JEDI Goes to Space

First steps in applying an atmospheric data assimilation framework to space weather

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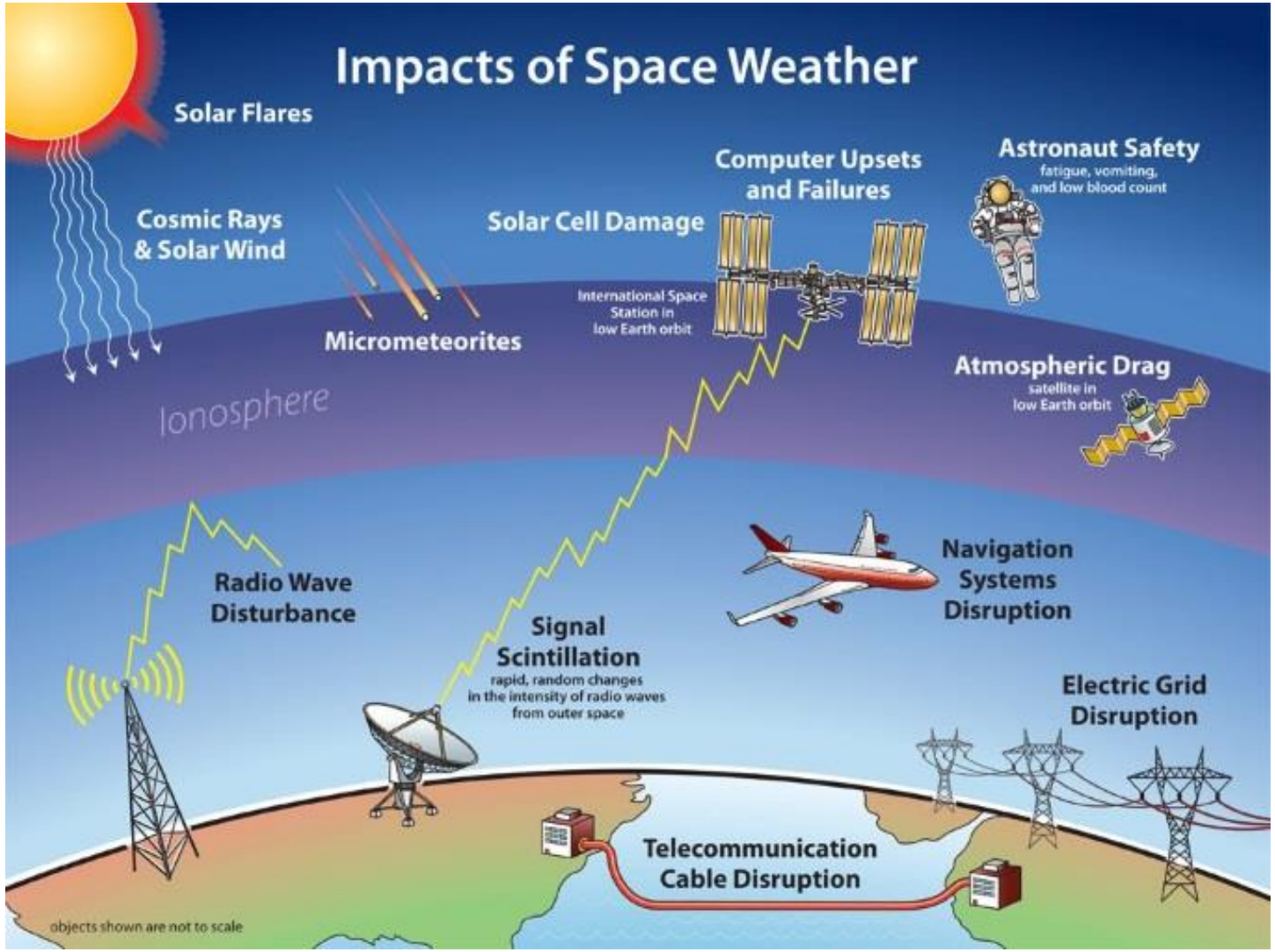
[1]US Naval Research Laboratory

