Leveraging GNSS Radio Occultation for Enhanced Ionospheric Monitoring and Space Weather Preparedness

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NOAA • NASA Space Weather Observations

Outline

- Introduction
- Space Weather Requirements: Ionosphere
- Ionospheric RO data sources
- One NOAA Space Weather Strategy
- SWPC Ionospheric Data Products
- Conclusions

Space Weather is a National Priority

- The effects of space weather pose significant and increasing societal, economic, national security, and health risks to the United States and nations worldwide.
- These include risks to the electric power grid; aviation operations; positioning, navigation, and timing (PNT) services; satellites and communications; human space exploration; and other space-based assets.
- The **effects of space weather is one of six critical societal challenges** that NOAA must address in order to provide actionable decision support that enables a space weather-ready nation.
- **Enhanced space weather decision support is a national imperative.**

NOAA’s Space Weather Charter

- **Building capacity to advance space weather policy**
  - Inception and implementation of National Space Weather Strategy and Action Plan
  - PROSWIFT (Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow) Act
- **Accelerating growth in NOAA and its space weather services**
  - Identify and sustain fundamental observations to support operations
  - Provide timely, accurate, and relevant models and forecast products
  - Transition scientific and technological advances into operations (R2O2R)
  - Support growing private sector activities to fill data and technology gaps and provide value-added services and products
- **Integrating approach and collaboration between research and operations**

Space Weather Requirements: Ionosphere

NOAA/NESDIS

NESDIS-REQ-4500.3

SPACE WEATHER NEXT PROGRAM OBJECTIVES

July 2023

Prepared by:
U.S. Department of Commerce
National Oceanic and Atmospheric Administration (NOAA)
National Environmental Satellite, Data, and Information Service (NESDIS)

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Table 18: Ionospheric Electron Density Profiles Observational Parameters

Observation Component	Threshold	Objective
Observational Extent	90–1500 km	
Vertical Resolution	10 km	1.5 km
Measurement Range	Ne: 10^{10}–10^{13} electrons m^{-3}	
Measurement Uncertainty	Ne: Less than ±max (3×10^{10} m^{-3}, 10%)	
Quantity of Global profiles per day	12,000	50,000
Median Data Latency	60 min	5 min

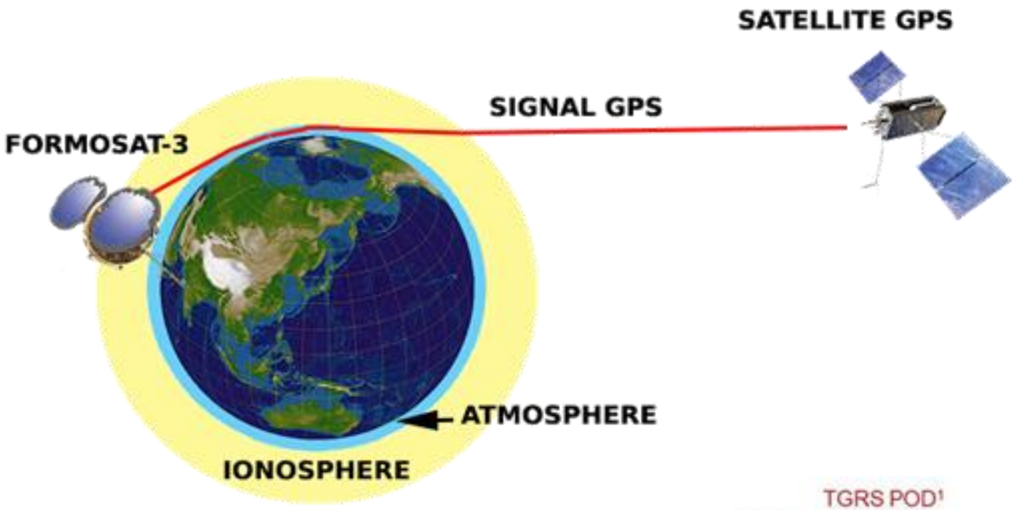
Table 19: Total Electron Content Observational Parameters

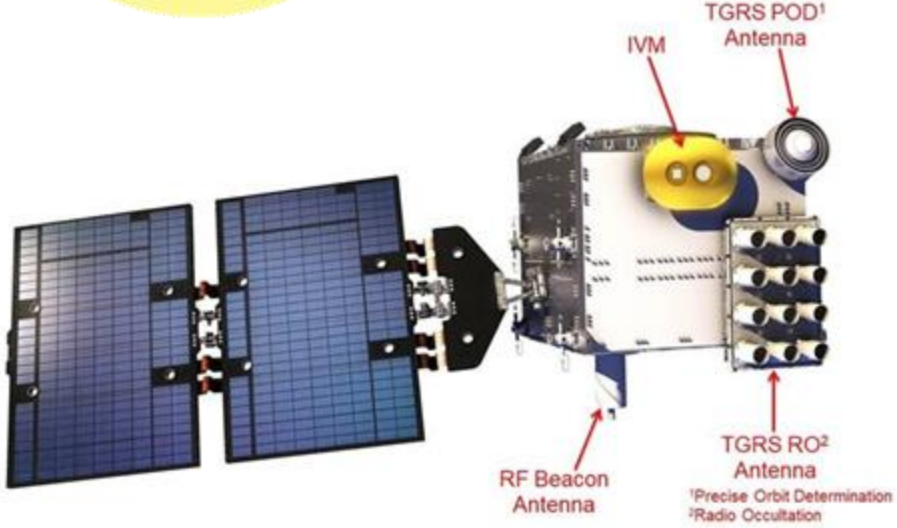
Observation Component	Threshold	Objective
Observational Extent	90–1500 km	
Measurement Range	1–200 TEC Units vertical equivalent	
Measurement Uncertainty	3 TECU	
Refresh Rate Quantity of Global profiles per day	12,000 observations day^{-1}	50,000 observations day^{-1}
Median Data Latency	60 min	5 min

