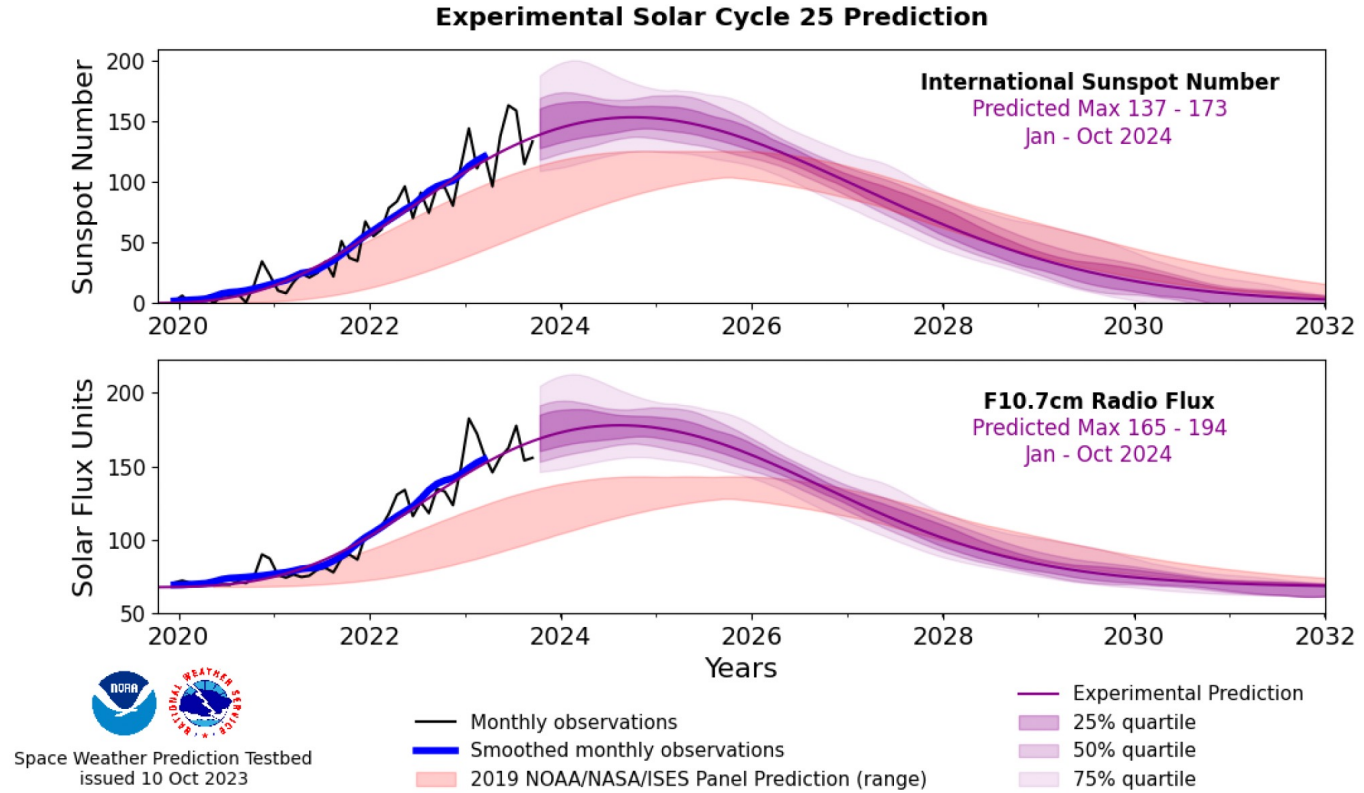
Space Weather Nowcast and Forecast

Tzu-Wei Fang

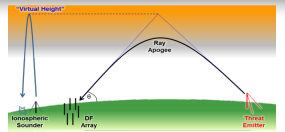
NOAA Space Weather Prediction Center, USA

Safeguarding Society with Actionable Space Weather Information

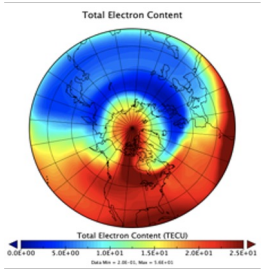
Solar Cycle and Solar Activities



Impact of Space Weather

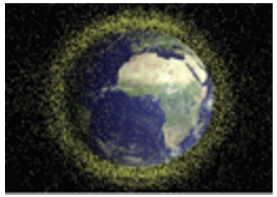


- **For HF communication:**
  - Changes in the Minimum Usable Frequency (LUF) due to D-region absorption (DRAP)
  - Changes in the Maximum Usable Frequency (MUF) associated with negative storm
  - Undulations in bottom-side F-region

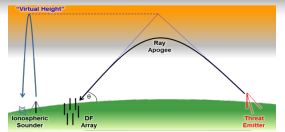


- **For satellite positioning, navigation, timing, and communication:**
  - Mesoscale structure and gradients in plasma density
  - Delay in navigation signal due to line of sight electron content
  - Small-scale ionospheric irregularities causing scintillations/fluctuation or complete loss of signal

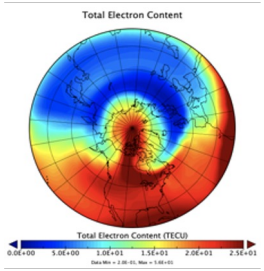
- **For satellite drag**
  - Neutral density and its uncertainty (for decision making, maneuver planning, orbit prediction, collision avoidance)



Impact of Space Weather

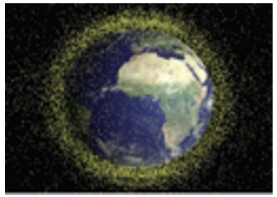


- **For HF communication:**
  - Changes in the Minimum Usable Frequency (LUF) due to D-region absorption (DRAP)
  - Changes in the Maximum Usable Frequency (MUF) associated with negative storm
  - Undulations in bottom-side F-region



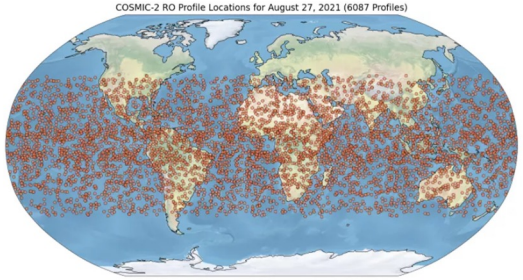
- **For satellite positioning, navigation, timing, and communication:**
  - Mesoscale structure and gradients in plasma density
  - Delay in navigation signal due to line of sight electron content
  - Small-scale ionospheric irregularities causing scintillations/fluctuation or complete loss of signal

