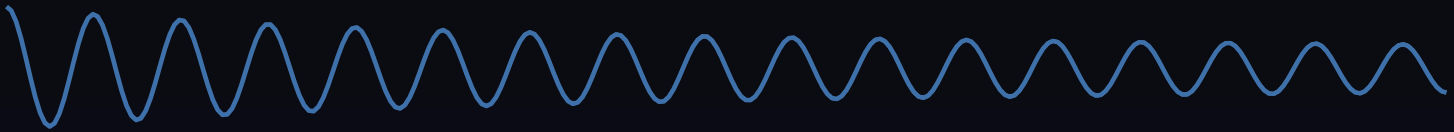


What actually arrives — **direct + reflected**

carrier frequency exaggerated for visualization. Reflected copy is also attenuated

From Signal to Measurement - GNSSIR

The expected signal — **direct only**



The reflected copy — **same frequency, shifted phase**

What actually arrives — **direct + reflected**

carrier frequency exaggerated for visualization. Reflected copy is also attenuated

GNSS expects **blue**.
The receiver instead gets **teal**.
That difference is why this looks like noise.

But everything we need to resolve **teal** from **blue** is already in the data:

→ The **reflected signal** — a delayed, attenuated copy

→ The **interference pattern** in the SNR

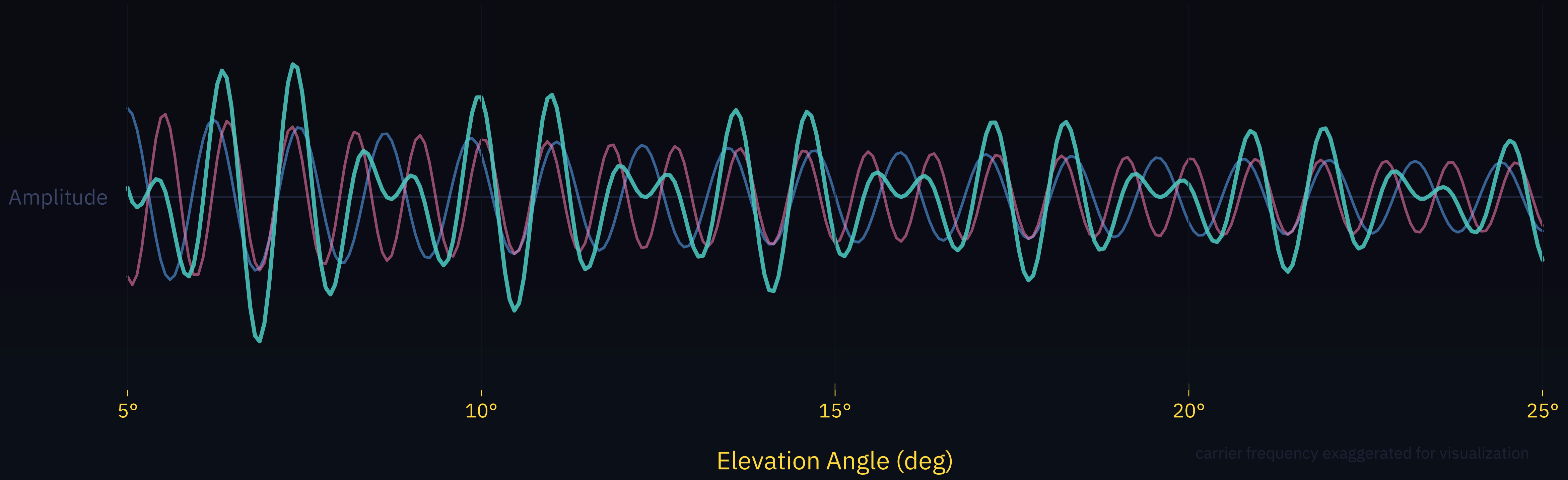
→ GPS wavelength **λ** (known)

→ Satellite **elevation angle** over time (known from ephemeris)

The "noise" encodes a measurement:
oscillation frequency → reflector height **H**

The Interference Signal Decomposition

H = 2 m · GPS L2 (λ = 0.244 m)

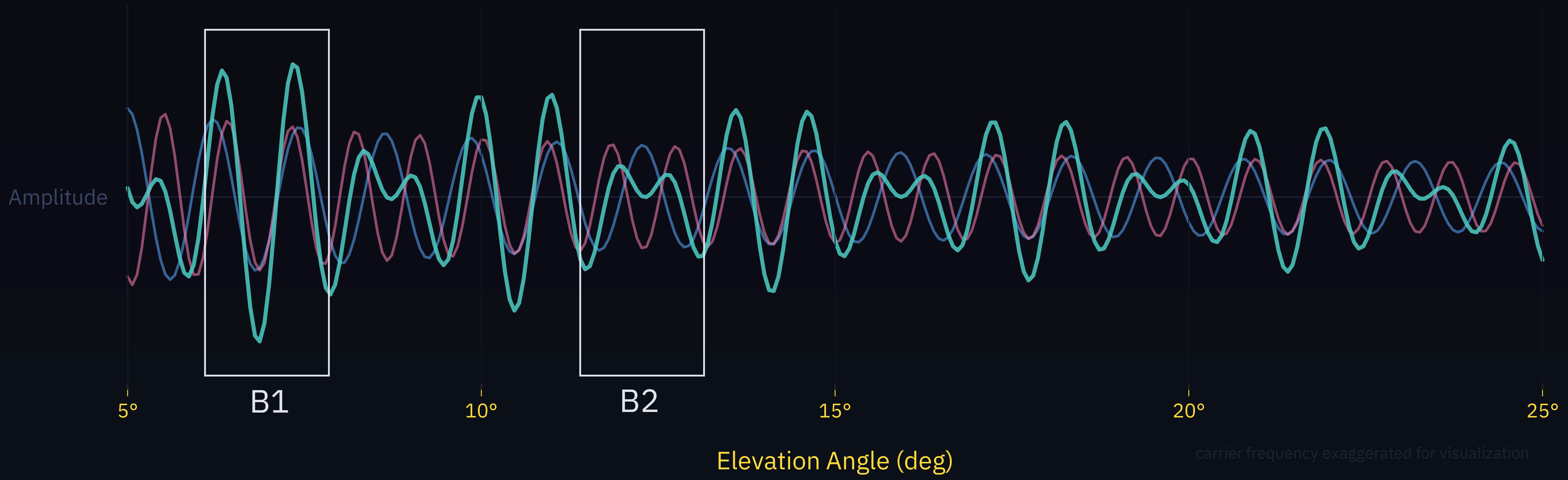


Blue = direct signal arriving at the antenna
Pink = reflected copy — same wavelength, shifted in phase
Teal = their sum — what the receiver actually sees

The Interference Signal Decomposition

H = 2 m · GPS L2 (λ = 0.244 m)

Direct Reflected **Sum**



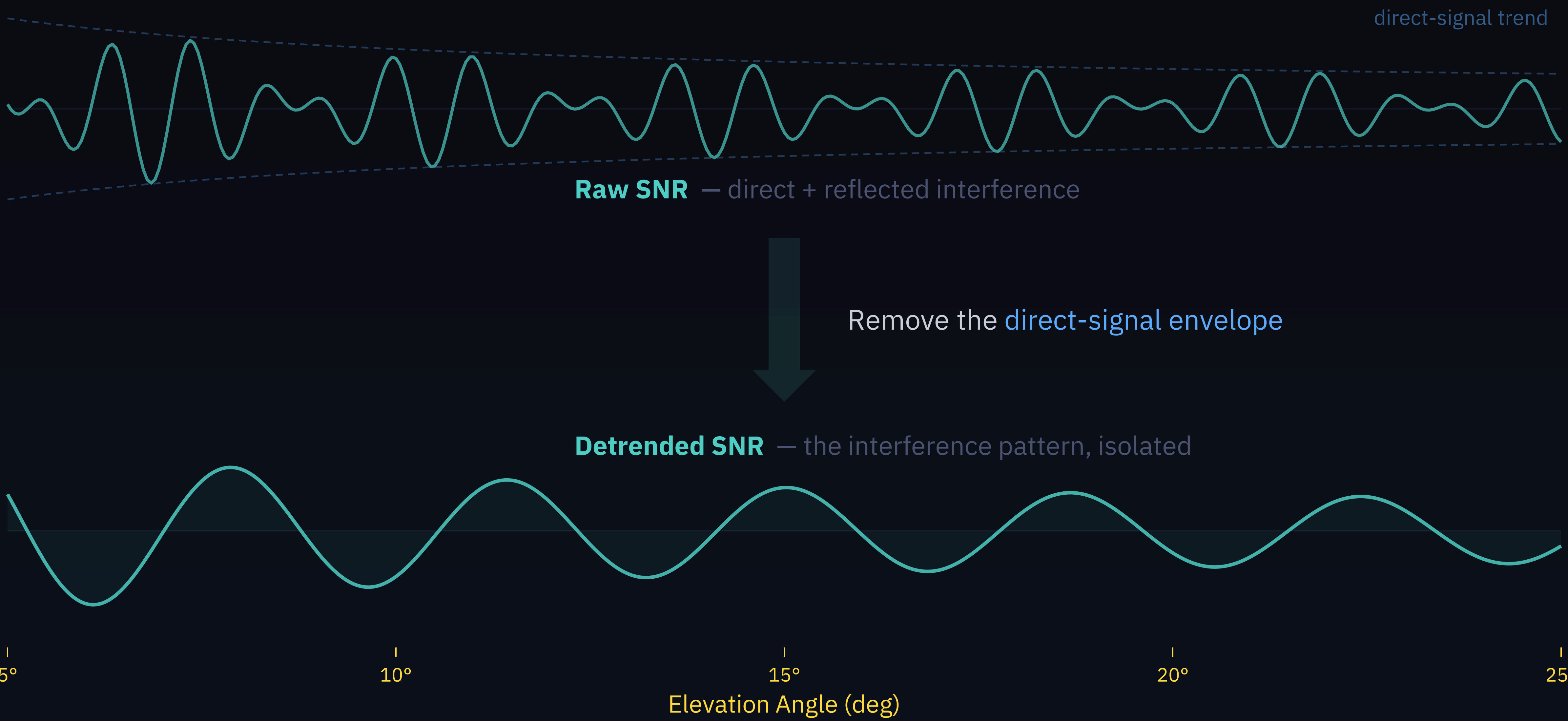
Blue = direct signal arriving at the antenna