[2]Joint Center for Satellite Data Assimilation

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Importance of space weather

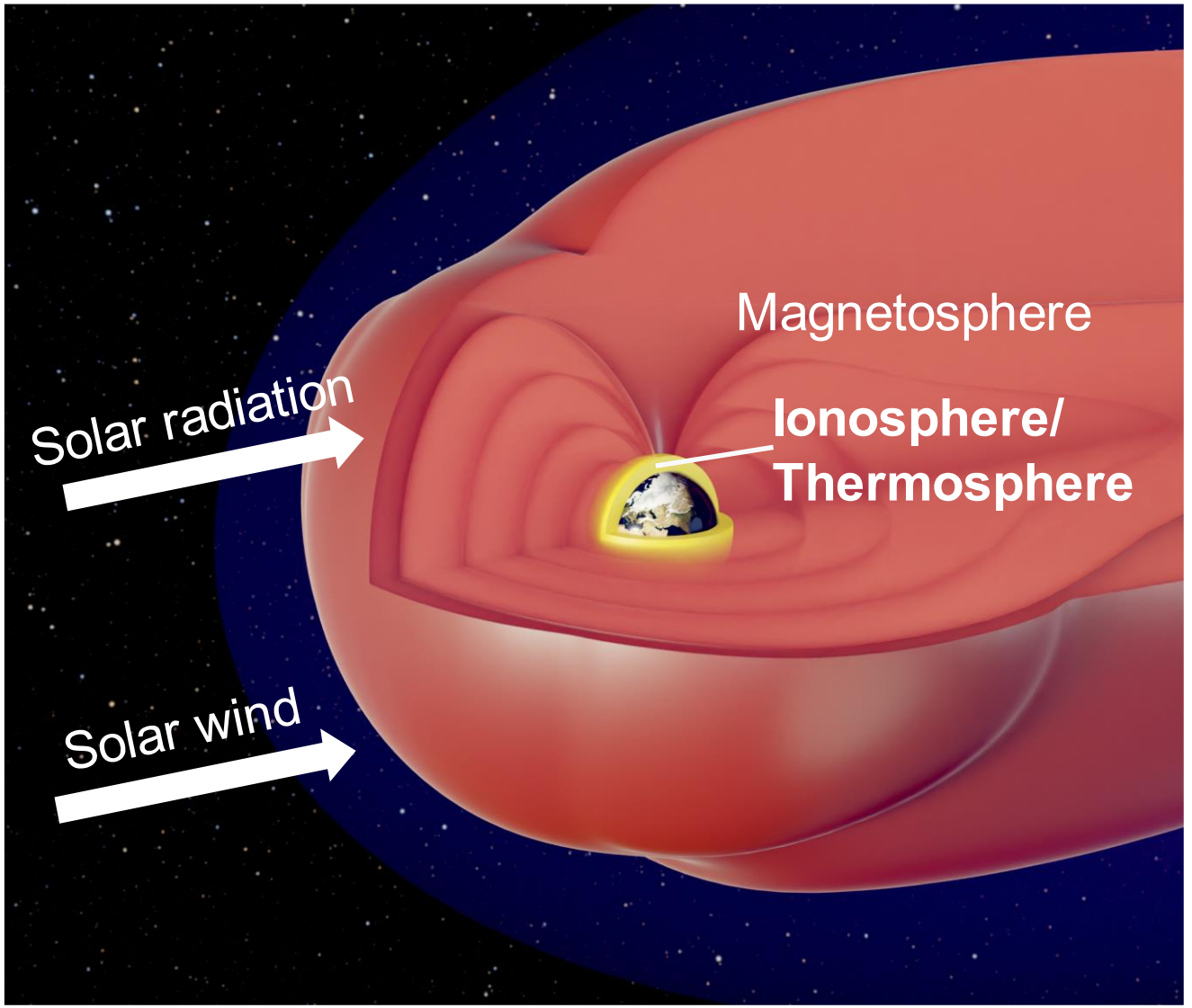


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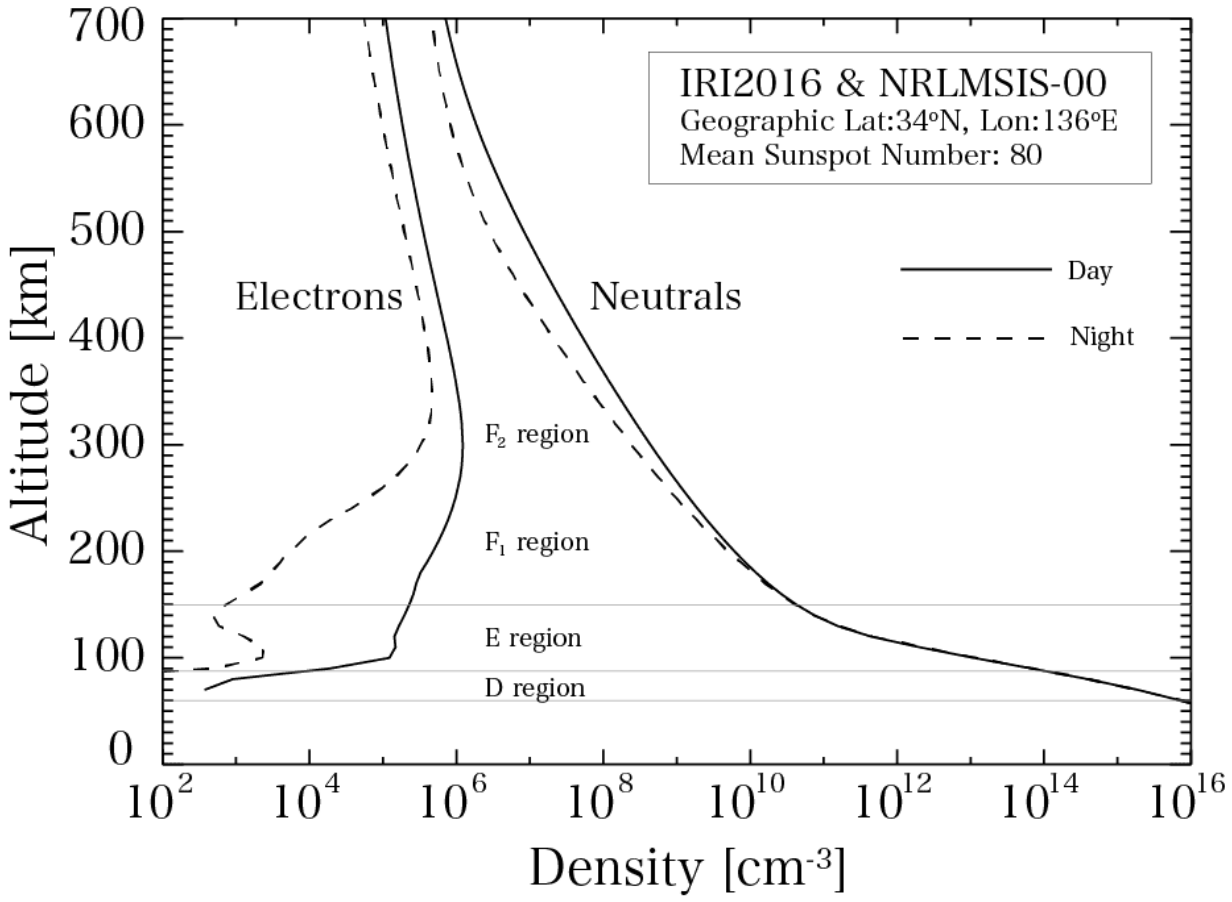
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Near-earth space environment

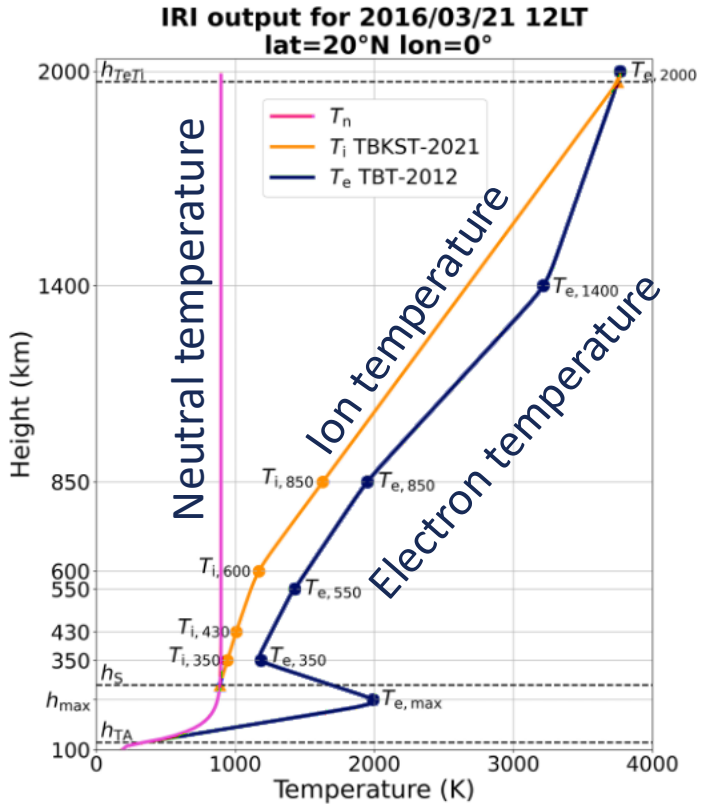
- **Ionosphere**: Population of ionized particles in the upper atmosphere
- **Thermosphere:** Neutral atmosphere at ionospheric altitudes
- **Magnetosphere**: Region beyond the ionosphere where the Earth's magnetic field affects plasma motion



Ionosphere/thermosphere density and temperature



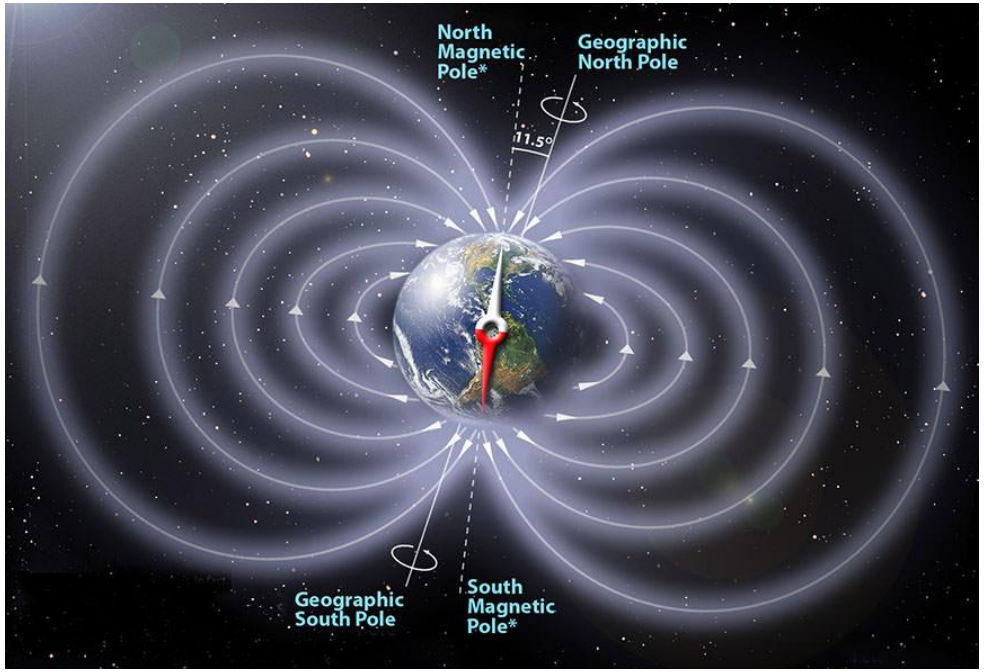
Electron and neutral density profiles. Although neutrals dominate the density, electrons and ions play a major role in the physics (image: Space Environment Laboratory, Japan)