- **For satellite drag**
  - Neutral density and its uncertainty (for decision making, maneuver planning, orbit prediction, collision avoidance)

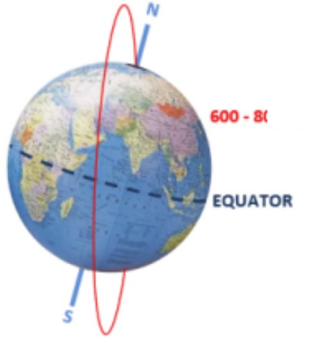


Radio Occultation Constellations and Data

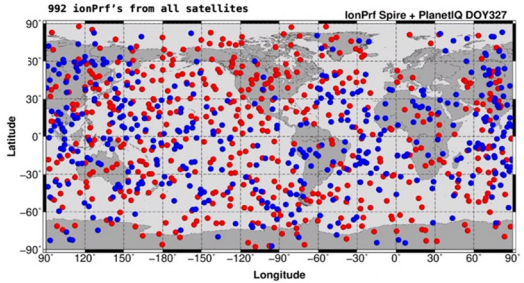
- **FORMOSAT-7/COSMIC-2**
- Achieved full operational capability on October 12, 2021 (Set 1)
- Six remote-sensing smallsats
- Multi-GNSS



- **Spire LEMUR cubesats**
- **PlanetIQ GNOMES microsats**
- Regularly expanding, 150+ satellites
- SSO
- Multi-GNSS



SUN-SYNCHRONOUS ORBIT (SSO)

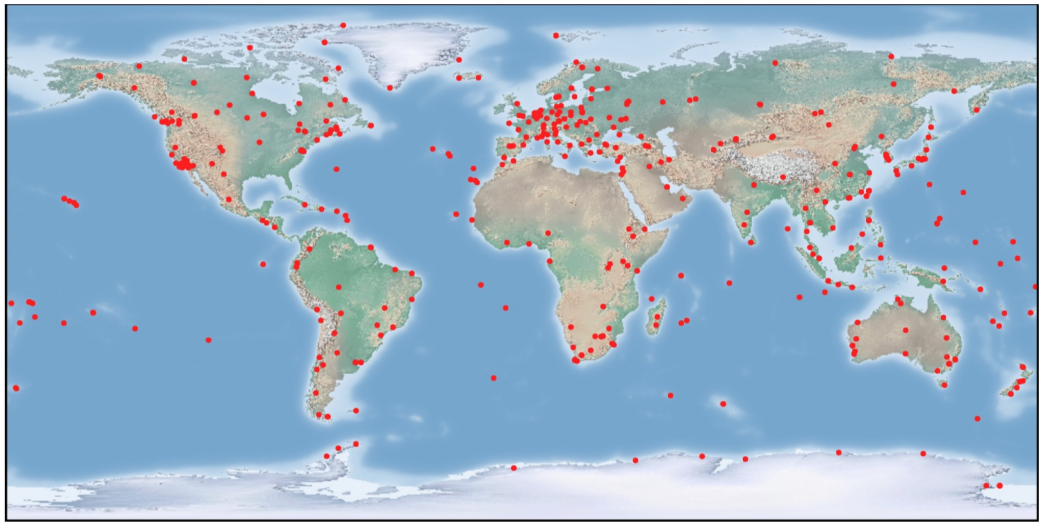


PlanetIQ
Spire

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

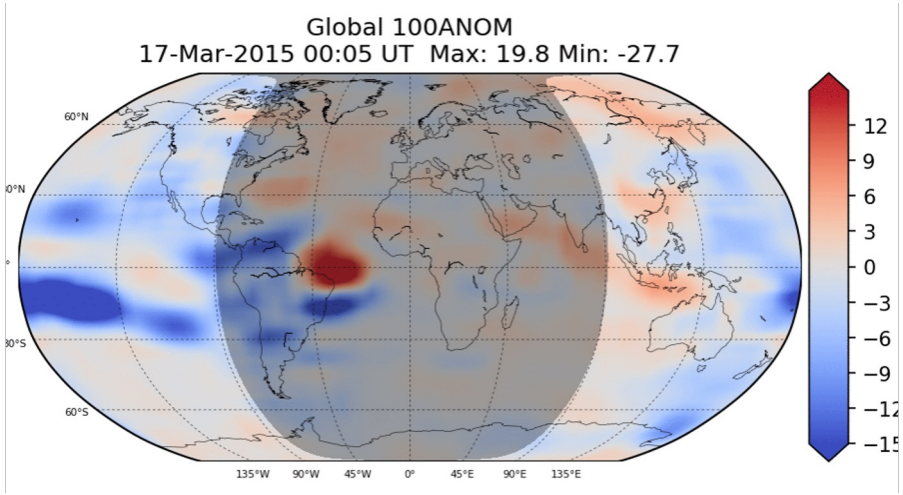
- **Ground GNSS networks - Scintillation:**
  - 50-100 Hz sampling rate
  - Typically newer installations
  - Variable antenna quality
  - Receiver calculated TEC, σ_ϕ, S4 etc.
  - Improved oscillator quality



IGS Stations, 2019

GloTEC

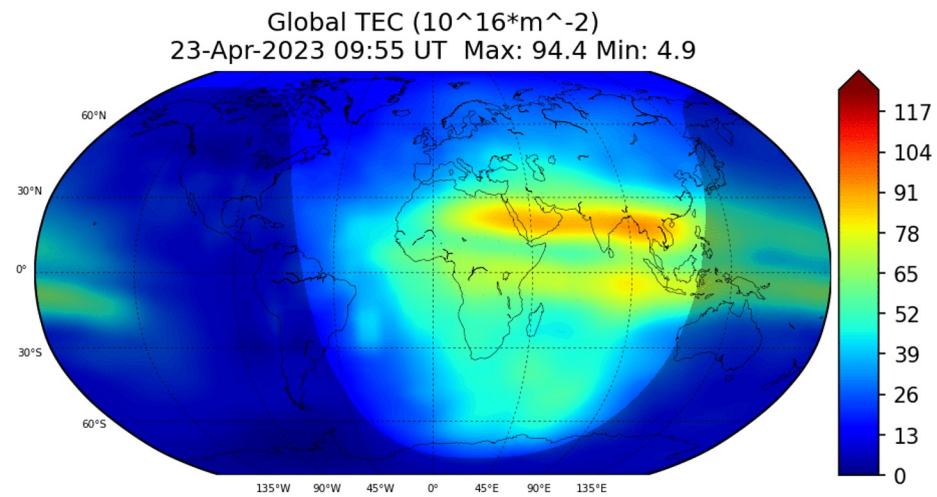
- GloTEC is a data assimilative model that ingests various TEC observations from ground-based and space-based platforms to optimally estimate global 3D electron density.
- The background model is IRI 2016 driven with real-time F10.7.
- Products include specifications for: **VTEC**, **NmF2**, **hmF2**, **MUF3000**, and **ionosphere profiles** that can be used for situational awareness, model validation, and evaluation of new data streams.



