

Thermosphere and Ionosphere Products and Services at NOAA SWPC

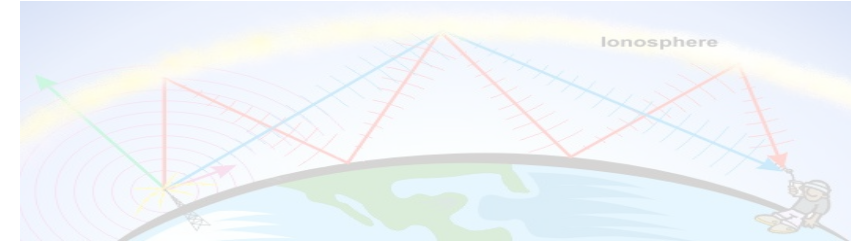
Tzu-Wei Fang

NOAA Space Weather Prediction Center

Why Space Weather Matters?

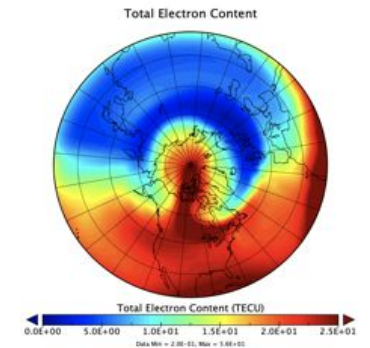
- **For HF communication:**

- Changes in the Minimum Usable Frequency (LUF) due to D-region absorption (DRAP)
- Changes in the Maximum Usable Frequency (MUF) due to the peak plasma density (NmF2) and height of peak (hmF2)
- Undulations in bottom-side F-region



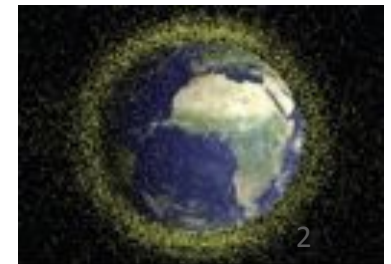
- **For satellite positioning, navigation, timing, and communication:**

- Mesoscale structure and gradients in plasma density (diffract radio signals and cause amplitude or phase fluctuation in GNSS signals)
- Delay in navigation signal due to line of sight electron content (position error)
- Small-scale ionospheric irregularities causing scintillations/fluctuation or complete loss of signal



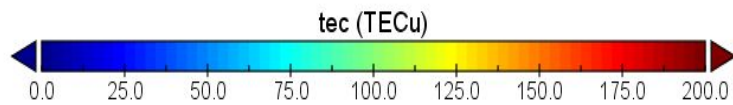
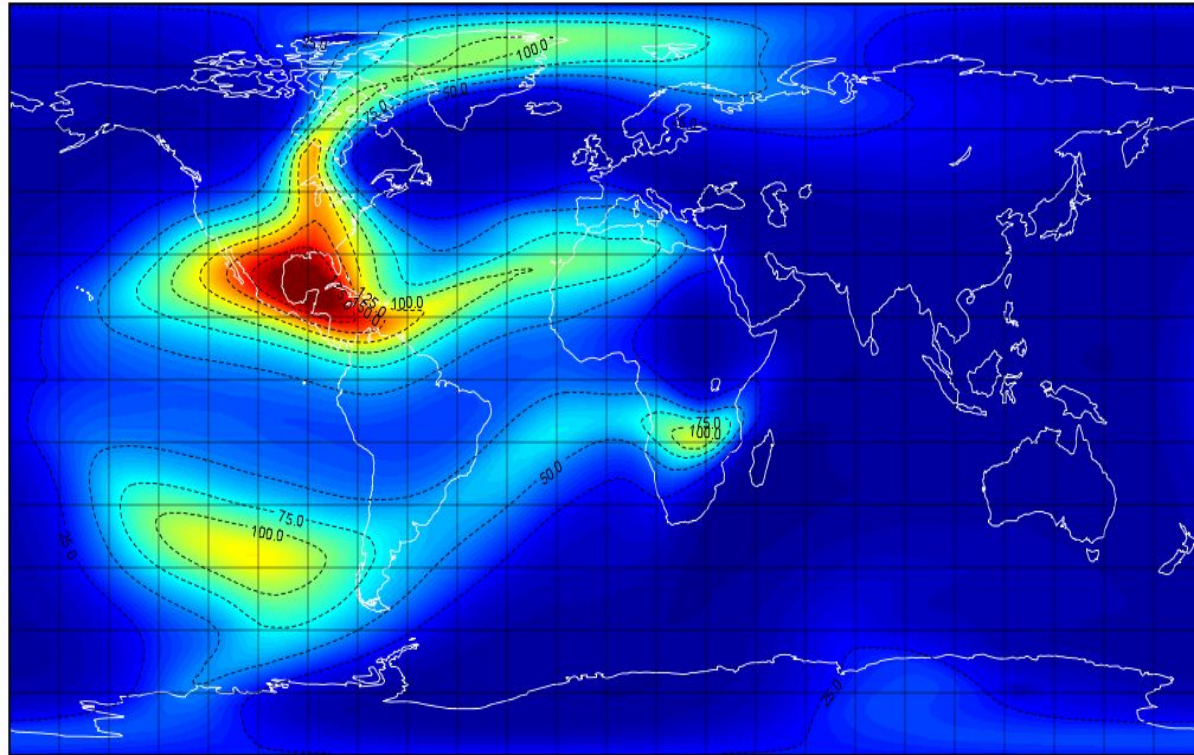
- **For satellite drag**

- Neutral density and its uncertainty (for decision making, maneuver planning)