Neutral, ion, and electron temperature profiles. Temperature difference between components can be considerable. (image: Bilitza+2022)

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Importance of magnetic field



Peter Reid, University of Edinburgh

Magnetic field strongly influences ion motion

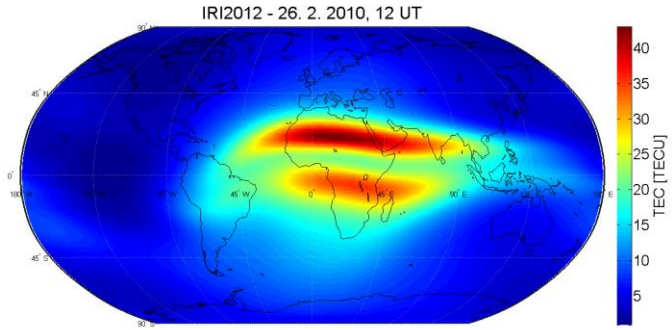
- Ions move easily along field lines
- Cross-field motion is driven by electric fields and/or collisions with neutrals
- Some models address this using field-aligned grids

Geomagnetic coordinates use latitude/longitude/altitude relative to geomagnetic poles rather than geographic poles

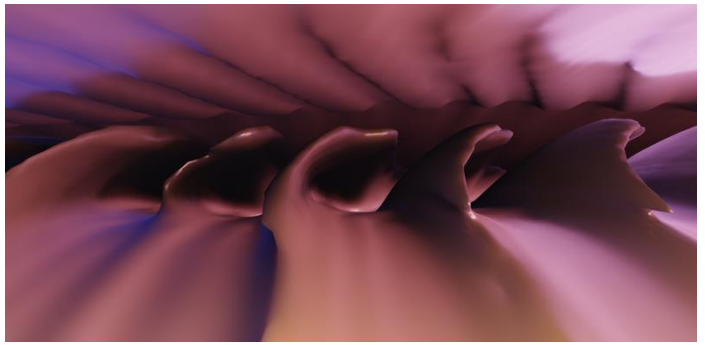
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Comparison of ionosphere models

Model	Description
SAMI3: SAMI3 is Another Model of the Ionosphere (Navy non-releasable code)	**Physics-based ionosphere model** that solves the Euler equations for multiple ion species with ionosphere-specific forcing terms
PyIRI: Python IRI (Publicly Available)	**Python re-write of IRI** (much faster than IRI)
IRI: International Reference Ionosphere (Publicly Available)	Empirical (statistical) model that provides **climatological average electron densities** given a date, time, and solar flux parameter



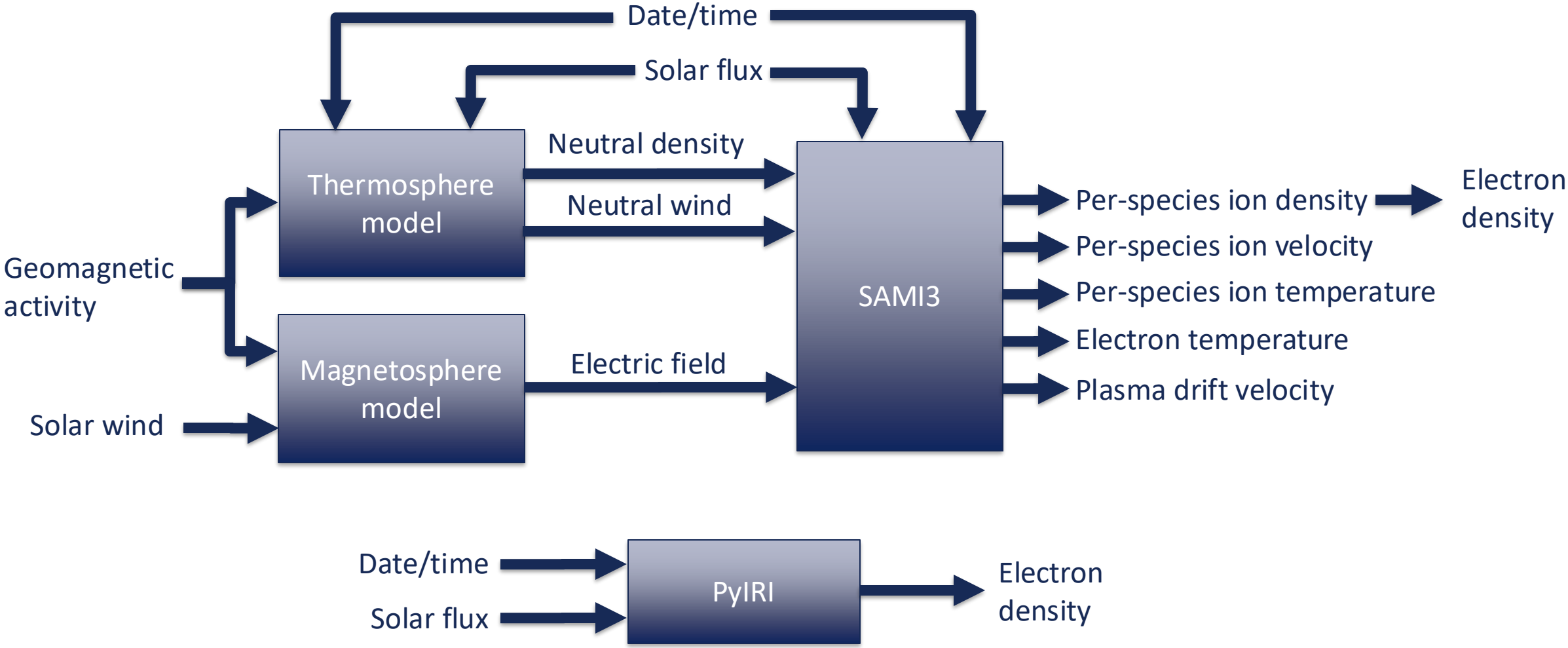
Global total electron density (TEC) from IRI (Najman+2014)



Electron density isosurfaces from a SAMI3 simulation

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Model inputs/outputs



Joint Effort for Data assimilation Integration (JEDI)

Joint Effort for Data Assimilation Integration (JEDI):

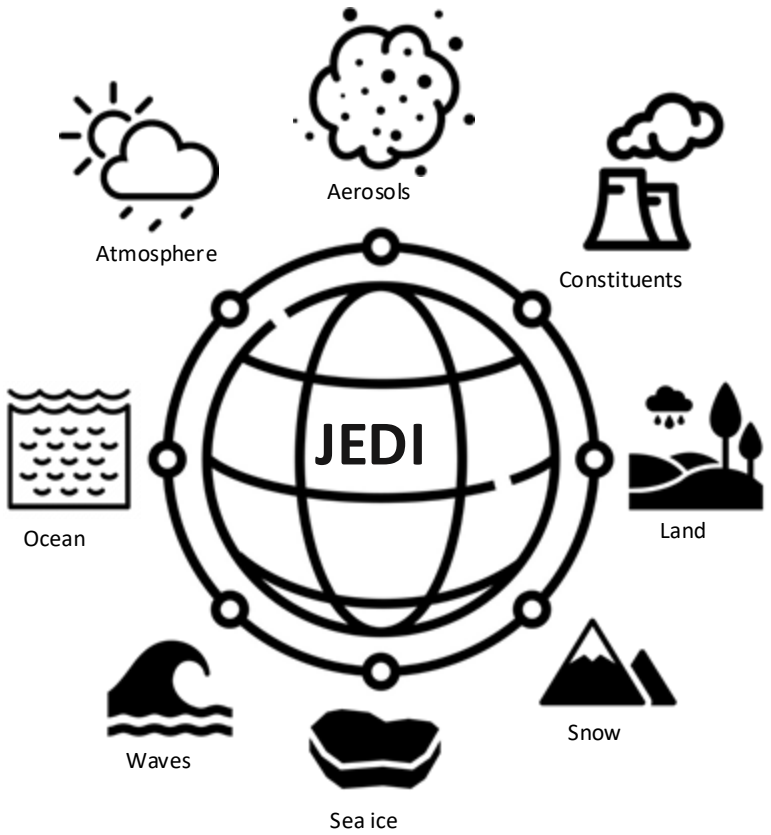
- Framework for DA development spearheaded by Joint Center for Satellite Data Assimilation
- Users: NOAA, NASA, US Navy, US Air Force, UK Met Office, others

