Space Weather Research & Technology Applications

SPARTA
Center of Excellence

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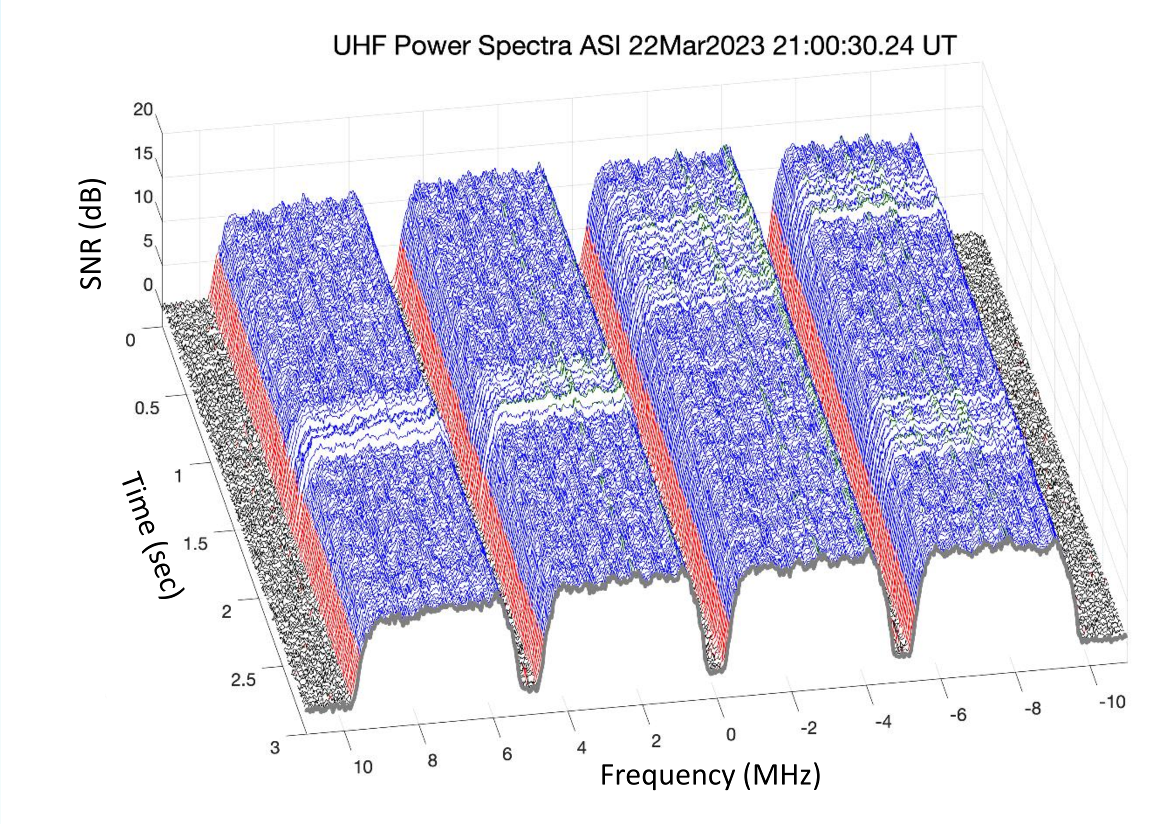
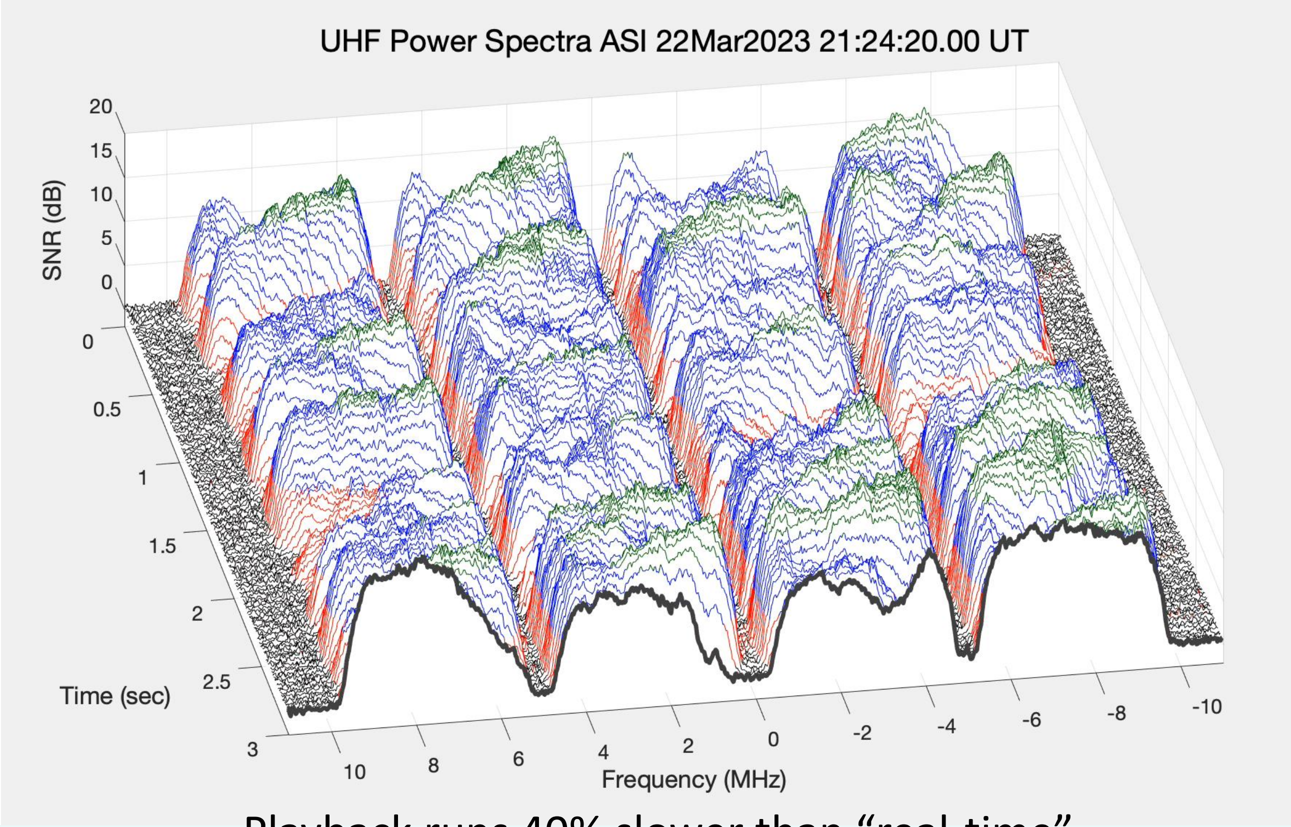
Shielding Users from Unexpected Scintillation Impacts
SPARTA SWxC
SPARTA SWxC - Space Weather Research and Technology Applications
Specifying and forecasting ionospheric irregularities and scintillation and
their impacts on Communication, Navigation and Timing Systems.
2