Radio Occultation (RO)

Satellite missions with RO capability:

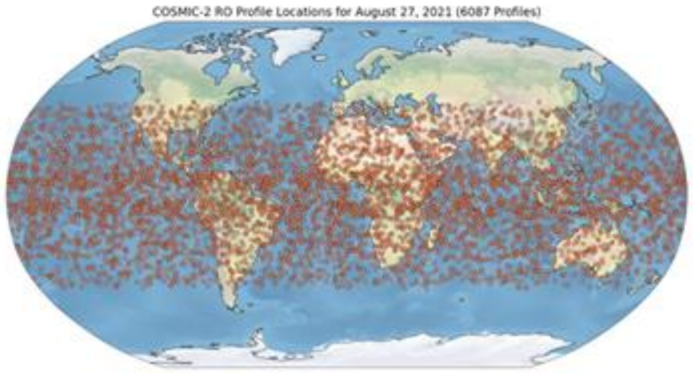
- CLARREO
- Microlab 1
- FORMOSAT-3/COSMIC
- **FORMOSAT-7/COSMIC-2**
- CHAMP
- GRACE
- Oceansat
- Sentinel-6 Michael Freilich
- GRAS sensor onboard MetOp satellite
- **Spire LEMUR cubesats**
- **PlanetIQ GNOMES microsats**



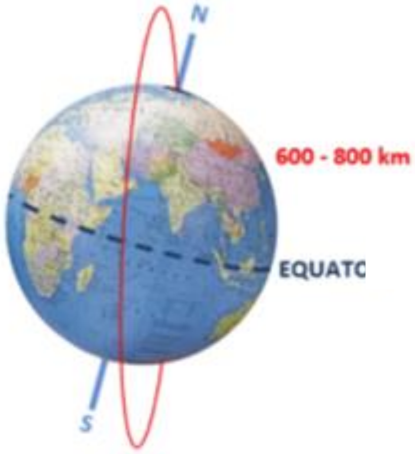


RO Constellations and Data

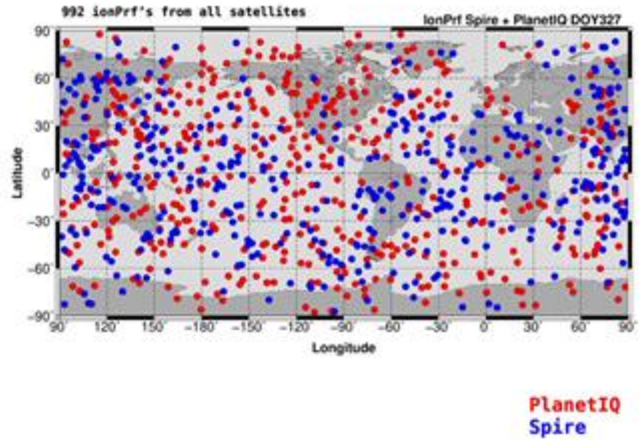
- **FORMOSAT-7/COSMIC-2**
- Achieved full operational capability on October 12, 2021 (Set 1)
- Six remote-sensing smallsats
- Multi-GNSS



- **Spire LEMUR**
- **PlanetIQ GNOMES**
- SSO
- Multi-GNSS



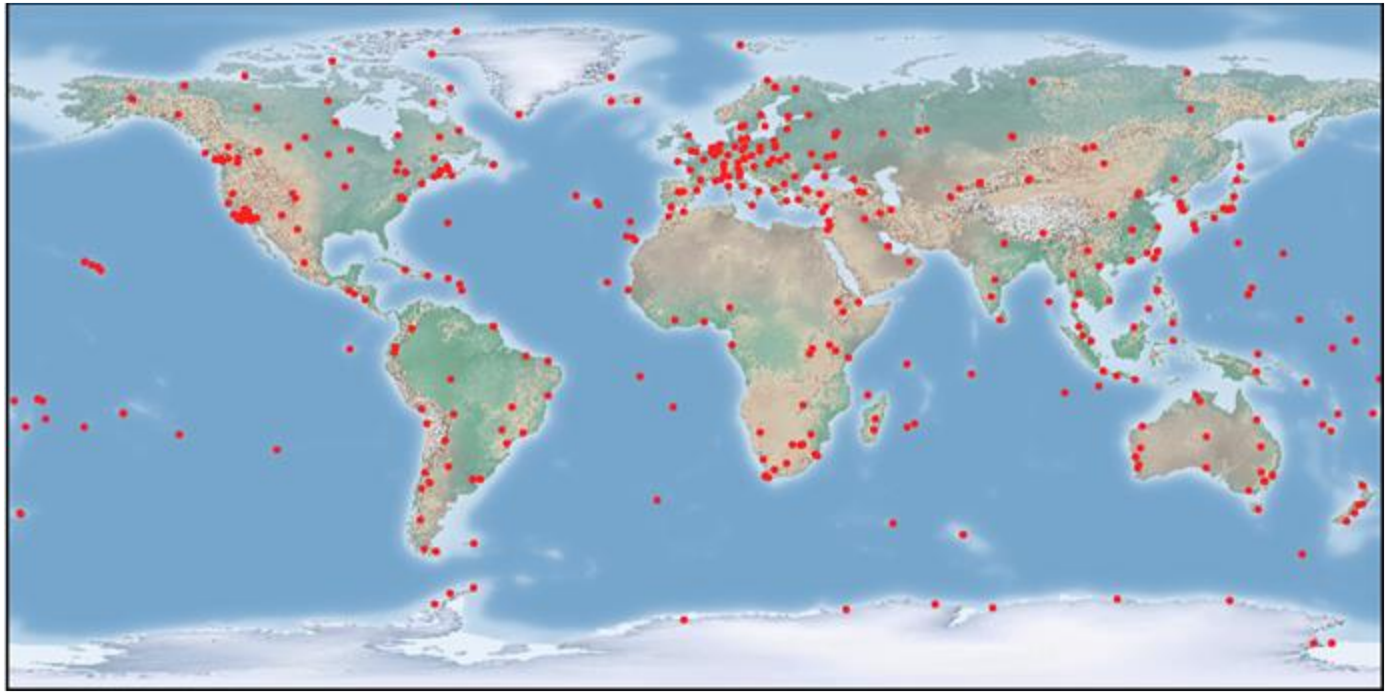
SUN-SYNCHRONOUS ORBIT (SSO)