Pink = reflected copy — same wavelength, shifted in phase

Teal = their sum — what the receiver actually sees

When blue + pink aligned (B1) → higher peaks · When offset (B2)→ reduced peaks

From Interference to Measurement



Raw SNR — direct + reflected interference

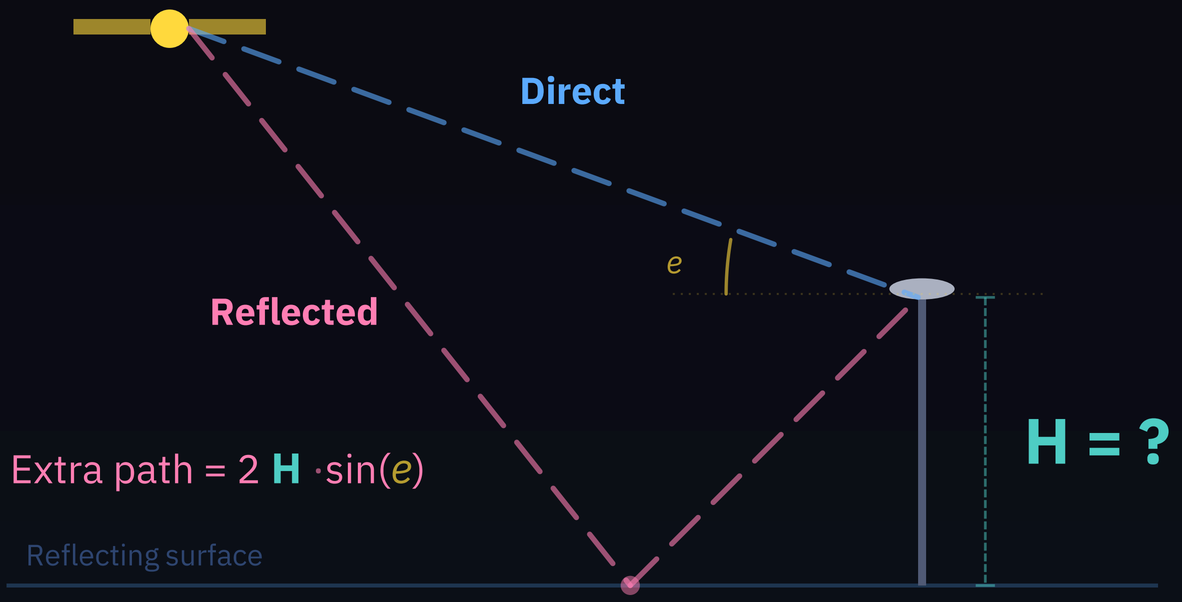
Remove the direct-signal envelope

Detrended SNR — the interference pattern, isolated

The oscillation frequency depends on one thing we don't already know: **how high the antenna is above the reflecting surface.**

Higher antenna = faster oscillation

What Height Explains This Signal?



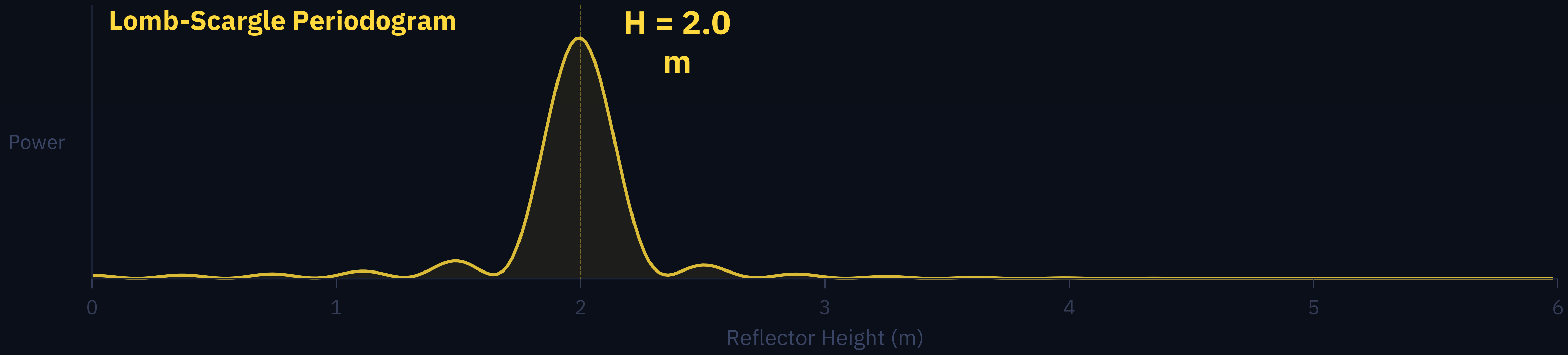
The only unknown is **H**.

Re-express the SNR in sin(e) — where the oscillation is truly periodic.

Spectral analysis asks: **what H best explains this pattern?**

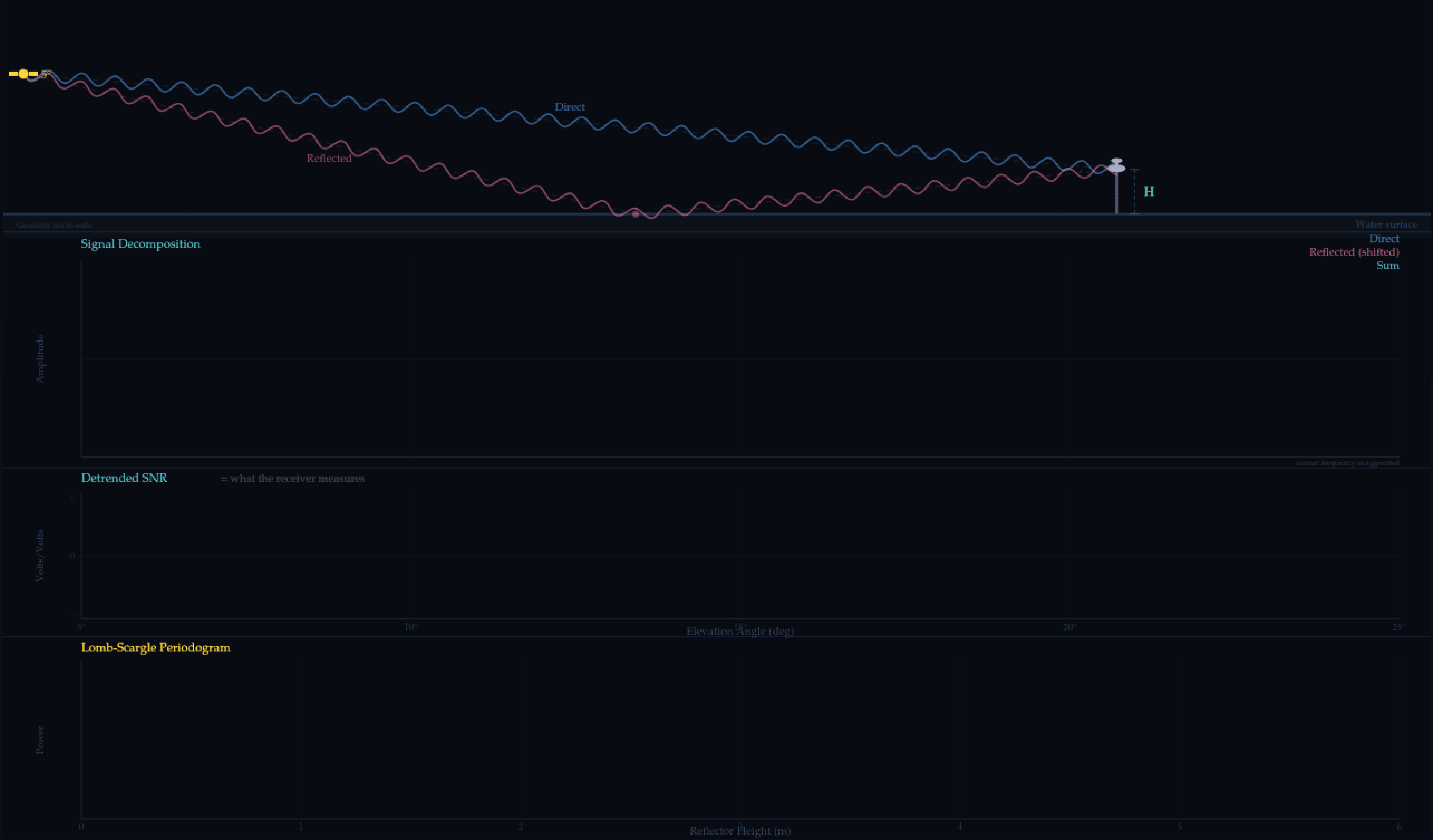
The peak tells us the reflector height — directly.