Scintillation Effects on the RF Spectrum

No Scintillation Case



Scintillation (S4 = 0.93)



Playback runs 40% slower than "real-time"

Legend: **RED** $\leq \langle P \rangle - 6$ dB; **GREEN** $\geq \langle P \rangle$

Dramatic effects in two-dimensions: time and frequency

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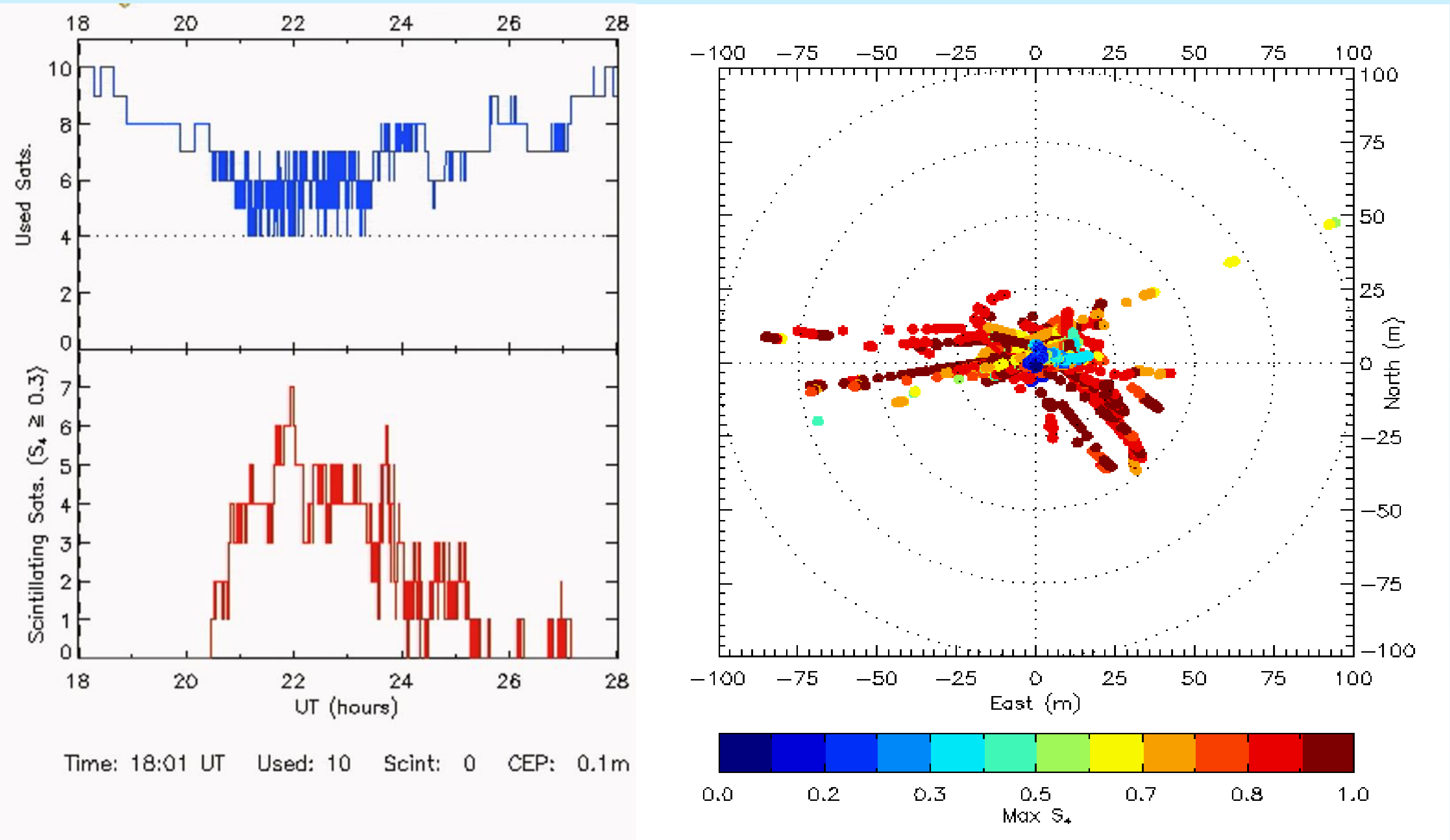
Scintillation Effects on GNSS Performance



GPS and other systems trying to track scintillated signals may suffer impacts on performance