Ground Receiver Data

- **Ground GNSS networks - Geodetic:**
- 30 sec (or 1 sec) sampling rate
- Good quality antenna (reduced multipath)
- Good phase data
- Low SNR resolution
- SNR is strongly HW and FW dependent
- Good TEC, ROTI, and σ_ϕ

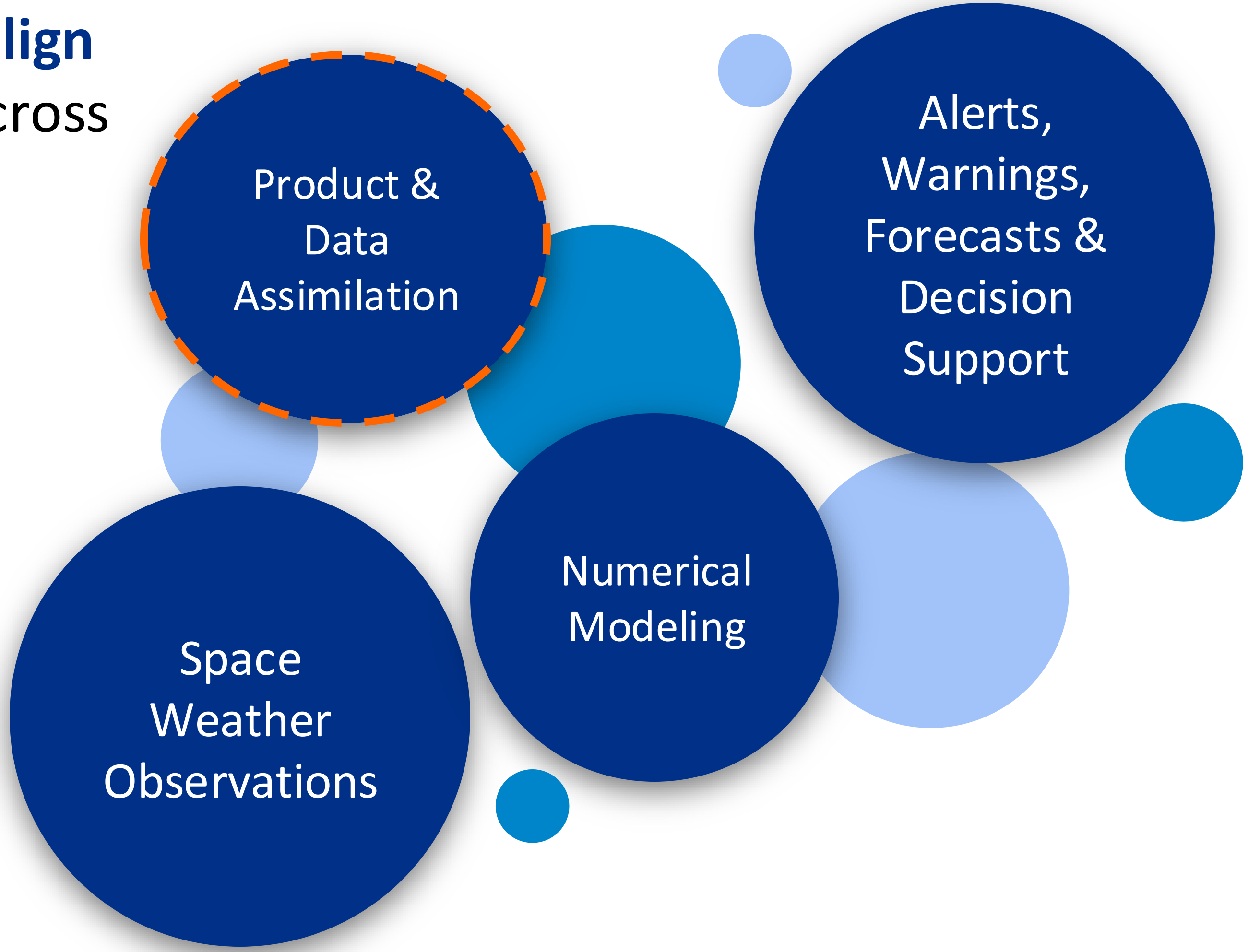
- **Ground GNSS networks - Scintillation:**
- 50-100 Hz sampling rate
- Typically newer installations
- Variable antenna quality
- Receiver calculated TEC, σ_ϕ, S4 etc.
- Improved oscillator quality



IGS Stations, 2019

Advancing the NOAA Space Weather Enterprise

- One-NOAA Space Weather Strategy to **align priorities** and **build connective tissue** across line offices
  - NESDIS
  - NWS
  - OAR



The Current Focus is on Three One-NOAA SWx Priorities

FY 2025

Data Assimilation

Integrate Space Weather numerical predication systems into the UFS in order to leverage all of the innovations for advancing the prediction of space weather.