f = 2**H**/**λ** → **H** = f**λ**/2



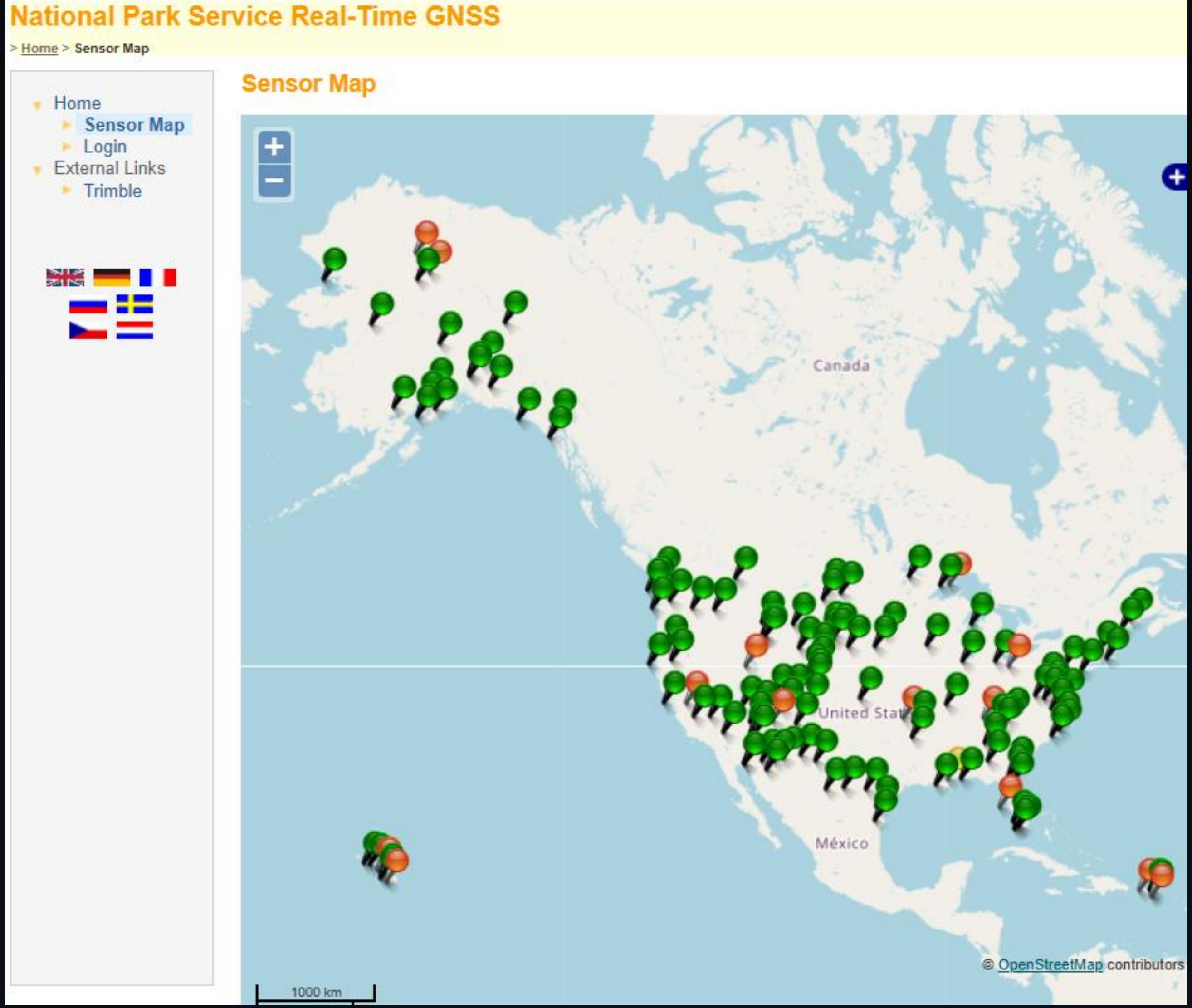
GNSS Interferometric Reflectometry — two paths, one signal

H = 2 m · GPS L2 (= 0.244 m)



NPS Station Network

- 60+ CORS stations across the NPS network
- Every station already records RINEX data
- Processing for reflector height using **gnssrefl** (developed by Dr. Kristine Larson)
- Starting with stations that have water-facing geometry and co-located reference gauges



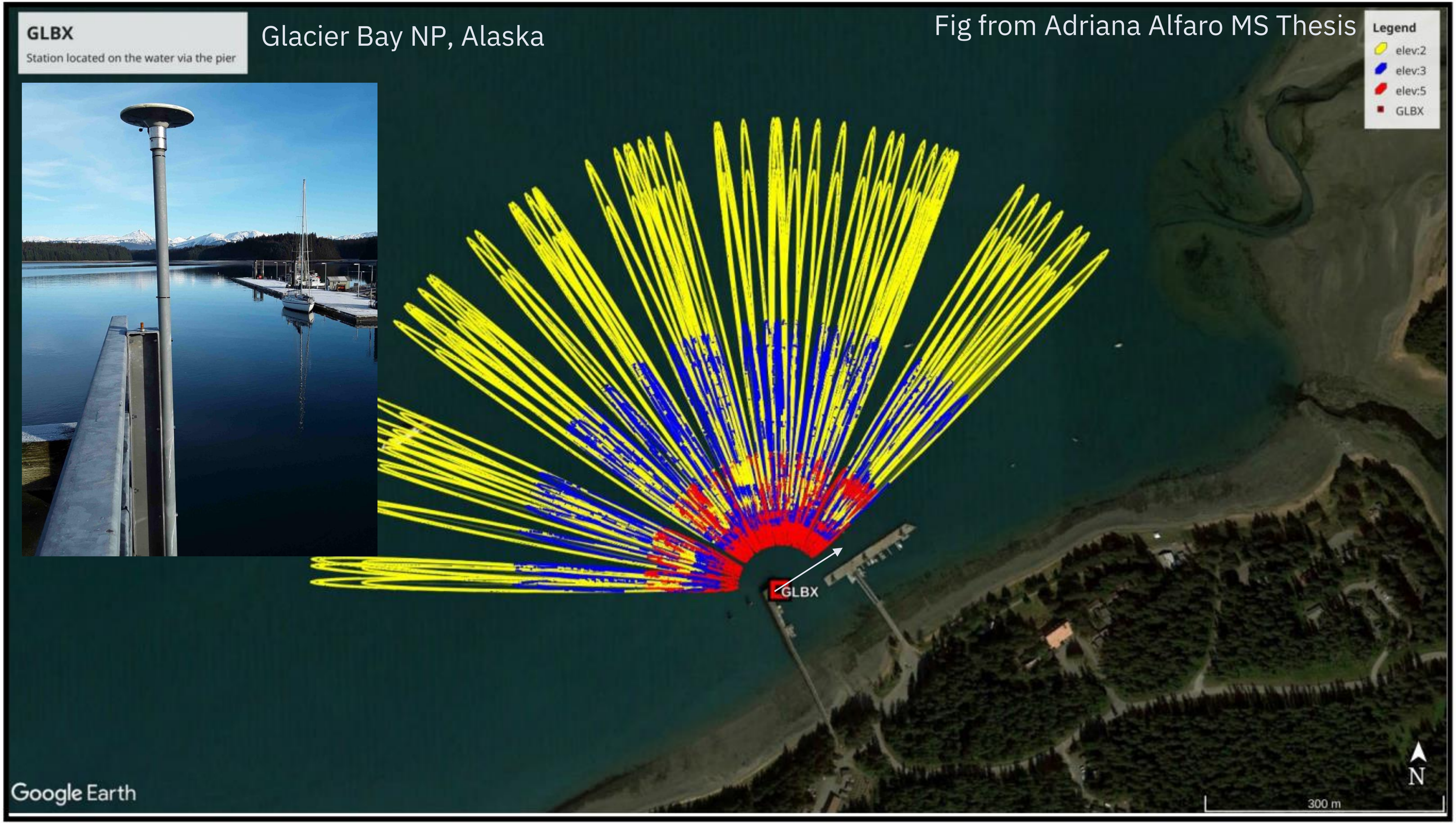
https://ntrip.nps.gov/Map/SensorMap.aspx