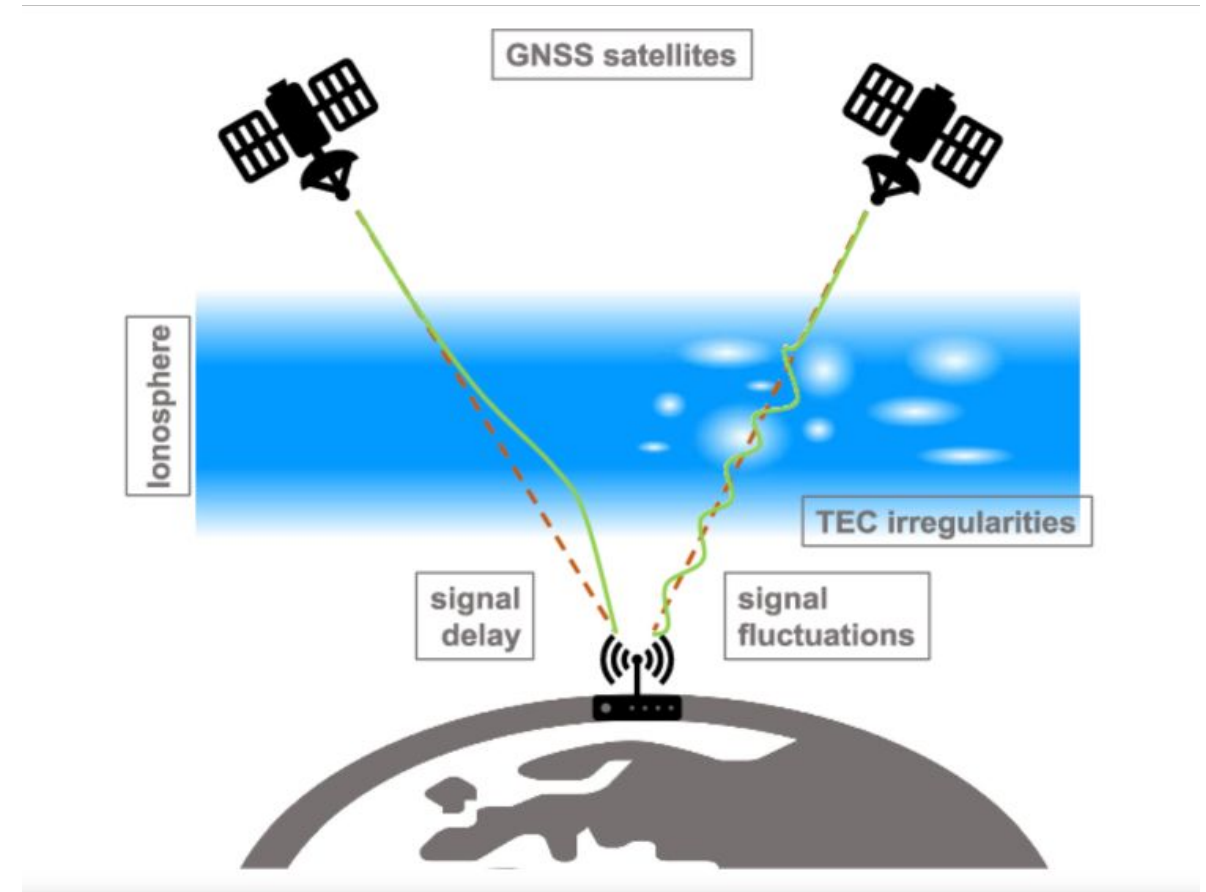
Weather in the Ionosphere

Large Scale



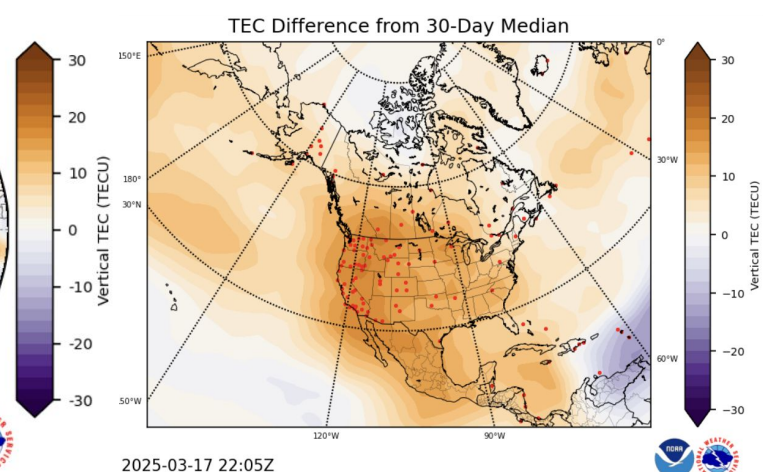
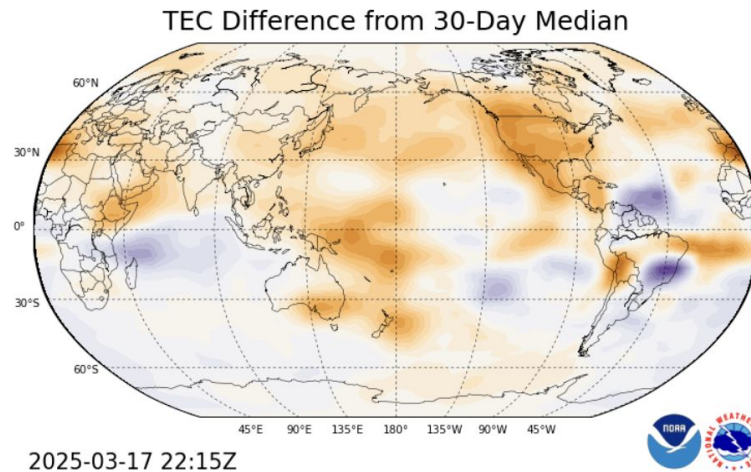
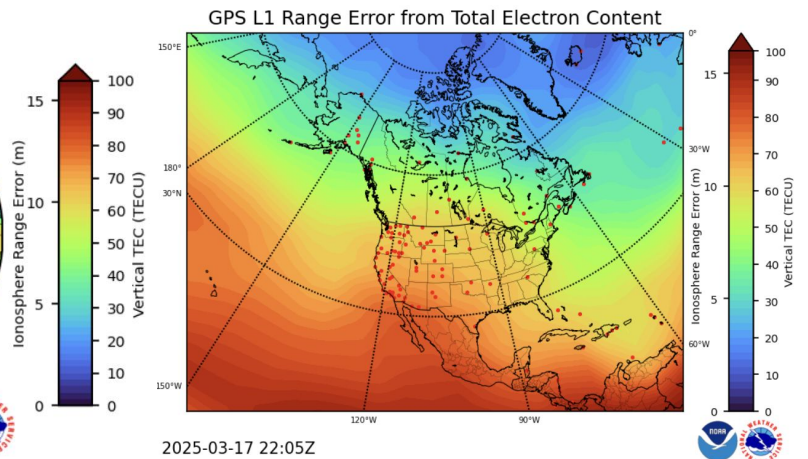
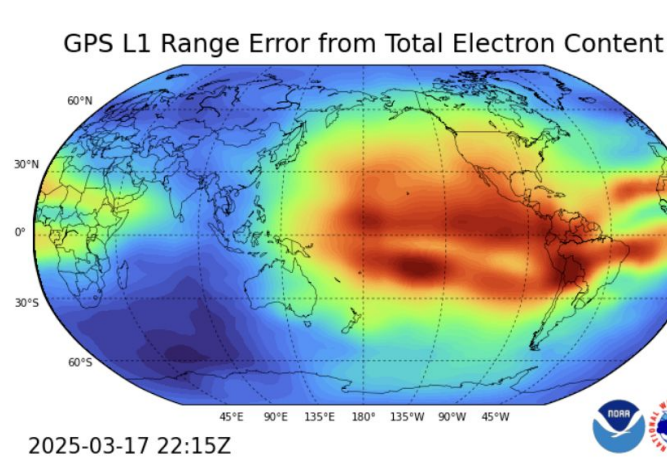
Data Min = 1.8, Max = 219.2, Mean = 32.0

Small Scale



GloTEC - Nowcast

- Global 3D electron density data assimilation, in operation on Feb 2025
- Provide global TEC map is provided on a 2.5° lat and 5° long grid every 10 minutes
- IRI-16 background model
- Data source
 - Real-time ground-based GNSS observations (IGS, UNAVCO, INPE, NRCan, RAMSAC, CDDIS, and more)
 - Real-time Space-based GNSS observations (COSMIC-2 RO)
 - Near future source: commercial RO
 - Possible future source: POD, Google data



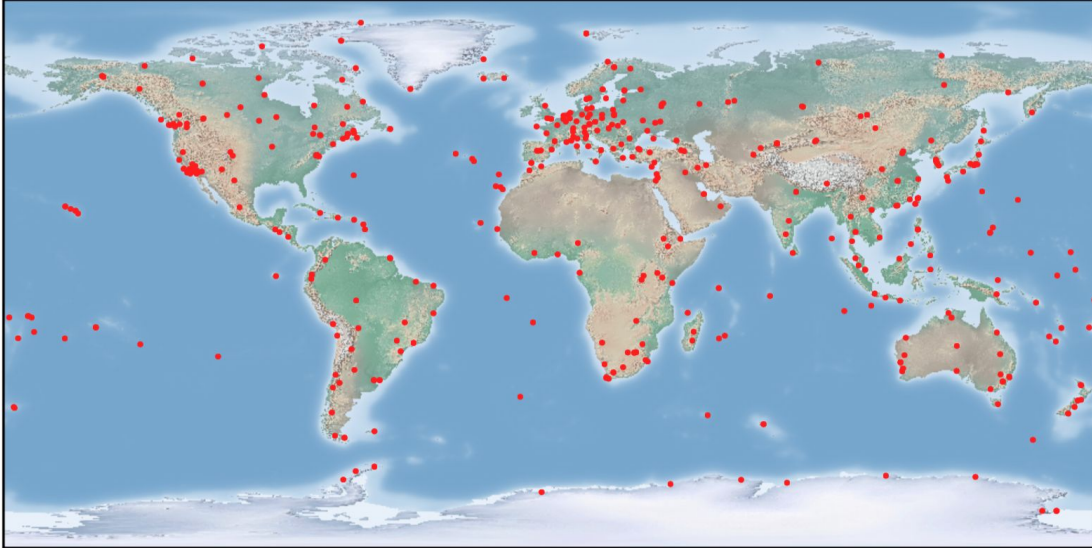
Website: <https://www.swpc.noaa.gov/products/glotec>

NCEI Archive: <https://www.ncei.noaa.gov/products/space-weather/ionospheric-program/total-electron-content>



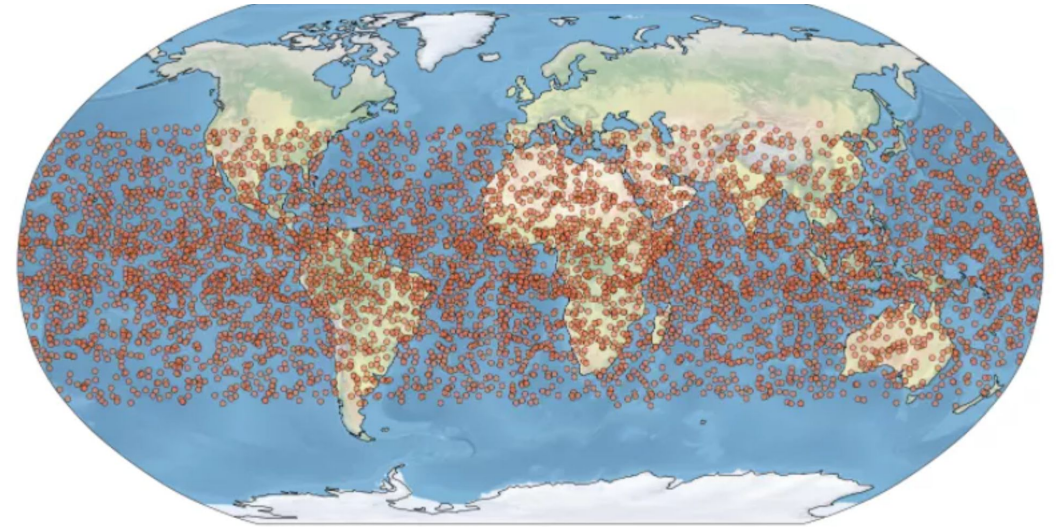
GloTEC Data Sources

Ground-based

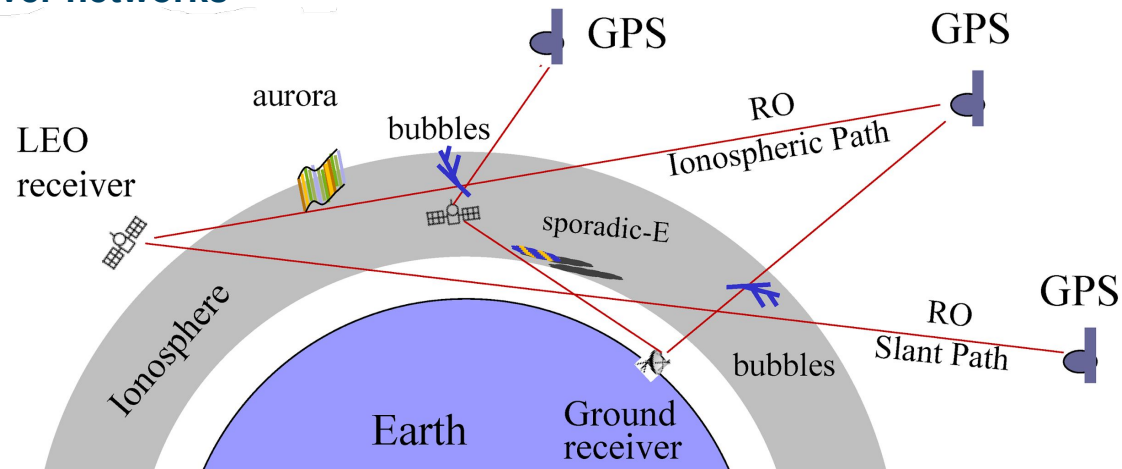


Geodetic ground receiver networks

Space-based (one day)