Space Weather Operations

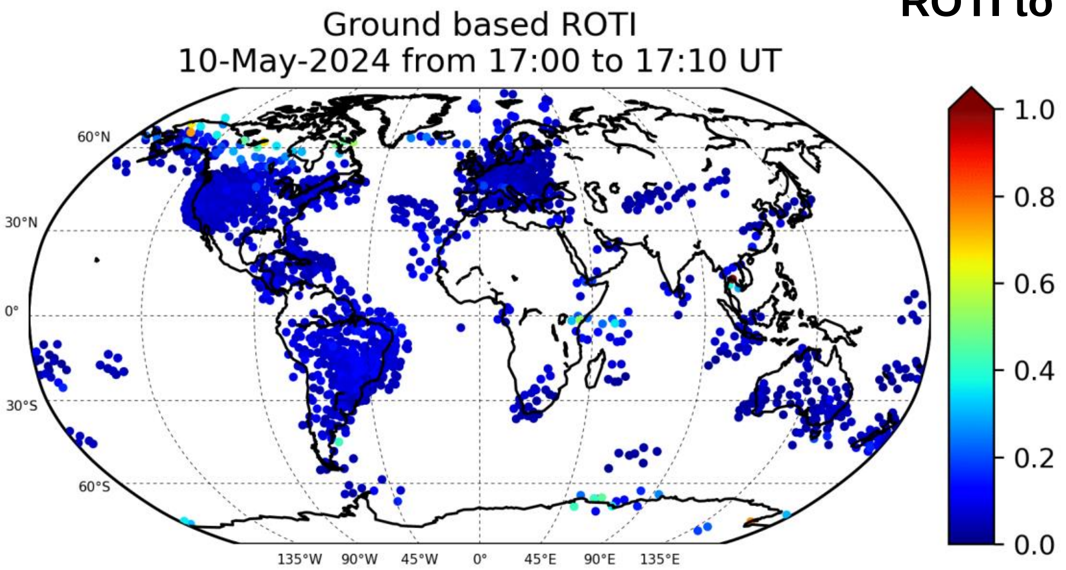
Enhance the way SWx functions to improve outcomes.

Research-to-Operations and Operations-to-Research (R2O2R)

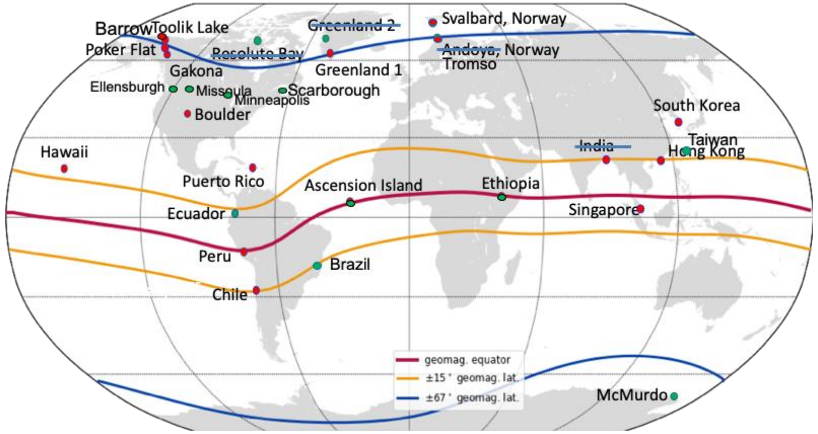
Accelerate the transition from development to deployment with rapid prototyping and the Space Weather Prediction Testbed to enable improved actionable space weather information.

Rate of TEC Index (ROTI)