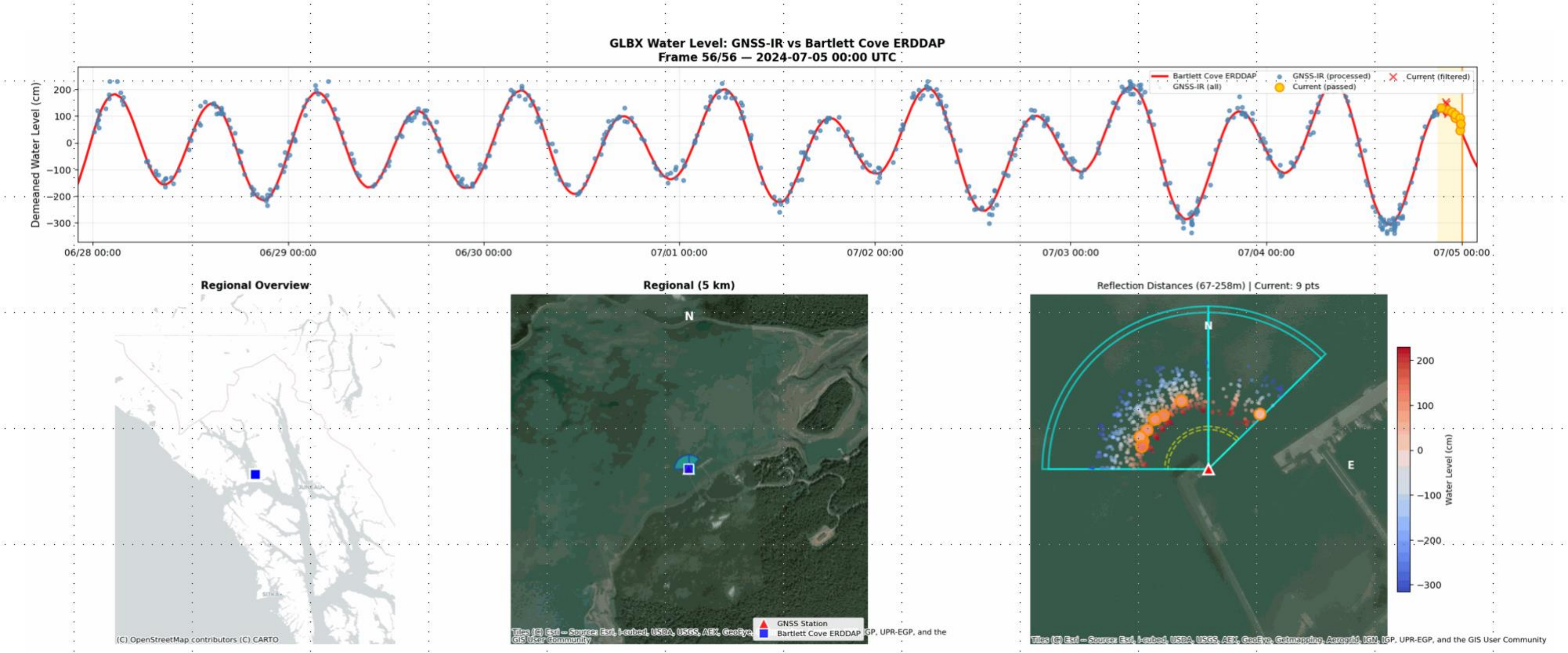
Glacier Bay NP, Alaska

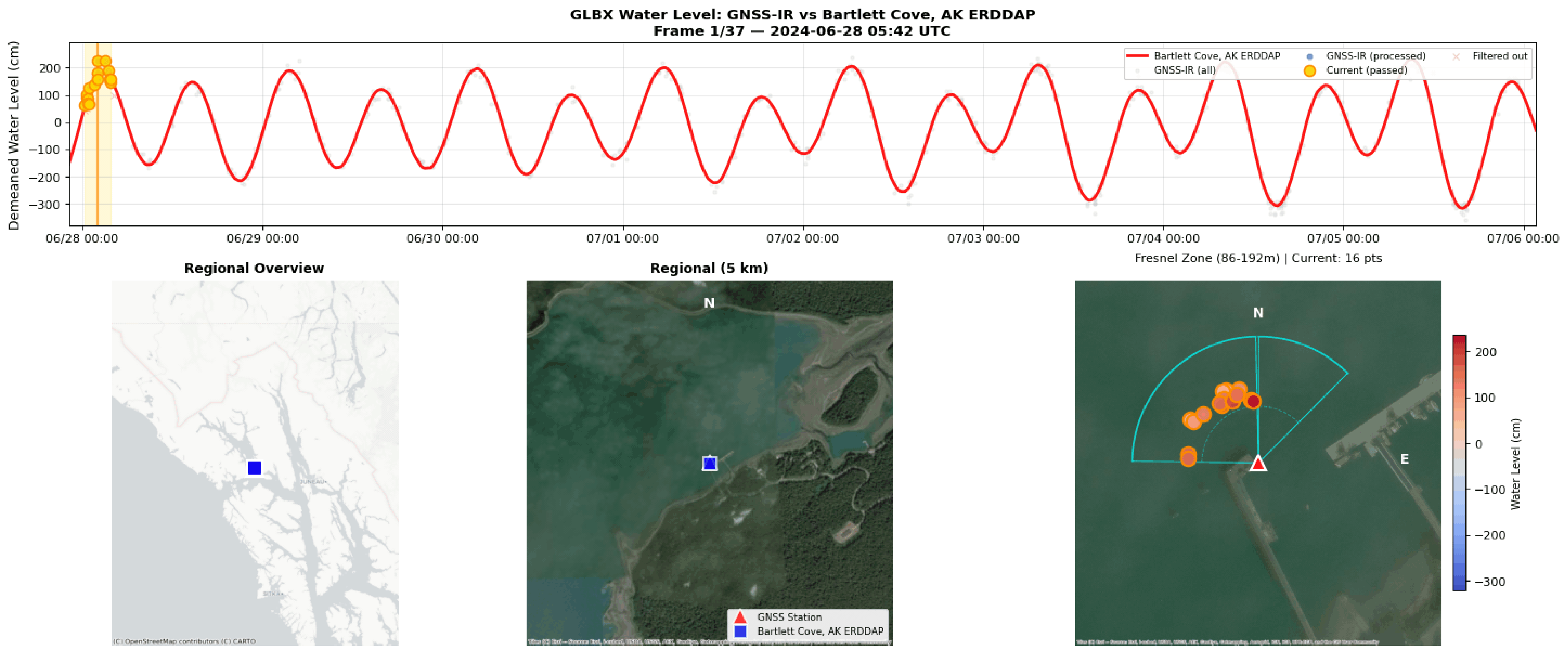
Fig from Adriana Alfaro MS Thesis

GLBX

Station located on the water via the pier




GLBX Water Level: GNSS-IR vs Bartlett Cove ERDDAP
Frame 56/56 — 2024-07-05 00:00 UTC
Demeaned Water Level (cm)
200
100
0
−100
−200
−300
06/28 00:00
06/29 00:00
06/30 00:00
07/01 00:00
07/02 00:00
07/03 00:00
07/04 00:00
07/05 00:00
Bartlett Cove ERDDAP
GNSS-IR (all)
GNSS-IR (processed)
Current (passed)
Current (filtered)
Regional Overview
(C) OpenStreetMap contributors (C) CARTO
Regional (5 km)
N
GNSS Station
Bartlett Cove ERDDAP
Tiles (C) Esri -- Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community
Reflection Distances (67-258m) | Current: 9 pts
N
E
Water Level (cm)
200
100
0
−100
−200
−300
Tiles (C) Esri -- Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community


GLBX Water Level: GNSS-IR vs Bartlett Cove, AK ERDDAP
Frame 1/37 — 2024-06-28 05:42 UTC
Demeaned Water Level (cm)
200
100
0
−100
−200
−300
06/28 00:00
06/29 00:00
06/30 00:00
07/01 00:00
07/02 00:00
07/03 00:00
07/04 00:00
07/05 00:00
07/06 00:00
Bartlett Cove, AK ERDDAP
GNSS-IR (all)
GNSS-IR (processed)
Current (passed)
Filtered out
Regional Overview
JUNEAU
SITKA
(C) OpenStreetMap contributors (C) CARTO
Regional (5 km)
N
GNSS Station
Bartlett Cove, AK ERDDAP
Fresnel Zone (86-192m) | Current: 16 pts
N
E
Water Level (cm)
200
100
0
−100
−200
−300

What Else Can You Measure?

Snow Depth

Reflecting surface rises as snow accumulates, decreasing H

Water Level

Tide gauge, storm surge, tsunami detection from H changes

Soil Moisture

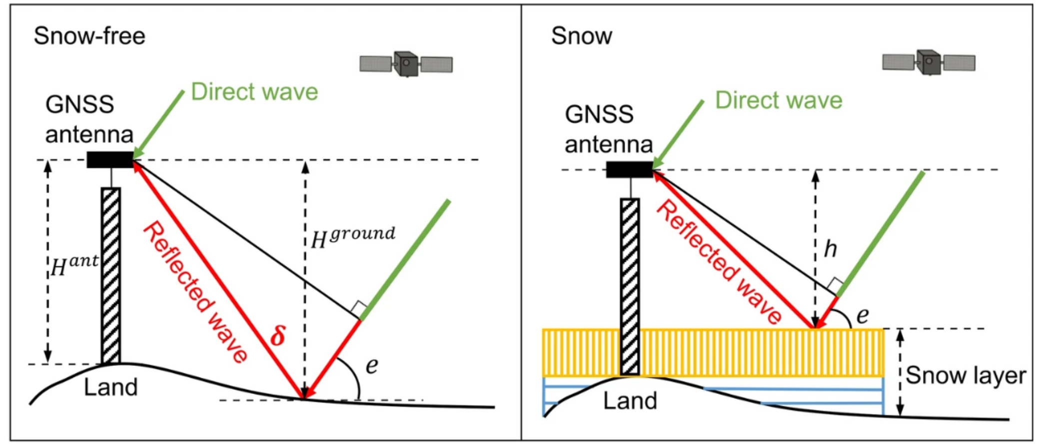
Reflection amplitude and phase shift reveal water content

Vegetation

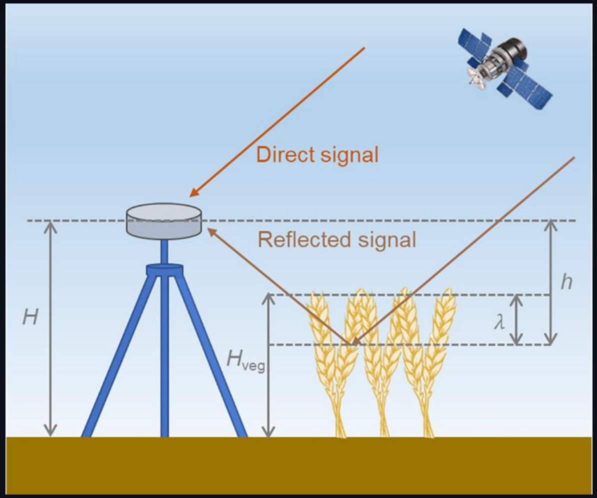
Effective reflecting surface rises seasonally with growth

Lake/Sea Ice

Reflection properties change dramatically with ice formation



Zhou et al., 2022



Sui et al., 2025

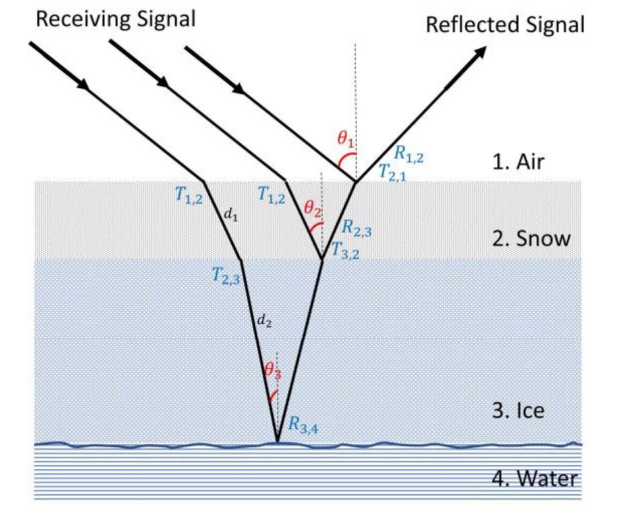
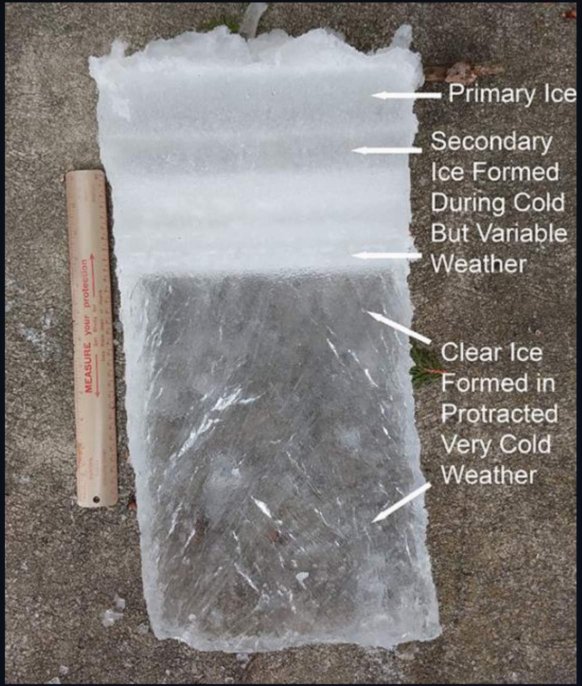


Figure 5-1. Schematic representation of the multi-layered reflectivity model used in this study. The diagram, adapted from Cardellach et al. (2012), illustrates the interaction of the incoming GNSS signal with different layers: air, snow, ice, and water. The signal undergoes reflection (R) and transmission (T) at each interface, with the angles of incidence (θ) changing as the signal passes through different media. The model accounts for the varying dielectric properties of each layer and their impact on the reflected signal received by the GNSS-R system.

