NOAA NESDIS
Space Weather Data Pilot Project

IROWG

Boulder CO - Sep 12-18 2024

National Environmental Satellite, Data, and Information Service

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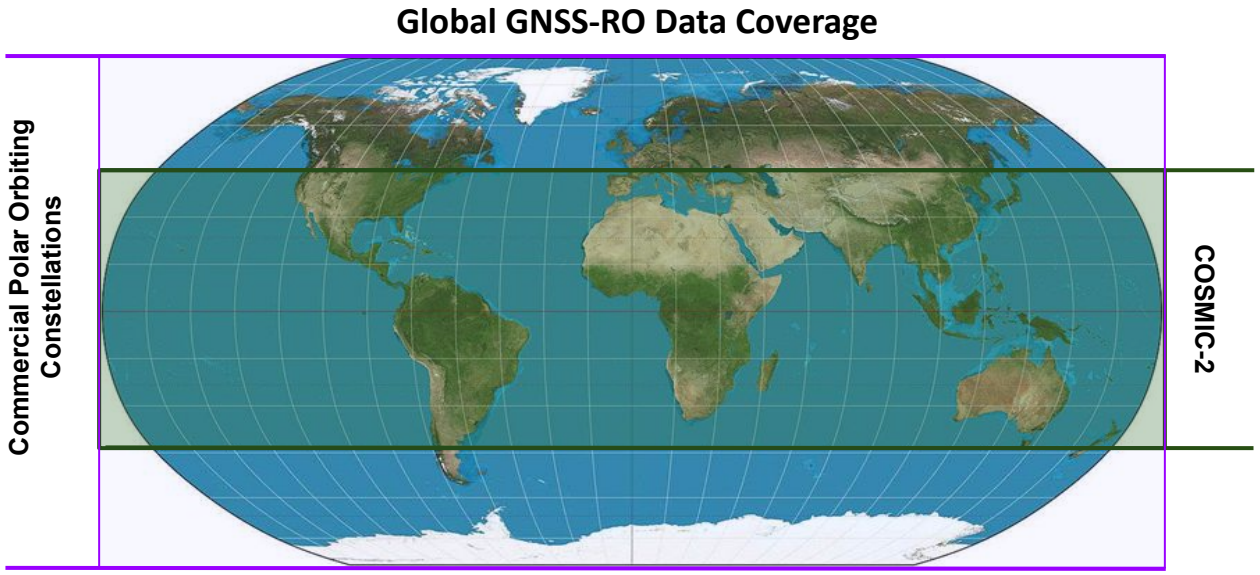
Agenda

- Space Weather Data Pilot Overview and Review
- Findings and Results
  - TEC
  - Scintillation
- Products and Use Cases
- Summary and Recommendations

Why Commercial Space Weather Data is Necessary

Commercial RO data is necessary to reach full global coverage (COSMIC-2 is not enough)

- Adding Commercial GNSS-RO data improves ionospheric model performance, coverage and nowcasting abilities
  - Greatly improves in regions without ground-based observation data
  - Complements COSMIC-2 coverage
  - Allows creation of global ionospheric products that rely less on just background models and more on observations
- Commercial satellites provide high-rate GNSS data when a scintillation event is detected
- Commercial GNSS-RO ionospheric data provides critical information for users of GNSS applications
  - Geomagnetic Storms can induce errors of: ***tens of meters***
  - User precision needed: ***several millimeters - one centimeter***



GNSS Use Case Applications

- Precision Agriculture
- Industrial Construction
- Precision Geodetic and Surveying
- Aviation, Drone and Maritime Operations
- Autonomous Vehicles
- Military Applications

Space Weather Data Pilot Awards

- On July 14, 2022, NOAA awarded contracts to three companies for the first Space Weather Data Pilot:
  - GeoOptics Inc. (Pasadena, CA)
  - Space Sciences and Engineering LLC, dba PlanetiQ (Golden, CO)
  - Spire Global Subsidiary, Inc (San Francisco, CA)
- Began Aug 1, 2022 for one year
  - 6-month Data Delivery period ended May 2023
  - PoP ended Aug 1, 2023
- License sharing option 3 - limited to U.S. Gov, Met centers, CGMS members
- Based on post-award developments, GeoOptics effort bilaterally concluded (and $$ de-obligated) in Nov 2022, prior to data delivery.

Pilot Measurement Objectives

Total Electron Content (TEC)

- TEC is ~ number of electrons encountered by a GNSS signal along the path to the RO or POD antenna
- TEC observations help specify the electron density structure in the ionosphere / plasmasphere
- From TEC vertical profiles, one can derive vertical electron density profiles (EDPs) and TEC gradients
  - Affects GNSS applications (e.g. loss of signal, large GNSS errors)
- Measurements typically at low rate (1 Hz)
- Absolute TEC Unit (TECU) uncertainty ($\leq$ 4 TECU Root Mean Square (RMS))
- Provide $\geq$ 500 compliant ionospheric tracks per day with duration of at least 8 mins

Scintillation

- Scintillation refers to rapid, localized, intense fluctuations in the ionospheric state
- Scintillation affects the power & phase of radio signals (GNSS L-band) propagating through the ionosphere
  - Affects GNSS applications (e.g. loss of signal, large GNSS errors) and trans-ionosphere communications
- Scintillation characterized by rapid fluctuations of two indices, Sigma-phi (phase) & S4 (amplitude)
- Measurements must be high rate (preferably $\geq$ 50 Hz) in order to capture the rapid changes
  - Download and provide data from at least 25% of tracks with onboard S4 > 0.2

TEC, Scintillation indices calculated from GNSS pseudorange, carrier phase, and signal-to-noise (SNR) measurements.

