IMPACT OF COMMERCIAL RADIO OCCULTATION DATA ON IONOSPHERIC DATA ASSIMILATION

COSMIC/JCSDA Workshop and IROWG-10 Meeting
Session: Ionosphere/Space Weather 1
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This talk

Guiding question: What is the impact of commercial radio occultation data on the specification of global ionospheric electron density and related parameters?

Part 1: The impact of COSMIC-2 RO total electron content (TEC) data relative to other common observation types (ground GNSS TEC and ionosondes)

- Vertical TEC (vTEC)
- Critical frequency of ionospheric F2 layer (foF2)
- Height of F2 layer critical frequency (hmF2)

Part 2: The additional impact of **commercial RO TEC data**

- foF2

What's an OSSE?

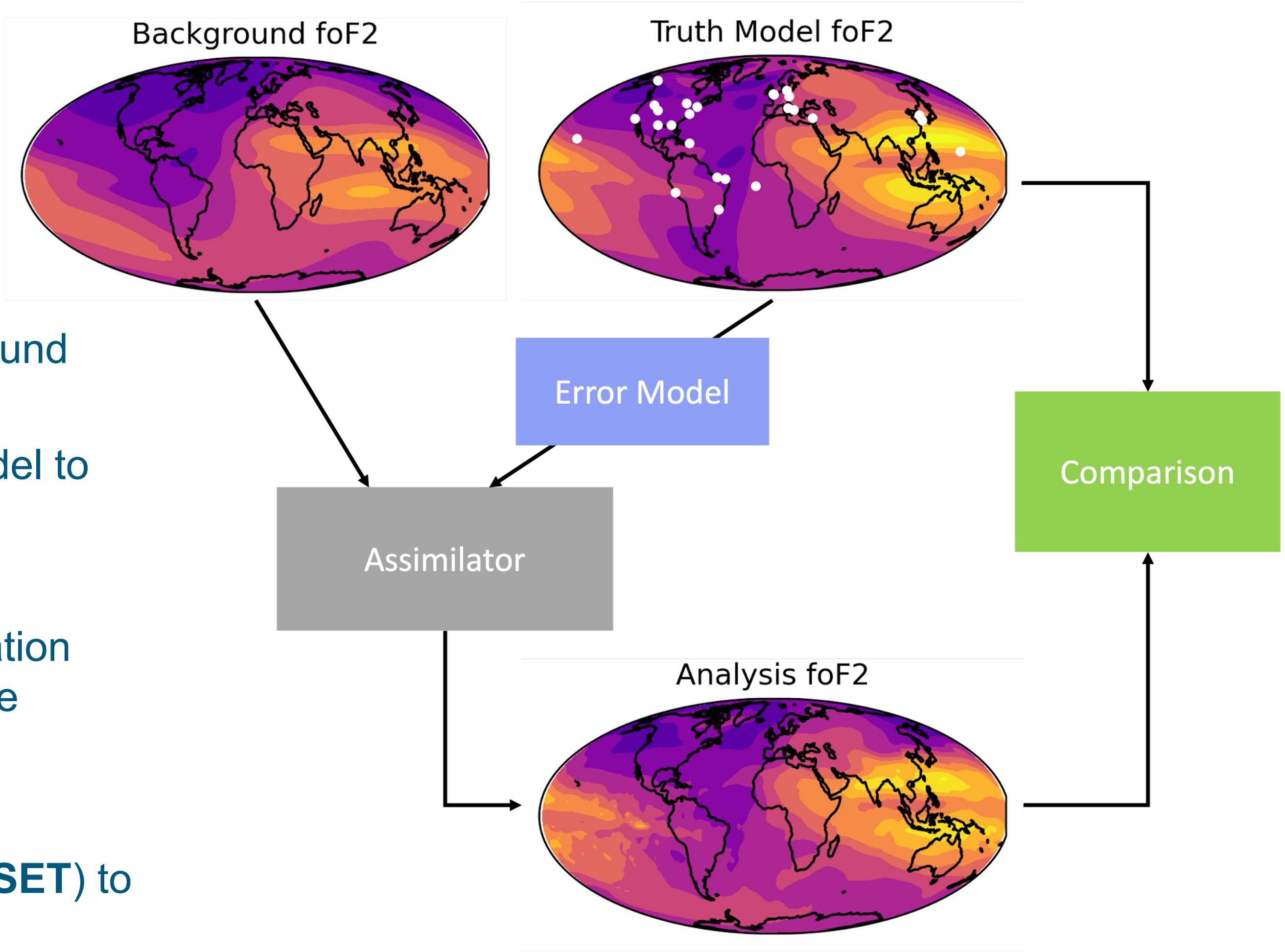
OSSE = **O**bserving **S**ystem **S**imulation **E**xperiment

It has three steps:

1. Generate synthetic measurements from a **truth model**
2. Assimilate these measurements and update a background model to make an 'analysis'
3. Compare the analysis and background to the truth model to compute metrics

Iterate on steps with different configurations of the observation system and choose the one that best meets the need at the minimum cost.

Orion Space Solutions has developed the OSSE Tool (**OSSET**) to perform OSSEs quickly and robustly.



PART I: IMPACT OF RO DATA

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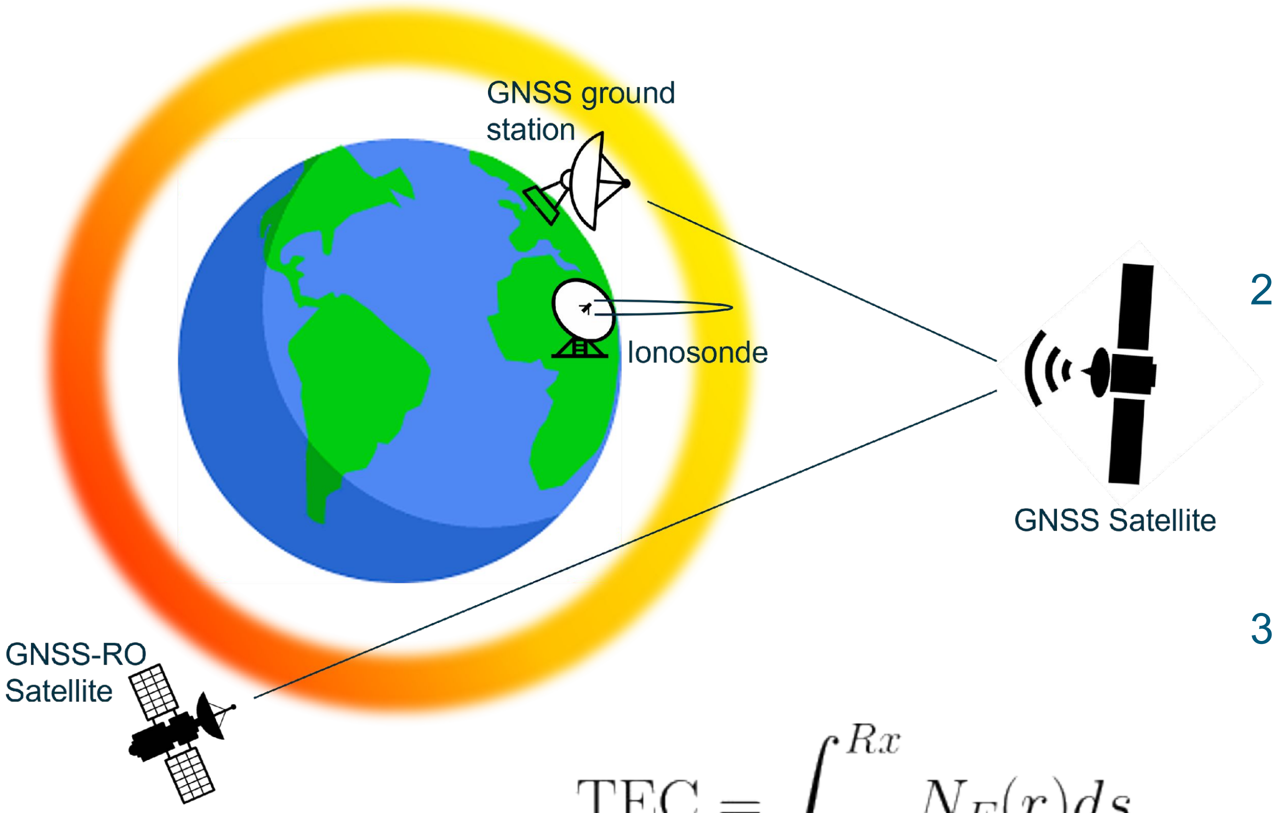
The ‘Big 3’ data types for ionospheric data assimilation



$$\mathrm{TEC} = \int_{Tx}^{Rx} N_E(r)ds$$

1. Ionosondes
   - Ionosondes record the time it takes for HF radiation to return to the ground after bouncing off the ionosphere. This delay can be inverted into a profile of electron density with altitude ne(z) for the bottom side of the ionosphere.

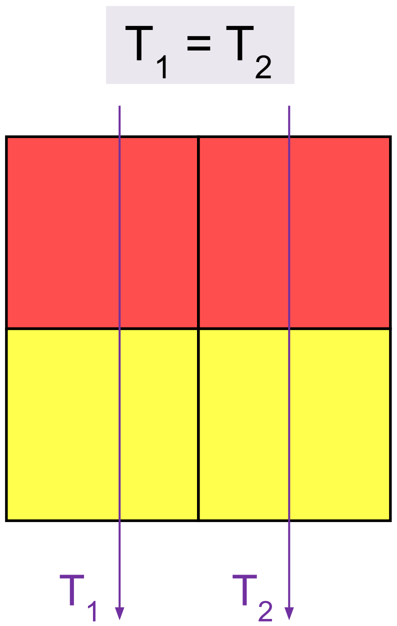
2. Ground GNSS TEC
   - GNSS satellites broadcast signals at multiple frequencies. The relative delay between these two signals can be used to calculate the total electron content (TEC) along the path

3. Radio Occultation
   - Same as Ground GNSS TEC, but the receiver is in low earth orbit.

Building Intuition

- Ground GNSS TEC has primarily vertical line integrals, and RO has primarily horizontal line integrals
- Simple example shown at right:
    - **The ionosphere has a vertical structure, but the ground GNSS measurements are not* sensitive to it**

*in this example



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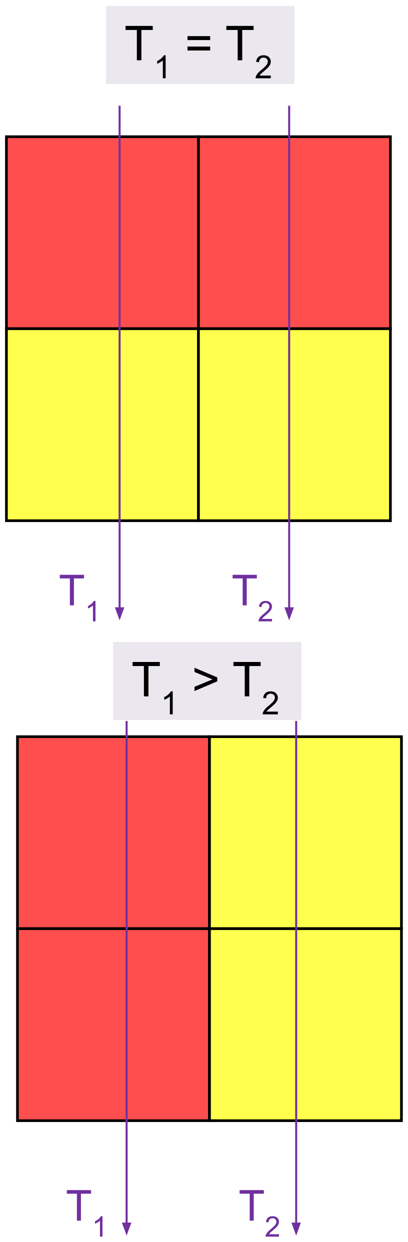
    - **However, these measurements *are* sensitive to horizontal structure**