Ghiasi et al., Thesis 2025

What about Ice?

Lake Ice Core

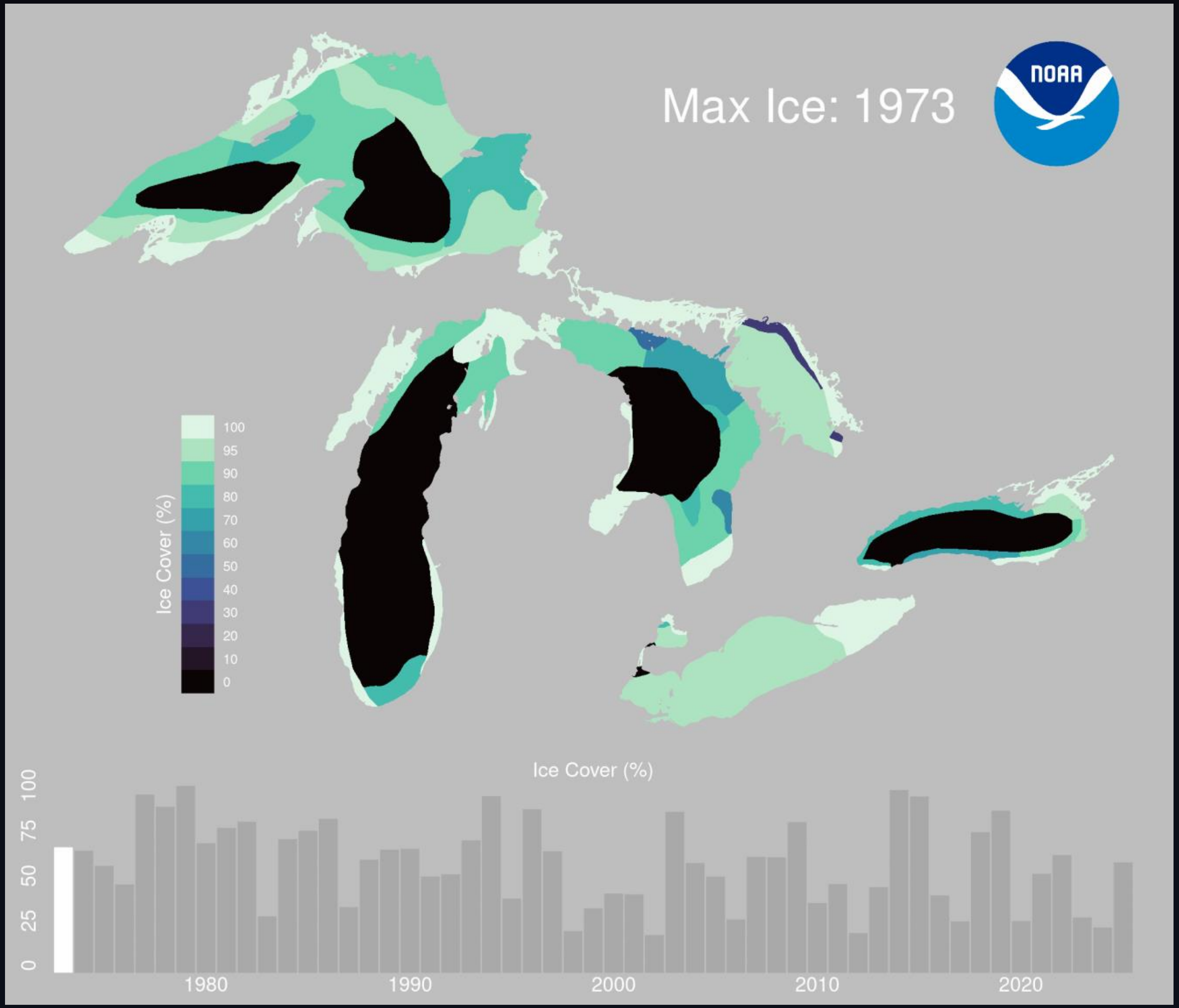


Frazil ice (foreground) and brash ice (background) in Lake Superior

Hummocked or piled plates or sheets of ice along the shore of Lake Superior.

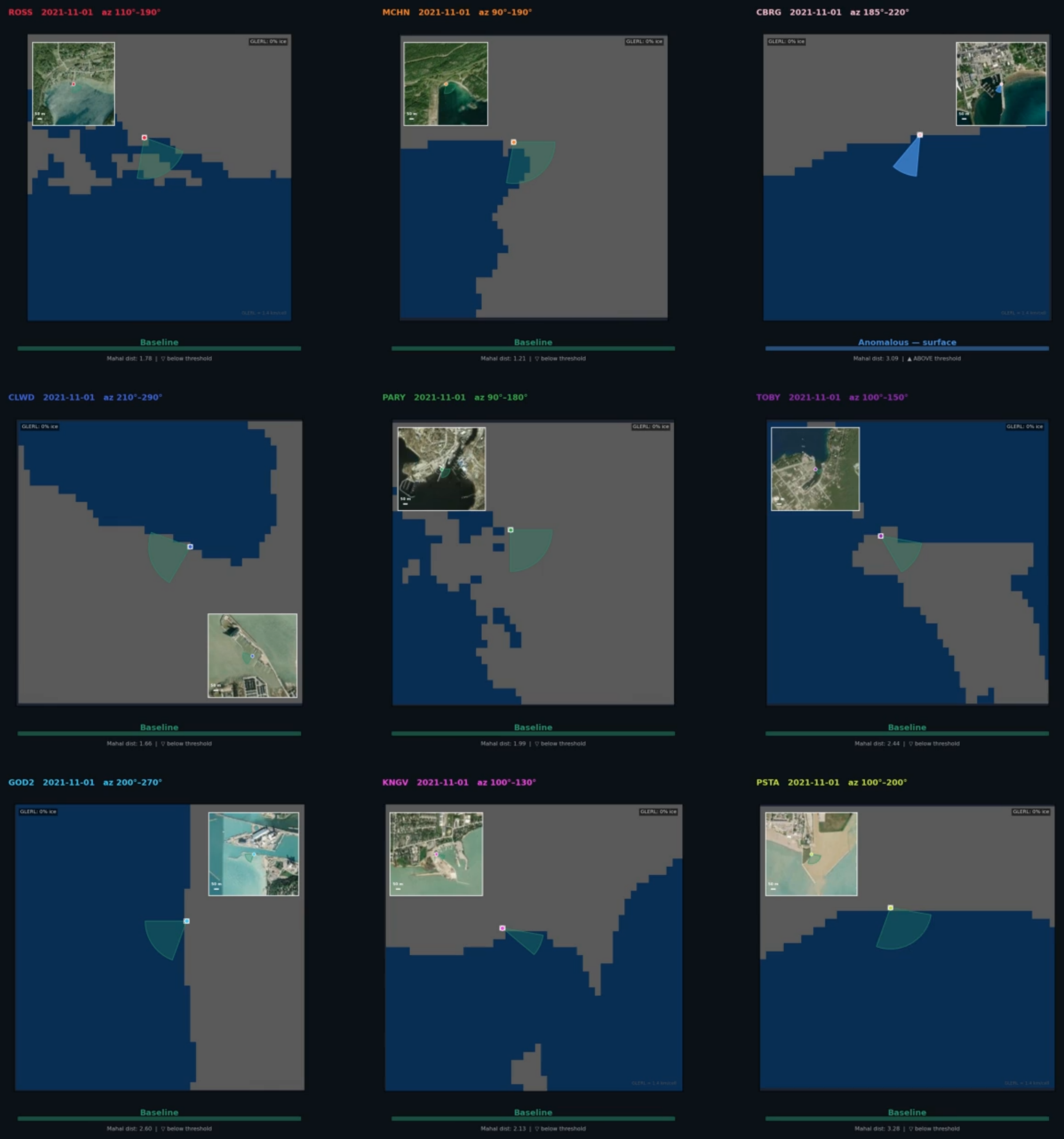
Image credits: M. Thoms/Minnesota Sea Grant. John A. Downing/Minnesota Sea Grant

Future ice work



https://www.glerl.noaa.gov/data/ice/

Future ice work



2021-11-01 GLERL Great Lakes Mean ice: 0%

"What can archived GNSS noise tell us about the surrounding environment?"

ACKNOWLEDGMENTS

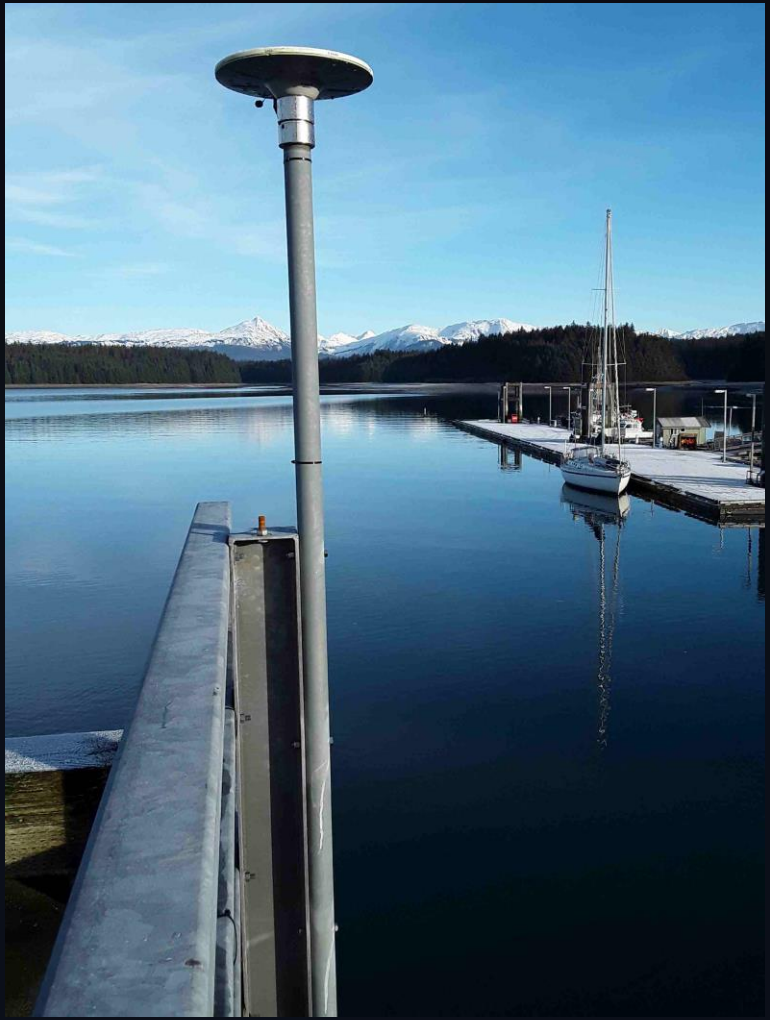
National Park Service · Kristy Tiampo · Adriana Alfaro · gnssrefl (Kristine Larson)