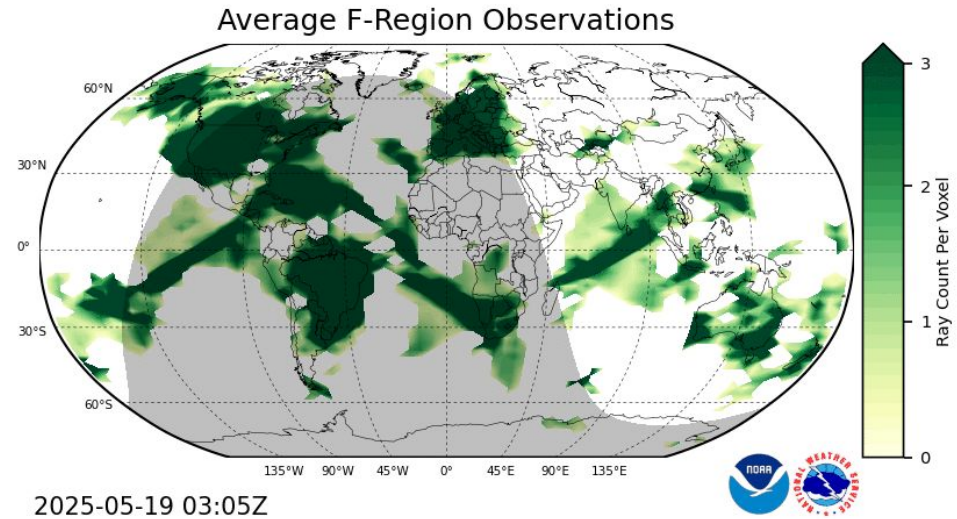


COSMIC-2 radio occultation coverage

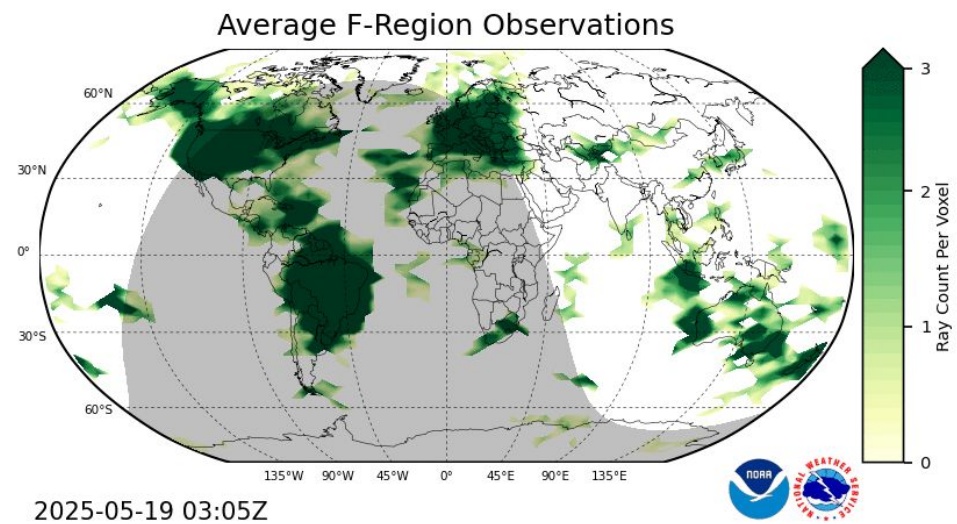


Real-time Space-based Data Coverage

100% data

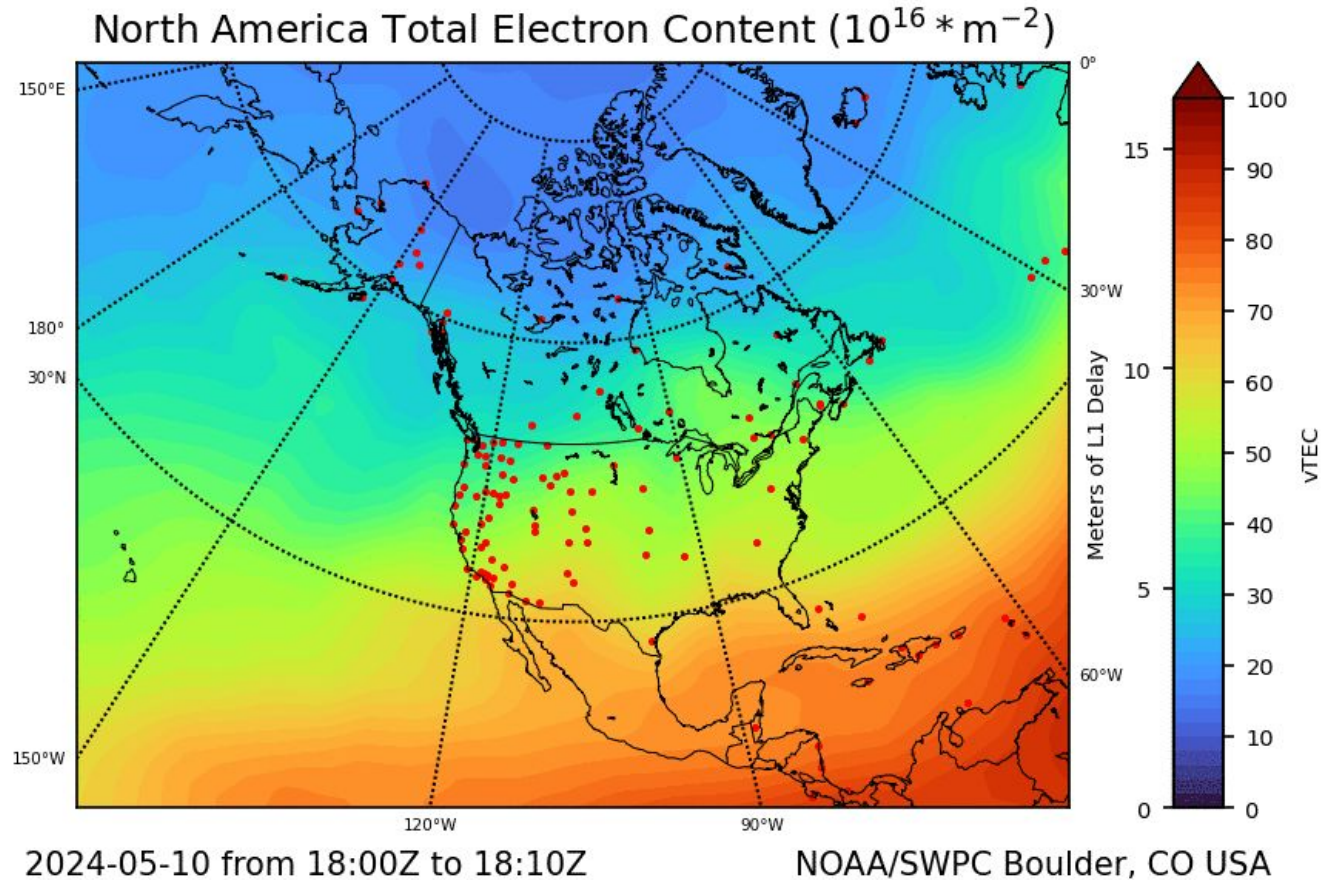


Real-Time (~10%)



Mid-Latitude Ionospheric Storm Enhanced Density

- May 10th Gannon storm response over the CONUS
- Storm onset at ~18:00UT
- Peak TEC observed: ~180 vTECU (nearly 30 meters)
- SED feature with sharp gradient – enhancements next to depletions
- Links to GNSS satellites from a single receiver impacted oppositely
- First order Klobuchar corrections are inadequate
- Tongue of ionization over Canada



SWPC Users and Ongoing Engagements

Aviation Users

- FAA WAAS
- The International Civil Aviation Organization (ICAO)

Space-based PNT (Iridium STL)

Space Industry (SpaceX, Rocket Labs)

Timing Applications (Endrun Technologies)