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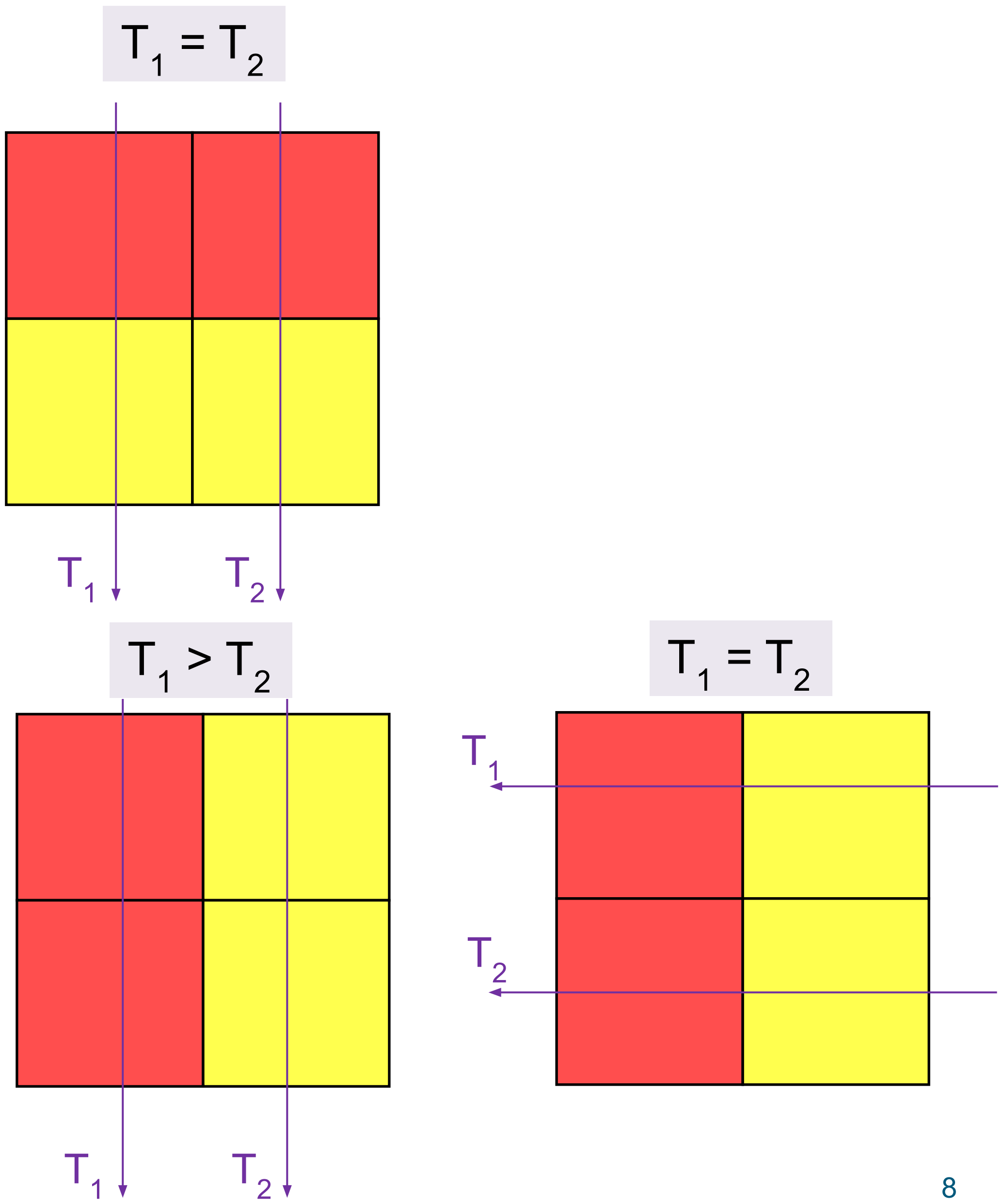
  - The ionosphere has a vertical structure, but the ground GNSS measurements are not sensitive to it
  - However, these measurements *are* sensitive to horizontal structure
  - **In contrast, Radio Occultation is not sensitive to this horizontal gradient**



Building Intuition

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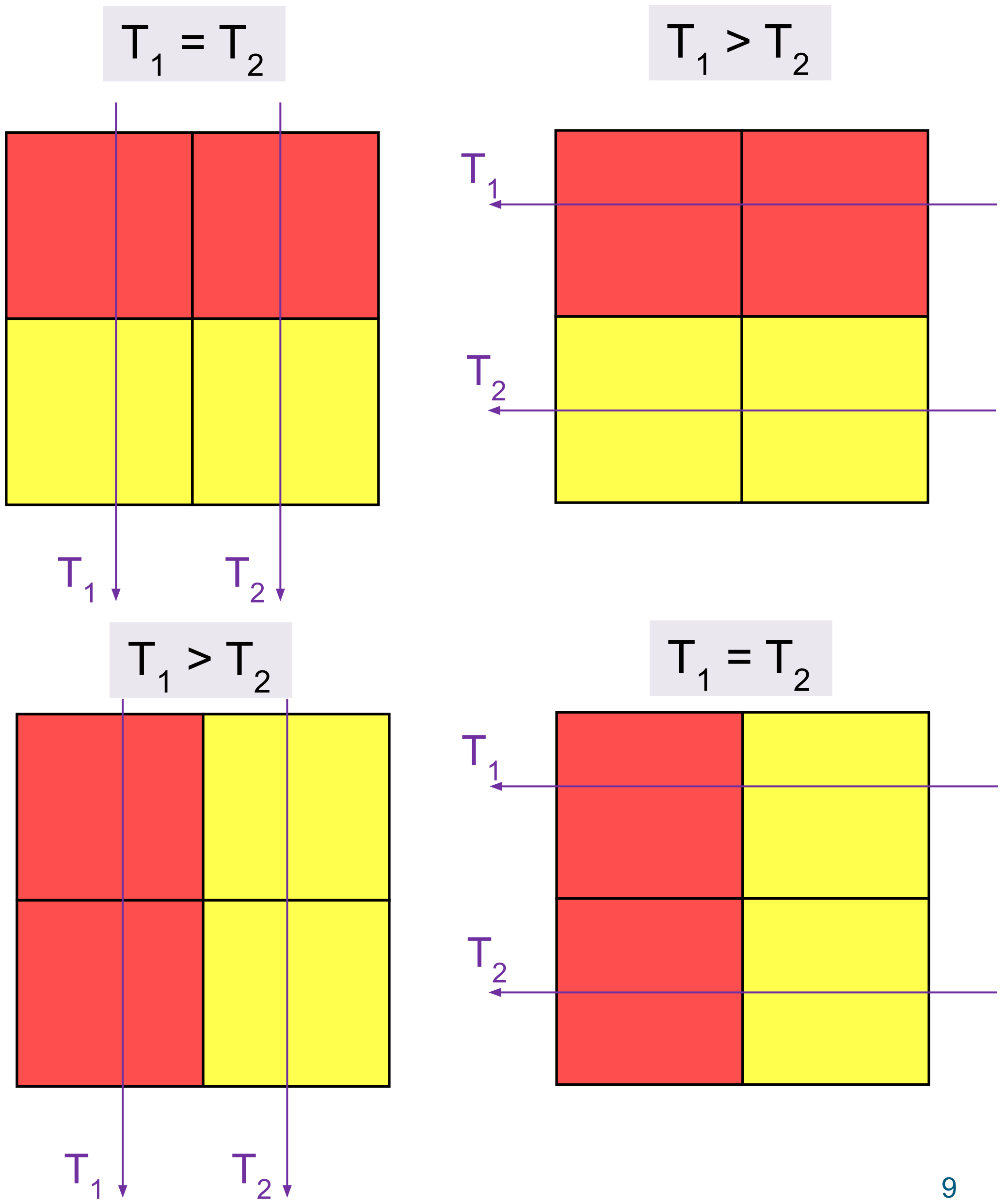
- Simple example shown at right:
  - The ionosphere has a vertical structure, but the ground GNSS measurements are not sensitive to it
  - However, these measurements *are* sensitive to horizontal structure
  - In contrast, Radio Occultation is not sensitive to this horizontal gradient
  - **But RO is sensitive to a vertical gradient**



Questions to Answer

- Q1: Does RO help specify vertical structure?
- Q2: Does Ground GNSS TEC help specify horizontal structure?
- Q3: Does the combination of RO and Ground GNSS TEC specify the ionosphere better than either of them in isolation?

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Our Process

1. Use the noisy truth model and OSSET to simulate data from ionosondes, ground GNSS TEC, and Radio Occultations

   Hughes, et al. (2022). On Constructing a Realistic Truth Model Using Ionosonde Data for Observation System Simulation Experiments. doi.org/10.1029/2022RS007508

2. Assimilate all unique combinations of this data
   - There are 2x2x3 – 1 = 11 options for how to do this

3. Compare the performance of each of these analyses to each other to understand relative merits of the “big 3” data types

Run Number	Run Name	Ionosondes	RO	Ground TEC
1	I	Yes	No	No
2	IGr	Yes	No	Yes, Relative
3	IRGr	Yes	Yes	Yes, Relative
4	IR	Yes	Yes	No
5	Gr	No	No	Yes, Relative
6	RGr	No	Yes	Yes, Relative
7	R	No	Yes	No
8	IGa	Yes	No	Yes, Absolute
9	IRGa	Yes	Yes	Yes, Absolute
10	Ga	No	No	Yes, Absolute
11	RGa	No	Yes	Yes, Absolute