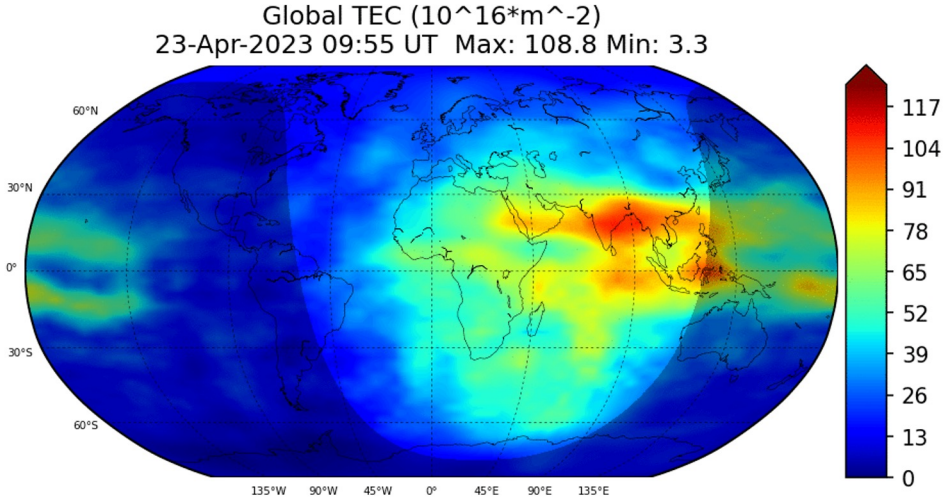
GloTEC VTEC

- GloTEC can ingest STEC from GNSS-RO or even from GNSS-R observations
- Working with UCAR to evaluate usage of commercial RO data
- Customer engagement to ensure these development are meeting customers' needs

A) Ground-stations only

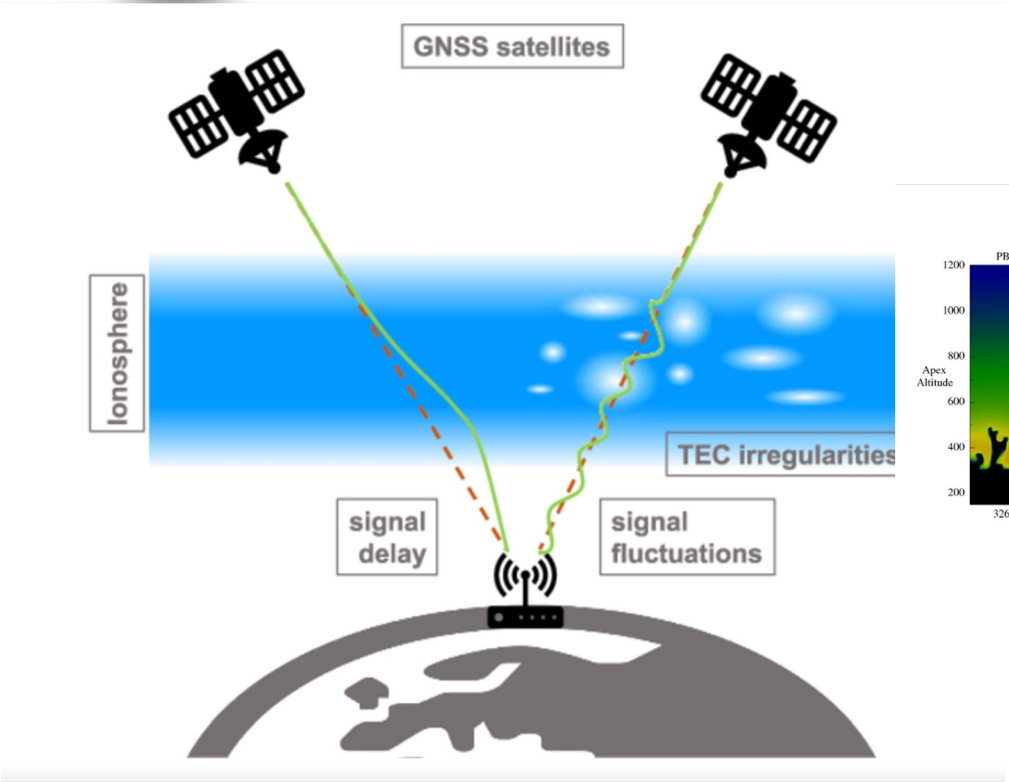


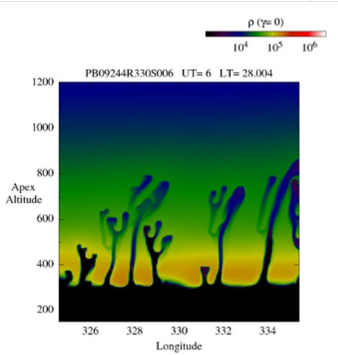
B) Combined ground-stations and RO



GNSS Positioning, Navigation, and Timing (PNT)