Receiver Manufactures

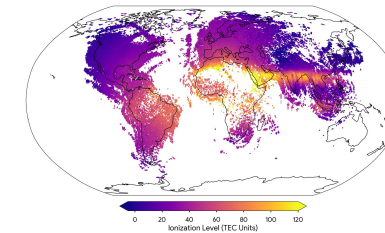
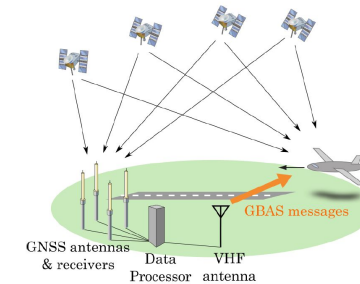
- Hexagon (Novatel)
- Trimble
- Septentrio
- John Deere

Precision Agriculture

Drone Community

DoD Users

Cell Phone Application (Google, Qualcomm, Zepher)



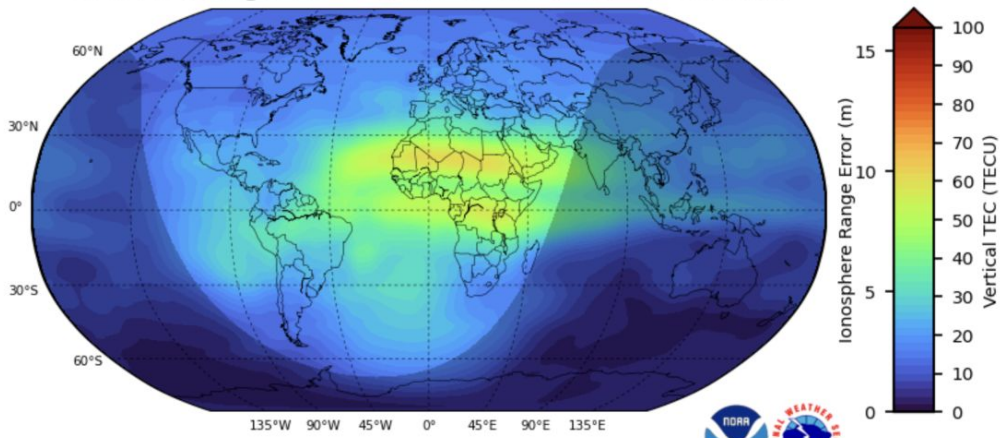


Nowcasting the ionosphere: Evaluating GloTEC for real-time GNSS corrections

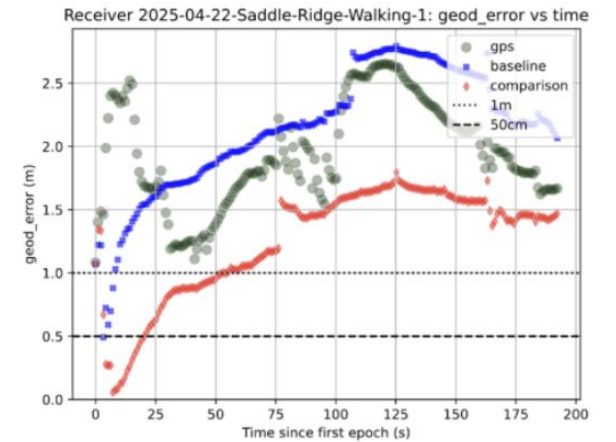
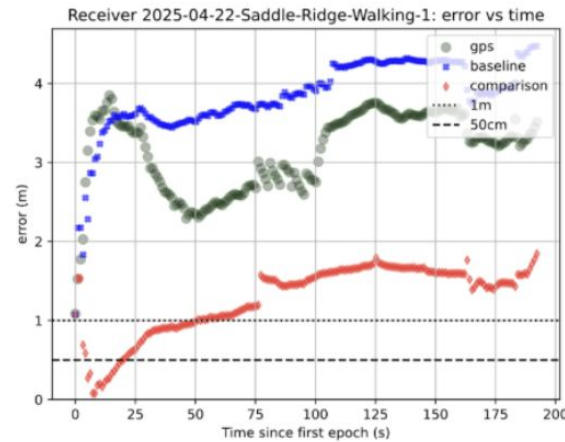
July 14, 2025 - By Sean Gorman

Est. reading time: 4:30

GPS L1 Range Error from Total Electron Content



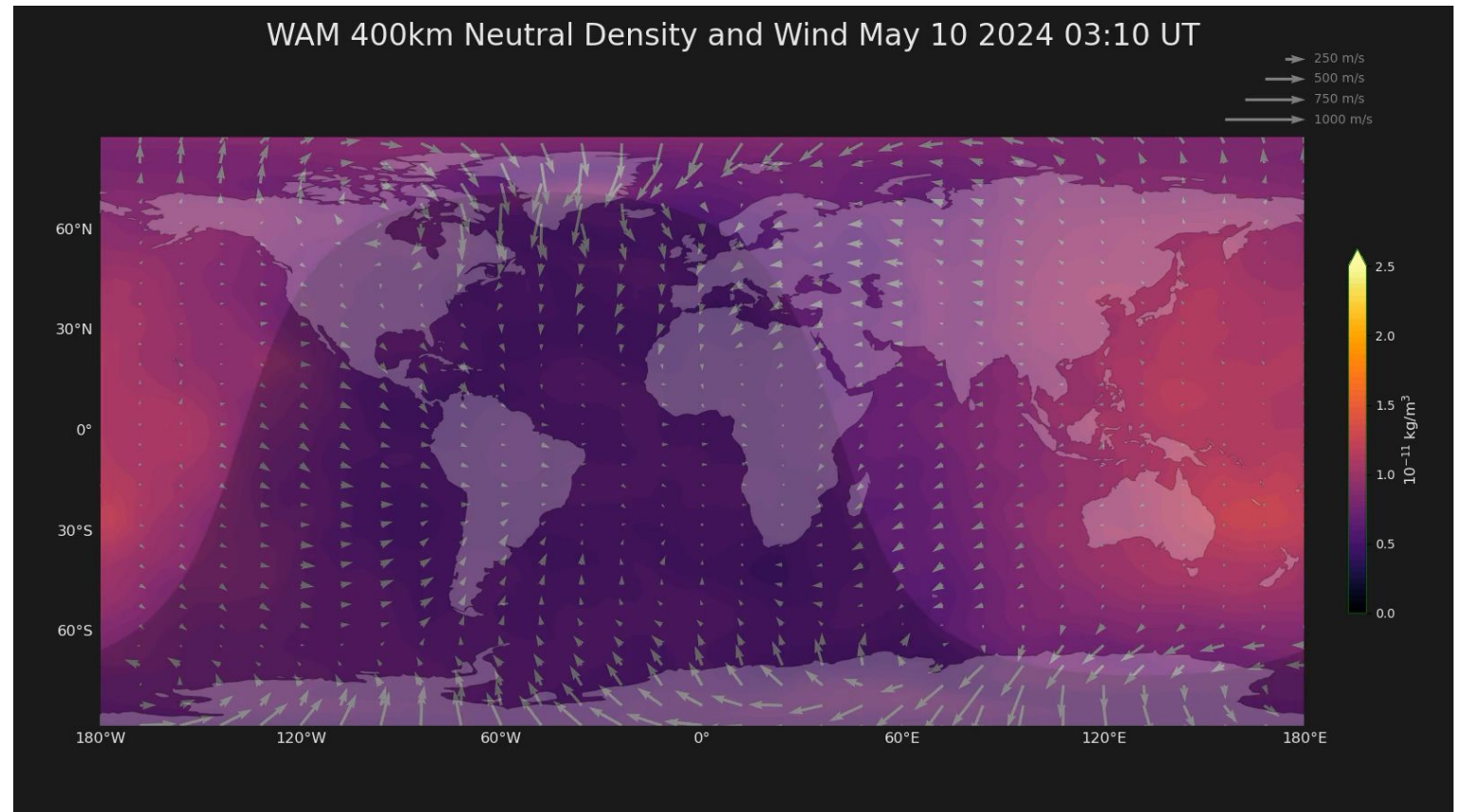
2025-07-14 14:15Z



	3D error (m)	2D error (m)
zephhr + GLOTEC	1.27	1.25
zephhr + predicted CODETEC	3.83	2.13
smartphone GPS	3.14	1.94

WAM-IPE (Whole Atmosphere and Ionosphere Plasmasphere Electrodynamics Model) – Nowcast and Forecast

- Physics-based model include lower atmosphere weather and processes
- WAM provides the 3D fields for neutral winds, temperature, density for drag. The plasma component, IPE, provides plasma densities and velocities, and temperatures in the ionosphere and plasmasphere for communications and navigation impacts
- In operation since July 2021 with the latest upgrade in Aug 2023. Two operational CONOPS provide T-I nowcast as well as forecast two days in advance