Maximum daily median latency of 30 minutes

Space Weather Data Pilot Team

National Environmental Satellite, Data, and Information Service

DEPARTMENT OF COMMERCE

SPACE WEATHER PREDICTION CENTER

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

UCAR

UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

University of Colorado Boulder

BOSTON COLLEGE ISRO INSTITUTE FOR SCIENTIFIC RESEARCH

AEROSPACE

EUMETSAT

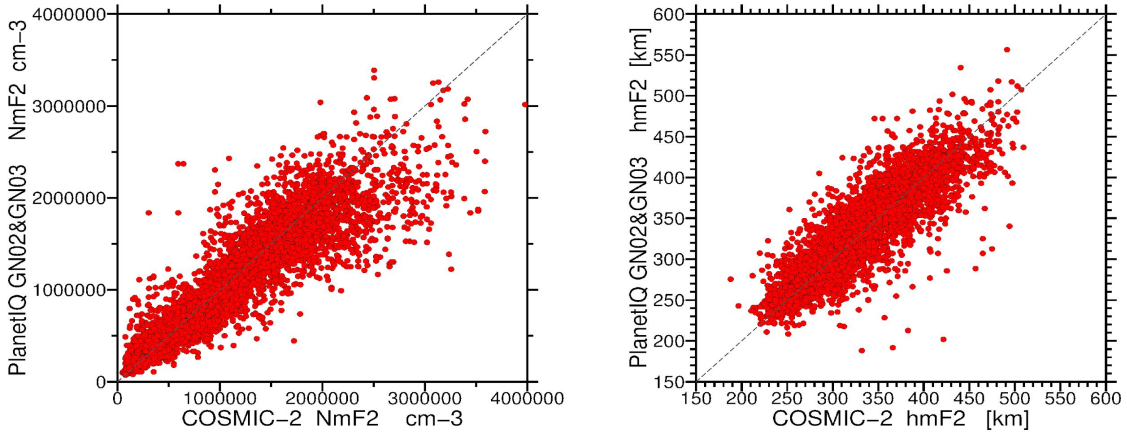
spire

PLANETiQ

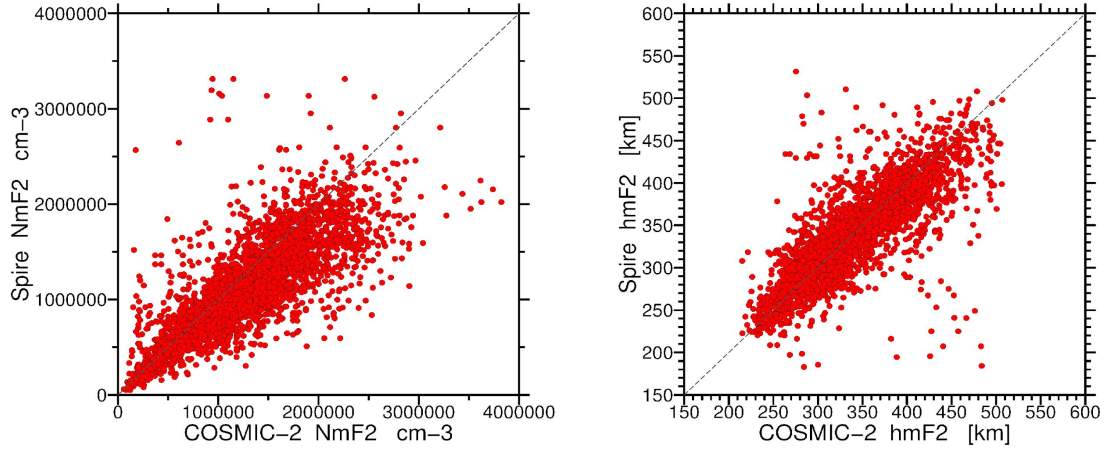
Findings - TEC/EDP Data Validation and Accuracy

- Very good EDP data validation ; assessment of ionospheric F2 layer peak parameters w/ COSMIC-2 EDP product

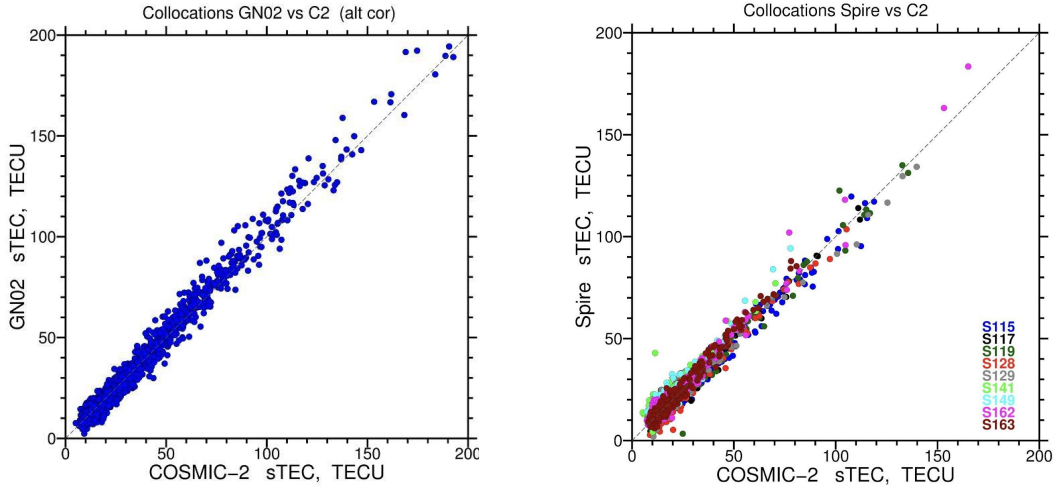
PlanetiQ v. COSMIC-2 Co-located Electron Density Profiles (EDP)
Electron Density Peak Density (NmF2) and Peak Height (hmF2) of F2 Layer



Spire v. COSMIC-2 Co-located Electron Density Profiles (EDP)
Electron Density Peak Density (NmF2) and Peak Height (hmF2) of F2 Layer