Our Data

Ionosondes

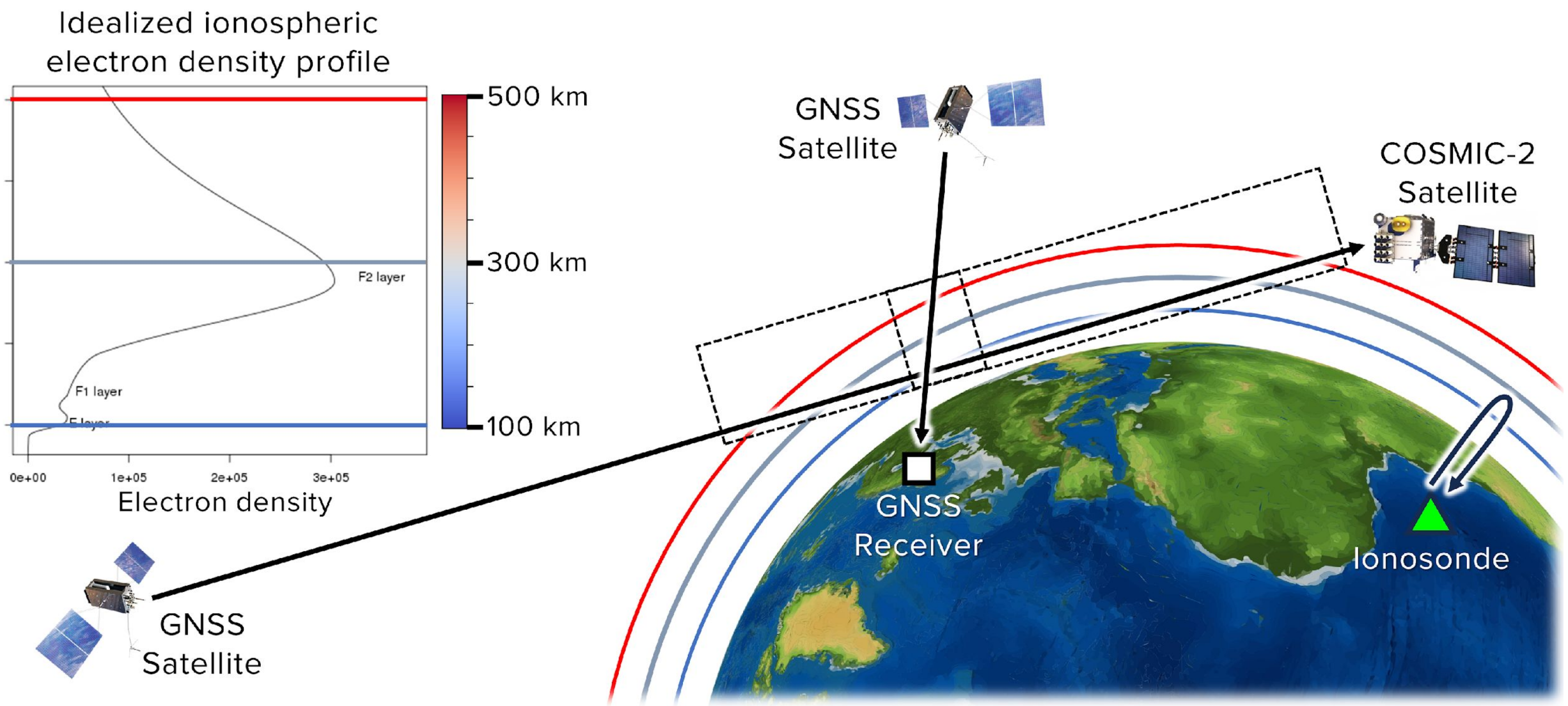
- 47 ionosondes located at green triangles in lower right map
- 15 minute cadence

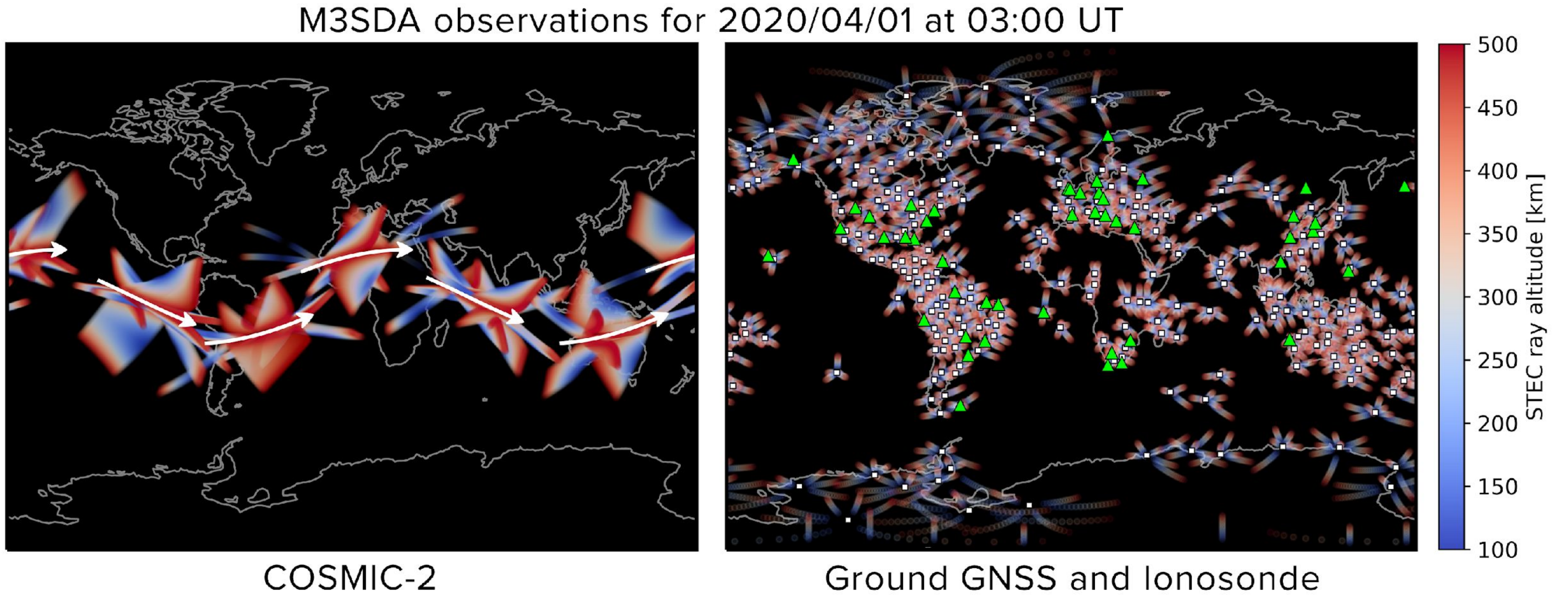
Ground GNSS TEC

- 262 ground GNSS stations located at white squares in lower right map
- 30 second cadence

Radio Occultation

- All 6 COSMIC-2 satellites
- 1 second cadence

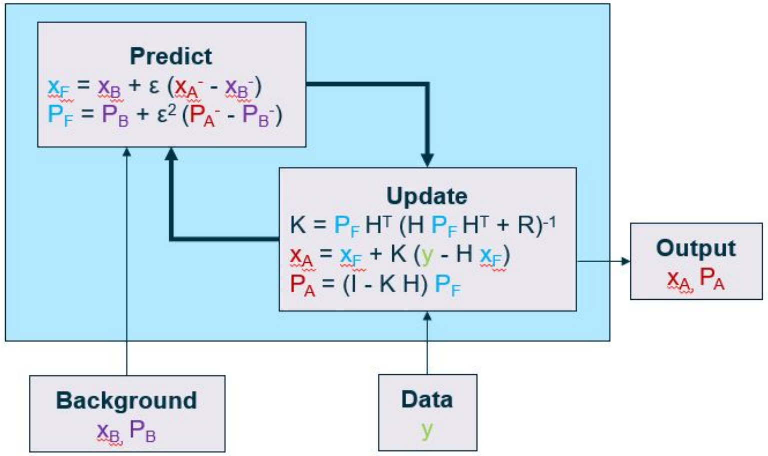




Our Assimilator

Algorithm

- We use the recently developed Modern Modular Model for Space Data Assimilation (M3SDA)
- M3SDA can use either a 3DVar or an Extended Kalman Filter (EKF) algorithm
  - In this work, we use the EKF
- M3SDA also cycles the covariance and state



Covariance

- The **data** variance is set at 35% for all data types.
- We assume that data errors are uncorrelated
- The **model** variance is set at 50% everywhere
- The horizontal correlation length is 7 degrees
- The vertical correlation length is 1/6th the altitude

Background

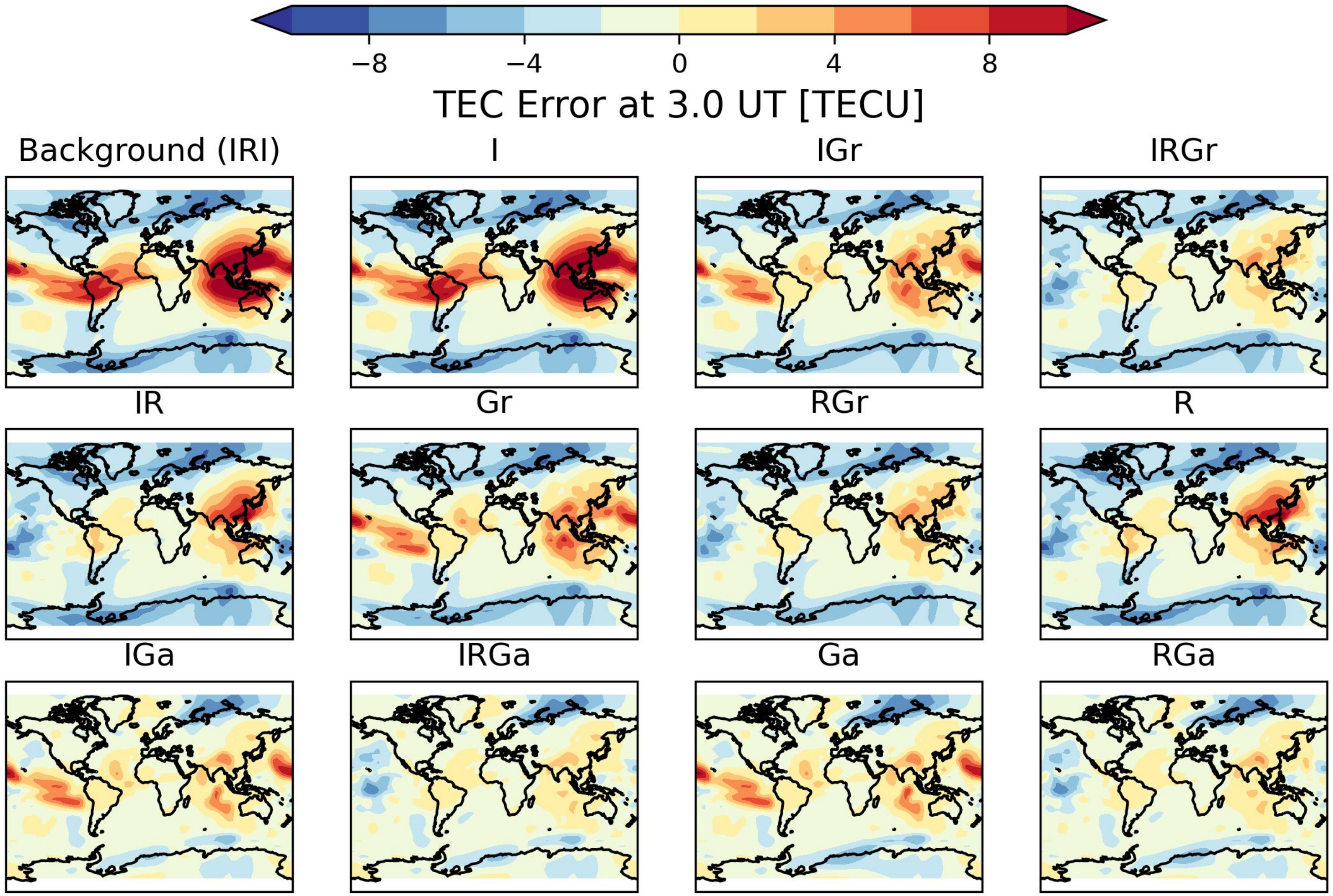
- We use IRI (via pyIRI python package) as our background

Grid

- We use a global 4x4 degree grid
- Vertical resolution is 5 km in the ionosphere and the extent is from 100 km to 20,000 km
- Timestep is 15 minute

Snapshot of Errors

- Errors in vTEC, foF2, and hmF2 are computed for all models
- vTEC is a measure of ***horizontal structure***, and fof2/hmF2 are measures of ***vertical structure***
- The vTEC errors at 3 UT are shown as color for each model
- The background overpredicts the TEC in the tropics, and underpredicts it in the arctic
- Some analyses correct the ***horizontal structure*** more than others, what do they have in common?