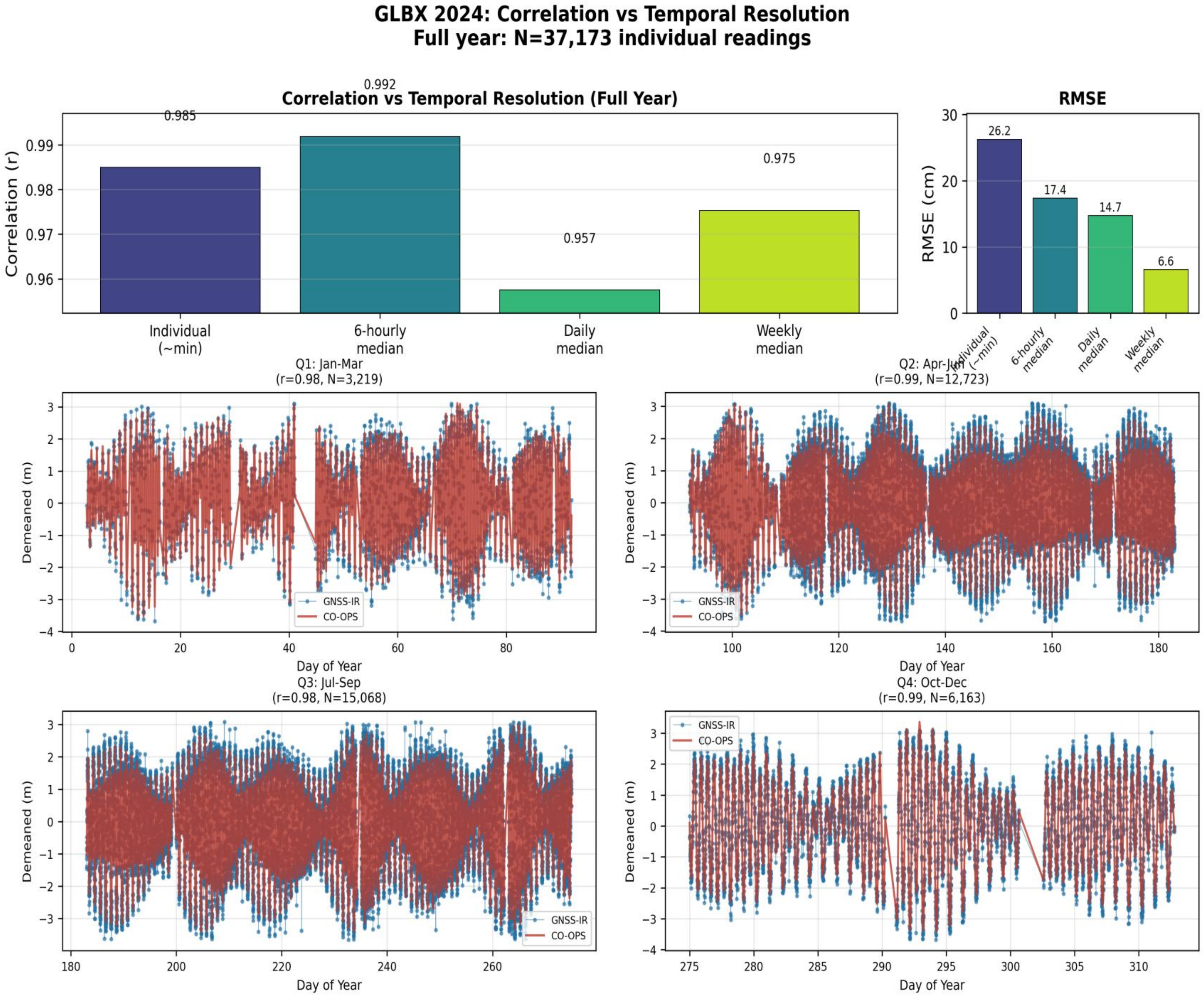
Joel Johnson · Kristy Tiampo

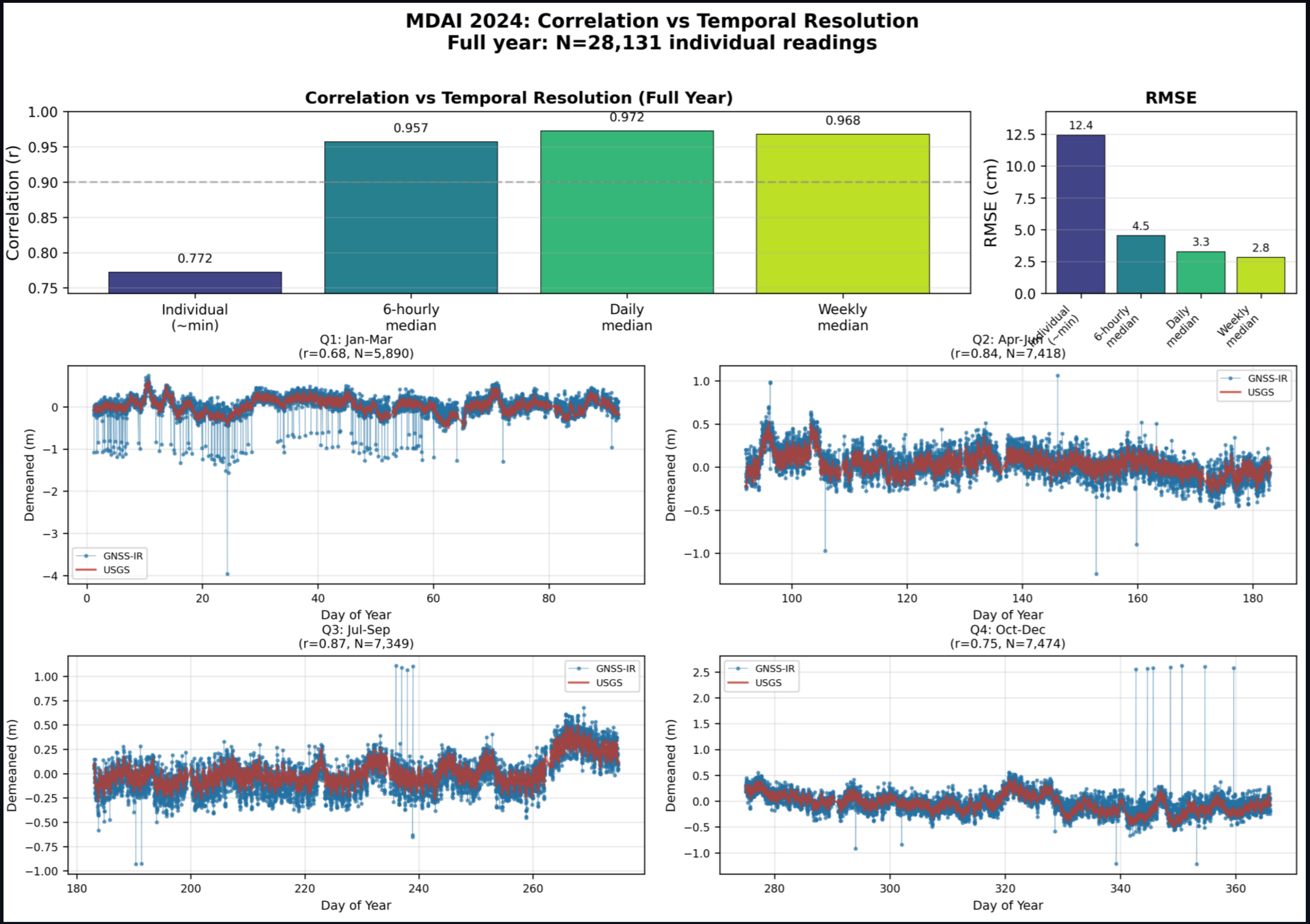
gnss-reflections.org

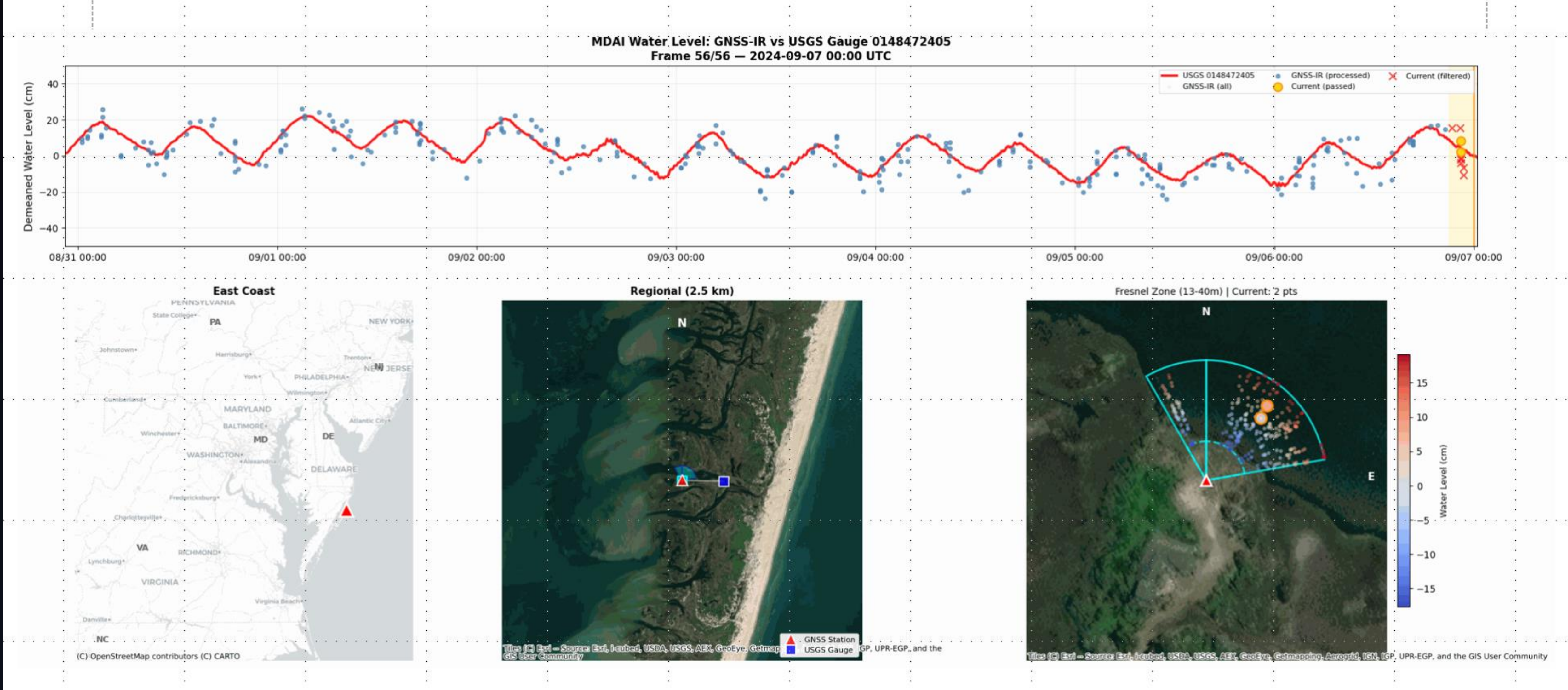
Code: https://github.com/jjohnson2701/gnssir-workflow

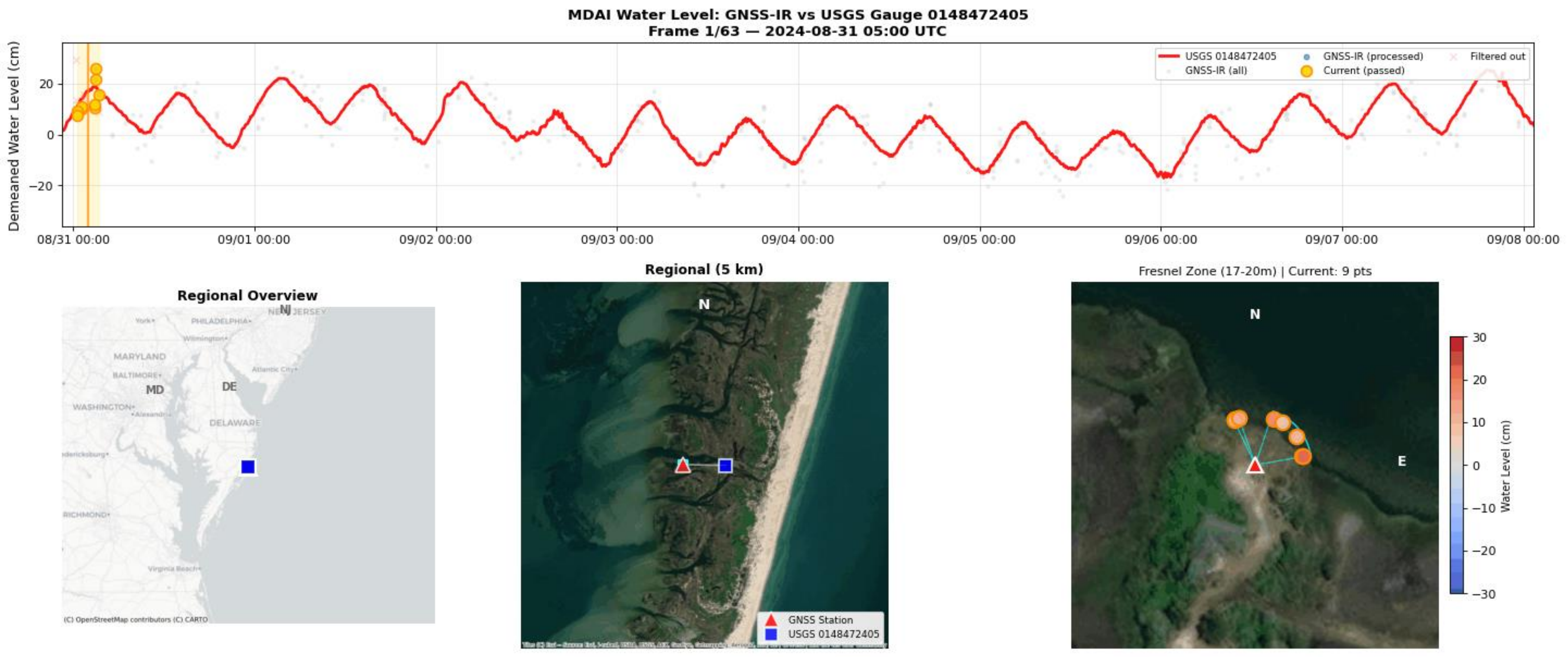
Supplementary slides

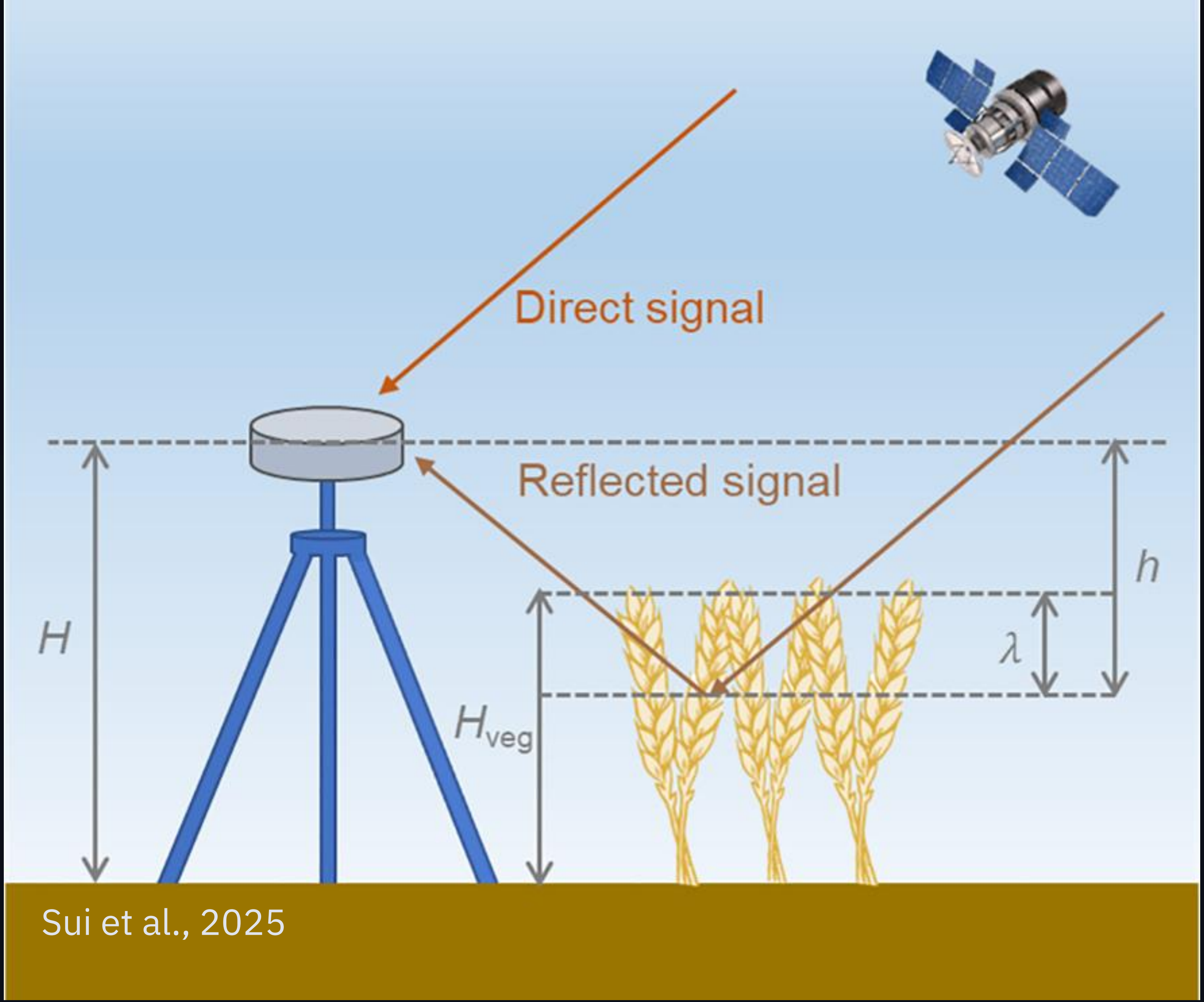



GLBX 2024: Correlation vs Temporal Resolution
Full year: N=37,173 individual readings
Correlation vs Temporal Resolution (Full Year)
Correlation (r)
0.985
0.992
0.957
0.975
Individual (~min)
6-hourly median
Daily median
Weekly median
RMSE
RMSE (cm)
26.2
17.4
14.7
6.6
Q1: Jan-Mar (r=0.98, N=3,219)
Q2: Apr-Jun (r=0.99, N=12,723)
Q3: Jul-Sep (r=0.98, N=15,068)
Q4: Oct-Dec (r=0.99, N=6,163)
Demeaned (m)
Day of Year
GNSS-IR
CO-OPS