ROTI to S4

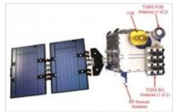


Real-time GNSS Scintillation Receivers



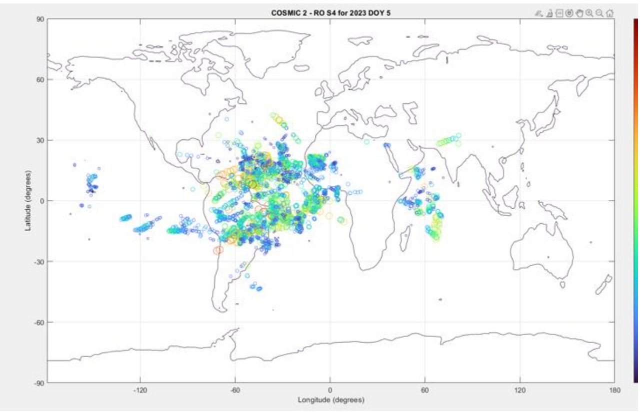
J. Morton

COSMIC-2 and Commercial Scintillation Products

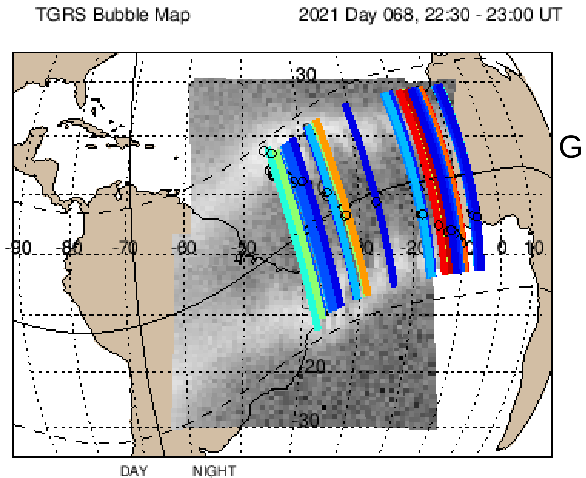


All-Clear

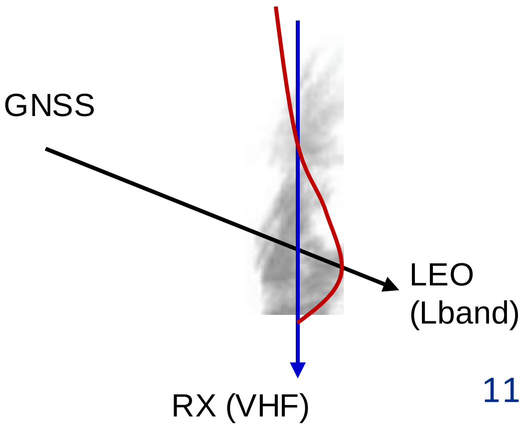
Geolocation



Bubble Map



Limb to Disk



: US Government Only

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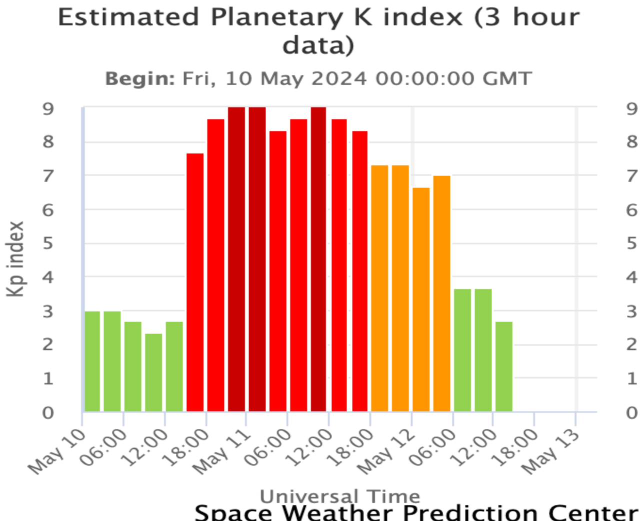
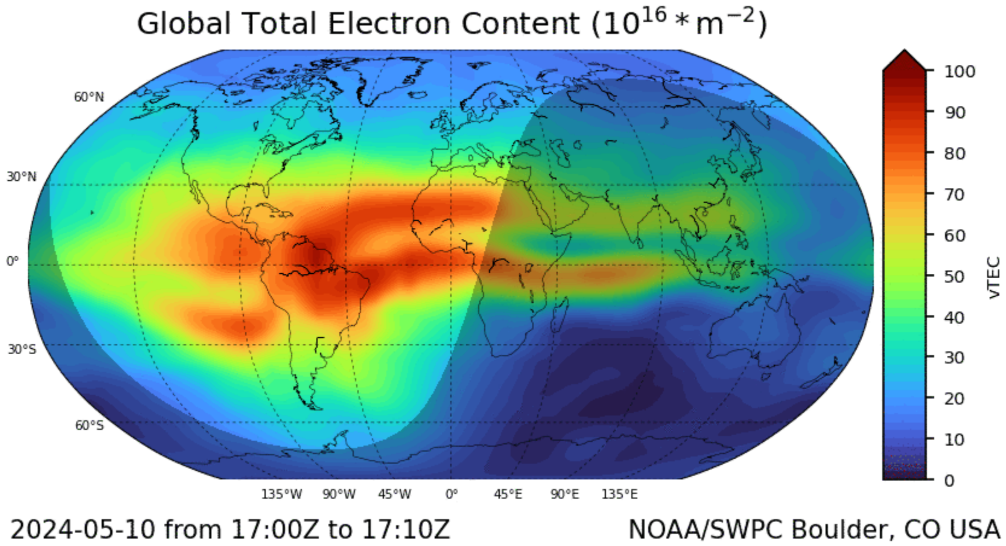
GNSS PNT and Satellite Communication

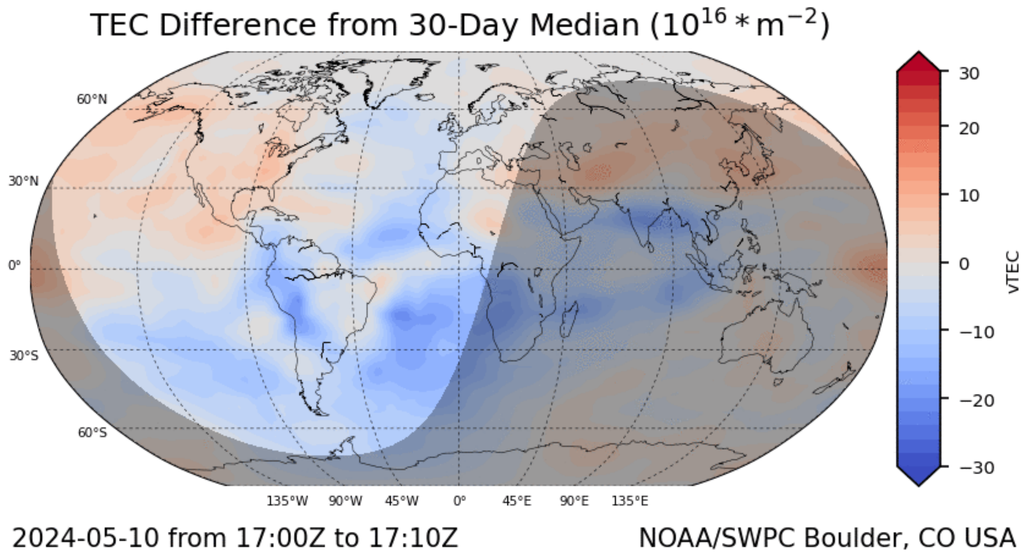
GloTEC (nowcast)

- Global 3D electron density data assimilation
- Gauss-Markov Kalman filter - GMRES solver
  - IRI-16 background model
- Real-time ground-based GNSS observations
  - IGS, UNAVCO, INPE, NRCan, RAMSAC, CDDIS, and more
- Space-based GNSS observations (RO)