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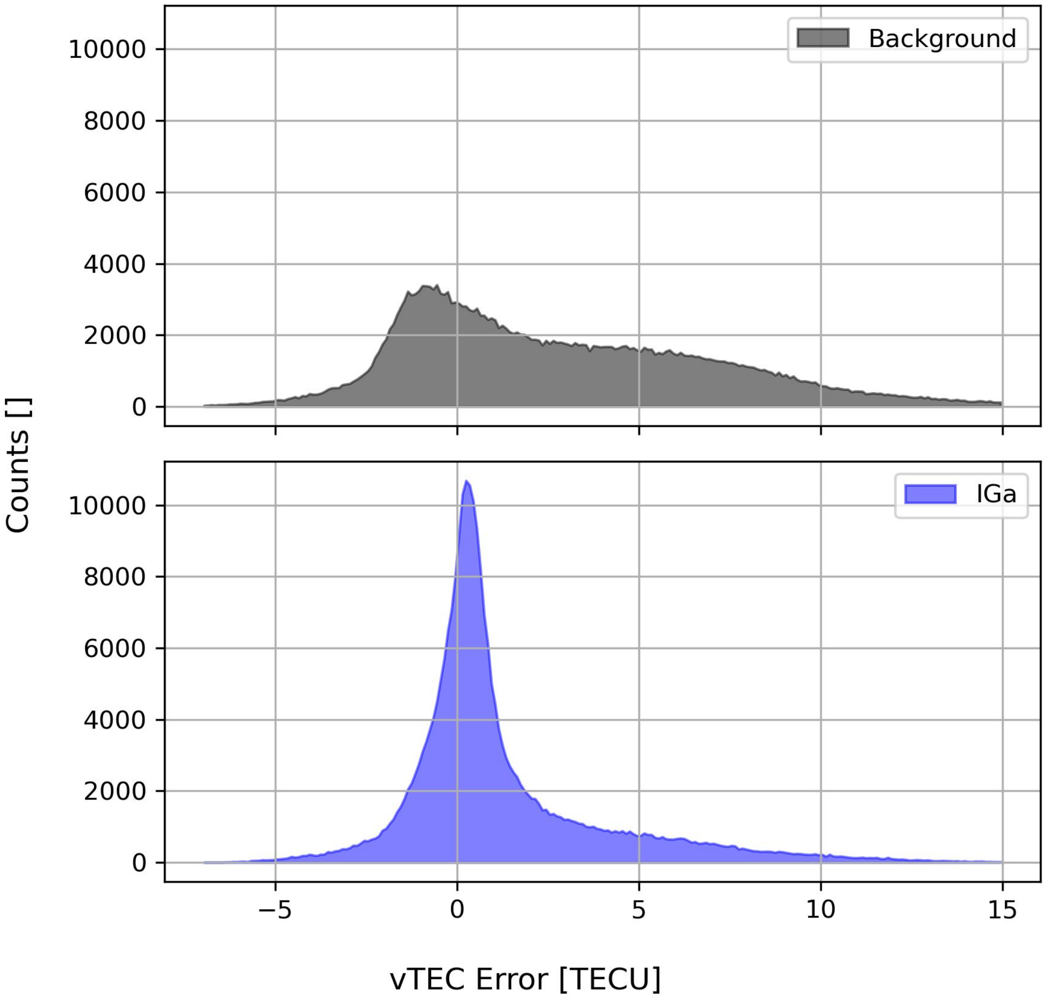
Summarizing the Errors



- The earlier figure showed errors at all places at one time
- Let's combine the errors at all places and times into a single histogram for each of the 12 cases (1 background and 11 analyses)
- Example shown for the background and one analysis
  - Note that the analysis leads to a tighter distribution with less bias
  - This narrower distribution is good

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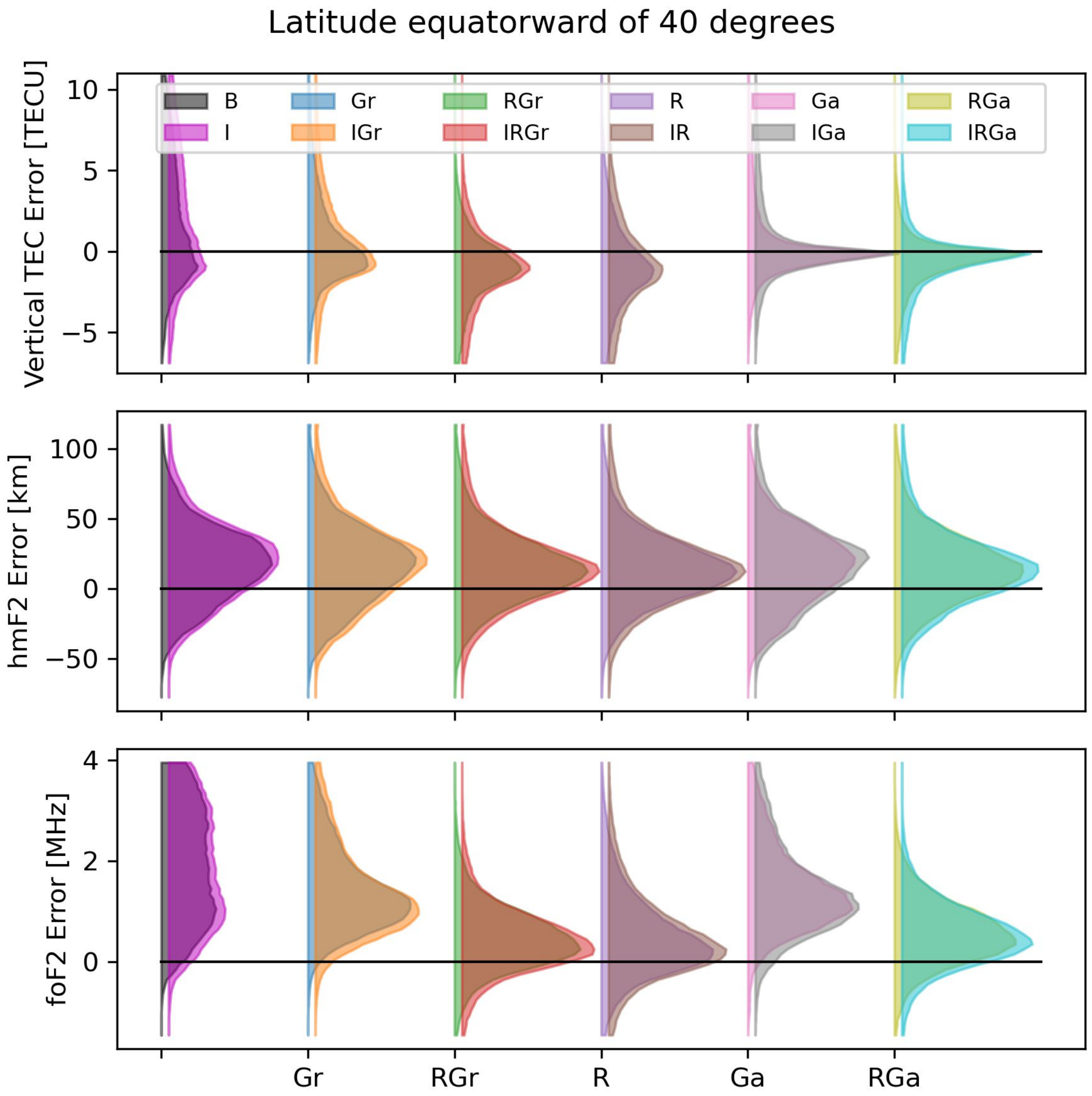
Histogram of Errors

Each shape is a histogram like the earlier example rotated by 90 degrees

In each pair of histograms, the one to the right ingested ionosonde data

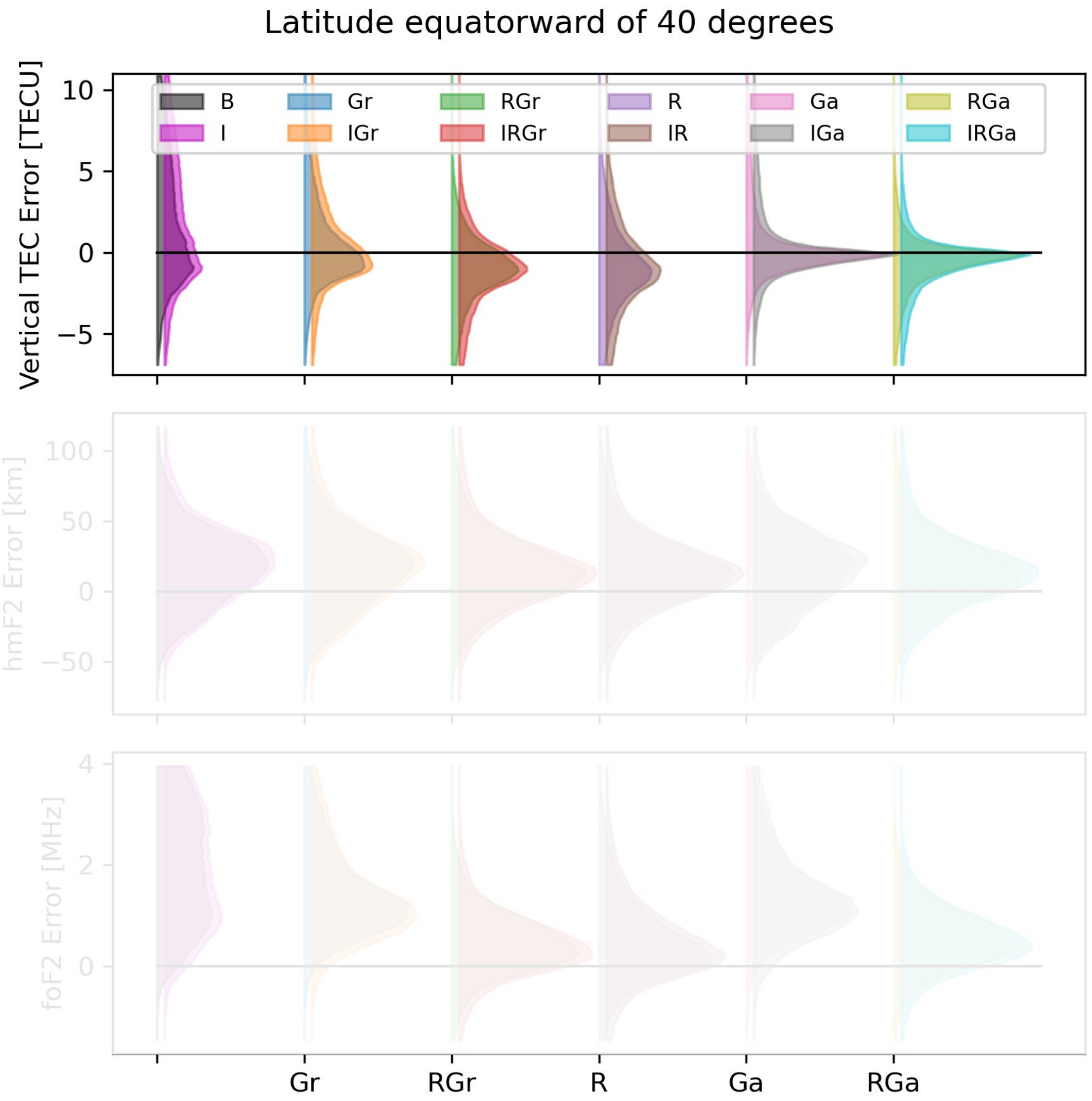
- Since there isn't that much ionosonde data available, it only creates a small change in this global metric