<https://www.swpc.noaa.gov/products/wam-ipe>

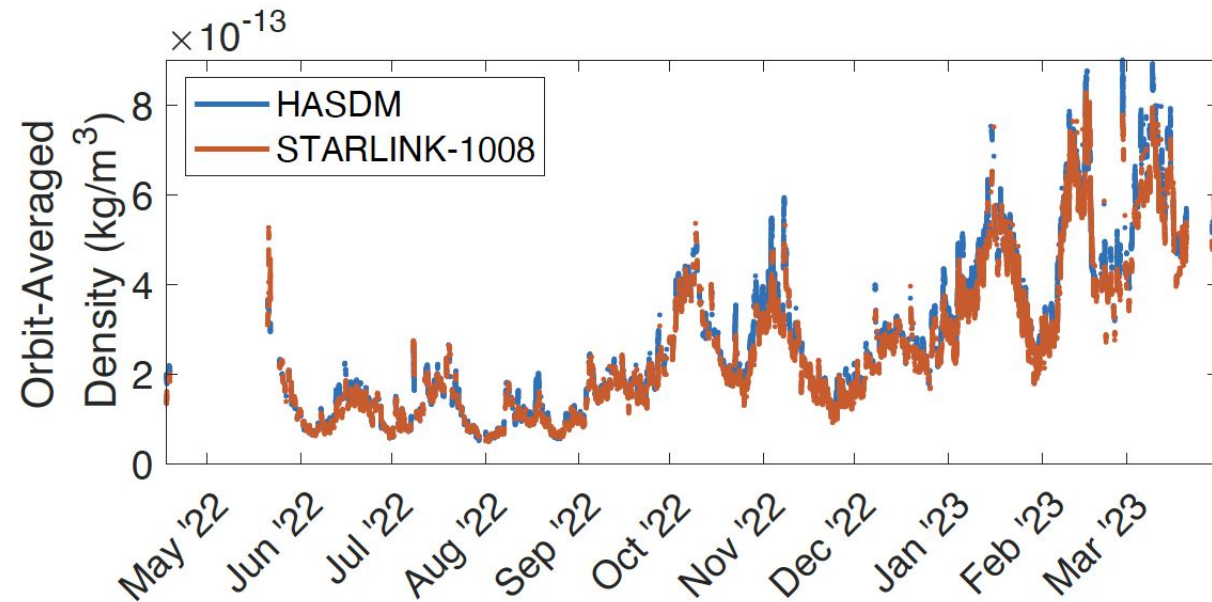


Neutral Density Estimation

Densities from 1 Starlink Satellite

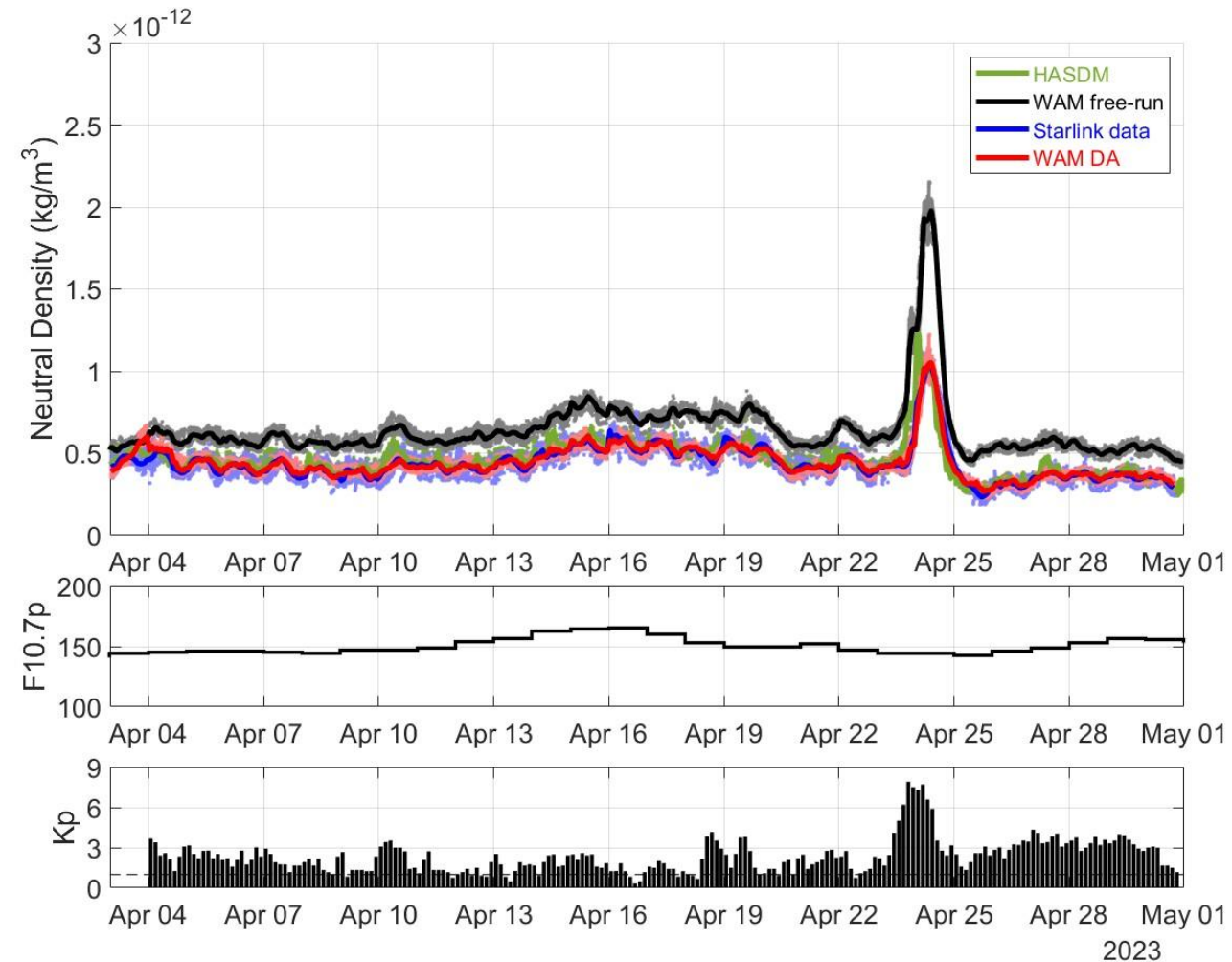
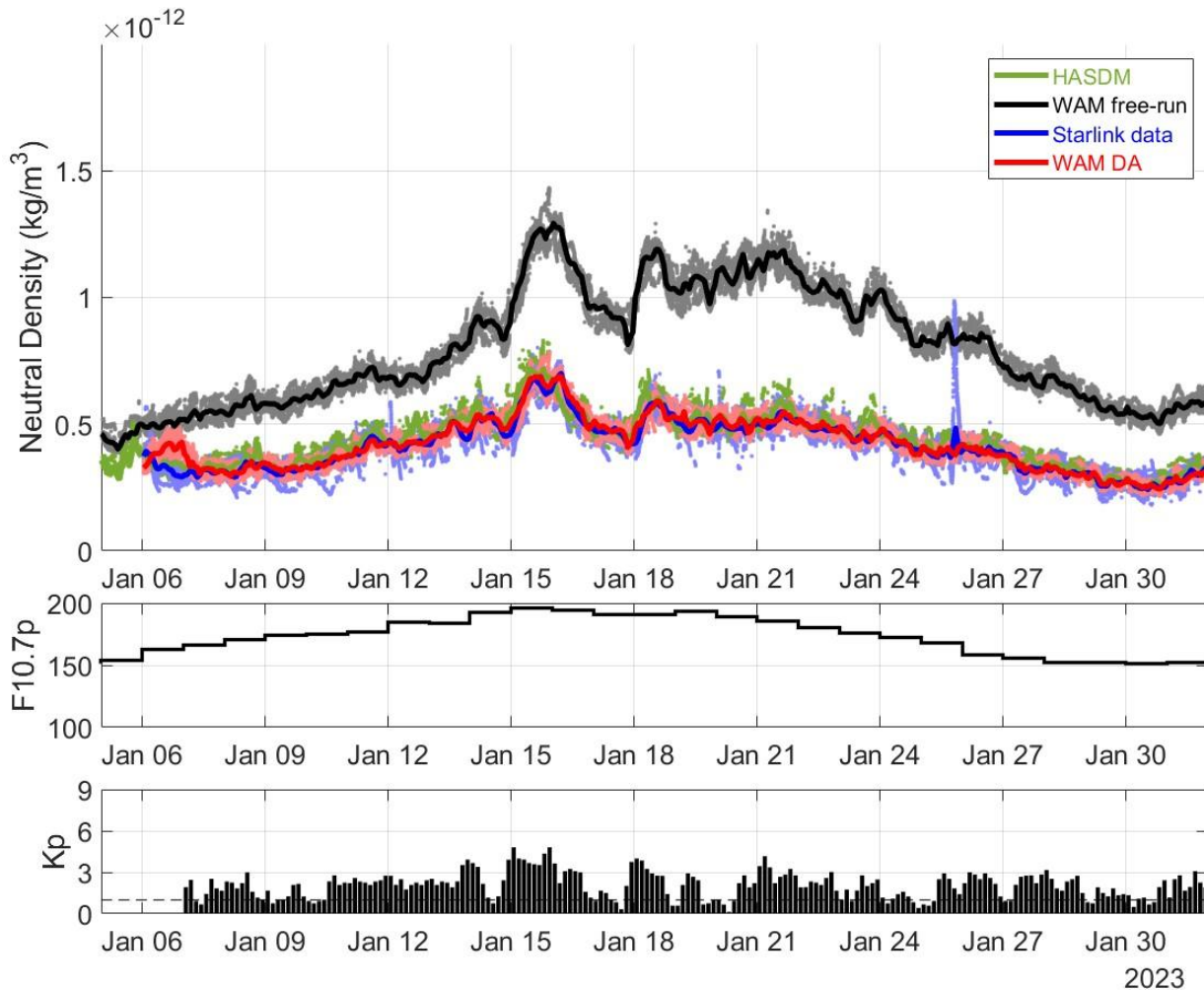
v1.0 densities:

- Very low bias/std with respect to HASDM
- E.g., STARLINK-1008:
Mean Bias (data/model): **-6.5%**
StD (data/model): **11.6%**



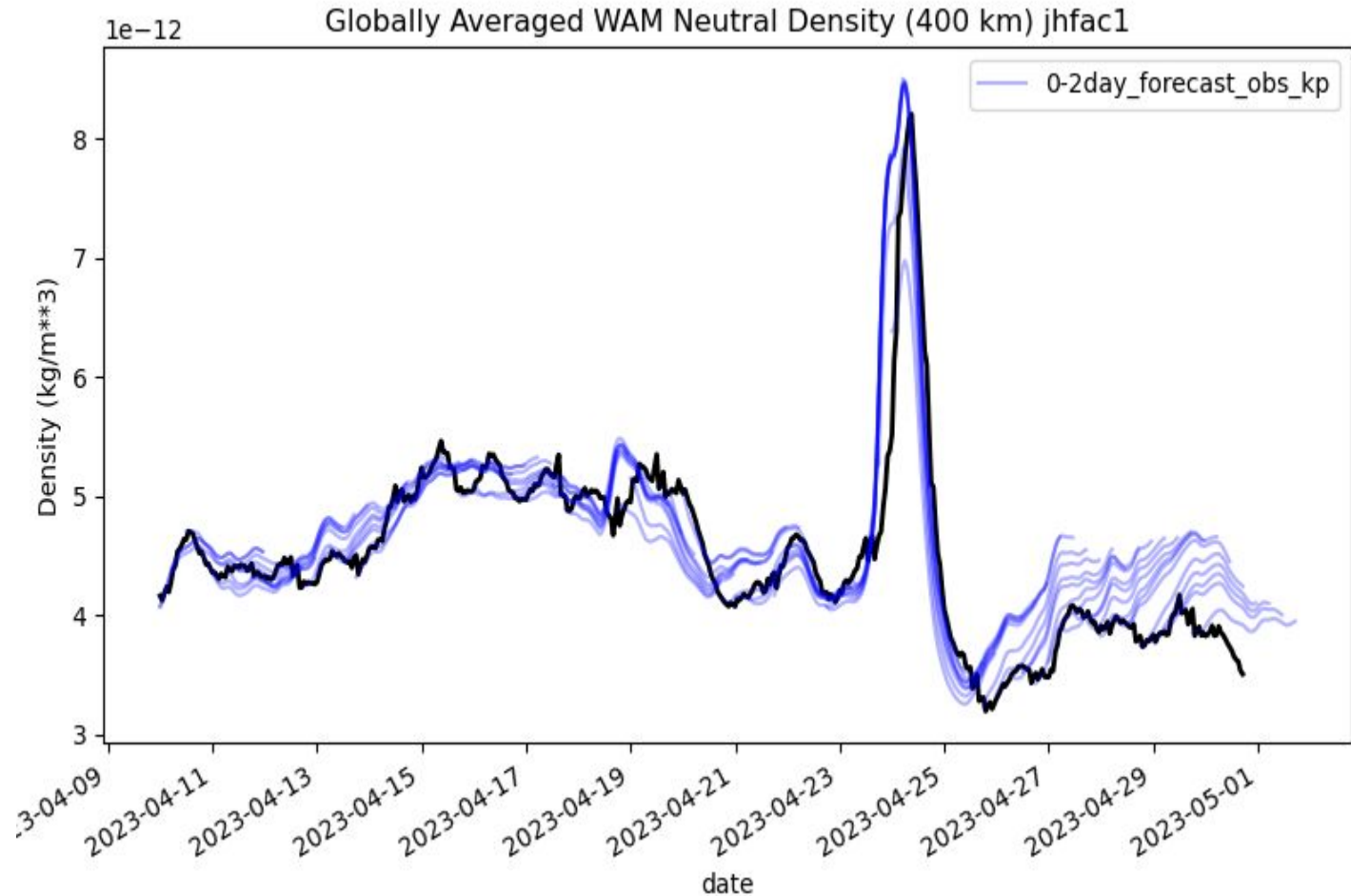
Eric Sutton (CU SWxTREC)

WAM-IDEA Neutral Density Data Assimilation (Nowcast)



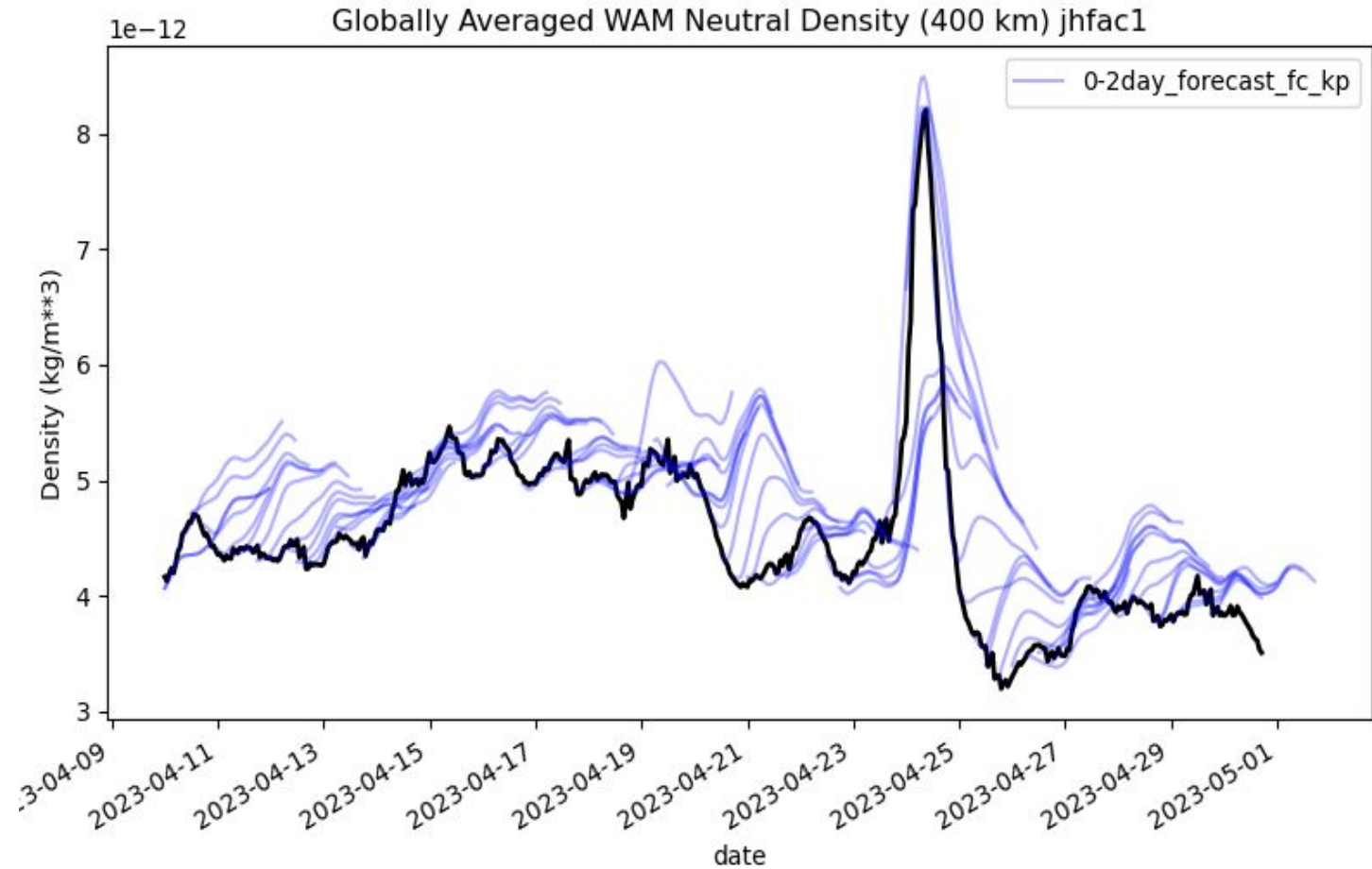
Forecast - Growth in Neutral Density Error with observed Kp

- 24-hr and 48-hr forecasts with new Kp relationship and observed Kp
- Little or no apparent bias in forecast
- RMSE i.e., growth in forecast error, 8.7% at 24 hours and 9.3% at 48 hours (check)
- The final neutral density uncertainty estimates will be the "sum" of the error after DA and the error growth in the forecast