https://www.swpc.noaa.gov/experimental/glotec



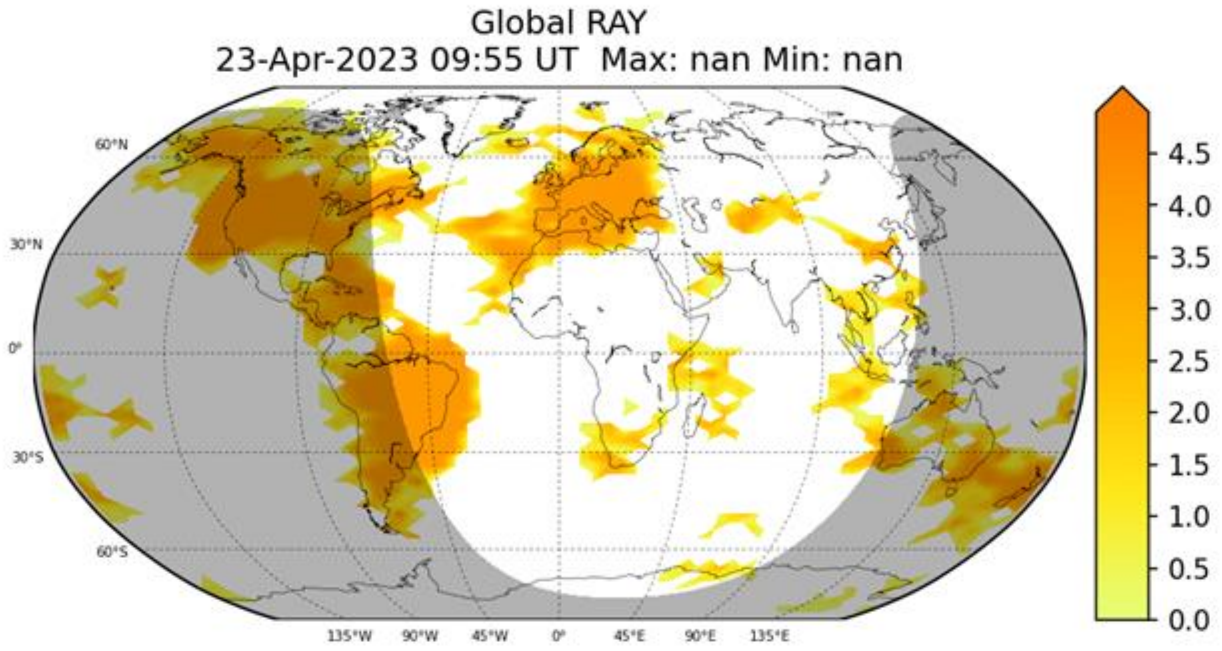




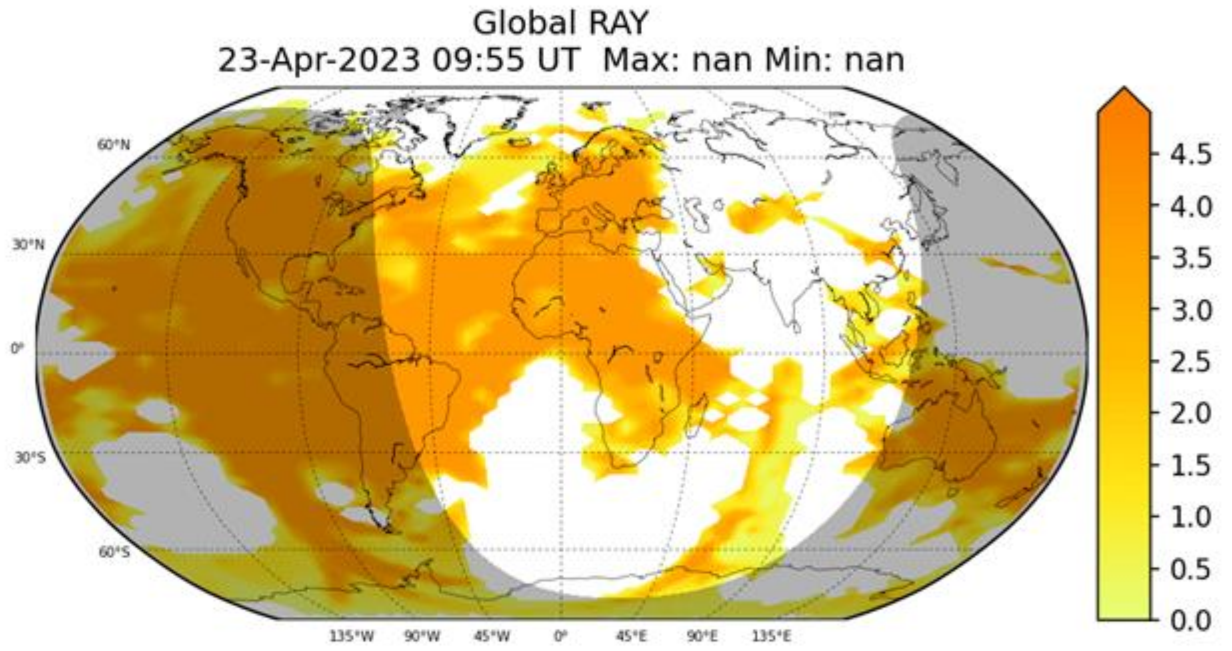
GloTEC Ray Segments

- Total observation rays in the F region voxels.
- Ingesting RO data significantly improves F-region ray-path density.