We currently limit this analysis to latitudes equatorward of 40 degrees so that we overlap with COSMIC-2 RO measurements



Relative Merits

1. [Top Panel] absolute Ground TEC (Ga) helps specify vTEC



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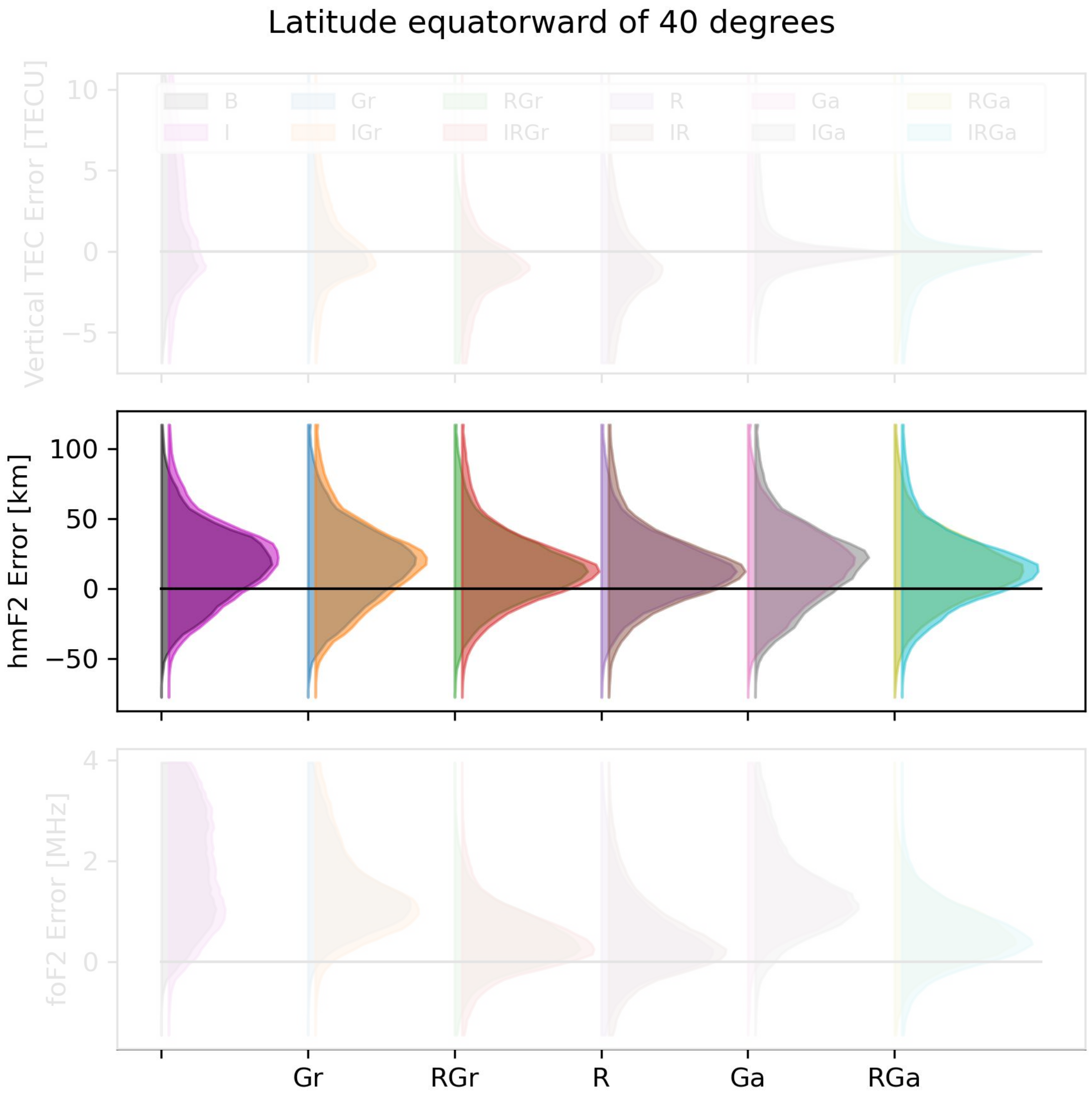
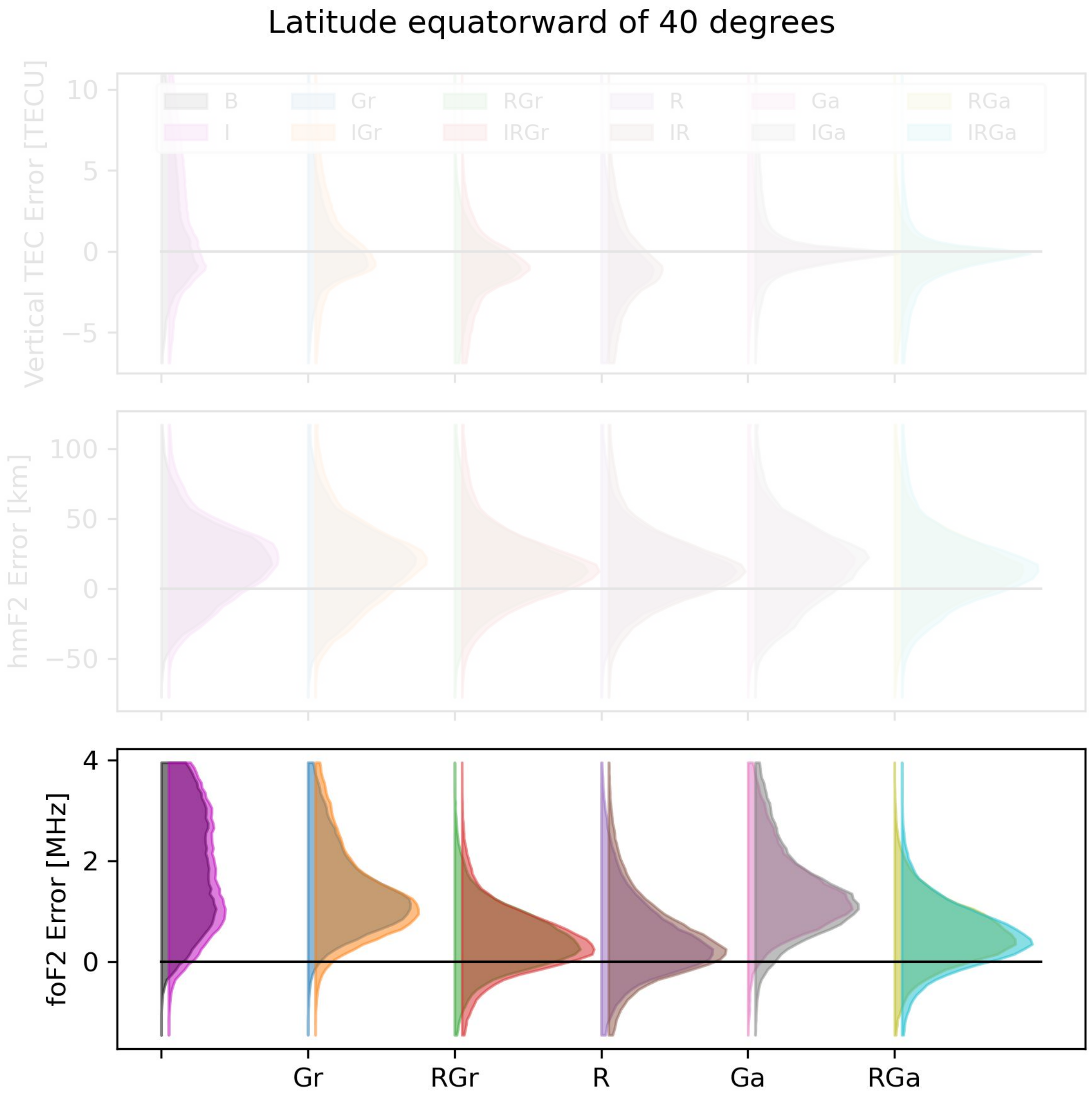
Relative Merits

1. [Top Panel] absolute Ground TEC (Ga) helps specify vTEC
2. **[Middle Panel] RO data helps specify hmF2**



Relative Merits

1. [Top Panel] absolute Ground TEC (Ga) helps specify vTEC
2. [Middle Panel] RO data helps specify hmF2
3. **[Lower Panel] RO data also helps specify foF2, but the addition of Ga reduces this**



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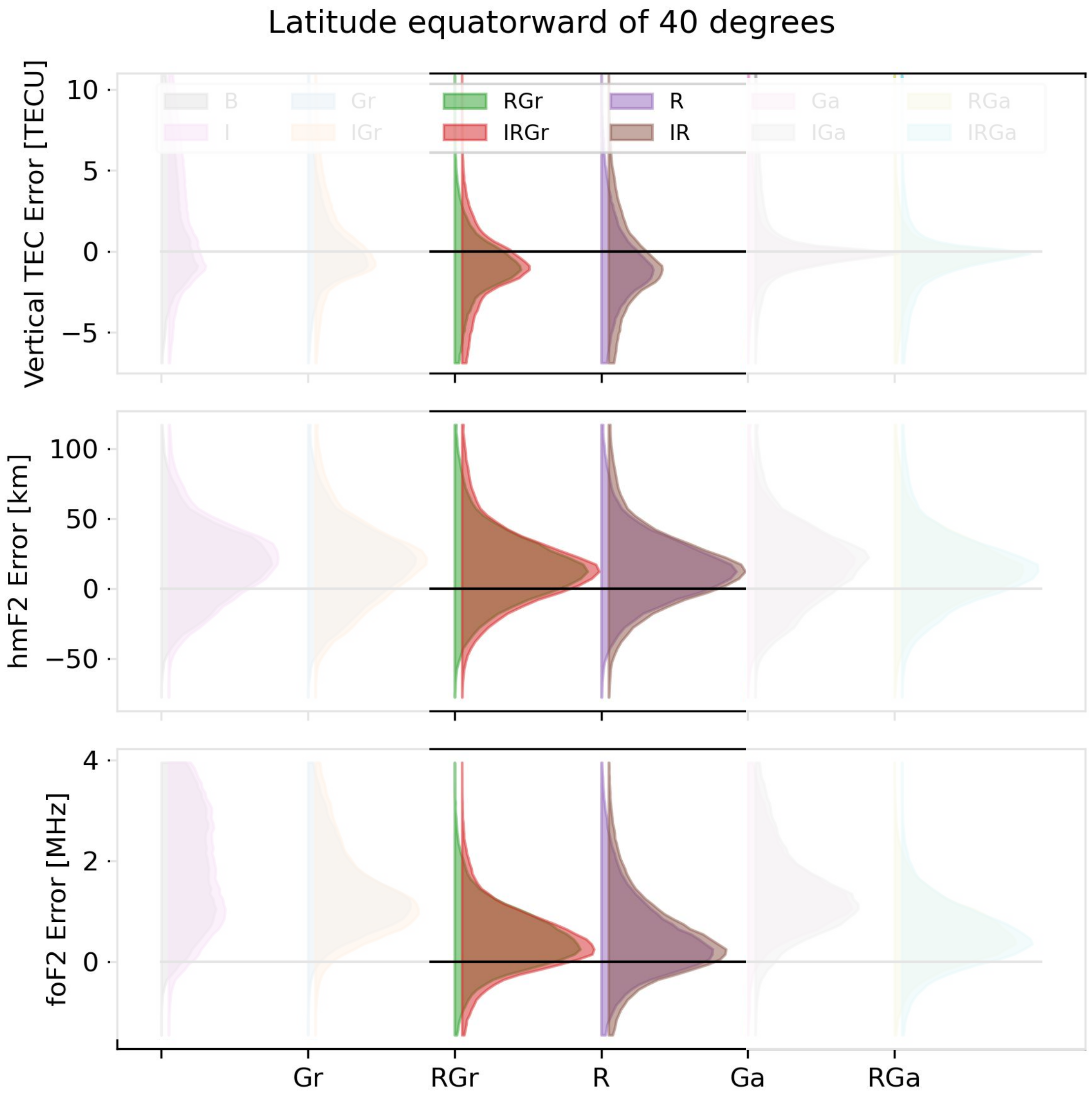
4. **[All] Relative Ground TEC does not add much to RO**