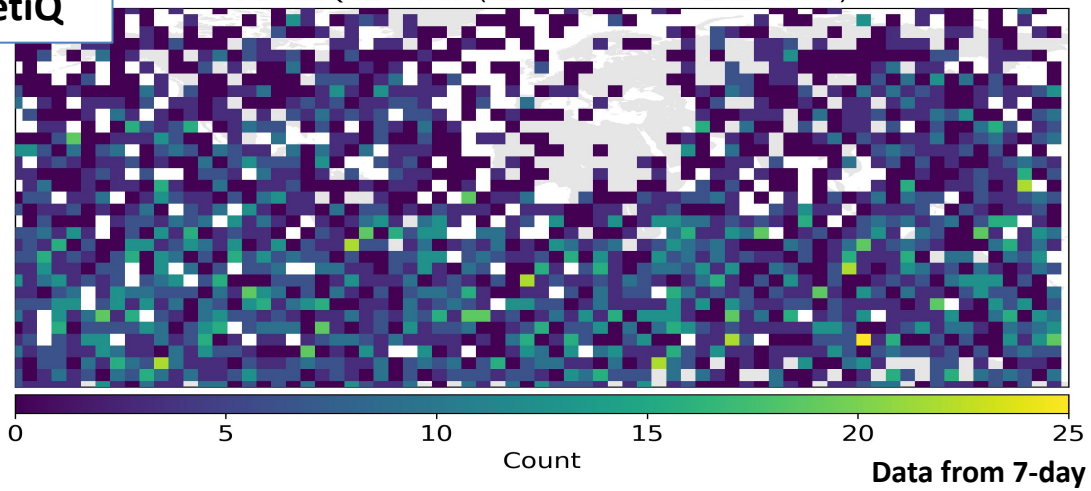
- Excellent TEC data validation w/ COSMIC-2 TEC product



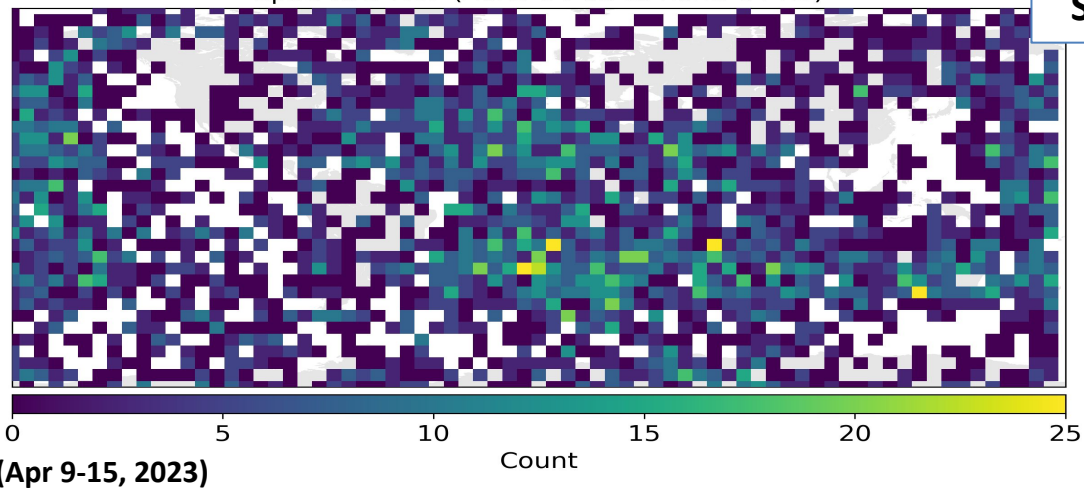
- TEC Accuracy:
  - Absolute TEC Unit Requirement:
    - ≤ 4 TEC Unit RMS
  - PlanetiQ: 4.6 TEC units
  - Spire: 4.7 TEC units