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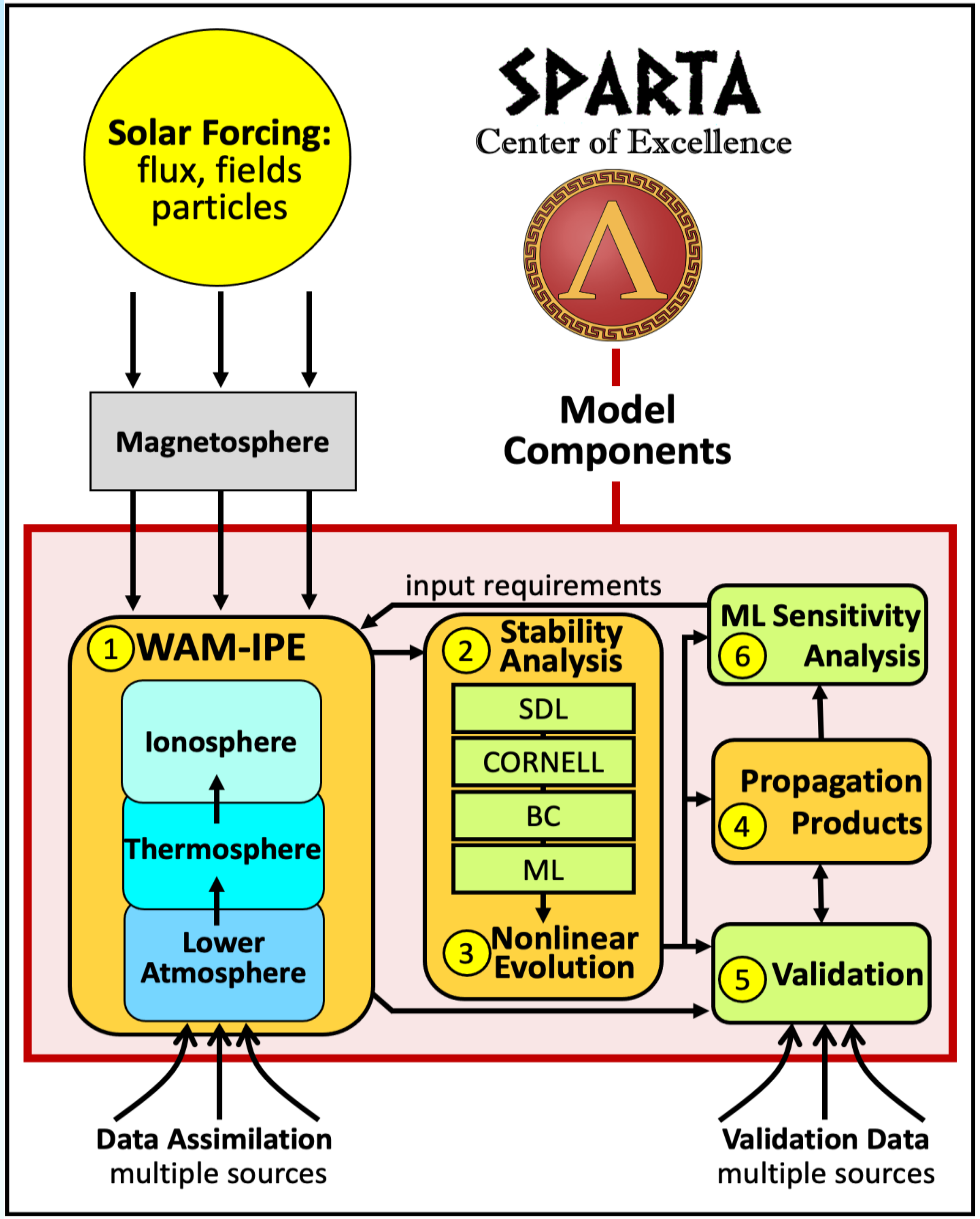
Modeling Components

- The ionosphere-thermosphere system is driven by solar forcing via the magnetosphere from above and terrestrial atmosphere forcing from below
- SPARTA is focused only on forecasting irregularities (and scintillation) given inputs from a background model that can provide the requisite ionospheric/thermospheric parameters
- The system is agnostic with respect to the background model employed: forecasts will improve as the background model improves



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There are three primary technical objectives for SPARTA:

1. Demonstrate a baseline capability to forecast ionospheric irregularities and associated scintillations on a global scale using inputs from WAM-IPE
   - Global (2-24 hour) validated forecasts
2. Implement deep learning algorithms to potentially demonstrate the capability to make forecasts in real-time
   - Necessary step to obtain rapid results with minimal loss of accuracy
3. Quantify the relationship between data input quality (accuracy, resolution, latency) and forecast skill as functions of location and geophysical conditions
   - Informs requirements for focused data collection architecture