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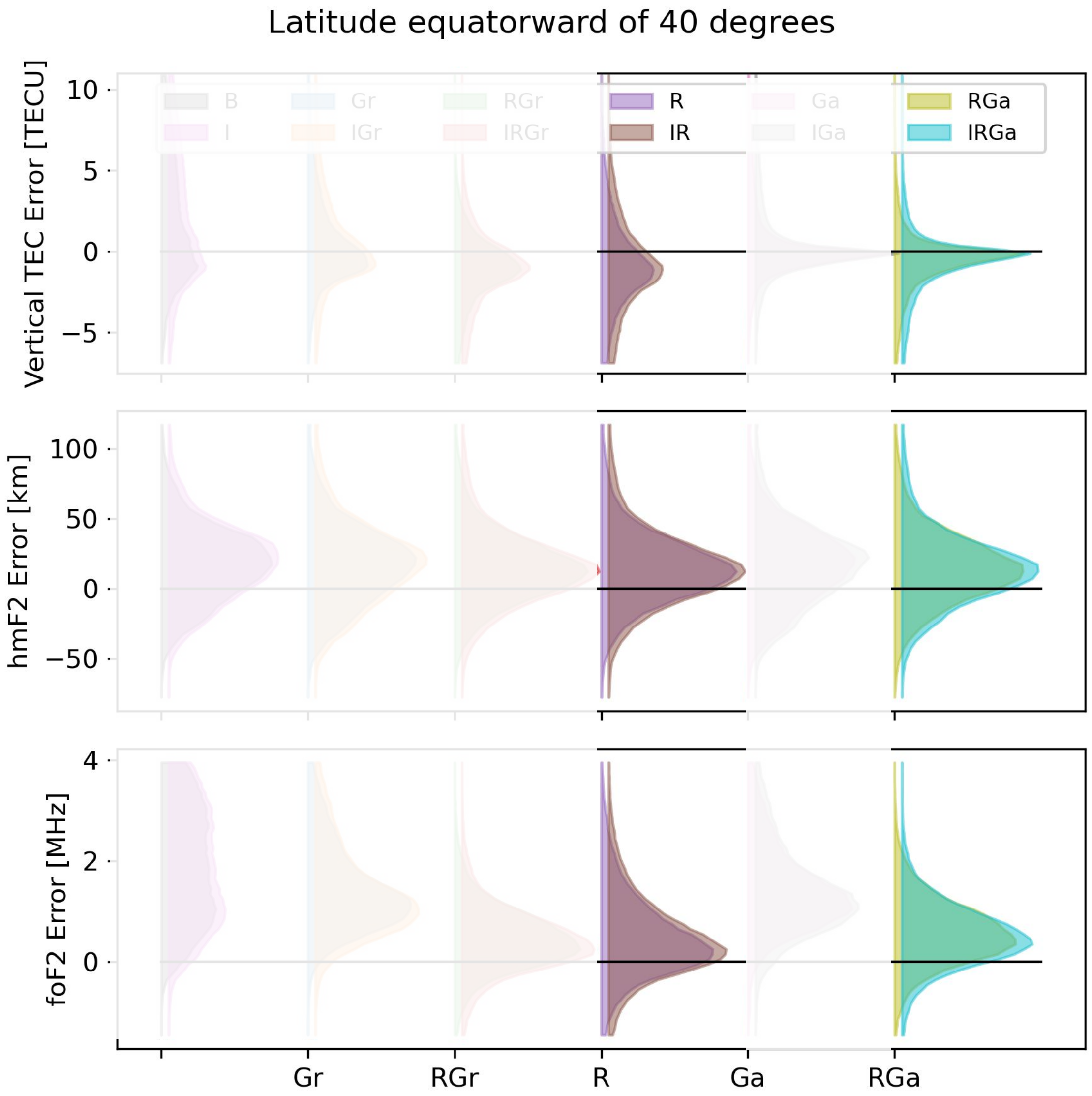
5. **[All] Absolute Ground TEC adds vTEC performance to RO, but takes away a small amount of performance in foF2**



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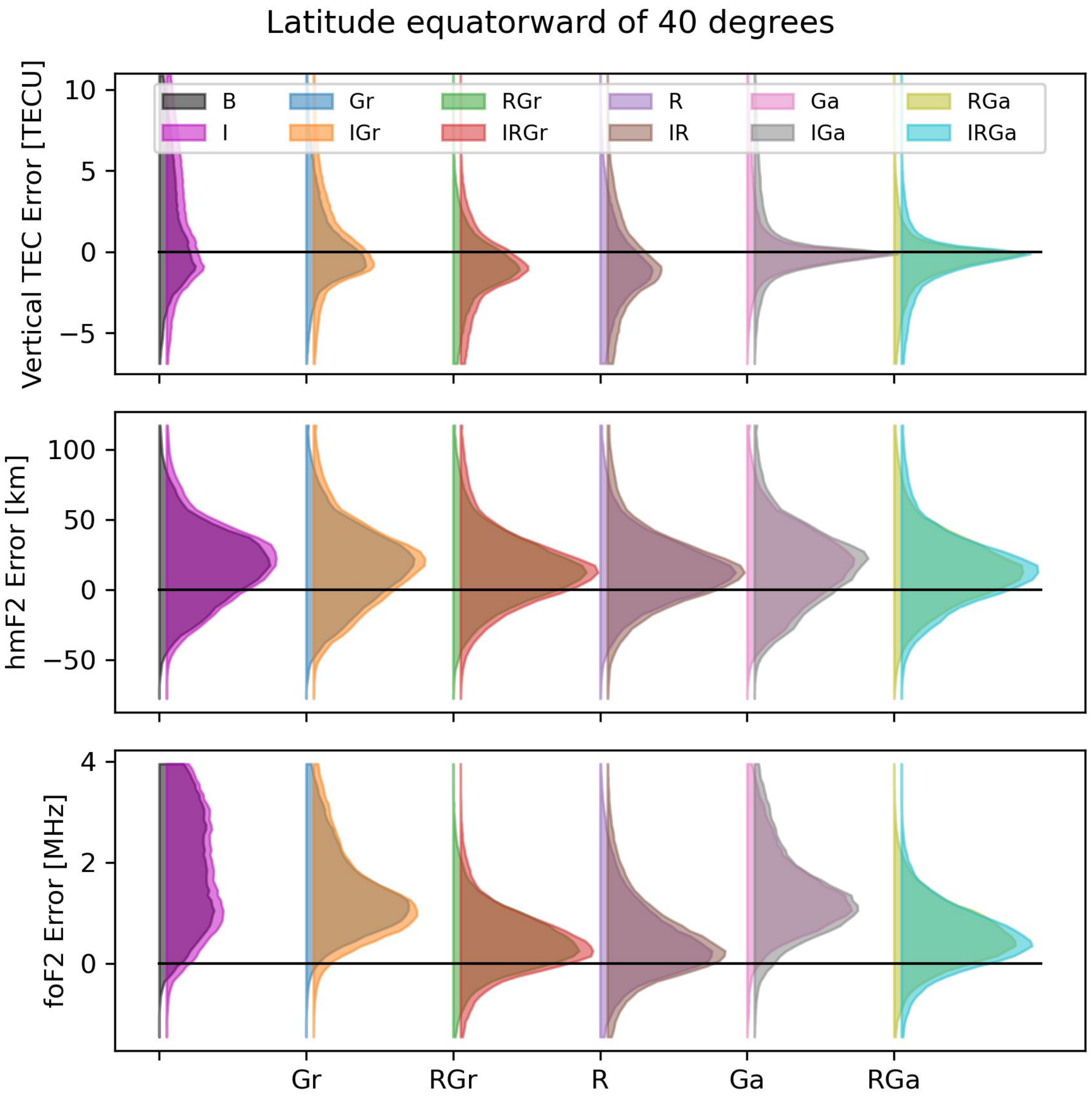
Let's revisit our three questions:

- Q1: Our proxy of vertical structure (fof2/hmf2 error) ***DOES*** improve with the addition of RO data
- Q2: Our proxy of horizontal structure (vTEC errors) ***DOES*** improve with the addition of Ground GNSS TEC, especially if it's ingested as absolute
- Q3: the combination of RO and Ground GNSS TEC ***DOES NOT*** surpass the performance of either on all three metrics