Findings - Spatial-Temporal Distribution of Data

PlanetiQ

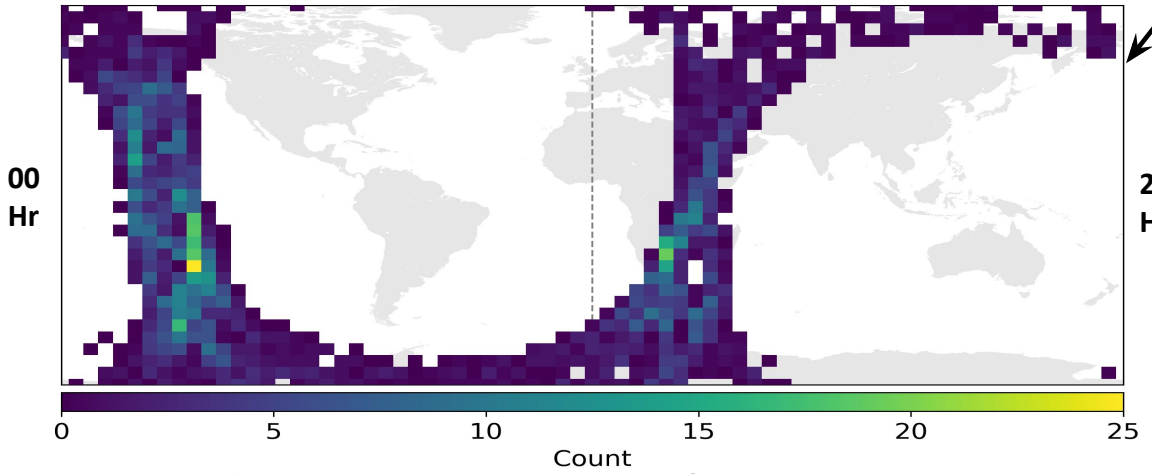


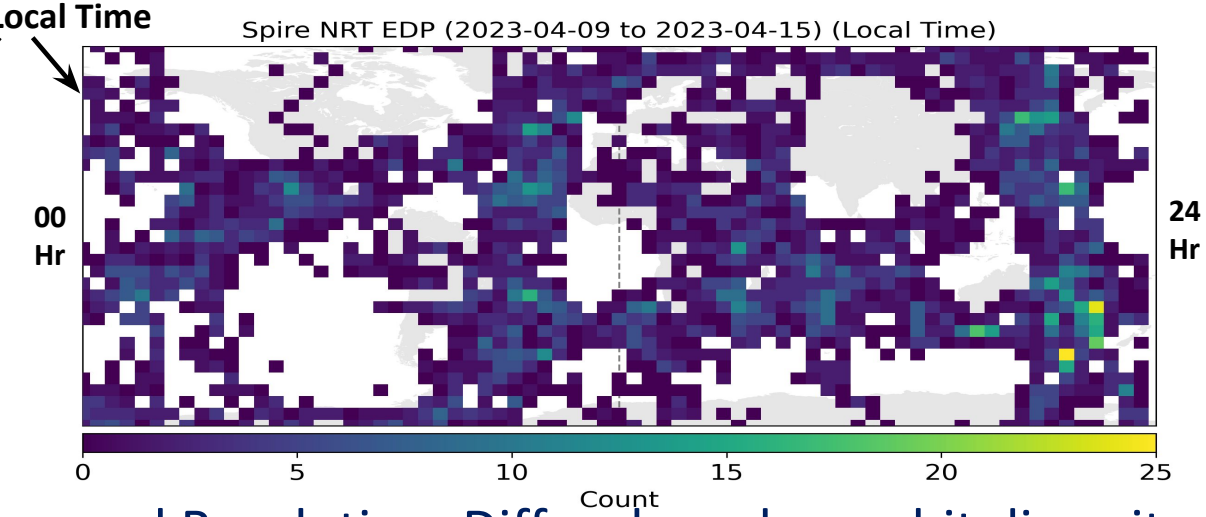
Spire



Data from 7-day period (Apr 9-15, 2023)

Lon = Local Time





- Spatial Resolution: Good for both vendors ; Temporal Resolution: Differs based on orbit diversity
- Spatial-temporal study needed to assess proper coverage & refresh of TEC and Scintillation

Findings - TEC Latency

- Latency measured takes into account both data and product latency
  - Data Latency: Satellite -> NCCF: Requirement is 30 minutes
  - Product Latency: Includes time for data processing at UCAR before final products ready for SWPC

*Median Latency of TEC Data *Based on period Mar 1 - Apr 30 2024 ; times rounded to nearest minute				
	Satellite to NCCF (SoW Requirement)	**NCCF to UCAR** (data check & transit)	**UCAR to SWPC** (Data Processing)	**Total** (Ready for SWPC ingest)
Spire	29 mins	3 mins	33 mins	65 mins
PlanetiQ	52 mins	3 mins	9 mins	64 mins

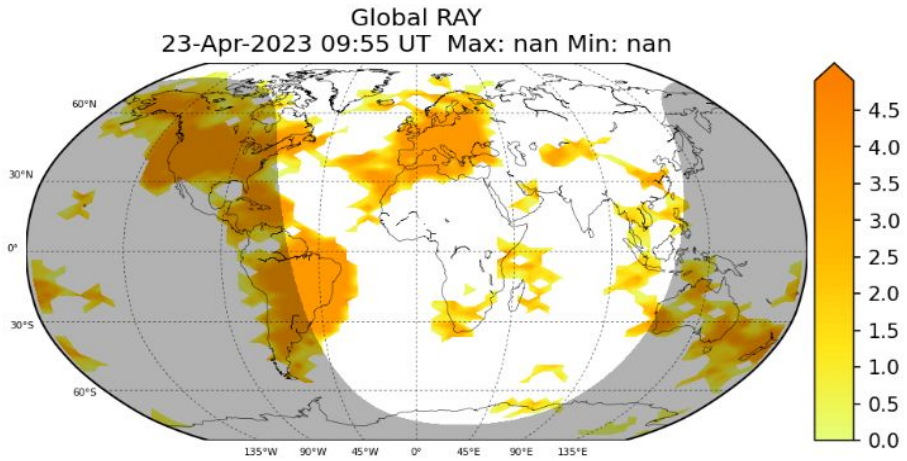
- PlanetiQ and Spire packaged data differently during the Pilot
  - PlanetiQ sent data in continuous streams
  - Spire sent data in numerous 1-min segments with varying latency ; added time to process the data

- Continued collaboration between NESDIS CDP, vendors and UCAR's Data Processing Center will help to streamline data processing.

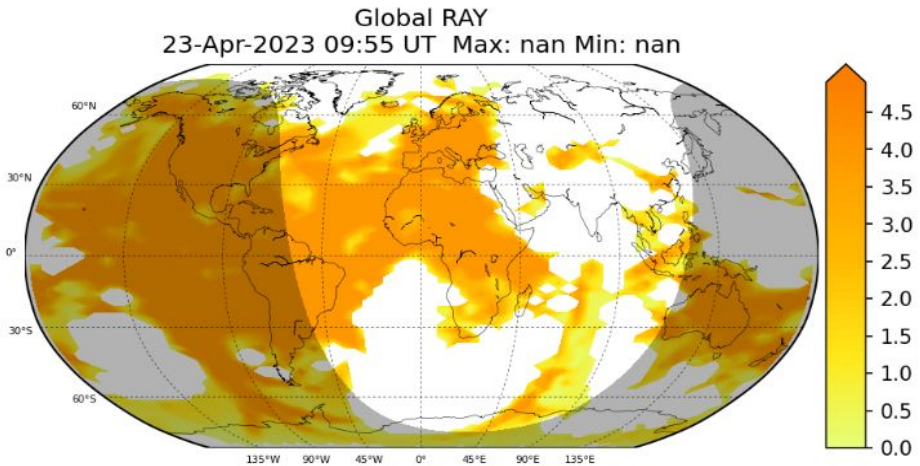
Findings - TEC Impact Assessment & Coverage

- TEC from all RO improves global coverage

GloTEC Model observation density (Ground data only)