Forecast - Growth in Neutral Density Error with forecast Kp

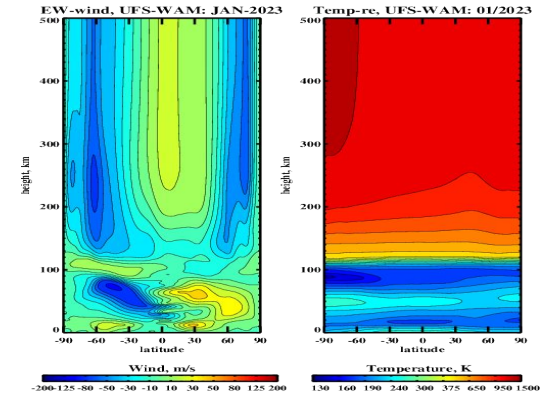
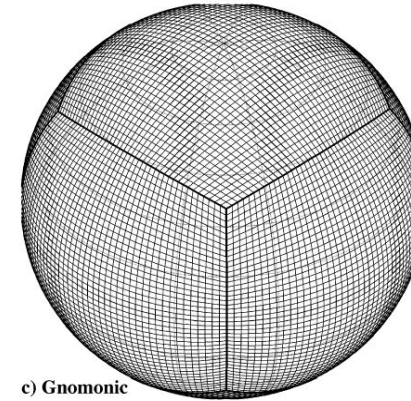
- 24-hr and 48-hr forecasts with new Kp relationship and observed Kp
- Positive bias in forecasts
- RMSE i.e., growth in forecast error
- The final neutral density uncertainty estimates will be the "sum" of the error after DA and the error growth in the forecast



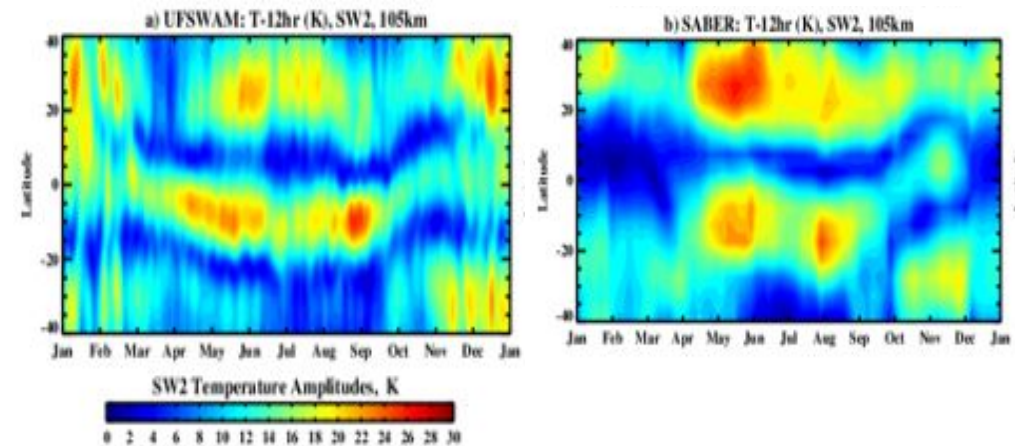
The Future: FV3-WAM for space weather application

Extension of the US weather model to the top of the atmosphere

- Finite Volume, non-hydrostatic, on cubed sphere, dynamical core
- Semi-implicit solver for vertical sound waves
- Multi-gases: separation of dry air to O, O₂, N₂ to enable variable specific heat Cp and gas constant
- Horizontal molecular diffusion
- Variable gravity to allow correct vertical expansion of the atmosphere for impact of neutral density on satellite drag
- 196 layers to top of thermosphere, ~500 km altitude
- Operational configuration planned at C96 horizontal resolution, ~100 km
- JEDI DA framework will be adapted
- Inclusion of upper atmosphere physics, coupling with plasma, solar EUV radiation, and geomagnetic activity

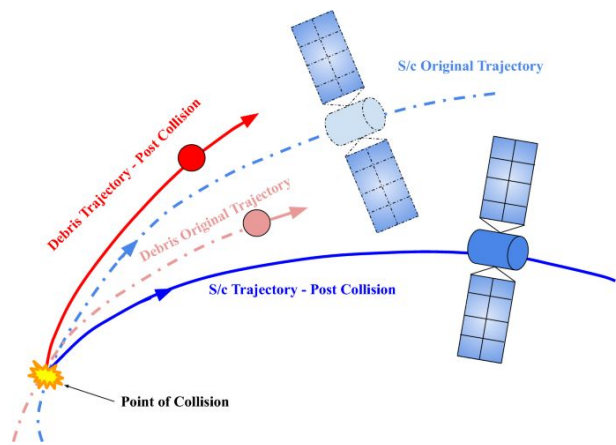


Seasonal variation of tides compared with SABER

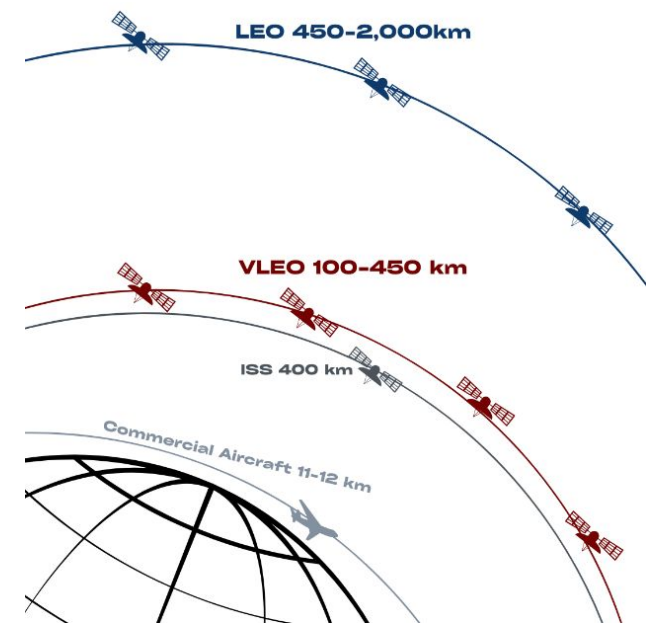
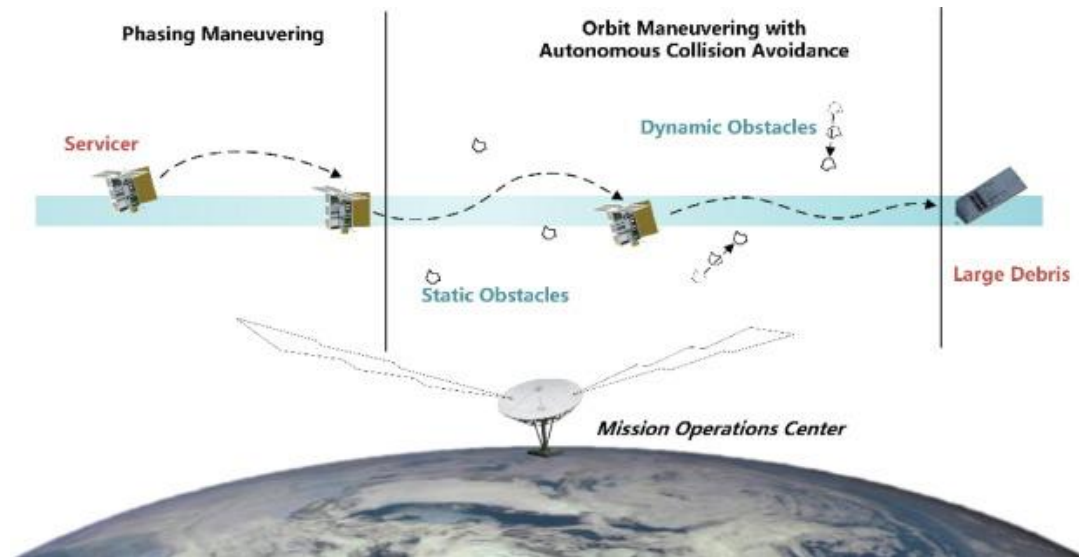