Solver:

- 3D-Var/4D-Var with FGAT, Hyb-3D-EnVar/Hyb-4D-EnVar, **EDA/LETKF/ETKF**

Applications focused to specific partner needs:

- Weather-Land (FV3-GFS, MPAS, NEPTUNE, LFRic), Marine (MOM6), Aero-Weather (FV3-GEOS), Trace-Gas (FV3-GFS), **Space Weather**



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Differences from typical atmospheric models

	Terrestrial weather models	SAMI3
Coordinate system	**Geographic** (latitude, longitude, altitude)	**Geomagnetic** (magnetic latitude, magnetic longitude, altitude)
Grids	Varied, but **vertical columns over a spherical shell** are common.	Grid follows magnetic field lines. Grid points **do not align in vertical columns**.
System of equations	Navier-Stokes, possibly with chemistry	Euler equations plus a subset of Maxwell's Equations, with ion chemistry
State variables	Neutral densities, velocities, temperatures	Per-species densities, **per-species temperatures**, **per-species velocities**

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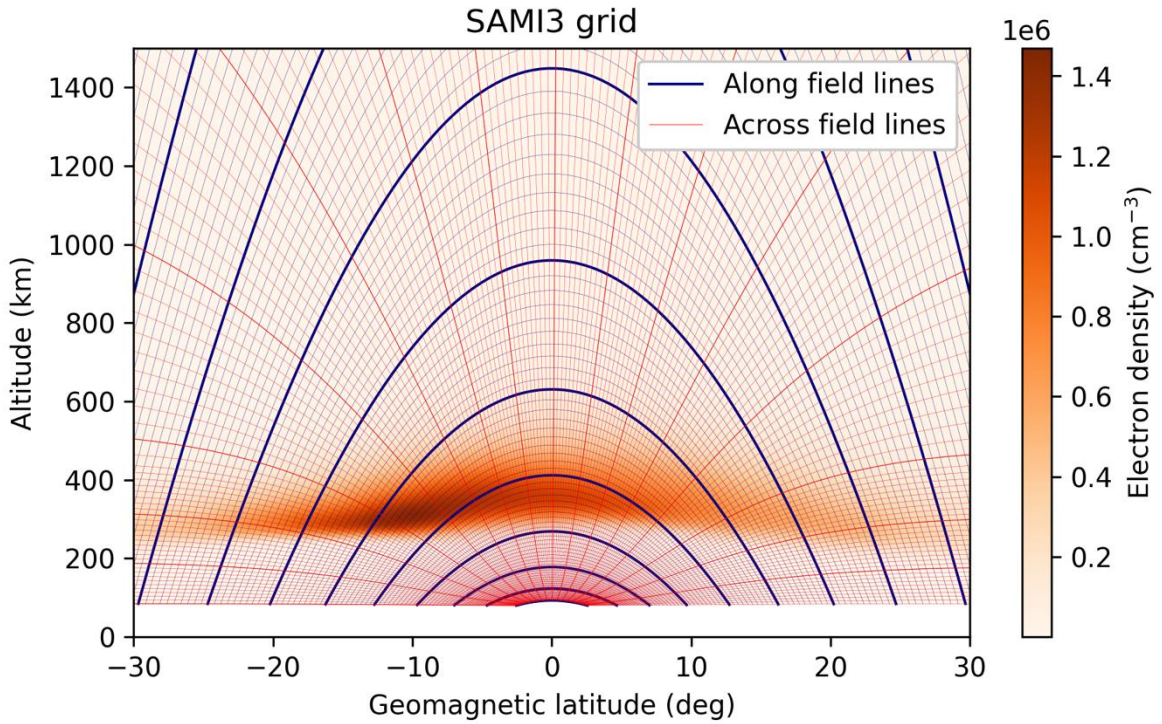
PyIRI-JEDI

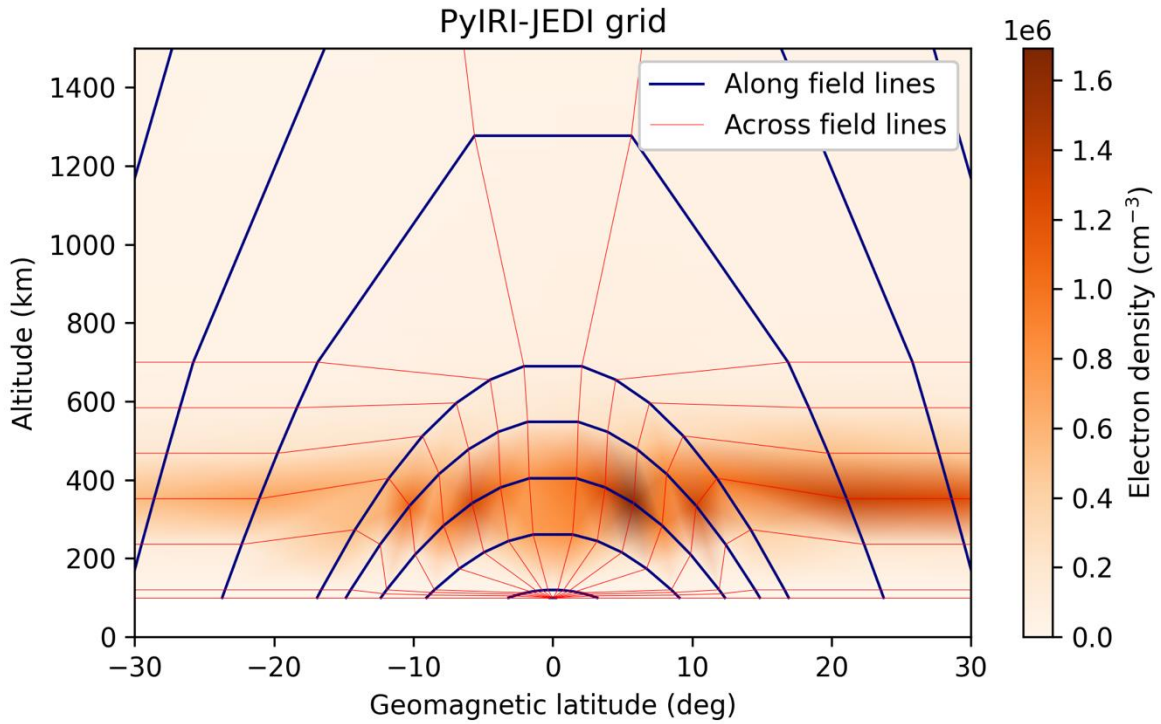
- Serves as a testbed for using JEDI with SAMI3
- **Publicly-available source code** of PyIRI **maximizes collaboration**
- Wrapper around PyIRI enables it to use **same JEDI interface as SAMI3**
  - Output interpolated onto a geomagnetic grid
  - Electron density divided across ion species
  - Output written in file formats resembling those used by SAMI3