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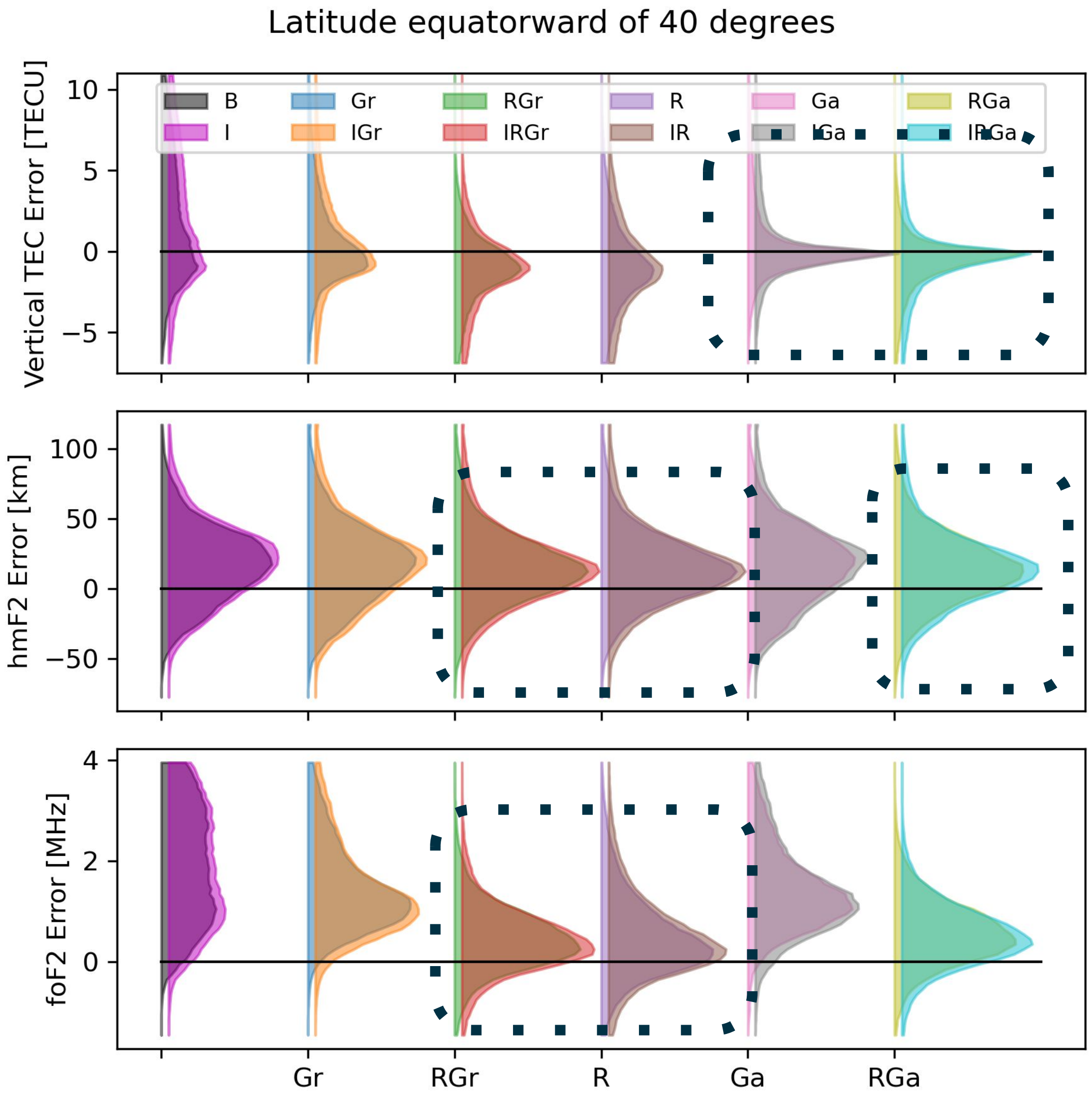
Takeaways

No one combination of data is the best for all three ‘simple’ metrics

- For vTEC, you want Ga or RGa
- For hmF2, you want anything with R
- For foF2, you want RGr or R

However, the inclusion of RO data has either a neutral (vTEC) or very positive (hmF2, foF2) impact.



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PART 2: IMPACT OF *COMMERCIAL* RO DATA

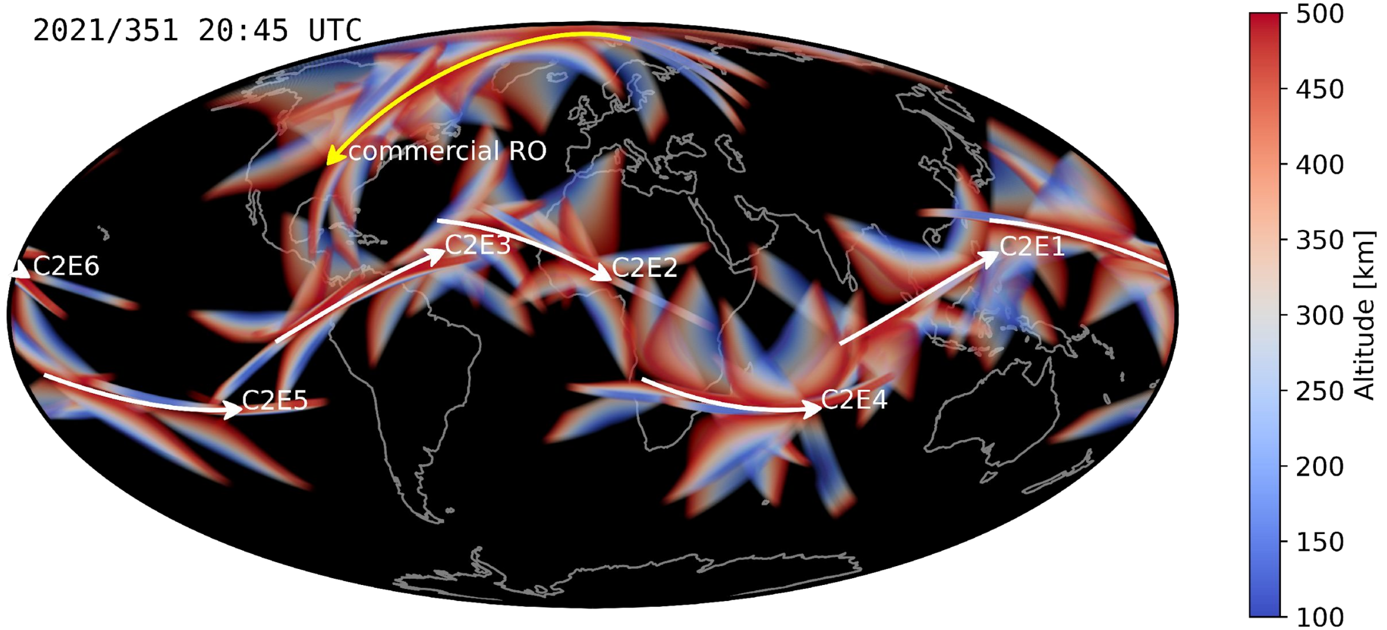
Commercial RO data OSSE details

- As part of the US Air Force Commercial Weather Data Pilot (CWDP) program, we evaluated PlanetiQ TEC data collected by their GNOMES-2 satellite from 10/2021-04/2022.
  - PlanetiQ measures TEC with 4 GNSS constellations
- This OSSE did not use the actual TEC measurements, but did use the GNOMES-2 and GNSS satellite positions to mimic real measurement coverage
  - 2021/12/17 podTc2 files

Analysis 1: The data types from part 1 (COSMIC-2 RO, ground GNSS, ionosonde)

Analysis 2: Run 1 + PlanetiQ

Example 15 minutes of ionospheric coverage



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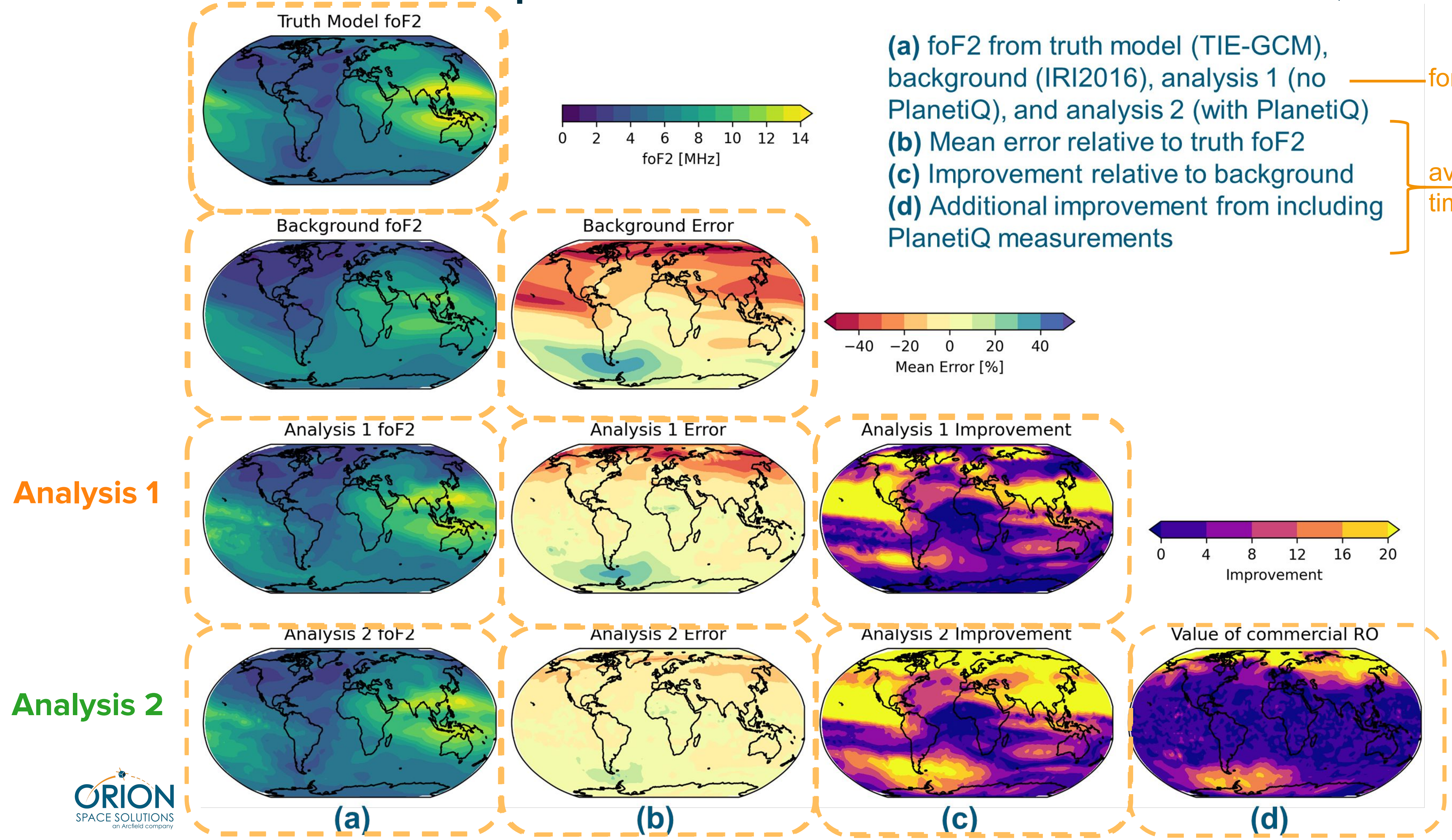
Results of foF2 specification OSSE with PlanetiQ

(a) foF2 from truth model (TIE-GCM), background (IRI2016), analysis 1 (no PlanetiQ), and analysis 2 (with PlanetiQ) — for a specific time of day

(b) Mean error relative to truth foF2
(c) Improvement relative to background
(d) Additional improvement from including PlanetiQ measurements