Other SWPC Products for Space Operations

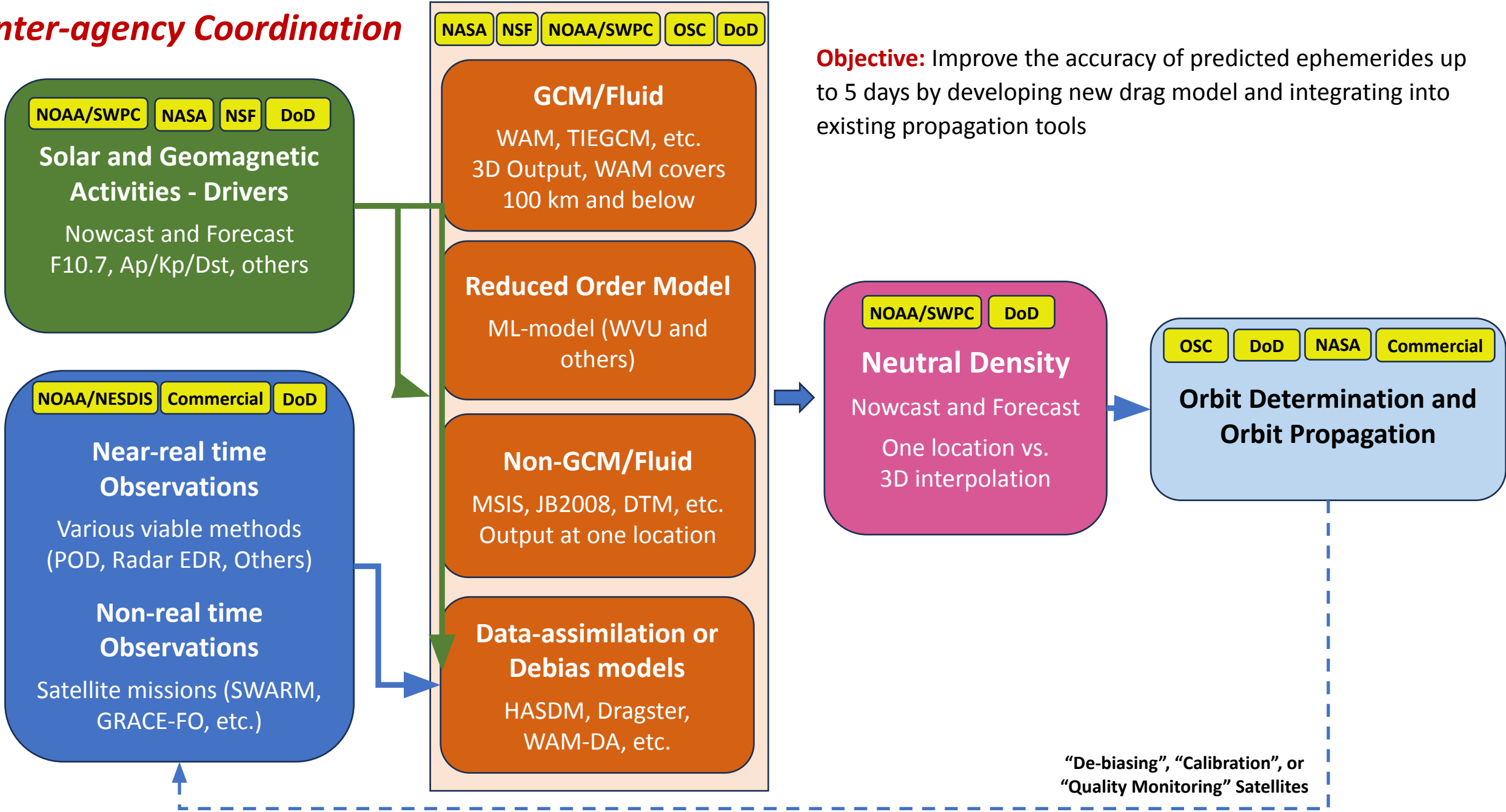
- F10.7 and Kp (Ap) – used in the empirical models for nowcast and forecast
- 3-day and 27-day F10.7 and Kp forecast (<https://celestrak.org/SpaceData/>)
- Geomagnetic storm progression (onset, peak, the end)
- Geomagnetic storm alerts, watches, and warnings
- Monthly updated solar cycle prediction



Conjunction Data Messages (CDM)



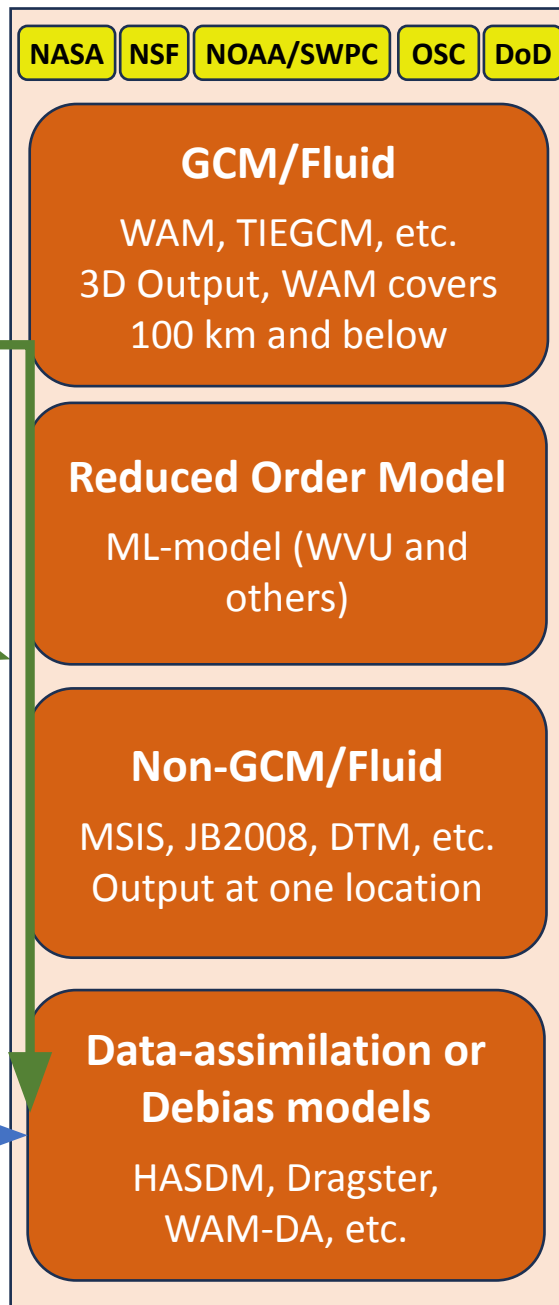
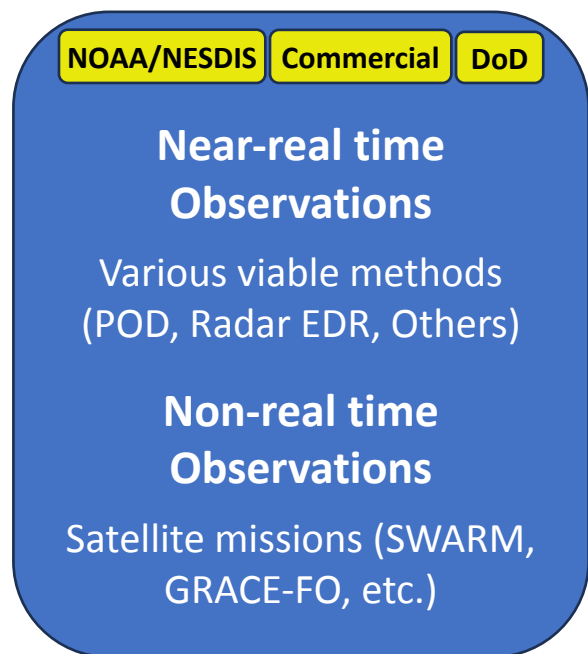
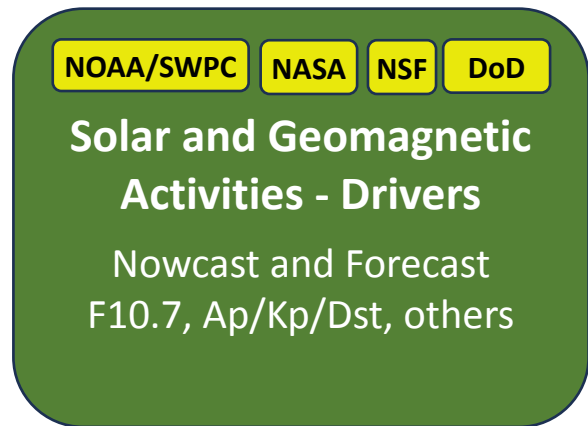
Inter-agency Coordination



Objective: Improve the accuracy of predicted ephemerides up to 5 days by developing new drag model and integrating into existing propagation tools

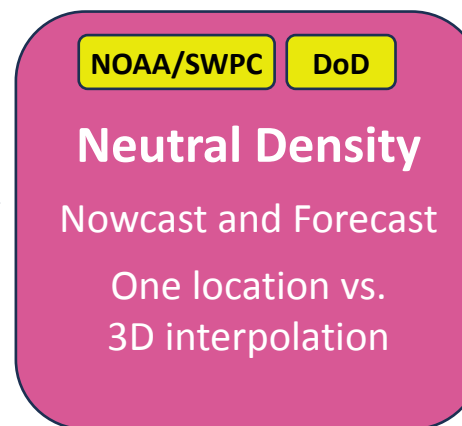
Improvement of SW Drivers

- Forecasting skill
- Driver uncertainties

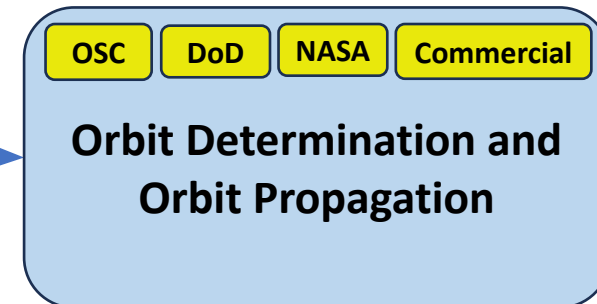


Improvement of model – nowcast and forecast

- Model physics and data enhancement
- Implement DA for better nowcast state estimation
- Better model for better forecast



Steps to integrate with TraCSS or other commercial tools?



Validation through OD/OP

- ODTK and other tools with sufficient objects
- Compare with performance with HASDM
- Correct way to validate with propagated ephemeris

“De-biasing”, “Calibration”, or
“Quality Monitoring” Satellites

Summary

- Future model development and flexible data assimilation system are critical to improve our forecasting skill.
- Data acquisition strategy for ground-based or space-based needs to be identified with a clear roadmap.
- With the rapid growth of the space industry and DoD's needs in the US, enhanced capability in space weather forecasting and impact-based assessment are urgently needed.