A) Ground-stations only



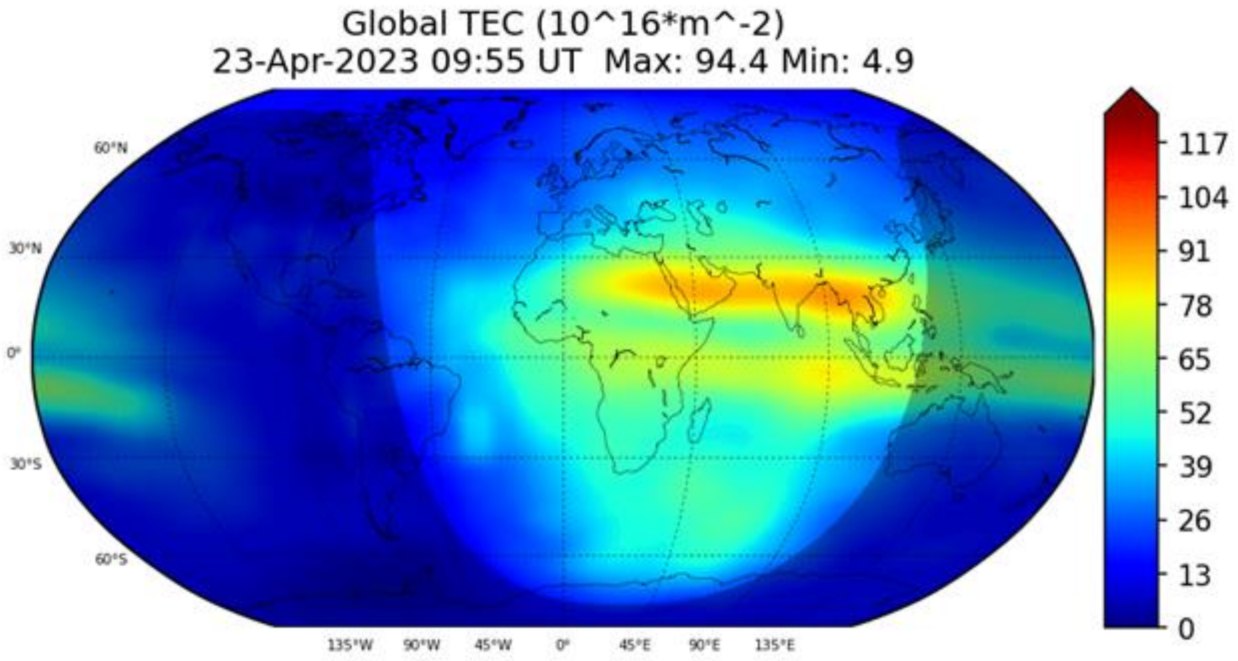
B) Combined ground stations and RO



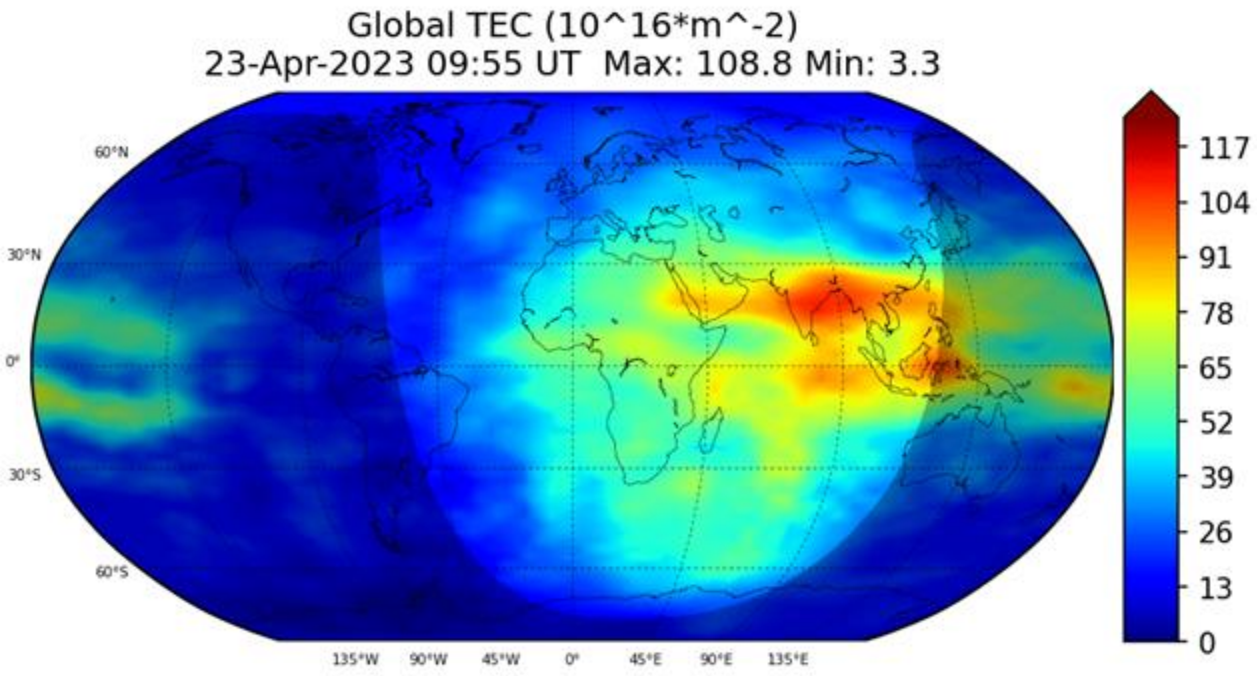
GloTEC VTEC

- GloTEC can ingest STEC from GNSS-RO or even from GNSS-R observations.
- The background model is IRI 2016 driven with real-time F10.7.