and Satellite Communications





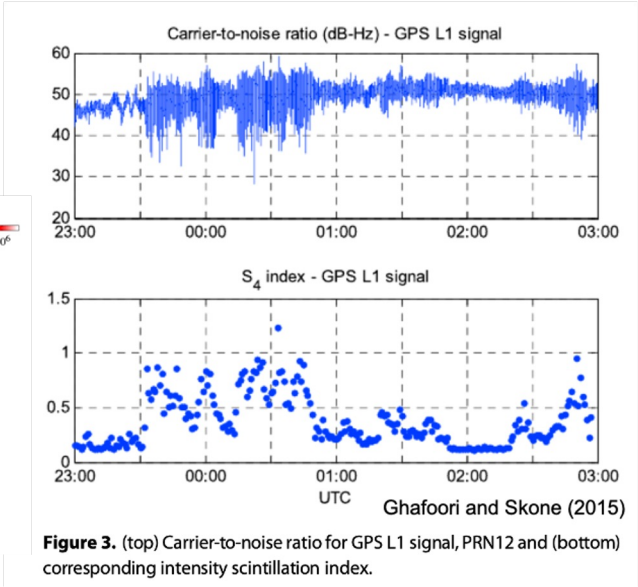
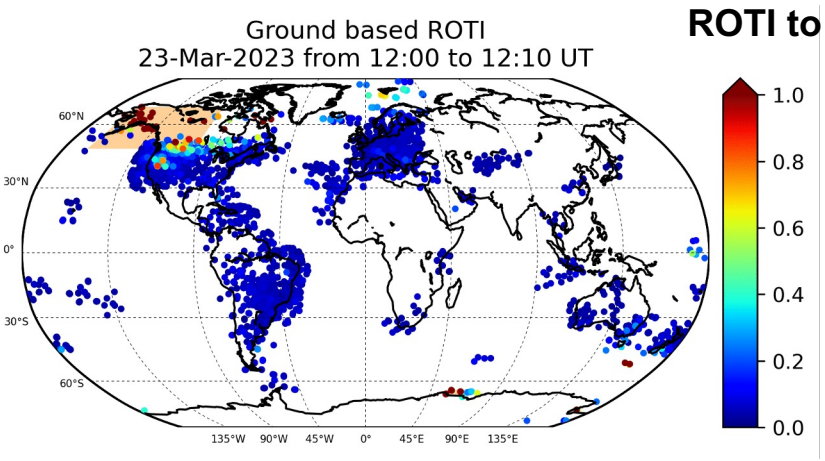


Figure 3. (top) Carrier-to-noise ratio for GPS L1 signal, PRN12 and (bottom) corresponding intensity scintillation index.

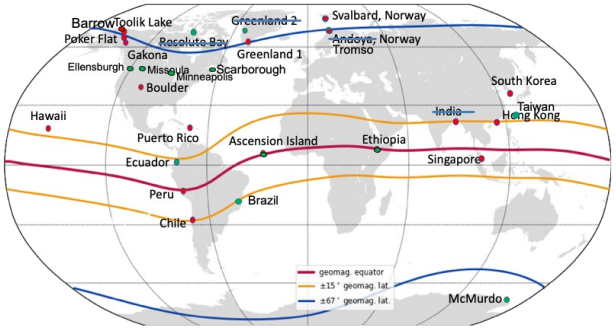
Amplitude scintillation (S4)

Phase scintillation (σ_ϕ)

Rate of TEC Index (ROTI)



Real-time GNSS Scintillation Receivers

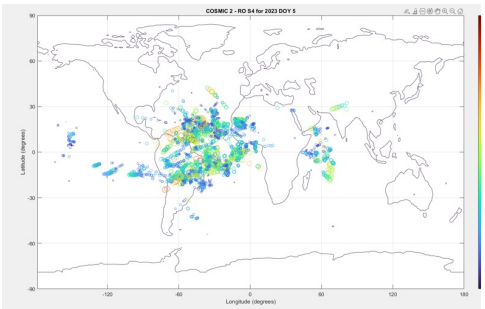


J. Morton

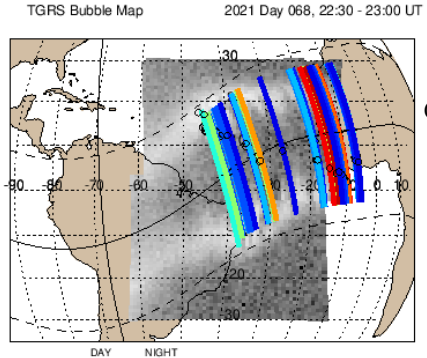
COSMIC-2 and Commercial Scintillation Products