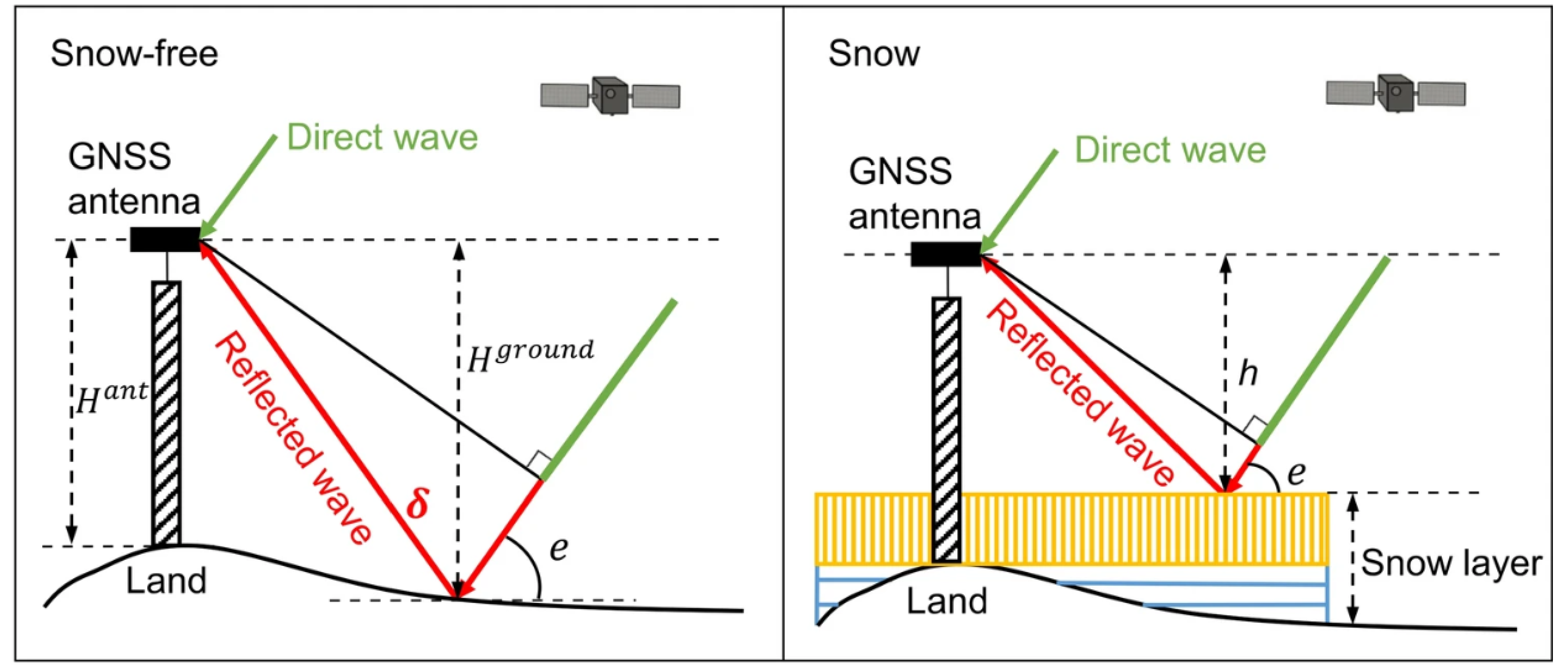

MDAI 2024: Correlation vs Temporal Resolution
Full year: N=28,131 individual readings
Correlation vs Temporal Resolution (Full Year)
Correlation (r)
1.00
0.95
0.90
0.85
0.80
0.75
0.772
0.957
0.972
0.968
Individual (~min)
6-hourly median
Daily median
Weekly median
RMSE
RMSE (cm)
12.5
10.0
7.5
5.0
2.5
0.0
12.4
4.5
3.3
2.8
Individual (~min)
6-hourly median
Daily median
Weekly median
Q1: Jan-Mar
(r=0.68, N=5,890)
Demeaned (m)
0
−1
−2
−3
−4
GNSS-IR
USGS
0
20
40
60
80
Day of Year
Q2: Apr-Jun
(r=0.84, N=7,418)
Demeaned (m)
1.0
0.5
0.0
−0.5
−1.0
GNSS-IR
USGS
100
120
140
160
180
Day of Year
Q3: Jul-Sep
(r=0.87, N=7,349)
Demeaned (m)
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
GNSS-IR
USGS
180
200
220
240
260
Day of Year
Q4: Oct-Dec
(r=0.75, N=7,474)
Demeaned (m)
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
GNSS-IR
USGS
280
300
320
340
360
Day of Year


MDAI Water Level: GNSS-IR vs USGS Gauge 0148472405
Frame 56/56 — 2024-09-07 00:00 UTC
Demeaned Water Level (cm)
40
20
0
−20
−40
08/31 00:00
09/01 00:00
09/02 00:00
09/03 00:00
09/04 00:00
09/05 00:00
09/06 00:00
09/07 00:00
USGS 0148472405
GNSS-IR (all)
GNSS-IR (processed)
Current (passed)
Current (filtered)
East Coast
PENNSYLVANIA
PA
NEW YORK
NJ
NEW JERSEY
MARYLAND
MD
DE
DELAWARE
VA
VIRGINIA
NC
(C) OpenStreetMap contributors (C) CARTO
Regional (2.5 km)
N
GNSS Station
USGS Gauge
Tiles (C) Esri — Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community
Fresnel Zone (13-40m) | Current: 2 pts
N
E
Water Level (cm)
15
10
5
0
−5
−10
−15
Tiles (C) Esri — Source: Esri, i-cubed, USDA, USGS, AEX, GeoEye, Getmapping, Aerogrid, IGN, IGP, UPR-EGP, and the GIS User Community

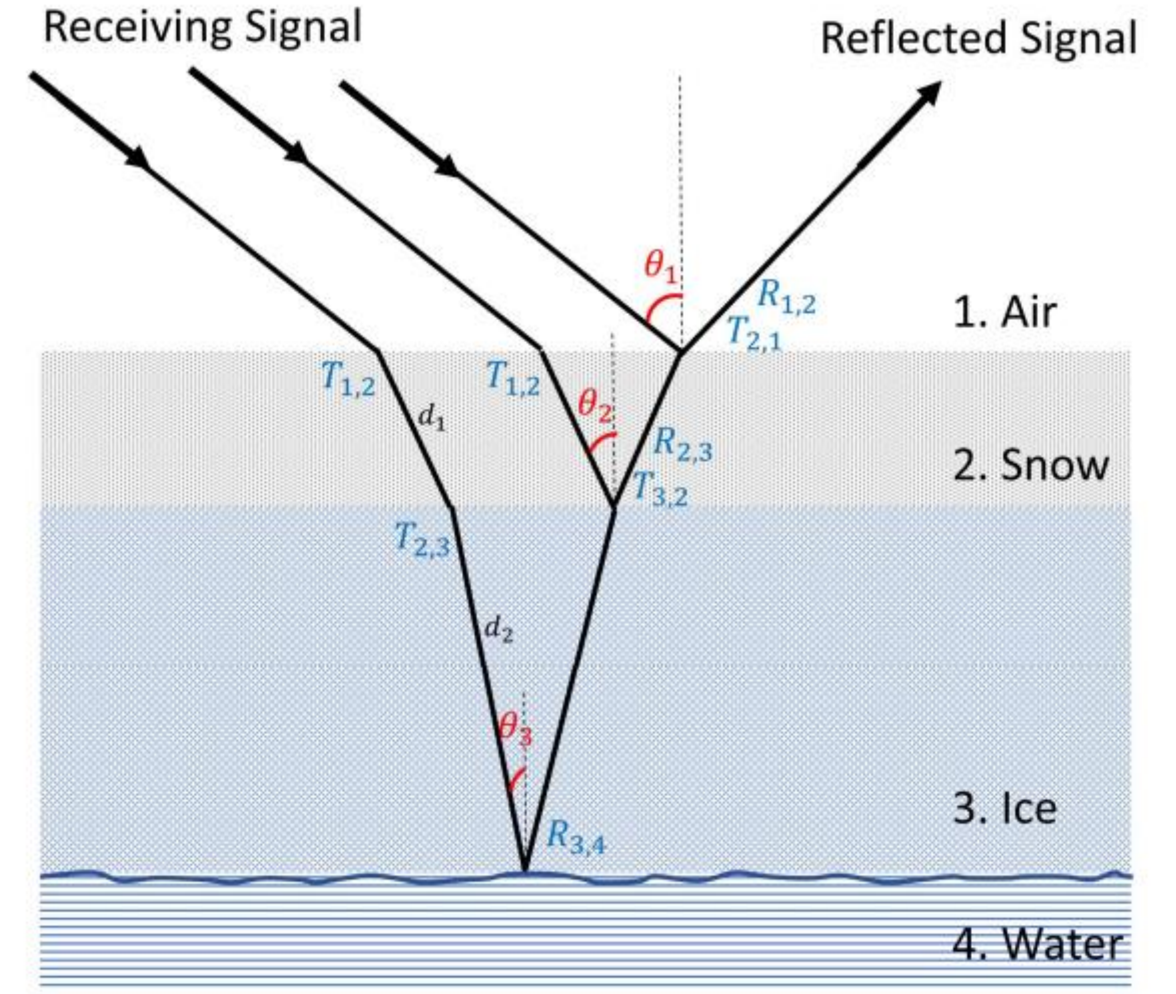

MDAI Water Level: GNSS-IR vs USGS Gauge 0148472405
Frame 1/63 — 2024-08-31 05:00 UTC
Demeaned Water Level (cm)
20
0
−20
08/31 00:00
09/01 00:00
09/02 00:00
09/03 00:00
09/04 00:00
09/05 00:00
09/06 00:00
09/07 00:00
09/08 00:00
USGS 0148472405
GNSS-IR (all)
GNSS-IR (processed)
Current (passed)
Filtered out
Regional Overview
NJ
NEW JERSEY
York
PHILADELPHIA
Wilmington
MARYLAND
BALTIMORE
MD
DE
Atlantic City
WASHINGTON
Alexandria
DELAWARE
Fredericksburg
RICHMOND
Virginia Beach
(C) OpenStreetMap contributors (C) CARTO
Regional (5 km)
N
GNSS Station
USGS 0148472405
Fresnel Zone (17-20m) | Current: 9 pts
N
E
30
20
10
0
−10
−20
−30
Water Level (cm)



Sui et al., 2025



Zhou et al., 2022



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Ghiasi et al.,
thesis 2025