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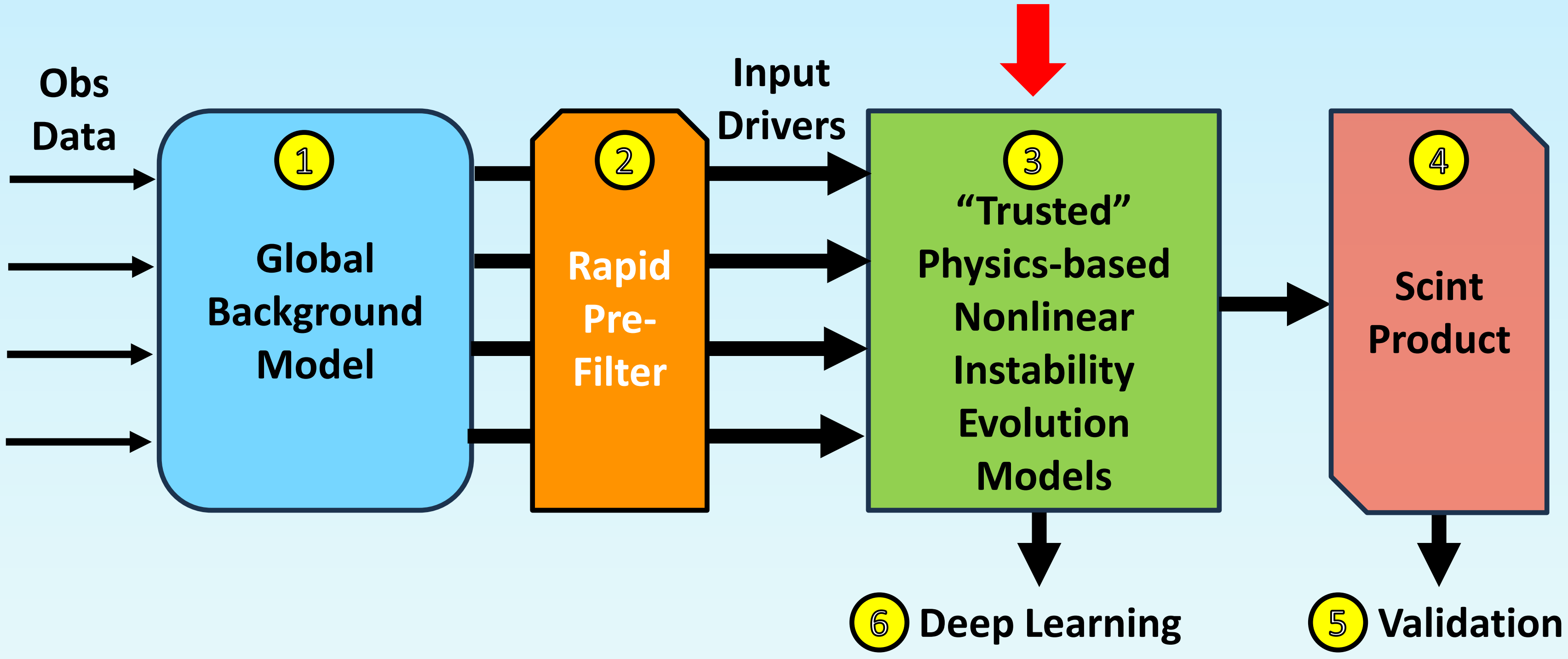
Visualization of the Generic Modeling Chain



- Any background model can be used in principle
- Focus is on establishing validity of physics-based instability evolution model
- ”Trusted” means good inputs produce good outputs: failure to perform means inadequate inputs

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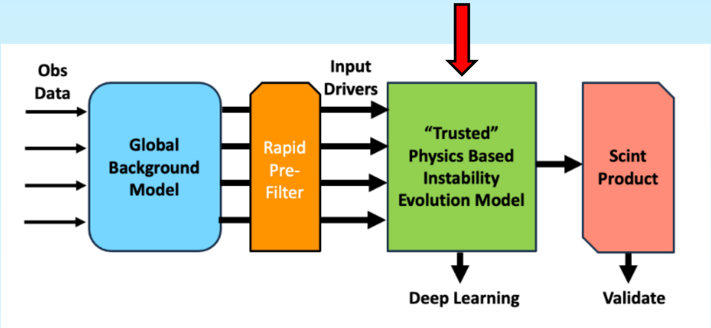
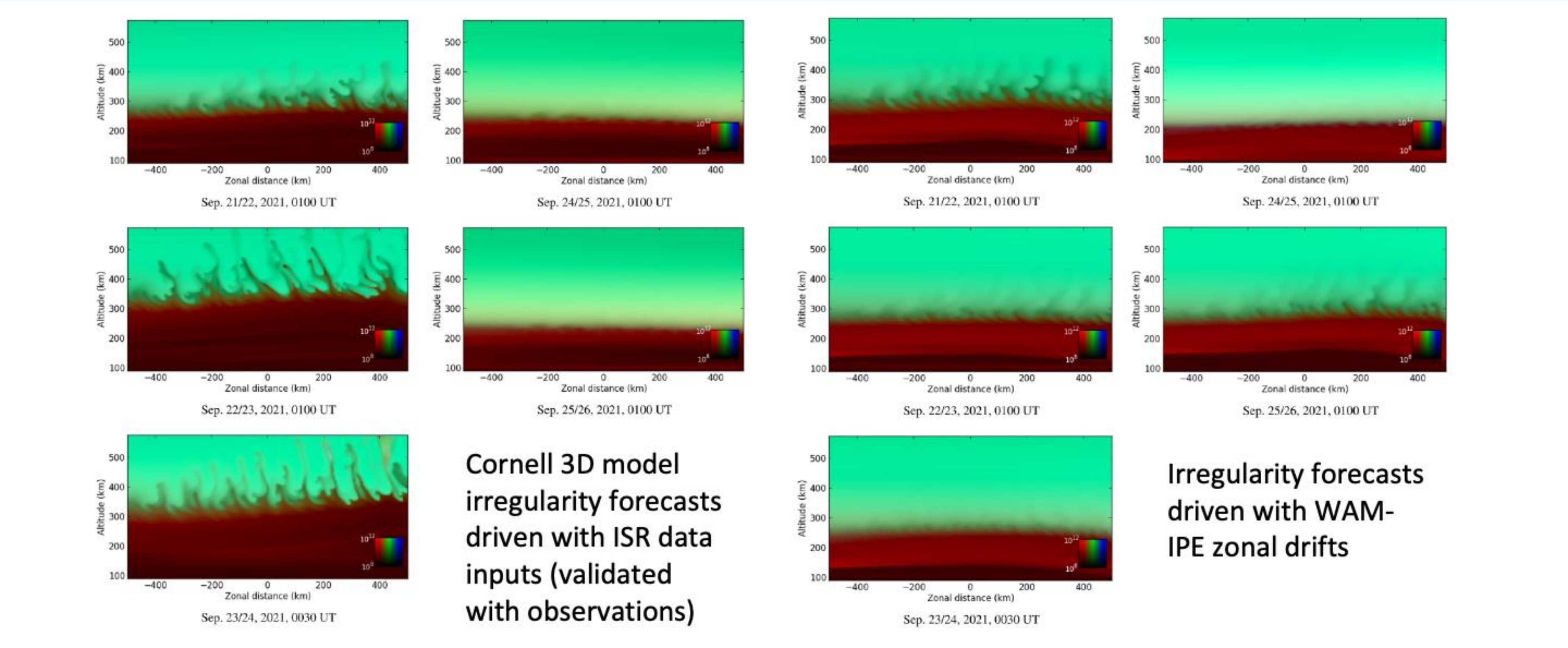
Nonlinear Evolution Models