All-Clear

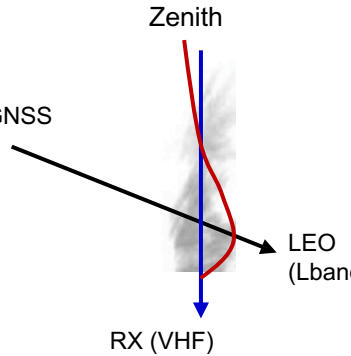
Geolocation



Bubble Map



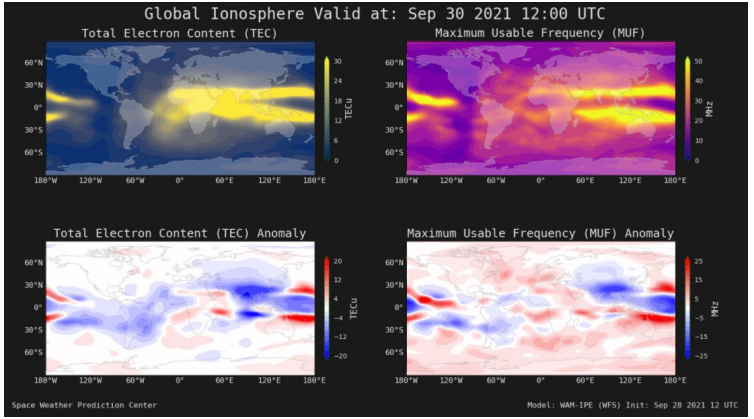
Limb to Disk

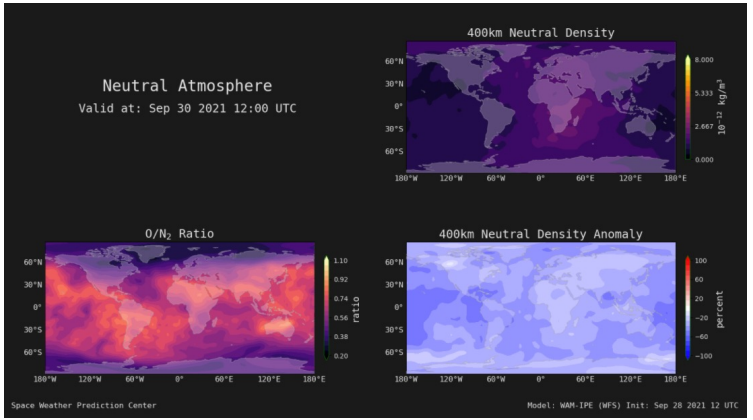


WAM-IPE Operational Model

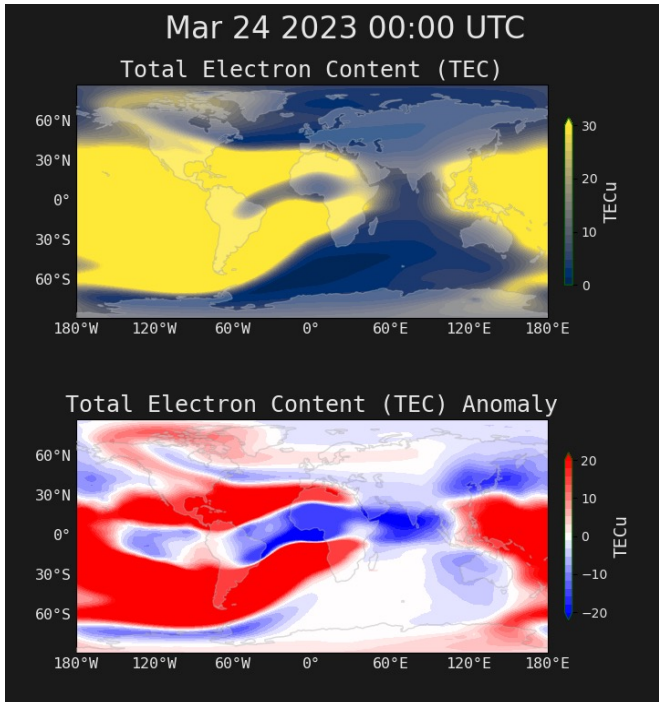
Whole Atmosphere and Ionosphere Plasmasphere Electrodynamics Model

- An extension of the US weather model to 600 km altitude and coupled with a plasma component of the atmosphere.
- Includes all the lower atmosphere weather and dynamics processes, as well as all the additional T-I physics (including electrodynamics and plasma processes)
- WAM provides the 3D fields for neutral winds, temperature, density, major species composition O, O_2, N_2. IPE provides plasma densities and velocities, thermal electron and ion temperatures in the ionosphere and plasmasphere 90 km to ~10,000 km
- WAM-IPE is in operation since July 2021. Two operational CONOPS provide T-I forecast two days in advance as well as nowcast. https://www.swpc.noaa.gov/products/wam-ipe



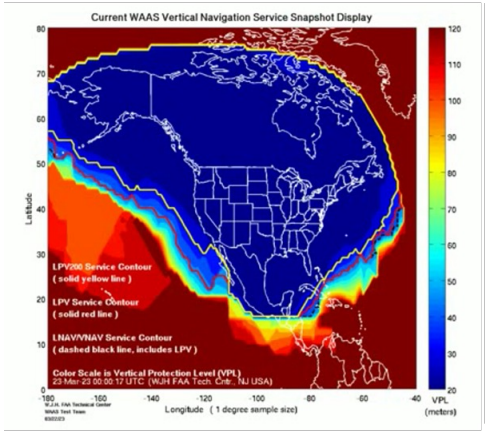


WAM-IPE captures the storm enhanced densities (SED) as it develops over the CONUS. At 00UT on March 24th the SED feature was well developed stretching from north west to south east across CONUS, which coincided with the outage of the WAAS commercial aviation navigation system, and reports of interference in airline satellite communication.



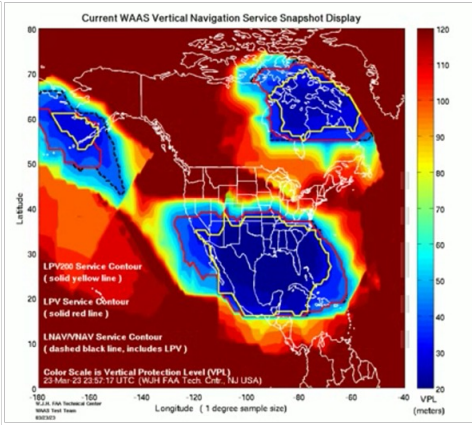
FAA Wide Area Augmentation System

WAAS 23 MAR/0017 UTC



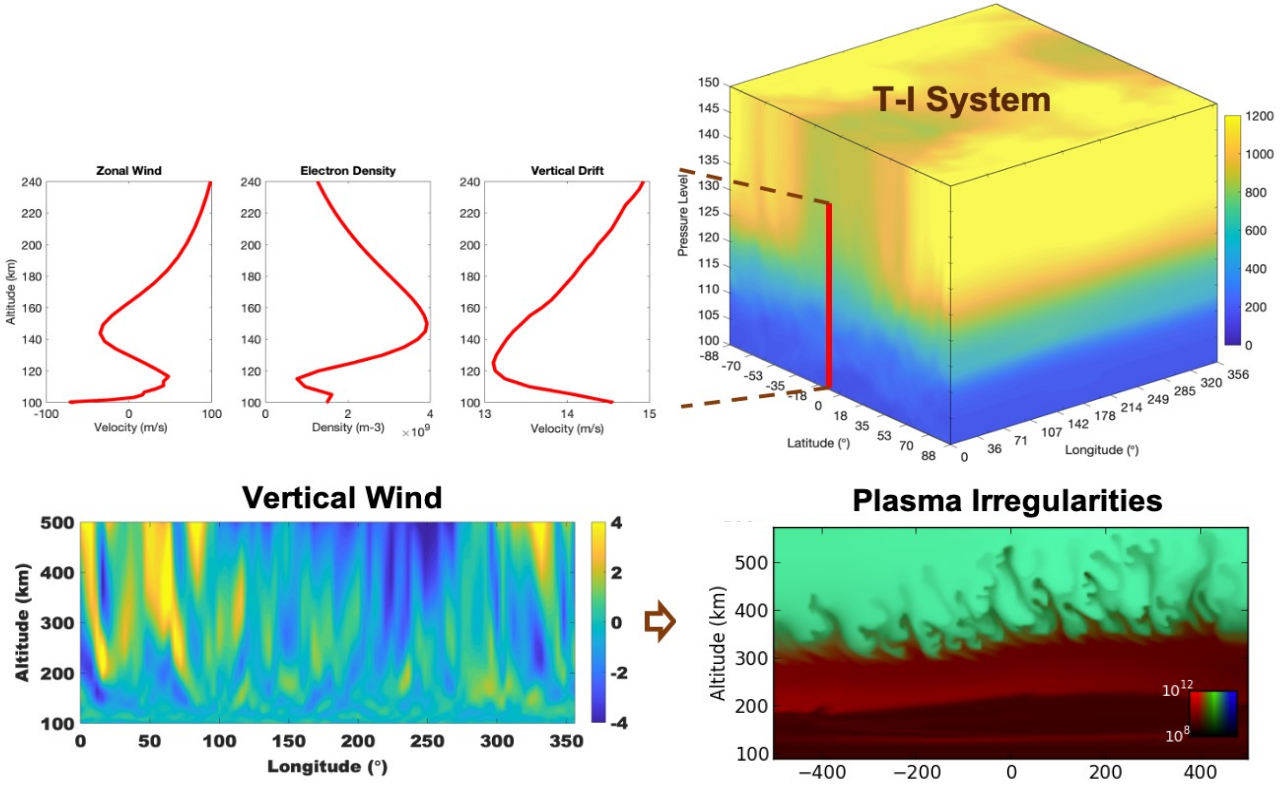
Quiet day before the storm: full WAAS coverage