A) Ground-stations only

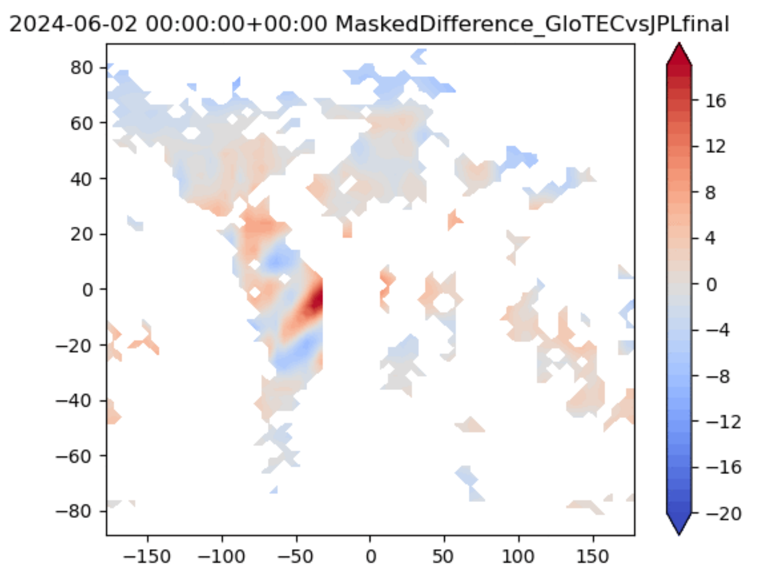


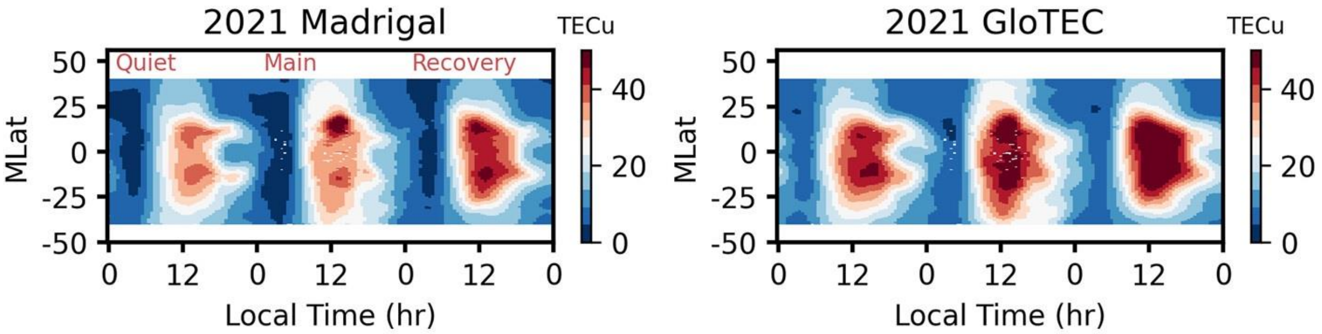
B) Combined ground stations and RO



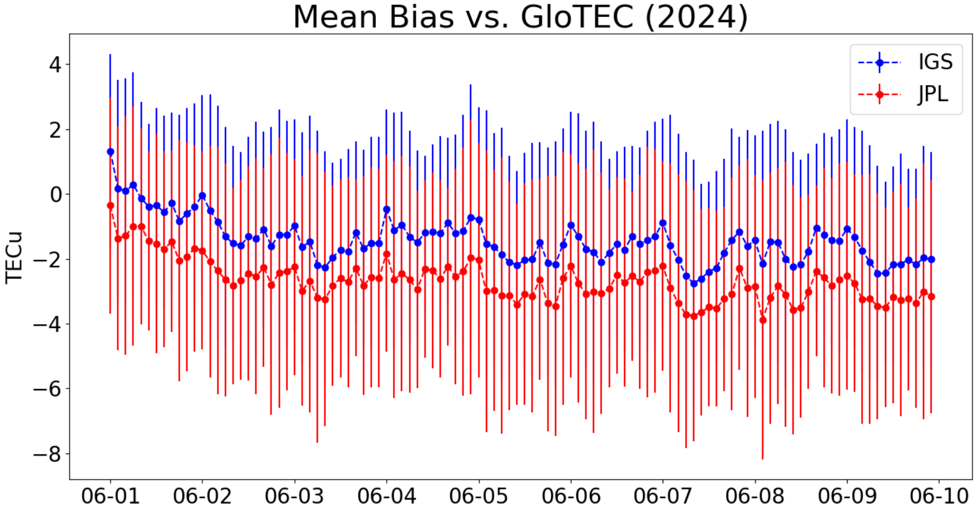
GloTEC TEC Bias Assessment

- Model performances during the storm periods have been previously evaluated by Chou et al. (2023).
- Compare GloTEC TEC results with the outputs from JPL-GIM, IGS, DLR, and MIT Madrigal at locations where GloTEC has data coverage and establish real-time V&V system to automatically evaluate model performance in operational setting.



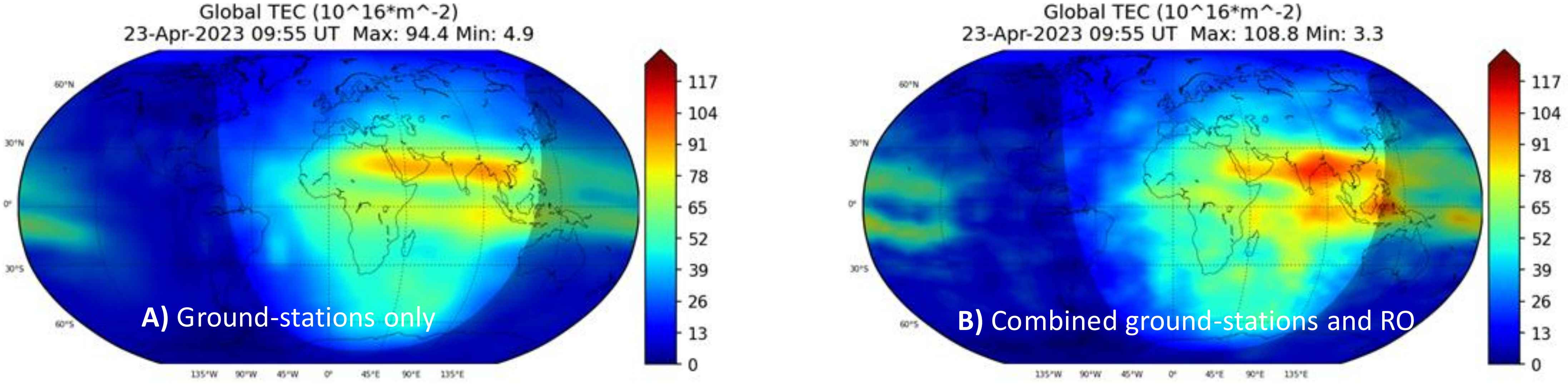


Chou et al. (2023)



Conclusions

- Space Weather is data starved.
- Data are needed to accurately drive magnetosphere, ionosphere, and thermosphere models and capture the spatio-temporal variability of the system with required fidelity.



- Recent studies have shown the need for global observation system to improve MIT predictions