- The nonlinear evolution models are the key to SPARTA's success
- The premise is that the models are of sufficient fidelity that, given accurate inputs for the state of the atmosphere, they can faithfully describe the evolution of the ionospheric plasma
- Poor performance then equates to poor inputs, and the model can be used to determine the types and quality of inputs needed to achieve a desired level of forecast skill
- This is extremely powerful for defining the number and quality of observables needed to forecast irregularities
- We believe the Cornell 3D model is close to meeting the trusted model standard for low latitude instabilities
- More model development is needed for other regions, but the extension to other instability environments is not overly difficult

Cornell 3D Model Demonstration

- The Cornell 3D Model driven with inputs derived from incoherent scatter radar observations correctly predicted gross instability development on 5 nights, whereas the same model driven with WAM-IPE was correct on only two (Hysell et al., 2022)
- More recently demonstrated similar performance using electric fields and winds from ICON



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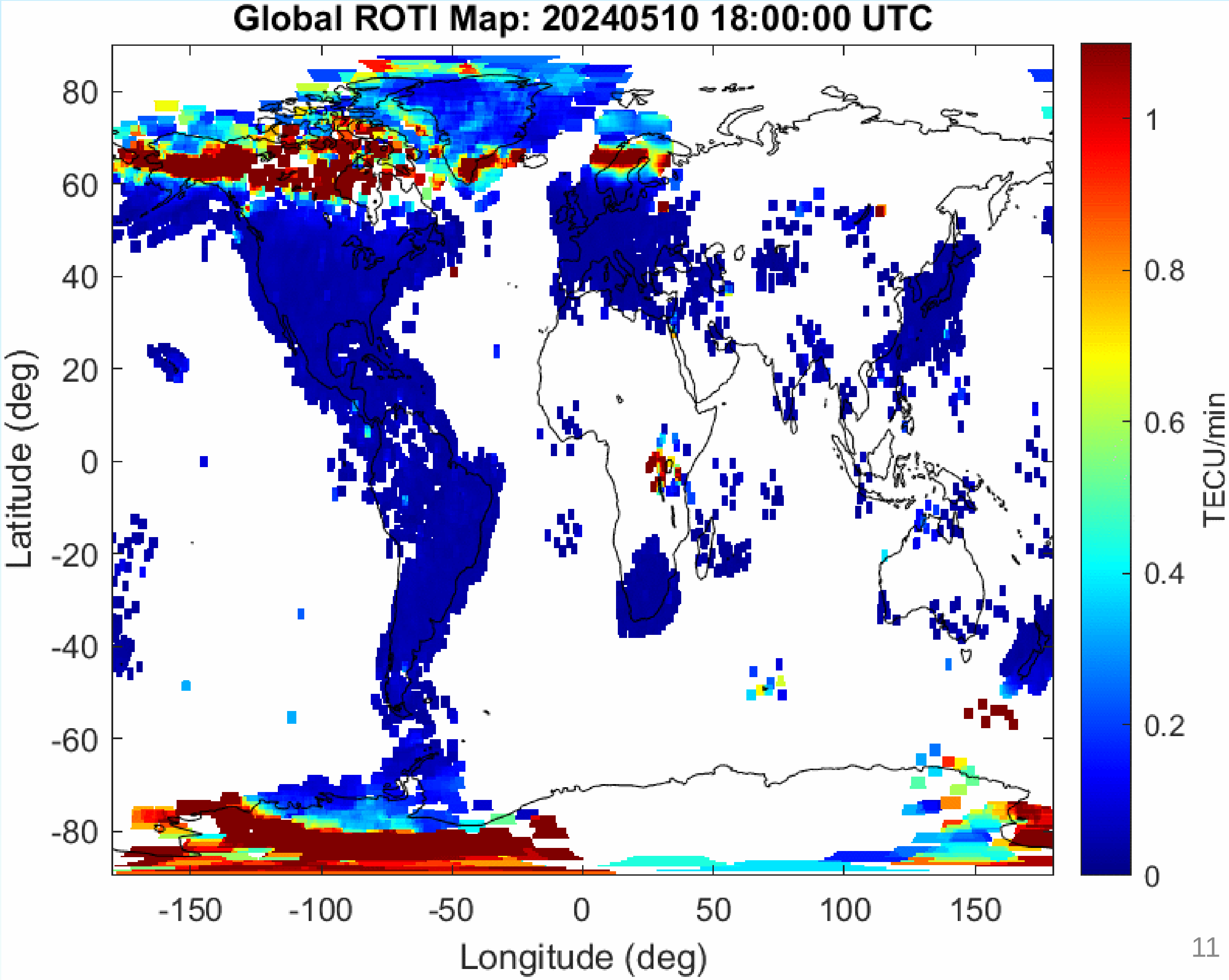
Challenges at Mid- and High Latitudes