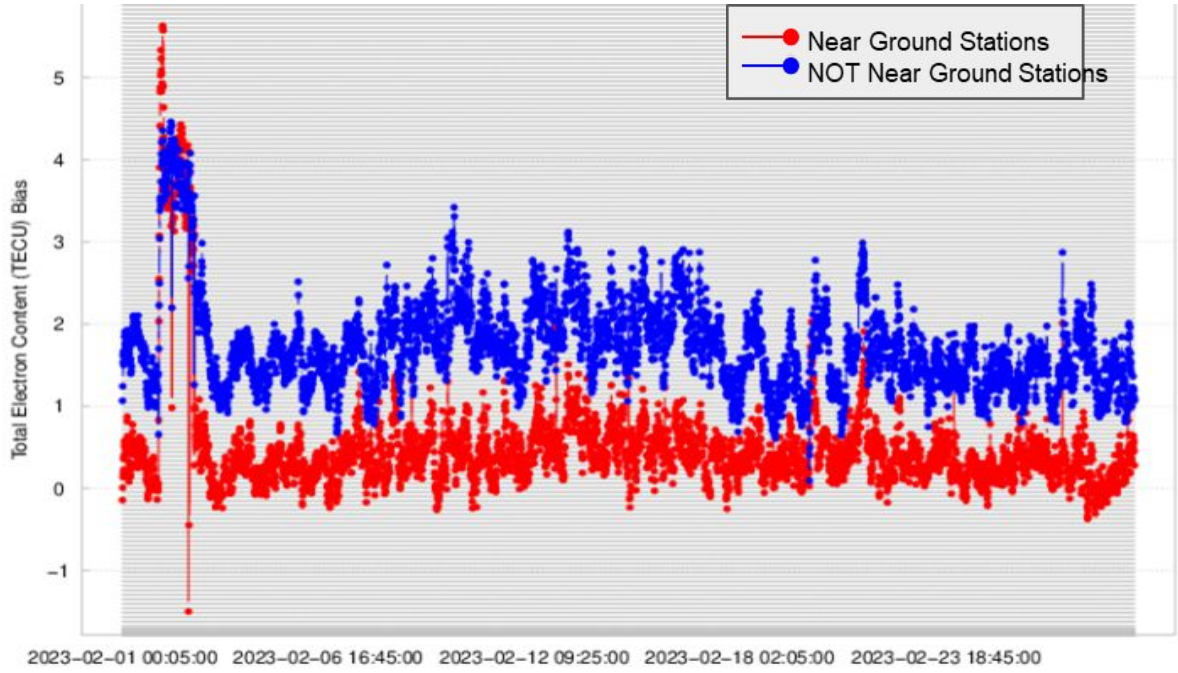


GloTEC Model observation density (Ground + all GNSS RO data)



- TEC from RO contributes more to model bias away from ground stations
  - RO contributes more to model performance in areas with less-dense ground station coverage
  - This is what we want to see

GloTEC Mean Bias between with and without RO in regions near vs. not near ground stations (does not include PiQ data)

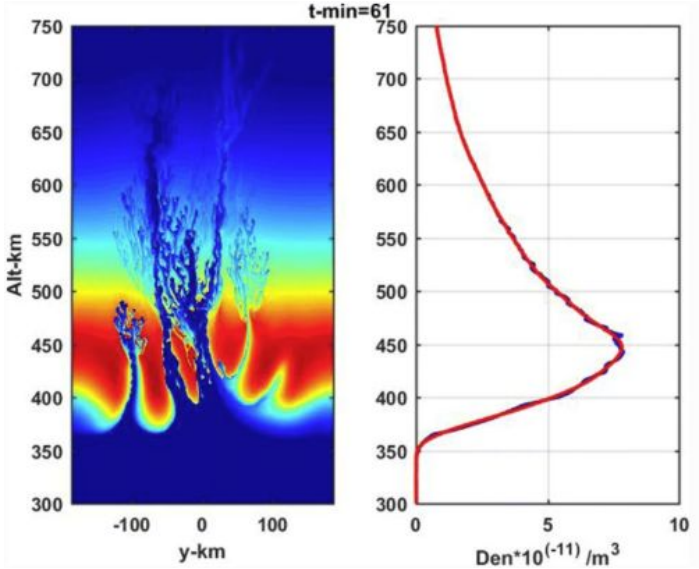


Commercial RO data improves TEC model performance – contributes to more useful TEC products

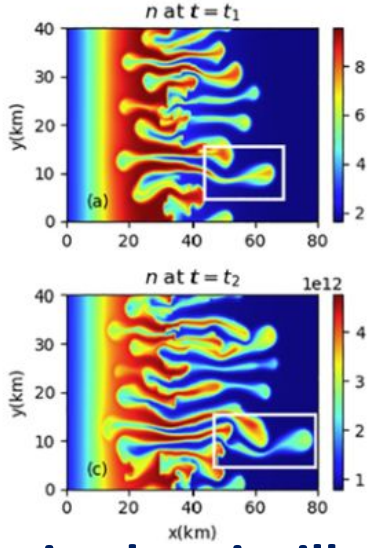
Scintillation - Low-Latitudes v. High-Latitudes

- High-latitude scintillation behaves very differently than low-latitude scintillation.
- Both regions differ in magnetic field geometry, irregularity structures, and drift velocities.
- COSMIC-2 Calibration/Validation can only address low-latitude scintillation data.

- Equatorial Regions:
  - Dominated by diurnal variations; Equatorial plasma bubbles typically occur post-sunset
  - More vertical structure
  - Peak heights typically higher (~ 450 km)



- High-latitude Regions:
  - Exhibits greater variability
  - Plasma drifts more rapidly
  - Plasma gradients are stronger
  - More horizontal structure
  - Peak heights typically lower (~ 350 km)



First comprehensive analysis/research on measuring high-latitude scintillation with GNSS-RO data