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Geomagnetic grid

- Grid **aligns with magnetic field**
- Native coordinates are geomagnetic
- Grid points concentrated at ionospheric altitudes





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Ionospheric observations: GNSS

Dual-frequency GNSS signals can be used to estimate **line-integrated electron density** along the ray path from transmitter to receiver (called total electron content or TEC)

Applies to ground-based receivers and also satellite-based (e.g. radio occultation)

Direct processing requires integral along a slant path; transforms can be used to estimate vertical integrals or profiles from the raw data

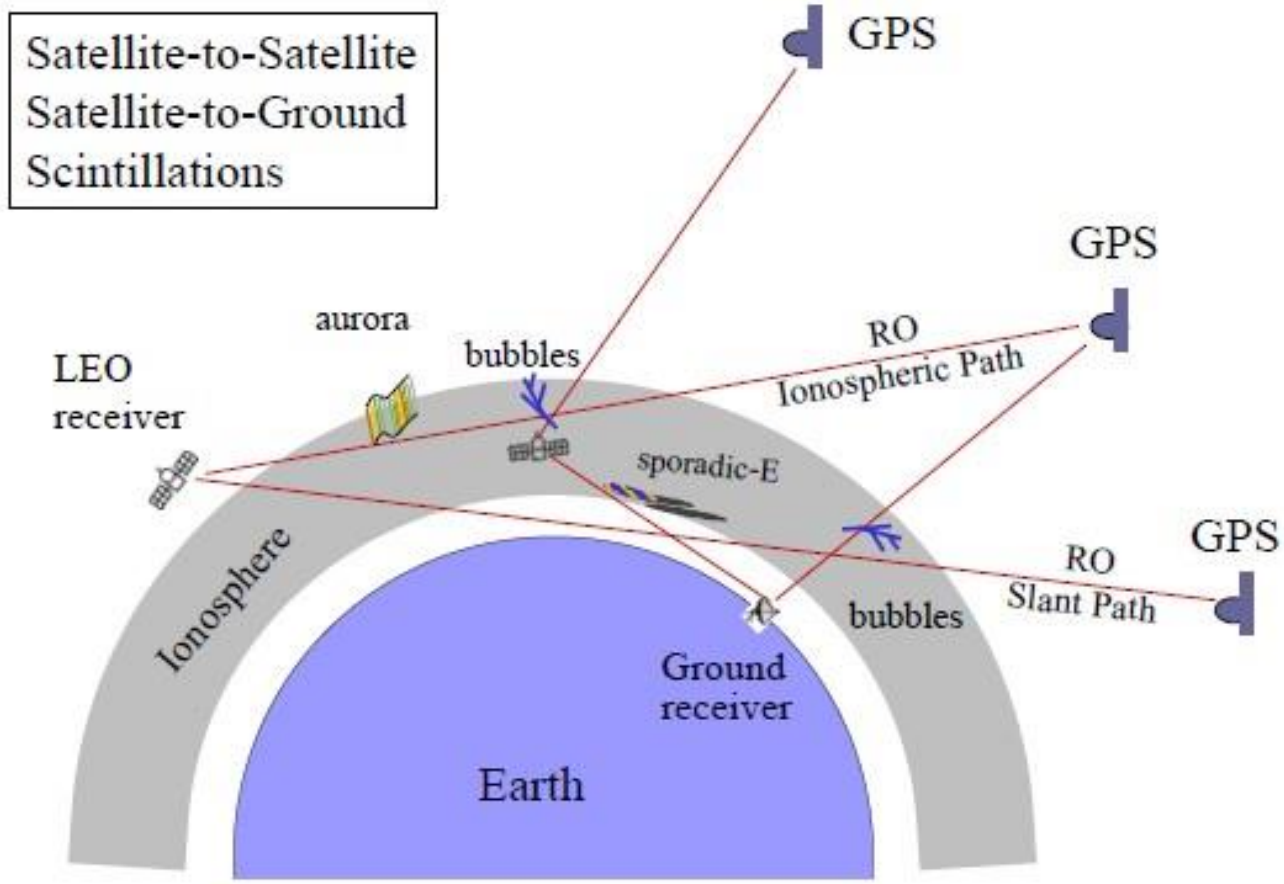
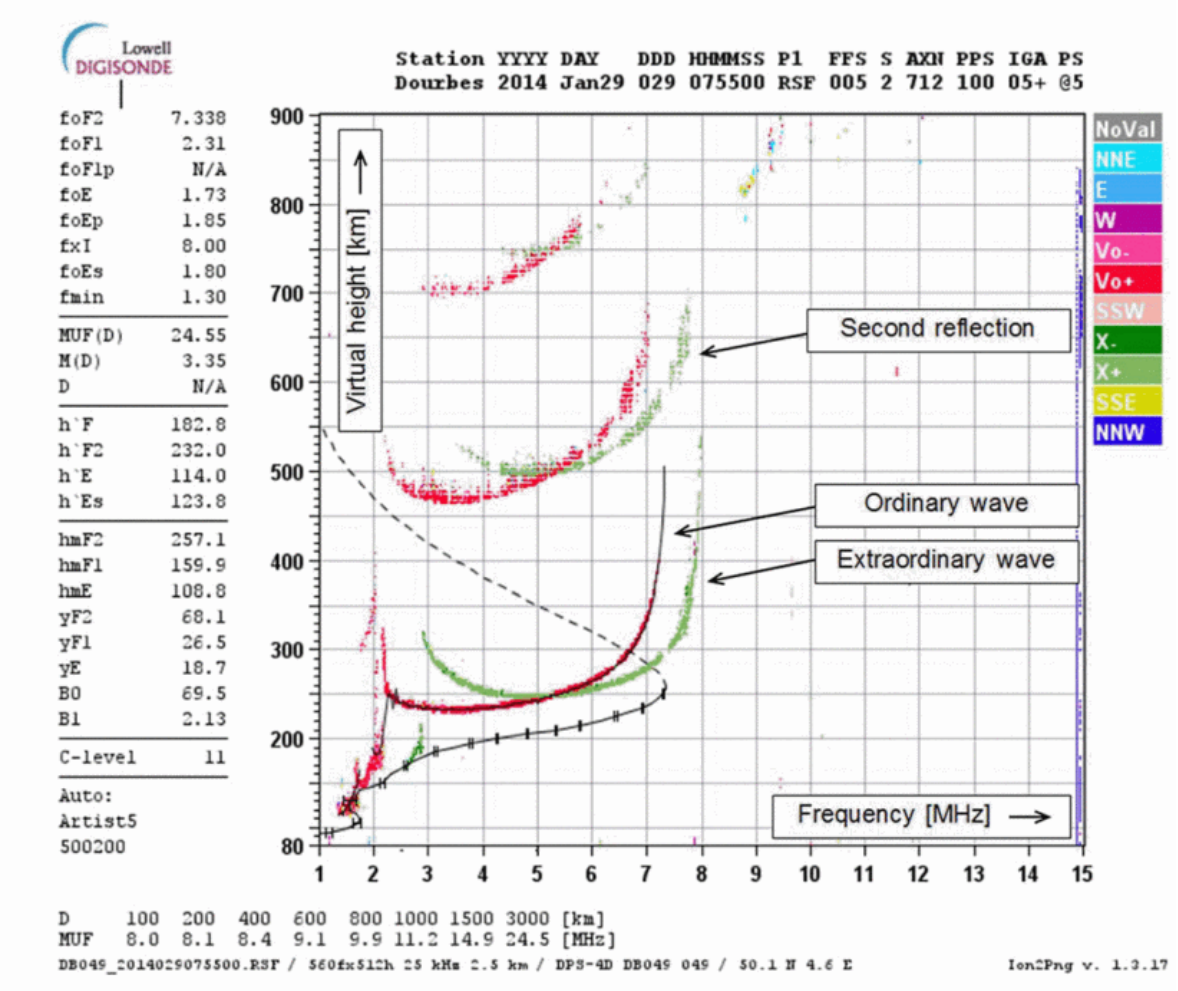