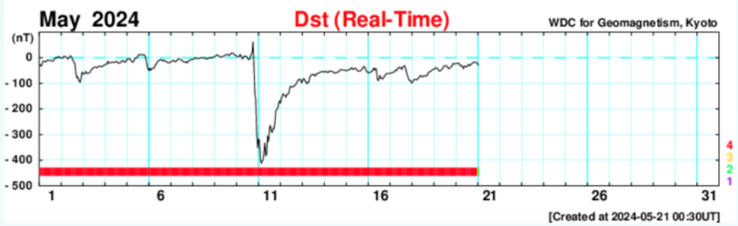
- Descriptions of the Rayleigh-Taylor Instability are more mature than mid- and high latitude instability models
- Fortunately there are a limited number of relevant plasma instabilities generating small-scale structure in the F-region ionosphere (very few with initials that are not G.D.I. – gradient drift instabilities)
- The challenge will be specifying the locations and magnitudes of gradients
- E-region instabilities important for radars, but not so much for scintillations (RO is a possible exception)
- SPARTA will lead with low latitudes, but there is great opportunity to show progress at mid- and high latitudes

May 10 Storm: Scintillation at All Latitudes for Hours

SPARTA will focus on this event for global scintillation forecasts in Year 1

- Characterize formation of small-scale irregularities and associate with macroscale features & dynamics
- Assess representation of relevant structures in background model
- Establish empirical relationships if necessary to bridge gaps between background model and nonlinear evolution models





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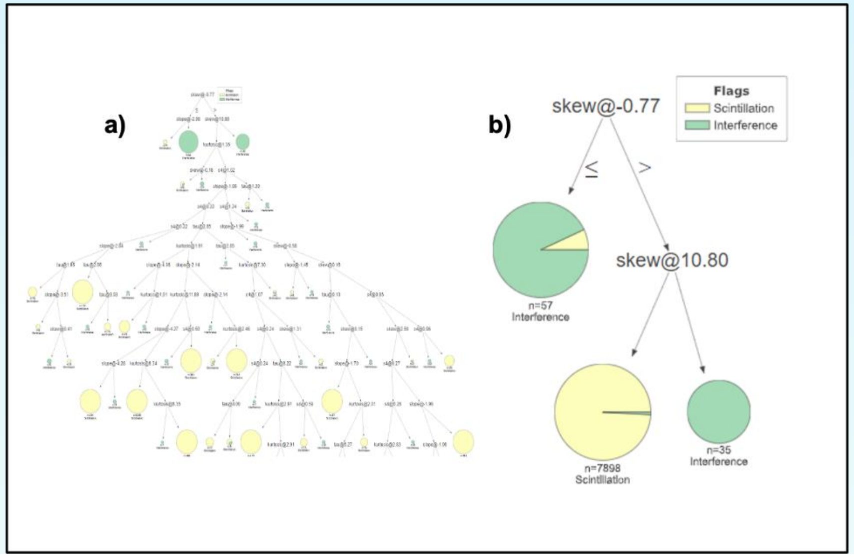
Machine Learning

Machine learning techniques will be applied in SPARTA primarily for two purposes:

1. Replace the physical instability forecast models (proxy, or emulator)
2. Perform analyses with the physical models to understand the sensitivities of the models to specific parameters/configurations and define the impacts of measurement error on forecast performance

- Item 1 above is more or less necessary for real-time operation
- Item 2 is necessary to understand the type, quantity, quality and resolution of observations needed to achieve a desired forecast skill
- The latter is a key contribution from the SPARTA SWxC
- We will also pursue ML-based "discovery science" with SPARTA using Master's degree students



a) Full decision tree analyzing five parameters to classify scintillation and interference; and b) pruned tree revealing that skew alone is an effective scintillation classifier.

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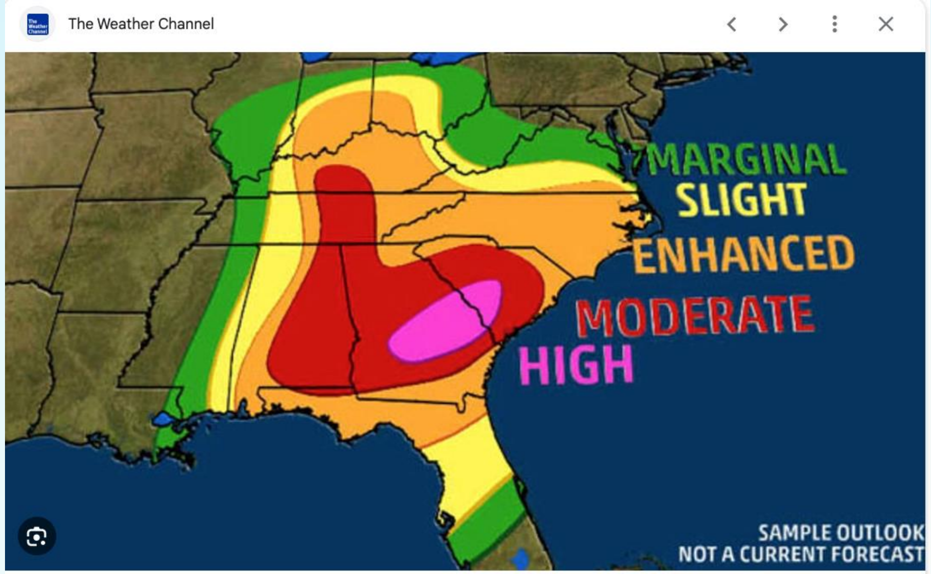
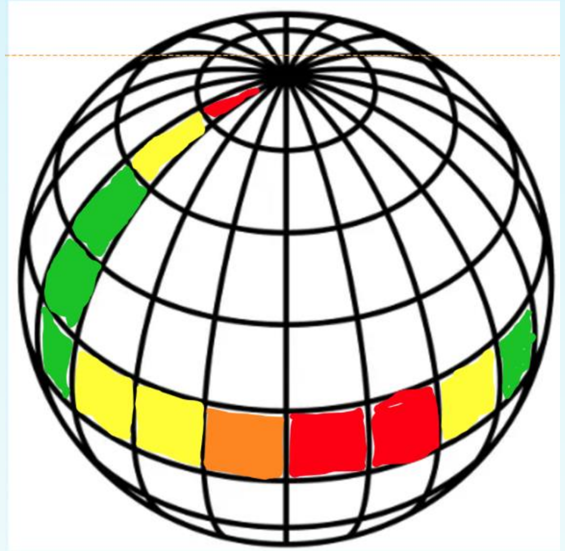
Products: Probabilistic Area Forecasts