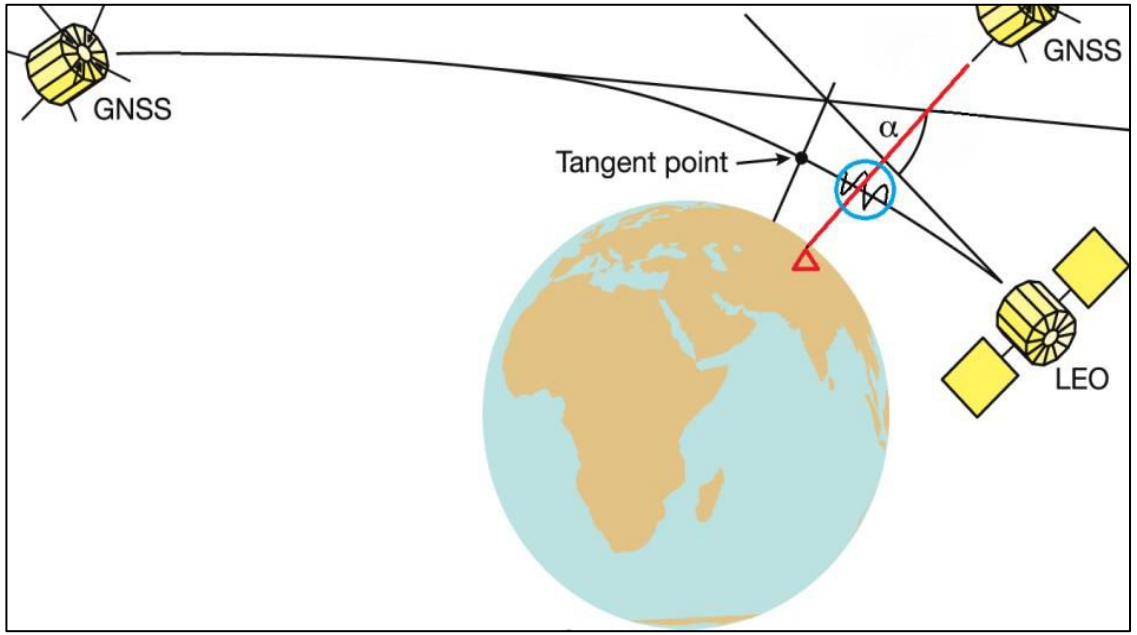
Findings - Scintillation Geolocation

- Problem 1: Geolocation method (Tangent Point) used for EDP and neutral atmosphere RO observations does not work for scintillation. Scintillation can occur anywhere along the RO ray-path.
- Problem 2: High-latitude scintillation behaves very differently than low-latitude scintillation.
- Geolocation schemes need validation with existing observations to properly determine location.

Why this is important:

  - To properly determine the location of the ionospheric irregularities causing scintillation
  - Validation of high-latitude scintillation

- Boston College (BC) & UCAR developed geolocation algorithms for low-latitude regions
  - COSMIC-2 validated the algorithm's performance
- BC & UCAR performed assessment with Comm RO
  - Only did assessment within +/- 30 degrees latitude
  - Vendor data verified well, but dataset was limited
- Future work needed for full validation of Commercial RO data for all latitudes



Findings - Scintillation Trigger Algorithm

- Problem: Triggering algorithm to download high-rate scintillation observations (50 Hz) was insufficient to capture all high latitudes scintillation events.
  - SOW requirement (S4 > 0.2) was too restrictive; unknown amount of scintillation cases likely missed

Why this is important:

  - To obtain adequate scintillation observations at all latitudes from LEO-based platforms

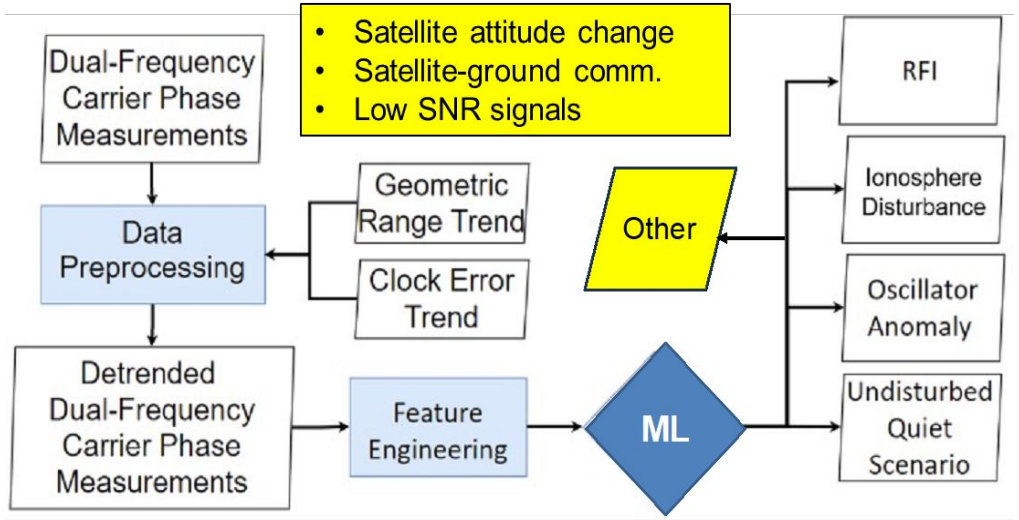
- Scintillation trigger threshold was dev'p under COSMIC-2 pgm and applied to this pilot (SoW)
  - Threshold worked for COSMIC-2's TGRS sensor
    - Further COSMIC-2 analysis confirmed the S4 threshold (S4 > 0.2) is adequate for low latitudes
- Conducted limited-data campaign w/ both vendors to provide all data for 72-hr window (May '23)
  - Low-latitudes: Vendor data performed well ; confirmed S4 threshold (S4 > 0.2) is adequate
  - High-latitudes: Vendor data showed scintillation events with very different signatures in the data
    - Scintillation events occurred with much lower S4 values
    - Scintillation events occurred with phase-dominant signatures
- Scintillation trigger algorithm needs adjusting to better capture high-latitude scintillation events
  - Must also consider the SNR vis-a-vis scintillation amplitude and the scintillation phase

Findings - Detection of Anomalous Data

- Problem: Anomalous vendor data & RFI can look like signatures similar to ionospheric scintillation.
- Methods needed to identify and isolate data anomalies and RFI from real scintillation; must perform in a time-sensitive manner and with all data; machine learning (ML) algorithms add value here.