Illustration of GNSS ray paths through the ionosphere (Wu 2020)

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Ionospheric observations: ionosondes

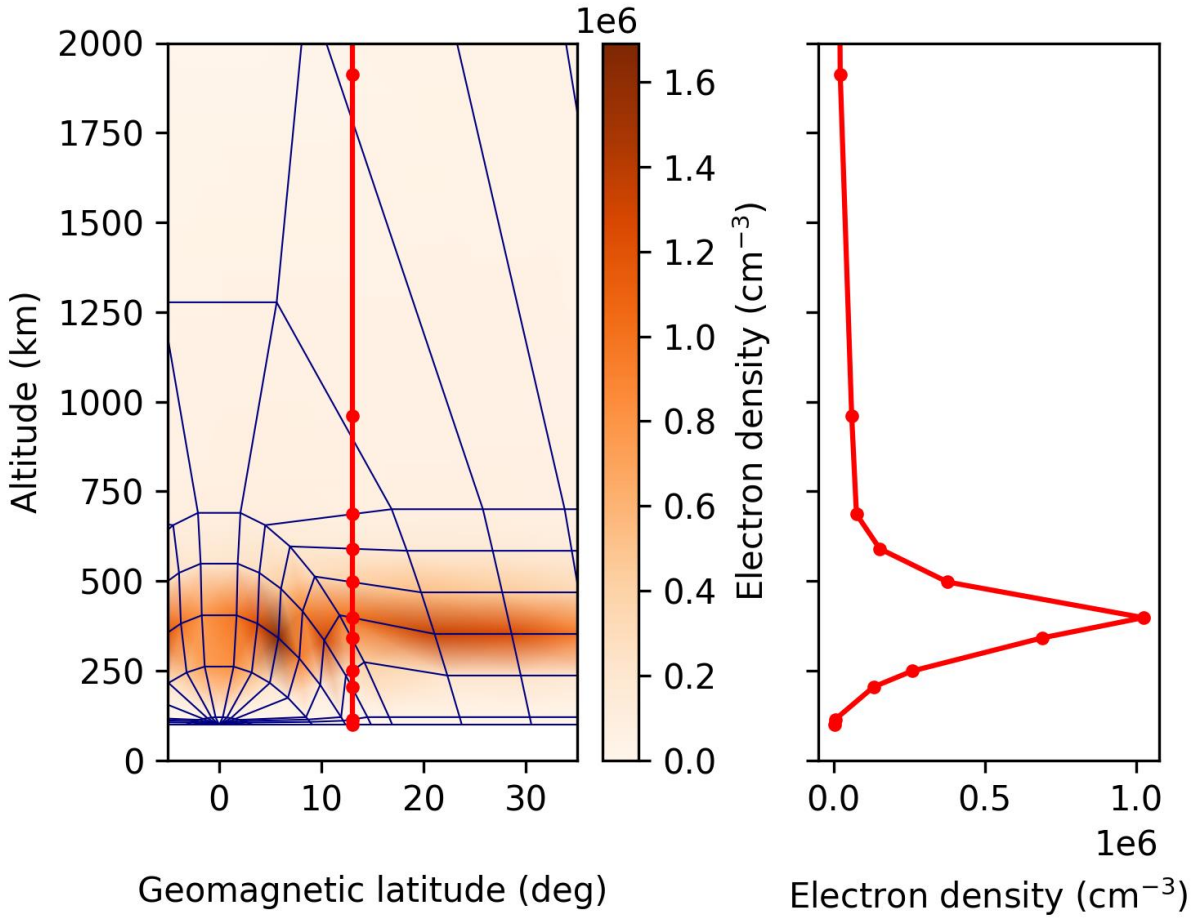
- An **Ionosonde** is a simple radar that points directly up into the ionosphere
- Return time depends on radio frequency and electron density
- Used to estimate bottomside density profile



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Grid interpolation

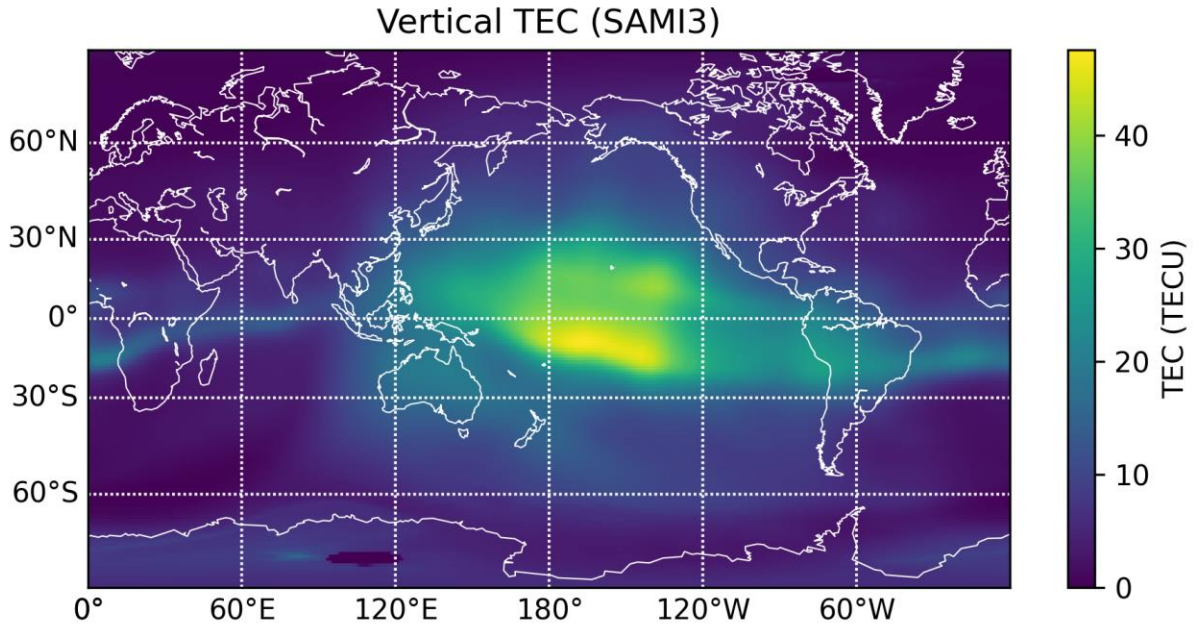
- JEDI observation operators operate on vertical columns
- Grid complexities not found in existing JEDI models:
  - **Grid points not in vertical columns** (requires custom interpolator code)
  - **Number of points varies with latitude** (addressed by storing interpolator output in an oversized buffer with fill values)
  - Latitude/longitudes in geomagnetic (not geographic) coordinates