- Forecasts will be probabilistic global over fixed areas
  - Resolution TBD, may depend on region
- Similar to probability maps for convective activity (i.e., thunderstorms)



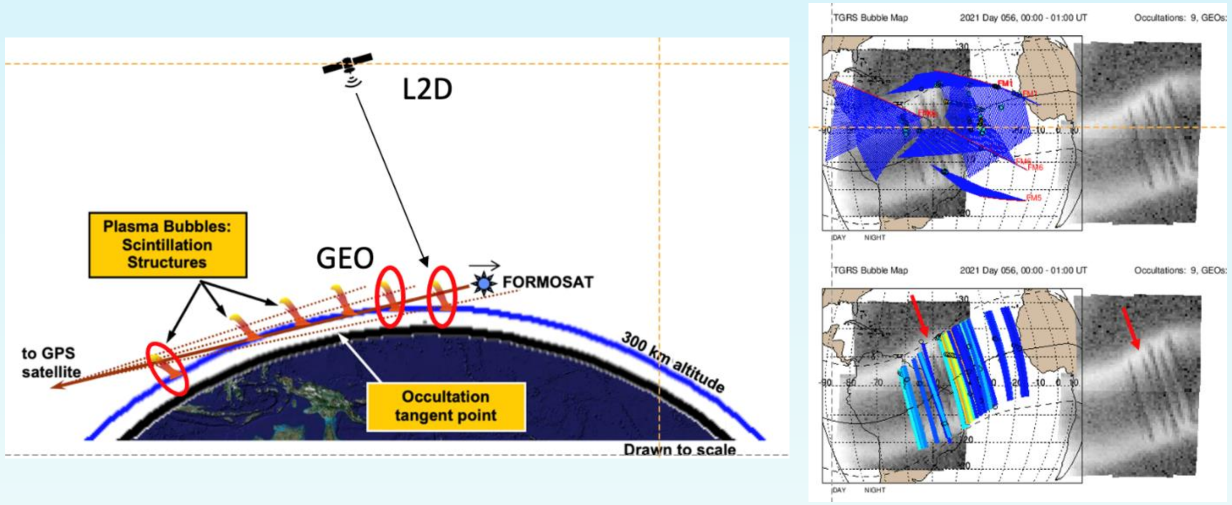
L-Band Scintillation Probability



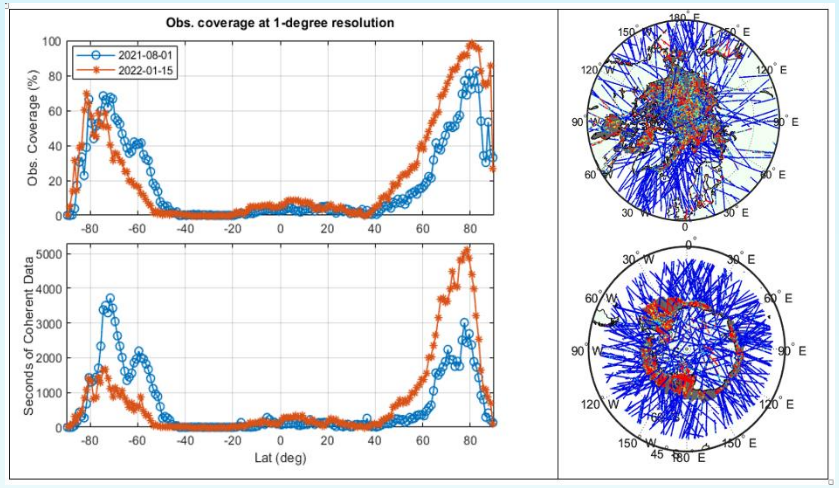
(notional)

Validation: Ground & Space-Based Data Sources

- Forecasts have little value if they cannot be verified
- Validation at high and low latitudes can be challenging (harsh remote areas, large ocean coverage, difficult to access); CHAIN offers more than 100 GNSS scint receivers across Canada
- Ground stations include Madrigal, SCINDA, LLISN, CHAIN, CU Boulder and others
- Space-based GNSS reflectometry and radio occultation



Radio occultation refers to measuring GNSS signals from a LEO satellite. As the LEO satellite sets (or rises) relative to the GNSS sat, the signal cuts through the ionosphere and experiences scintillation when irregularities are present. BC has the capability to characterize the irregularities and associated overhead scintillation from such measurements.



GNSS reflectometry observations can map TEC structure. The left panel shows % coverage and data volume as a function of latitude; coverage maps of the northern and southern polar caps for a single day are shown far right. The technique works well over ice and ”smooth” ocean surfaces