WAAS 23 Mar/2357UTC



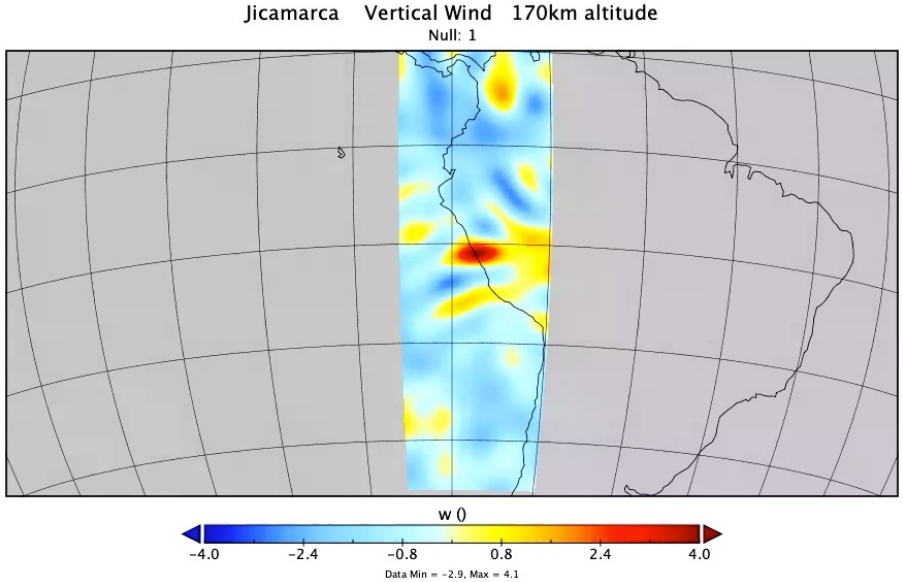
Vertical error limits exceeded over large part of continent due to geomagnetic storm.

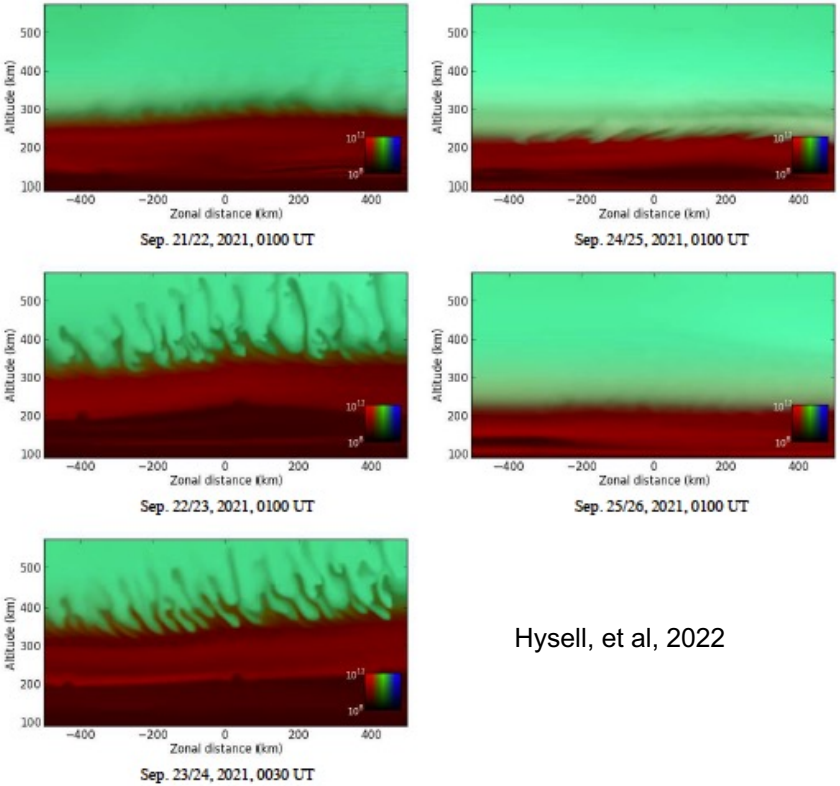
Forecasting the Small-scale Plasma Irregularities



Funded by NSF SWQU AGS 2028032

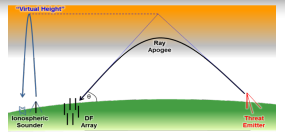
Forecasting the Small-scale Plasma Irregularities



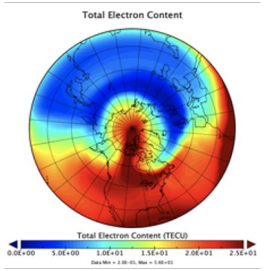


Hysell, et al, 2022

Impact of Space Weather

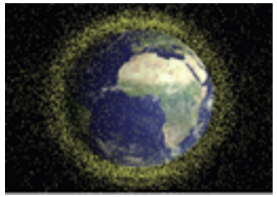


- **For HF communication:**
  - Changes in the Minimum Usable Frequency (LUF) due to D-region absorption (DRAP)
  - Changes in the Maximum Usable Frequency (MUF) associated with negative storm
  - Undulations in bottom-side F-region