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Observation operators

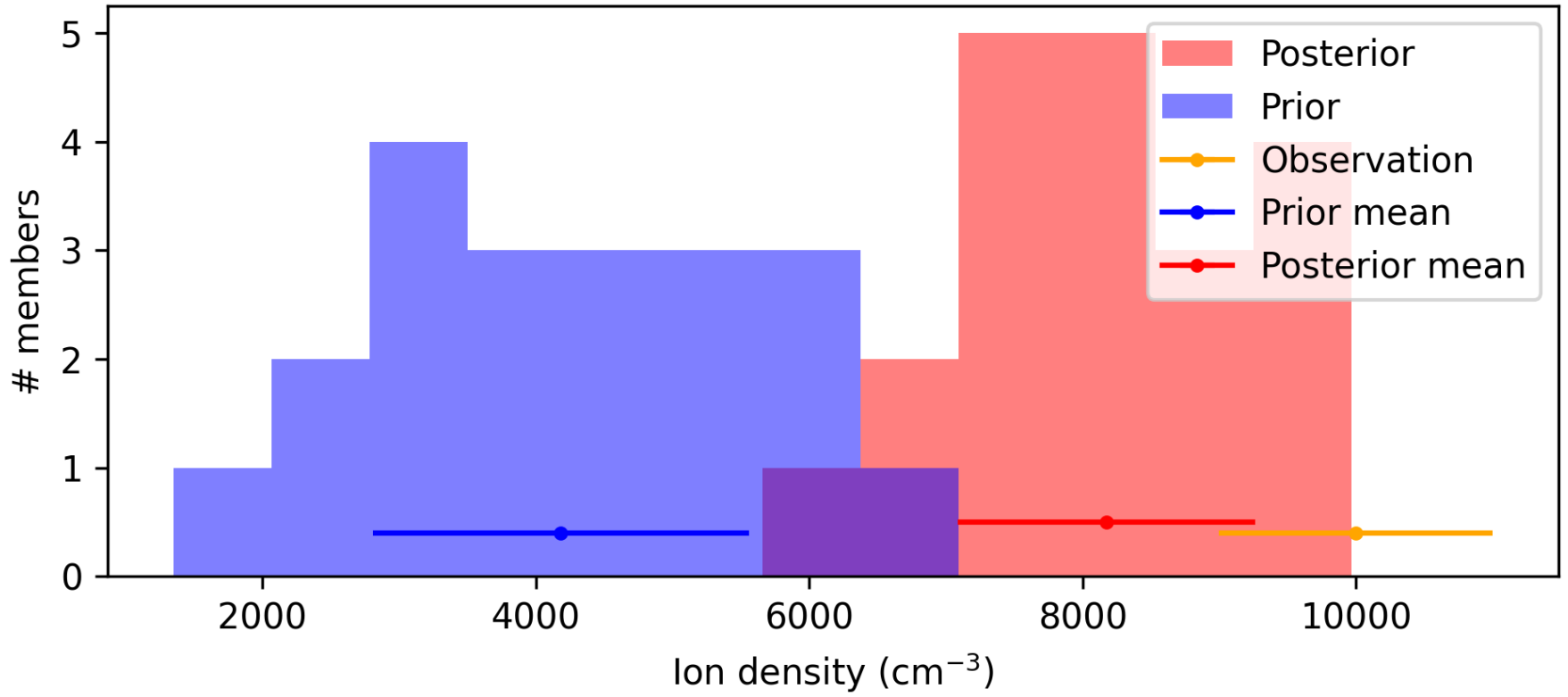
- Two observation operators implemented so far:
  - **Generic point observation** operator that returns a state variable at a given latitude, longitude, and altitude
  - **Vertical total electron content** (TEC) operator that gives the integral of electron density above a given latitude and longitude



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Preliminary ETKF results

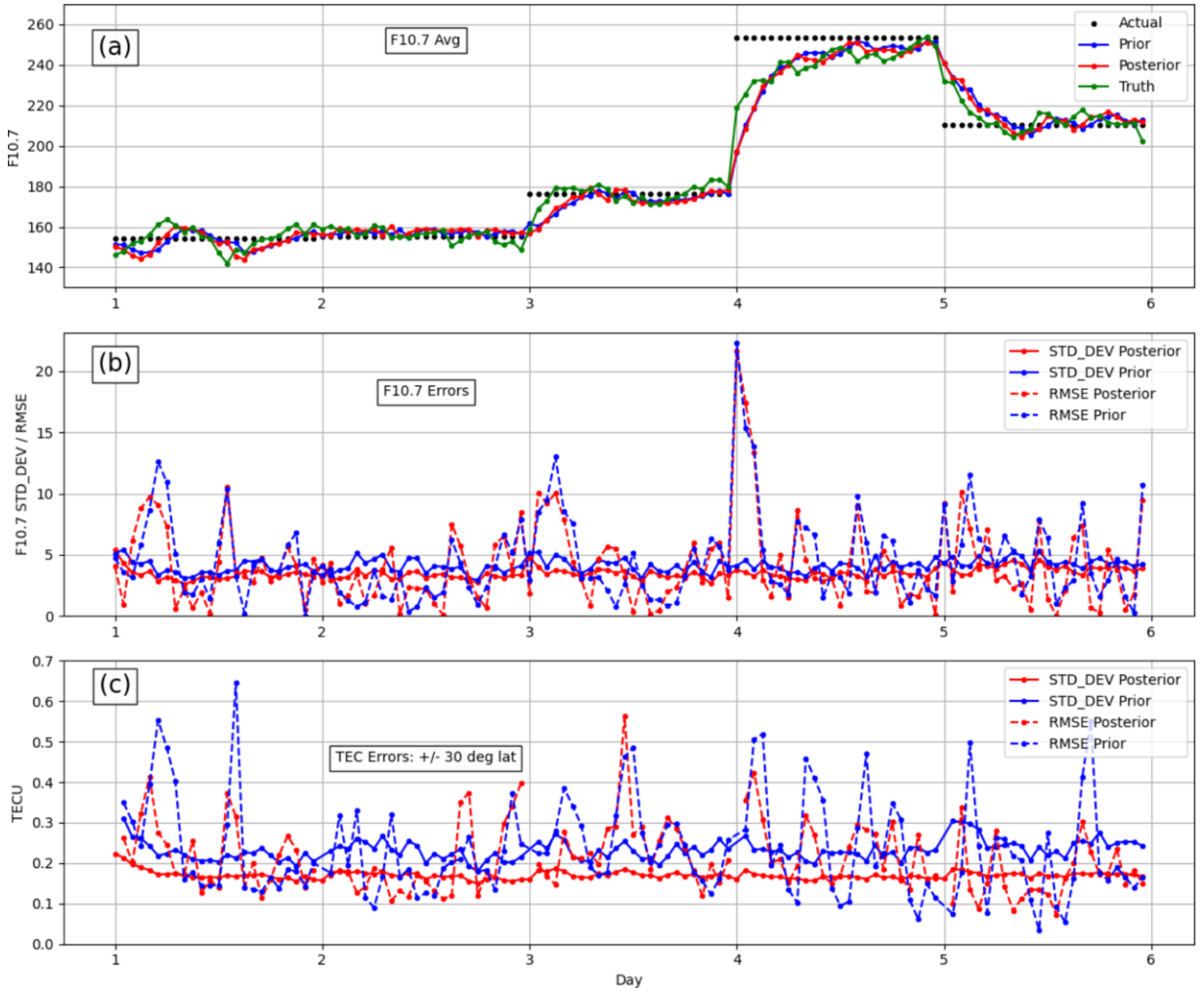
- Sanity checks pass for single observations with a 20-member ensemble



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Importance of parameter estimation

- Hodyss+2022 tested an ETKF algorithm with a simple heuristic model and with SAMI3
- Showed SAMI3 states are highly correlated due to strong dependence on global parameters
- Demonstrated importance of parameter estimation for F10.7 solar radio flux (proxy for EUV flux)



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Summary

- SAMI-ETKF/PyIRI-ETKF
  - **Interfaces to JEDI** are implemented
  - Observation operators implemented for point and vertical TEC observations
- Next steps:
  - More **observation operators**: Ionosondes, slant TEC, radio occultation
  - Further testing with both PyIRI and SAMI3
  - Implement parameter estimation

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Ionospheric DA in JEDI

- Goal: Operational JEDI-(L)ETKF to update a SAMI3 ensemble
  - JEDI LETKF with all localization weights set to 1, so effectively ETKF
- Current effort: Integrated PyIRI into JEDI with output on a SAMI3-like grid.
  - PyIRI-JEDI provides a means to develop and test within JEDI community:
    1. JEDI interfacing with geomagnetic grids
    2. IODA ingesting ionospheric observations and ionospheric obs operators
    3. Parameter estimated JEDI ionospheric ETKF
  - PyIRI-JEDI allows for integration of ionospheric ctests within the develop code base
- Progress to date:
  - Have interface between PyIRI and OOPS, passes tests with a simple obs operator that reads the model state at a specified index
  - Current work focuses on integrating geomagnetic grid interpolator into OOPS, and creating observation operators