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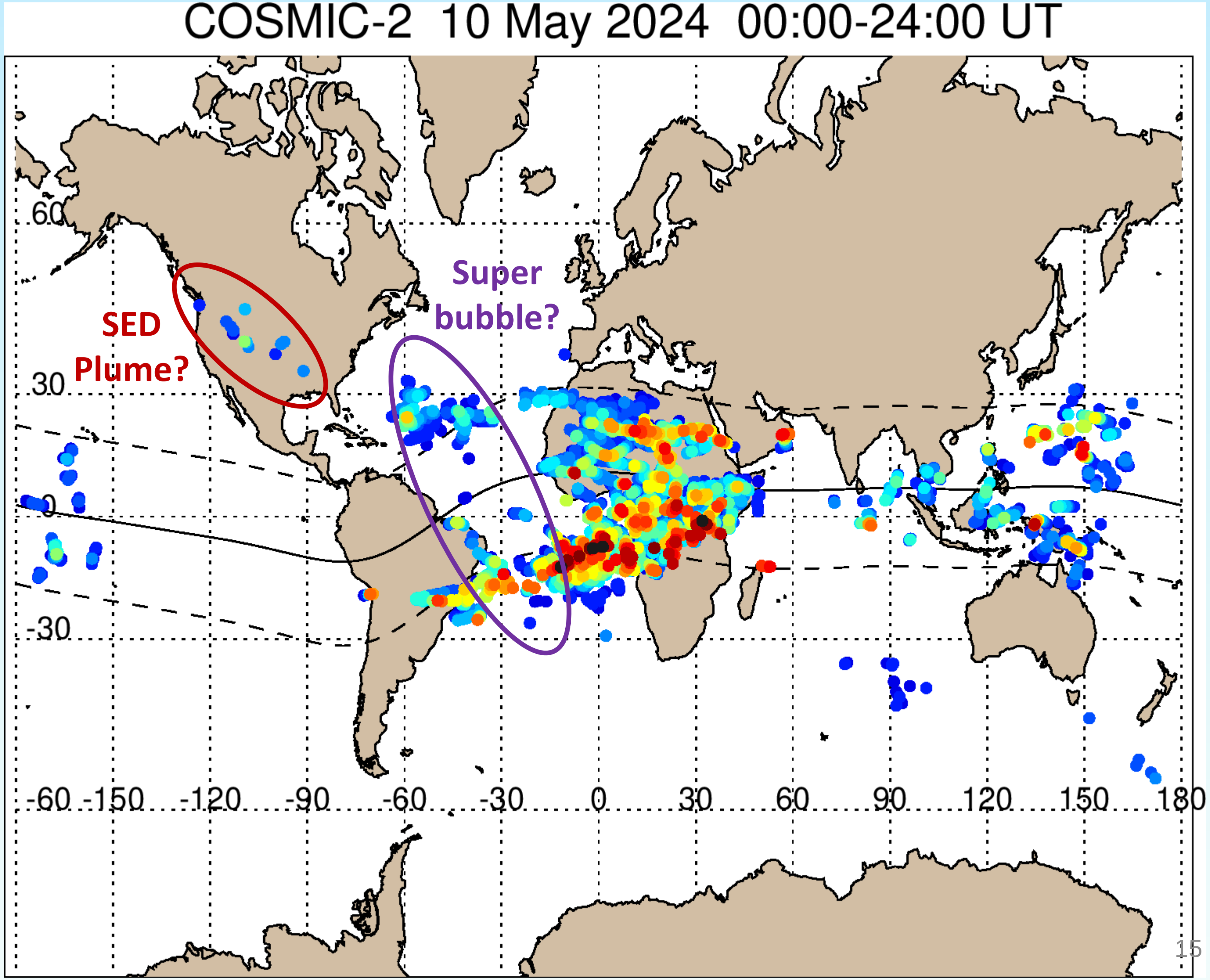
COSMIC-2 Validation

- Unprecedented detection of irregularities with radio occultations
- Storm-time fields overcame dominant negative seasonal control of bubbles in the American sector
- Mid-latitude irregularities clearly detected
- Additional RO data being analyzed for high-latitudes



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"We are SPARTA"

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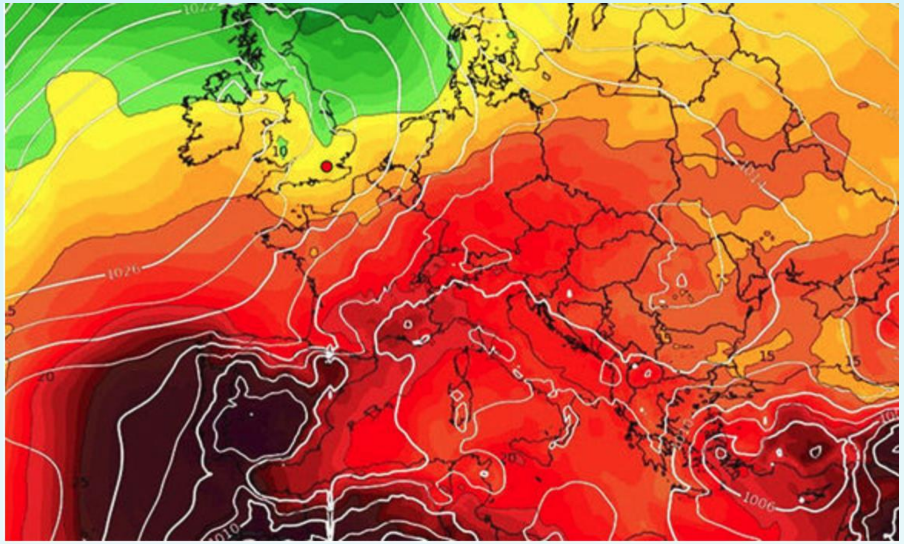
Additional Elements

Special Forecast Focus Periods



- Leverage ISR World Days
- Intensive radio occultation data periods
- Community-focused data collection

Forecast Challenge:

COMMUNITY
COORDINATED
MODELING
CENTER

Replace WAM-IPE inputs with [your model here] via NASA CCMC (open access); verify background model performance for scintillation forecasts

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SPARTA plans to:

1. Establish baseline scintillation forecast performance with NOAA's existing operational model
2. Demonstrate fast, AI-based forecast algorithms to replace cumbersome physics-based models
3. Quantify performance shortfalls and document what is required to achieve a desired scintillation forecast skill; i.e., define what observations are most important, to what accuracy, resolution, etc.
4. Develop robust modular irregularity/scintillation forecast algorithms that can be readily driven by a range of background models to support users of space-based RF systems

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Thank you for your attention.

Questions?