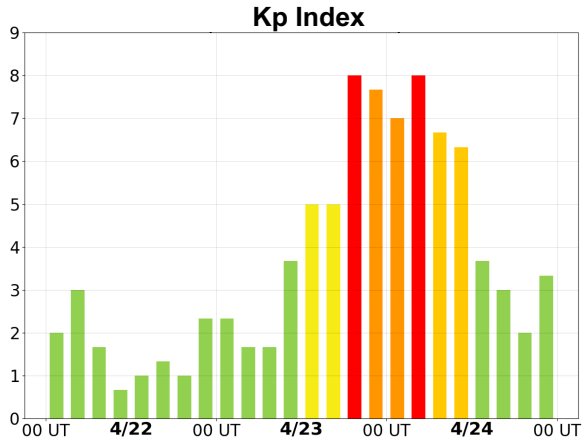


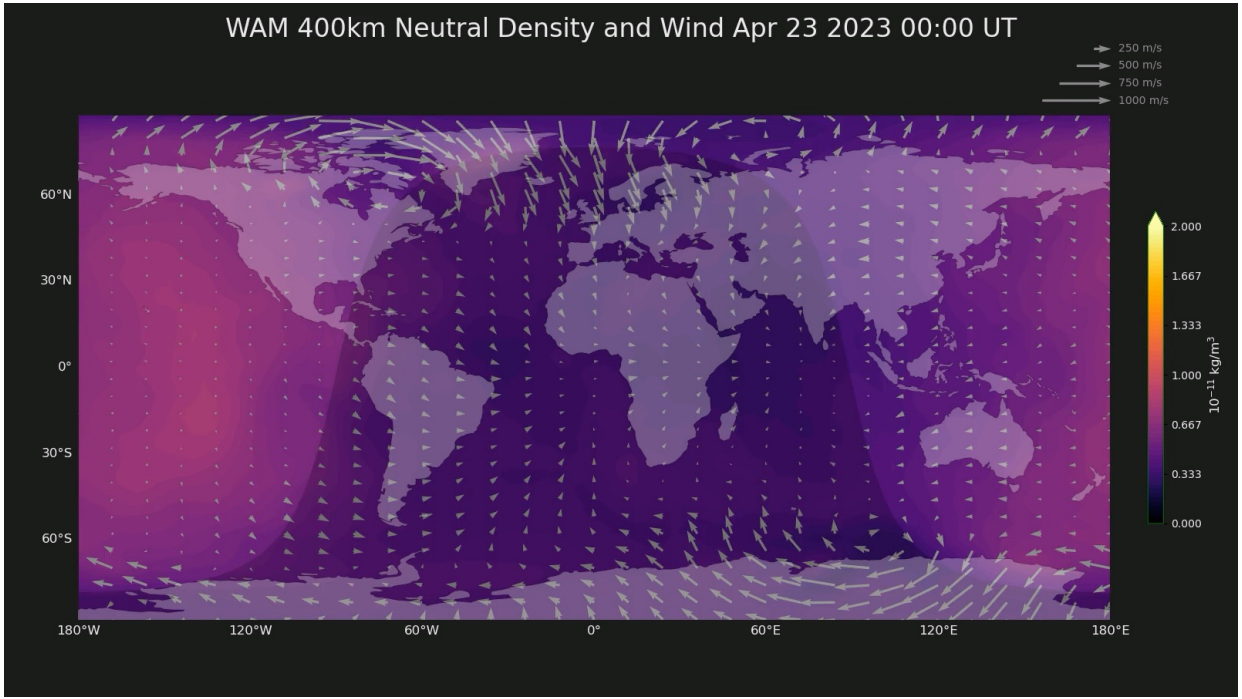
- **For satellite positioning, navigation, timing, and communication:**
  - Mesoscale structure and gradients in plasma density
  - Delay in navigation signal due to line of sight electron content
  - Small-scale ionospheric irregularities causing scintillations/fluctuation or complete loss of signal

- **For satellite drag**
  - Neutral density and its uncertainty (for decision making, maneuver planning, orbit prediction, collision avoidance)

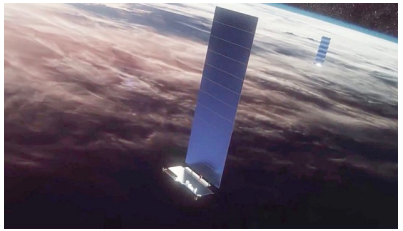


Geomagnetic Storm 23-24 April 2023





Outcomes from SpaceX Starlink Engagement



- Better understanding of the current and future needs of a satellite company that operates a large number of constellations.
- Make space weather forecasts accessible and useful to satellite industries and their operations.
- With Starlink providing one-year satellite ephemeris free of charge and possible continuously low-latency data for real-time operation, an NOAA-funded project to estimate neutral density environment and improve DA system is making great progress.

Space Weather

RESEARCH ARTICLE
10.1029/2022SW003193

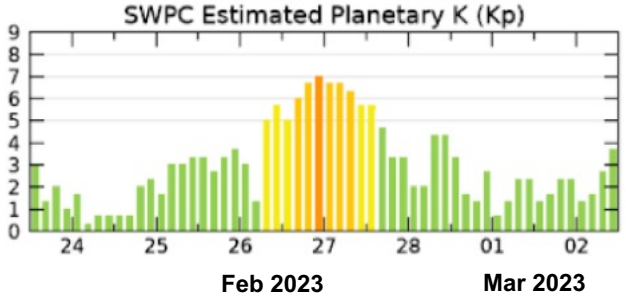
Key Points:

- Geomagnetic storms lead to thermosphere expansion and increase satellite drag
- National Oceanic and Atmospheric Administration's coupled Whole Atmosphere Model and Ionosphere

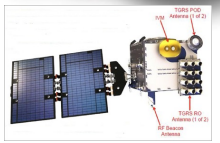
Space Weather Environment During the SpaceX Starlink Satellite Loss in February 2022

Tzu-Wei Fang[1], Adam Kubaryk[1,2], David Goldstein[3], Zhuxiao Li[1,2], Tim Fuller-Rowell[1,2], George Millward[1,2], Howard J. Singer[1], Robert Steenburgh[1], Solomon Westerman[3], and Erik Babcock[3]