Why this is important:

- Data anomalies often result in rapid SNR changes which appear as scintillation amplitude spikes
- Ascertain contaminated data to reduce false positives
- Help determine the cause of anomalous data

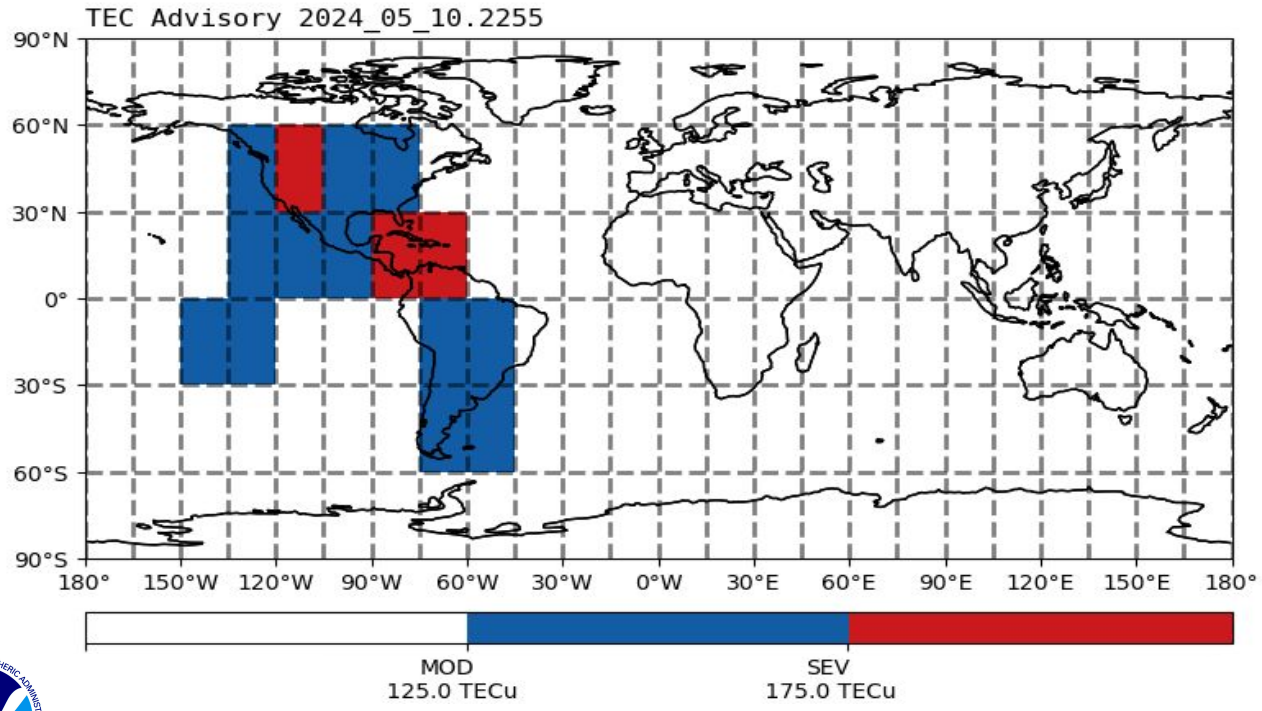


- Univ of Colorado developed ML algorithms to identify spurious features and separate them from real scintillation
  - ML methods showed good promise in performing this function
  - Results also confirmed vendors can detect scintillation
- Vendors provided satellite attitude and ground station communications information
  - Results helped to confirm and identify sources of anomalous signatures
- Future work needed to expand anomaly identification methods and also to investigate scintillation geolocation algorithms to demonstrate sensitivity in relation to spurious features

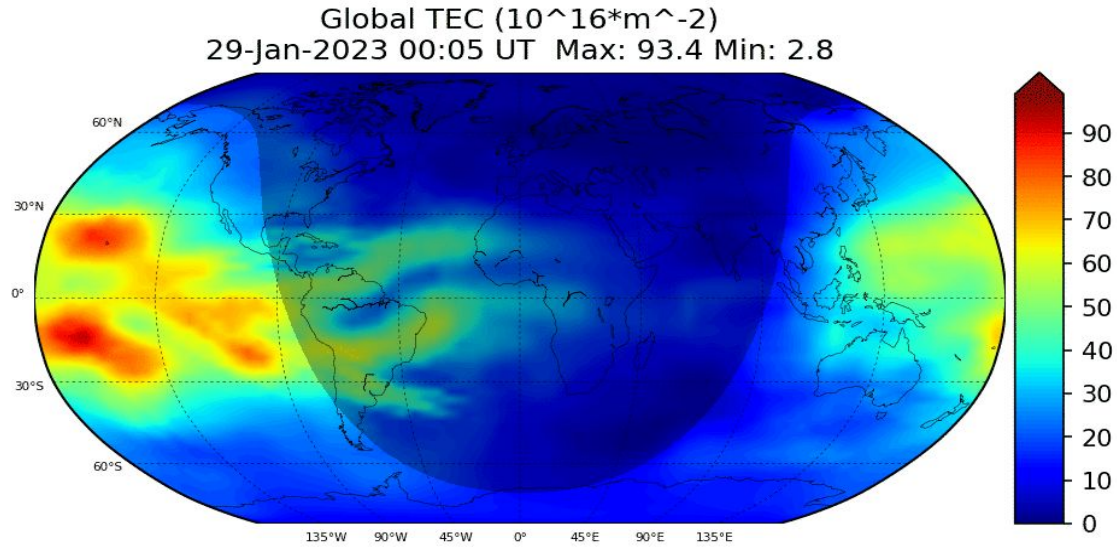
Products and Use Cases - TEC

- Current uses:
  - Incorporate into GloTEC model (ground, COSMIC-2)
  - Issue ICAO-mandated advisories (see below)
  - Bias-correction in WAM-IPE model (GFS-coupled)
  - Supports USSF operational tools & general community

TEC Advisory Map from the May 10, 2024 Geomagnetic Storm



- Future uses:
  - Extend GloTEC to incorporate Comm RO
    - TEC latency should be ≤ 30 mins