— averaged across all times throughout the day



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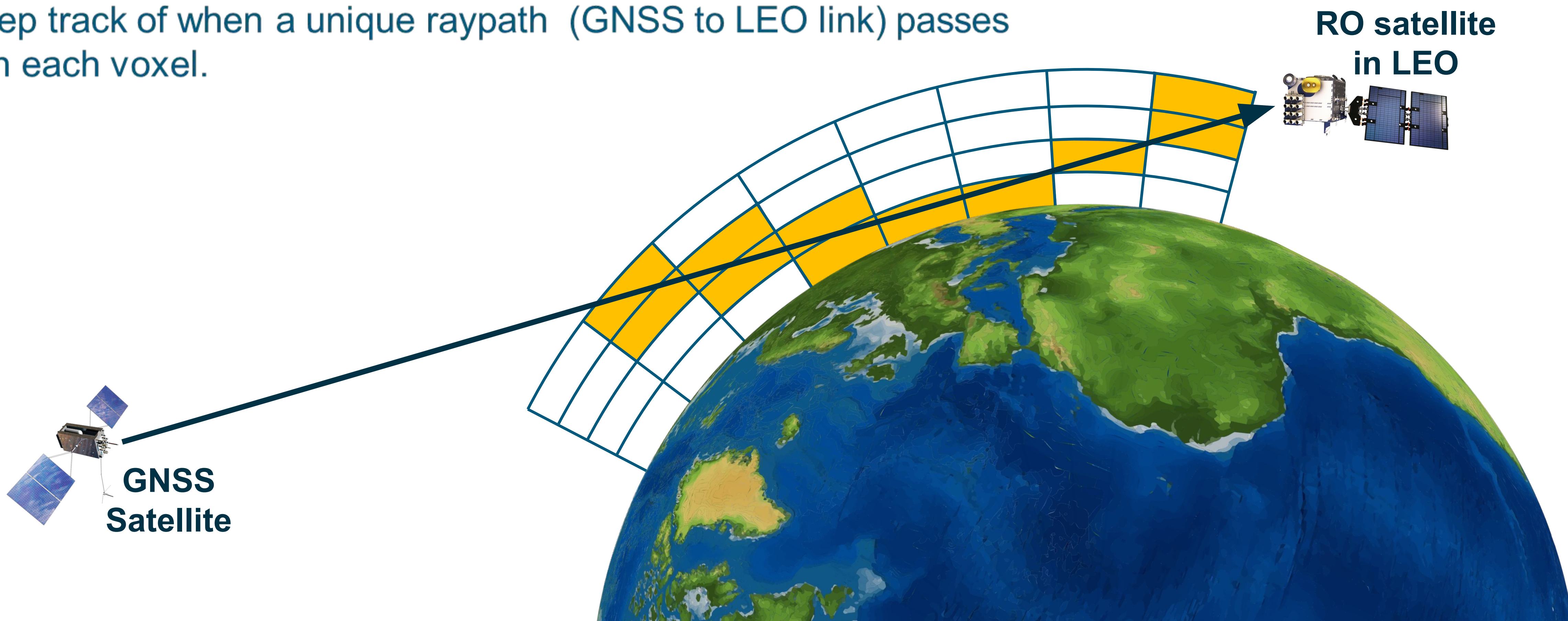
Coverage Analysis Method

We split the ionosphere into voxels:

- Global 2.5° × 2.5° latitude/longitude
- 10 km altitude spacing from 100 to 1000 km
- 10 minute timestep

and keep track of when a unique raypath (GNSS to LEO link) passes through each voxel.



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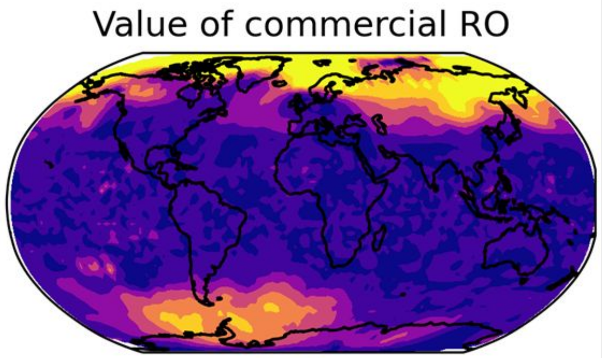
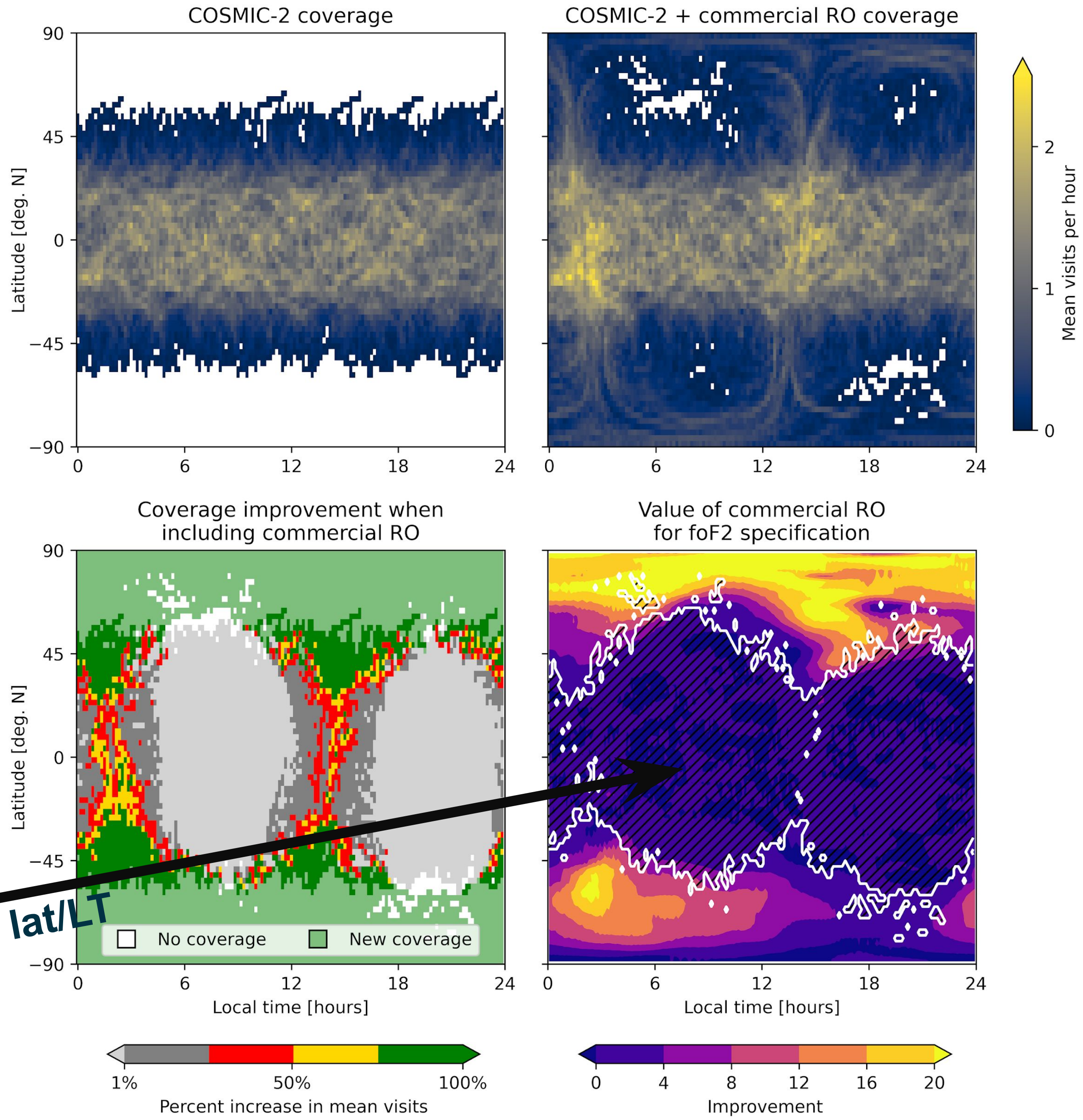
OSSE results compared to coverage

- Top two plots show coverage at 300-310 km altitudes (near hmF2/foF2) for COSMIC-2 and COSMIC-2+PlanetiQ
- Bottom left plot shows coverage increase from the one PlanetiQ satellite

- **Areas with new or >75% increase in coverage see significant foF2 improvements**





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More information

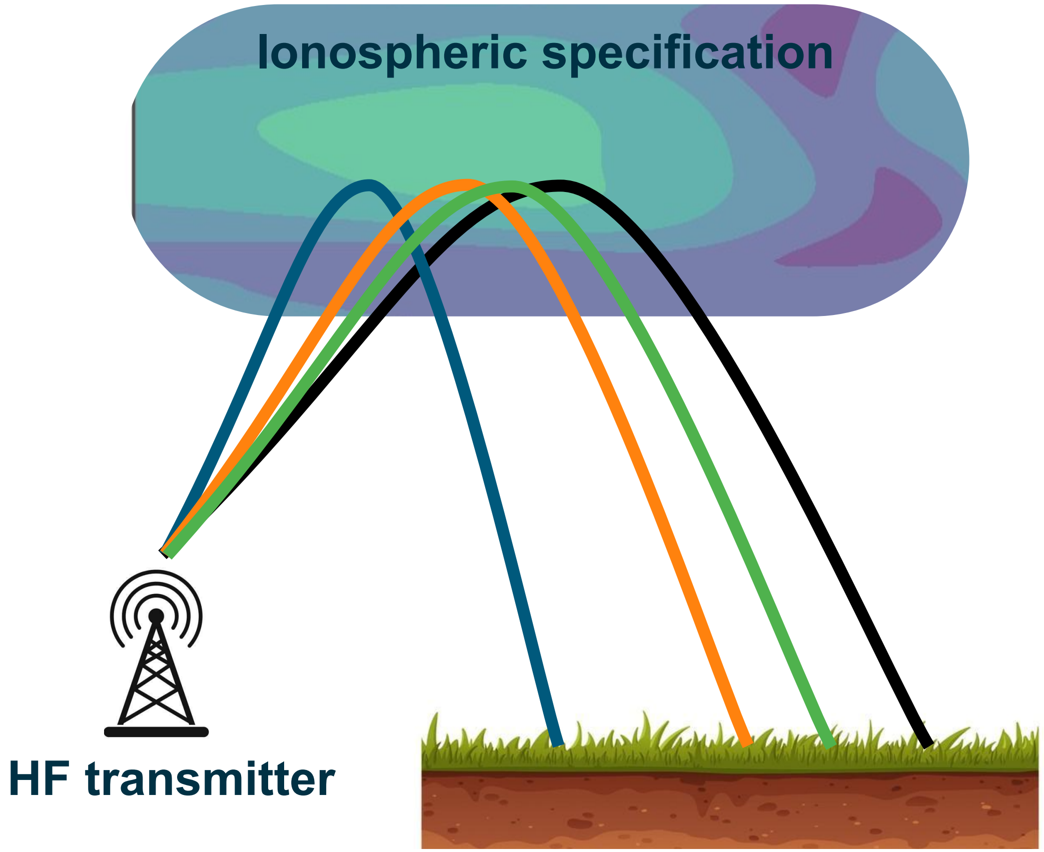
Part 1:

Joe Hughes, *Relative Merits of Ionosondes, Ground GNSS TEC, and Radio Occultations for Ionospheric Data Assimilation.* Geospace Data Assimilation Working Group (GeoDAWG) seminar, May 2024. https://youtu.be/Zoak22k2UUI

Paper on the same topic including HF propagation impact is in preparation

Part 2:

J. Hughes, I. Collett, et al., *Evaluating the impact of commercial radio occultation data using the observation system simulation experiment tool for ionospheric electron density specification* Front. Astron. Space Sci., 2024. https://doi.org/10.3389/fspas.2024.1387941



Truth
Background
Analysis without RO
Analysis with RO

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THANK YOU

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Joe Hughes' GeoDAWG seminar

Commercial RO OSSE paper

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