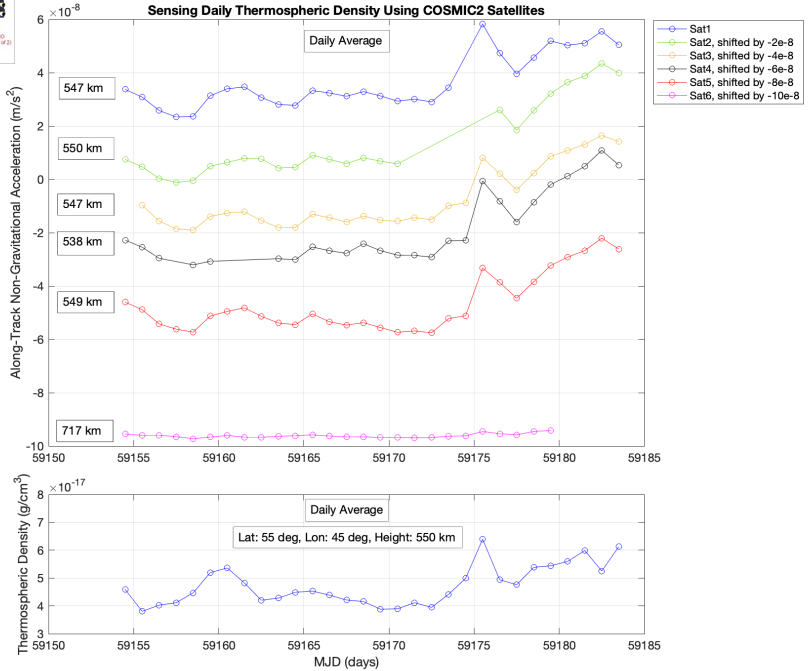
[1]NOAA Space Weather Prediction Center, Boulder, CO, USA, [2]CIRES, University of Colorado Boulder, Boulder, CO, USA, [3]SpaceX Starlink, Hawthorne, CA, USA



Neutral Density Estimation

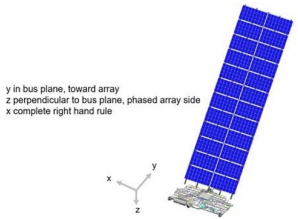


COSMIC-2 Mission

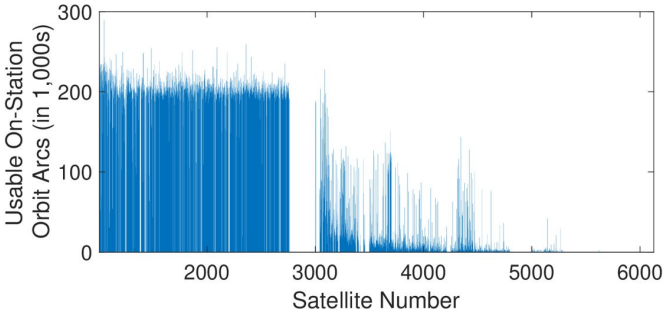


Courtesy of Jian Yao and COSMIC Team

SpaceX Starlink

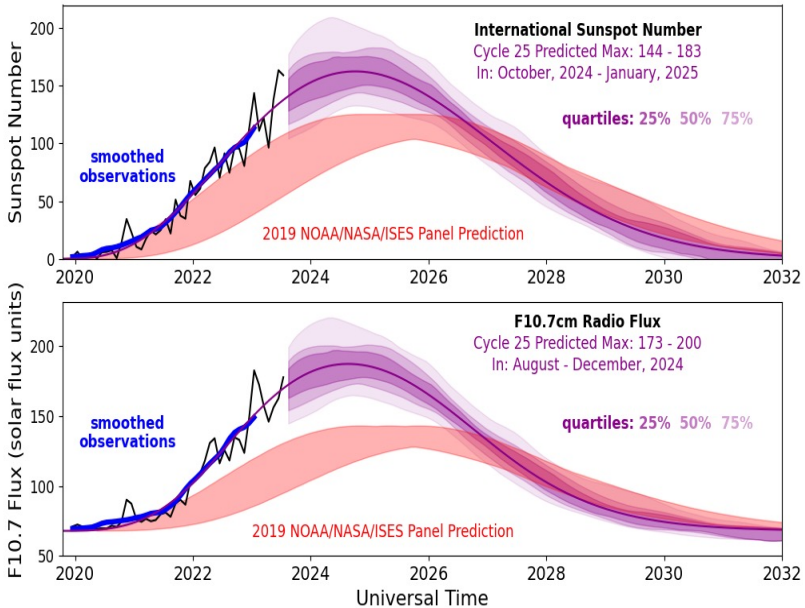


- Position & velocity ephemeris
- Attitude & panel articulation
- Estimated non-conservative accelerations
- Initial satellite geometry
- Time period: April 2022—April 2023
- ~3,900 satellites (v1.0, v1.5, v2-mini)
- ~1 minute cadence
- ~250 GB

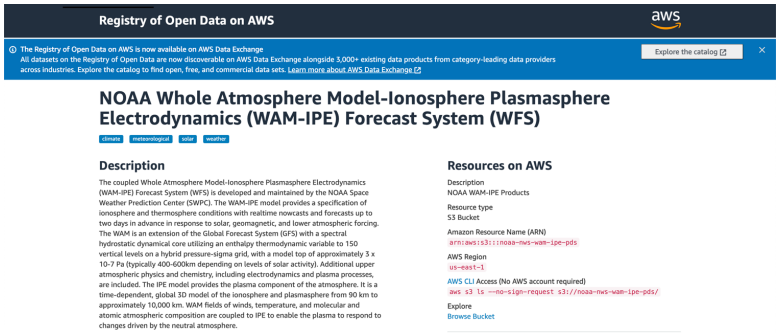


Courtesy of Eric Sutton and the Starlink Team

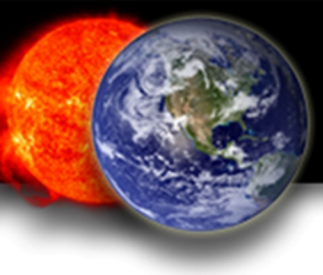
SWPC's Customer Engagement



https://registry.opendata.aws/noaa-nws-wam-ipe/



Space Weather Testbed Exercise with Satellite Industry



Questions and Feedback?

Tzu-Wei.Fang@noaa.gov