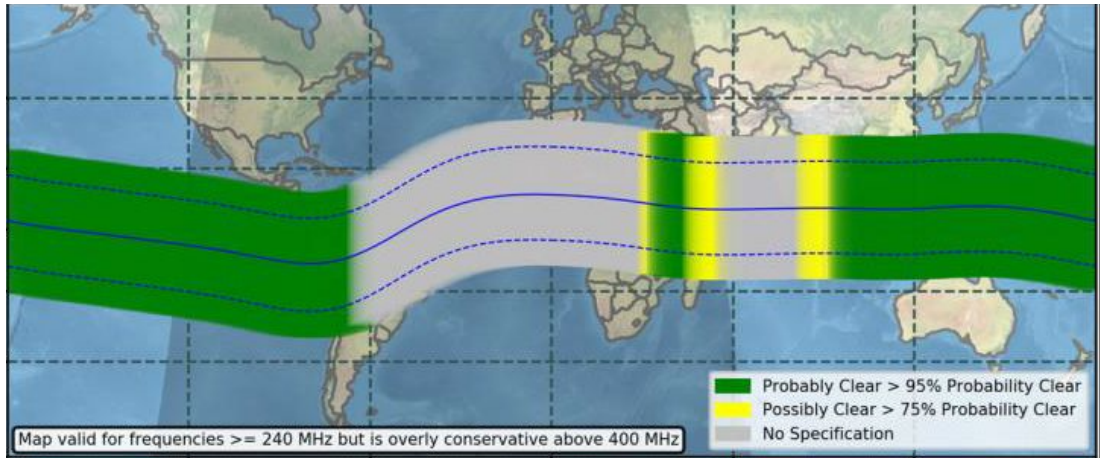
Global Total Electron Content (GloTEC) Model (ground+Spire+PlanetIQ)

Products and Use Cases - Scintillation

- Current uses:
  - Products built from ground receivers only
  - Issue ICAO-mandated advisories (similar to TEC)
  - Supports GNSS Receiver companies, FAA, USSF/USAF, Space companies, SatCom users
- Future uses:
  - Expand products to use GNSS-RO scintillation measurements
  - Leverage COSMIC-2 Program for product development (see right)
    - **Bubble Map:** Indicates regions where scintillation-causing plasma irregularities ("bubbles") are occuring ; maps scintillation longitudinally along magnetic field lines
    - **All Clear Map:** Indicates when scintillation is *not* a factor to consider ; useful for RFI attribution
    - Future work: Expand All Clear Map to L-Band frequencies ; Possibly incorporate commercial RO

Bubble Map Product

All Clear Product



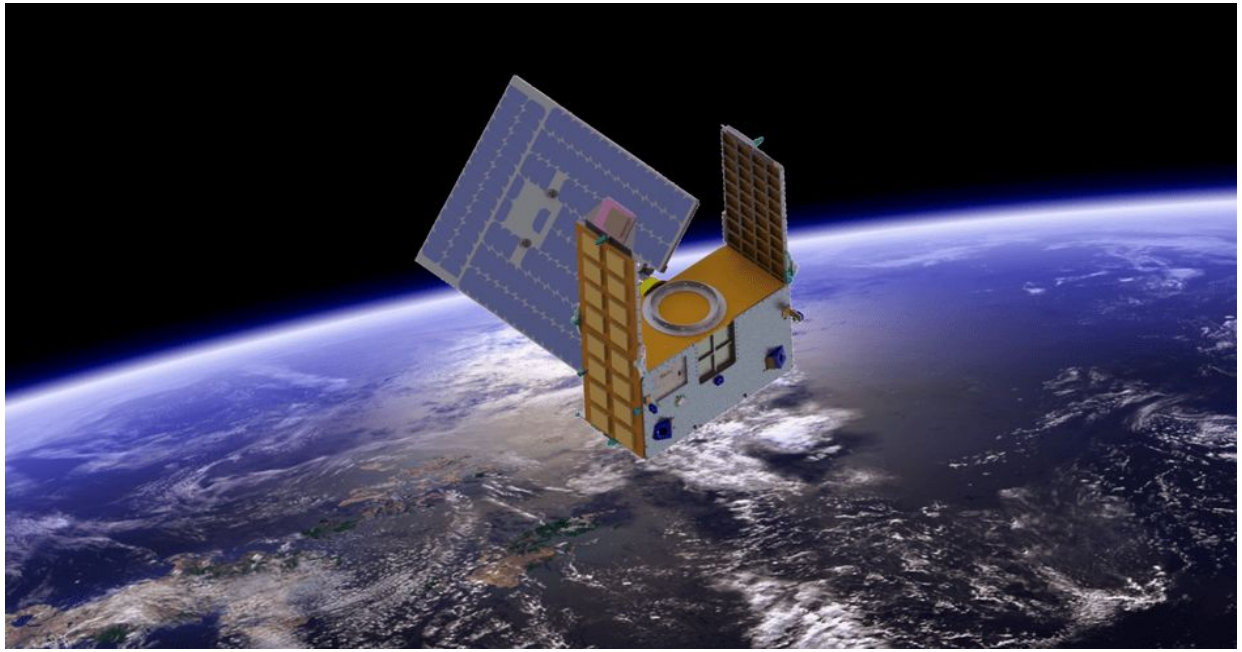
Summary and Recommendations

- Both vendors were compliant and cooperative
  - Delivered 6 months of excellent data of mostly acceptable quality
  - Supported all technical questions
  - Provided a 3-day targeted scintillation data campaign at no additional cost
- Pilot Team made substantial advancements ; groundbreaking work w/ high-lat scintillation
  - TEC and Low-latitude Scintillation not far from operational readiness
  - High-latitude Scintillation needs more extensive analysis, assessment, and evaluation
- Final report available: Space Wx Data Pilot Executive Summary
- NESDIS Decision: Not to proceed to another pilot at this time
- NESDIS CDP will continue to explore avenues to further ionospheric measurement readiness and incorporate this into their planning process
  - Continue to cooperate with SWPC, NESDIS SWO, and the COSMIC-2 program in potential future opportunities with focus on low-latency TEC and equatorial scintillation
  - IDIQ-2 structure allows for potential operational data buys of ionospheric data


Thank You!

Space Weather Data Pilot Spacecraft

PlanetiQ



[PlanetiQ via SpaceNews]

- 2 6U (40 kg) micro-satellites participating
- 2 upward looking Precise Orbit Determination (POD) antennas and 2 limb pointing radio occultation antennas
- POD antennas used for ionosphere profiling

Spire

[Spire via SpaceNews]

- ~ 25 3U (10 kg) micro-satellites participating
- 1 upward looking POD antenna and 1-2 limb pointing radio occultation antennas
- POD + RO antennas used for ionosphere profiling