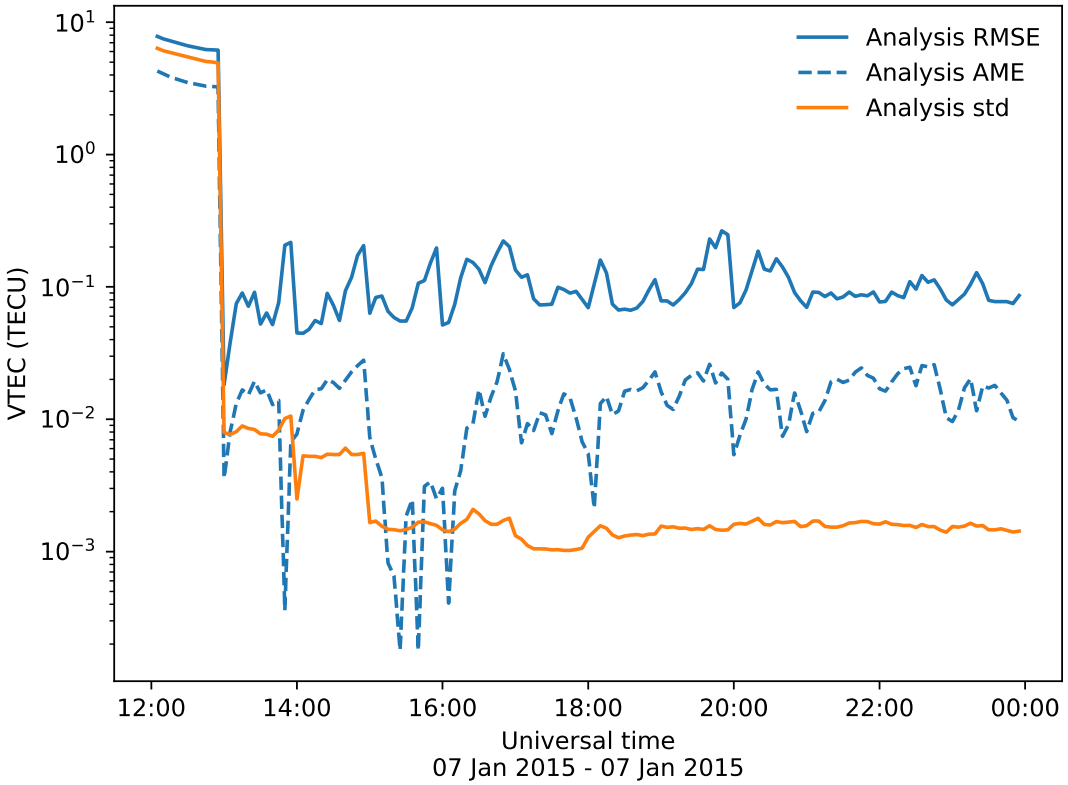
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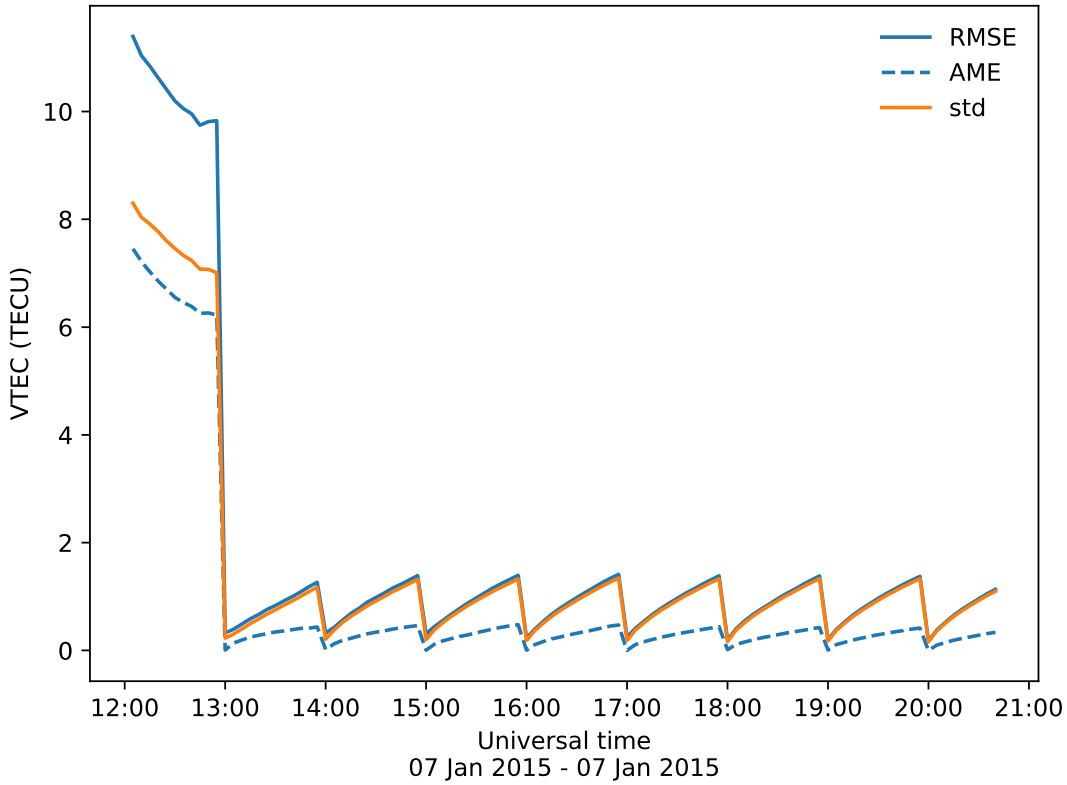
Ionospheric ETKF DA

- Why are we starting with the ETKF?
  1. SAMI3 model forced with winds from an empirical (statistical) neutral atmosphere model has extremely low dimensionality. With only a few observations and using parameter estimation on the solar forcing variables an extremely low RMS error DA system was created (relative to state-of-the-art ionospheric DA systems).
  2. Next goal is forcing the SAMI3 model with the Navy's 0-500km neutral atmosphere model. This bumps up the dimensionality of the system and we will need to upgrade to an LETKF.
  3. Final goal will be coupled ionospheric-neutral atmosphere DA system which will be LETKF based (Our current DA system for 0-500km neutral atmospheric model is LETKF and we are integrating it now into JEDI)

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Importance of parameter estimation





SAMI3-LETKF, synthetic VTEC obs without parameter estimation: **Ensemble spread (orange curve) collapses rapidly**

SAMI3-LETKF, synthetic VTEC obs with parameter estimation for F10.7 and Ap: **Ensemble spread tracks closely with RMSE**

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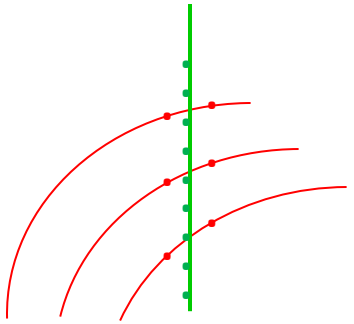
Ionospheric obs in JEDI

Geomagnetic State Space:
Pass vertical column or columns of data? (location of state-space file?)

Observation Operators:
linear interpolator, vertical interpolator over layers, etc...???

Ionospheric Observations:
Ionosondes, ground-based GPS, radio occultation, SSUSI, SSULI, LEO sats? NRL UV sats?

Convert Geomagnetic State Space to a column?



H(x)

Slant TEC

