New Research Needs:

The Ionospheric State and Irregularities Panel

Key Questions:

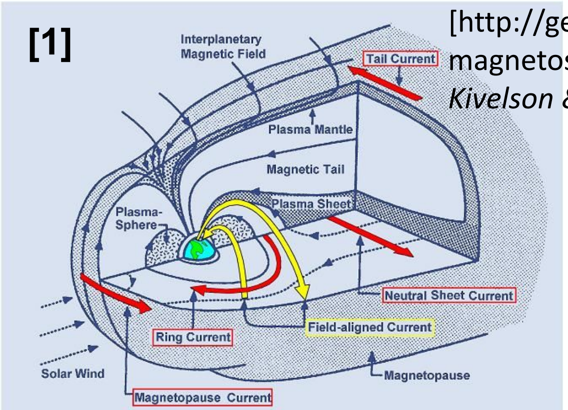
1) What do we need to understand to enable predictive capability of the following topics of the thermospheric and ionospheric state and irregularities?
2) What are the research needs to make progress on that understanding?

Moderator: Anthea Coster, Committee

Seebany Datta-Barua	Illinois Inst. of Technology	Assoc. Professor, M&AE **(Irregularities and Impacts on GNSS)**
Charles S. Carrano	Boston College – ISR	Principal Scientist **(Scintillation and Impacts on Systems)**
Gregory P. Ginet	MIT – Lincoln Laboratory	Senior Staff **(IT Impacts on HF Radio Propagation)**
Jonathan B. Snively	ERAU – CSAR	Professor/ Director of CSAR **(Lower-IT Dynamics and MSTIDs)**
Sean Bruinsma	CNES Space Geodesy Office	Head **(IT Large-Scale State, Densities, and LSTIDs/-TADs)**

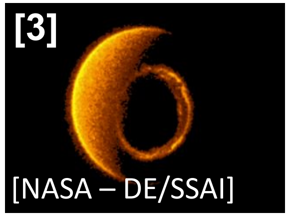
Space Weather Operations and Research Infrastructure Workshop: Phase II, Tuesday, April 12, 2022, 1100 ET

Ionospheric State: Latitude and Scale Dependence

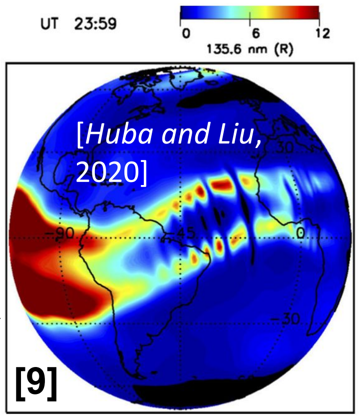


[http://geomag.org/info/magnetosphere.html; *Kivelson & Russel*, 1995]

Solar and Magnetospheric Input

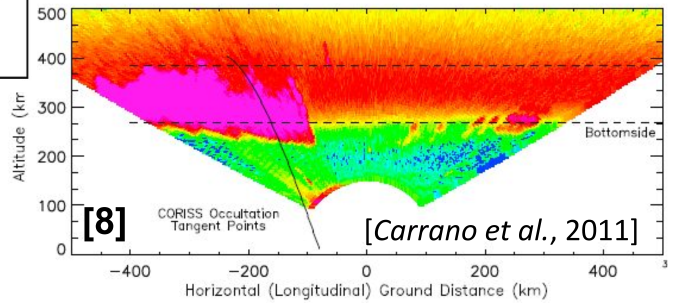


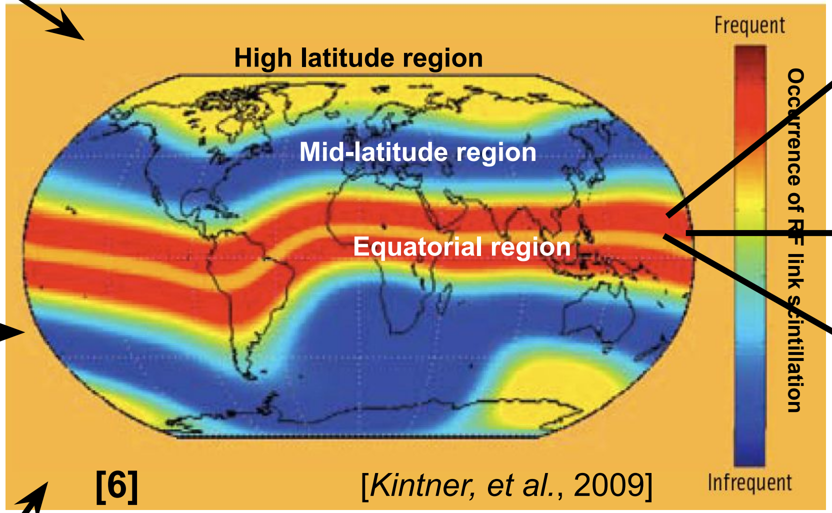
UV image of aurora

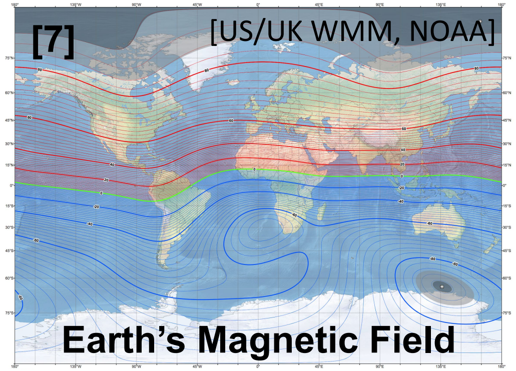


Spread-F (Modeled)

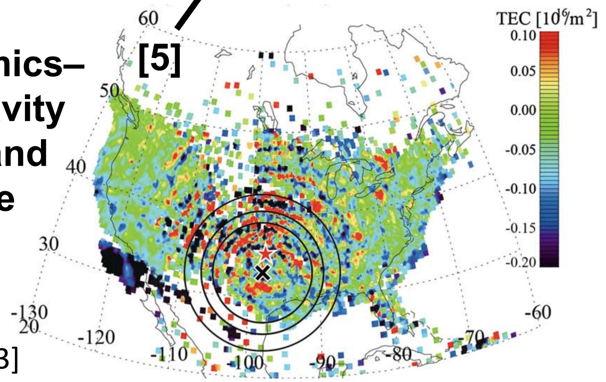
Radar scan showing low-latitude inhomogeneity



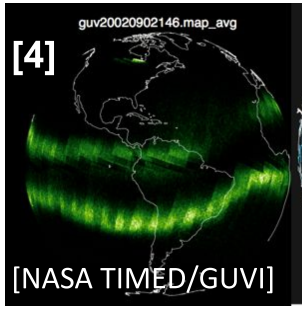




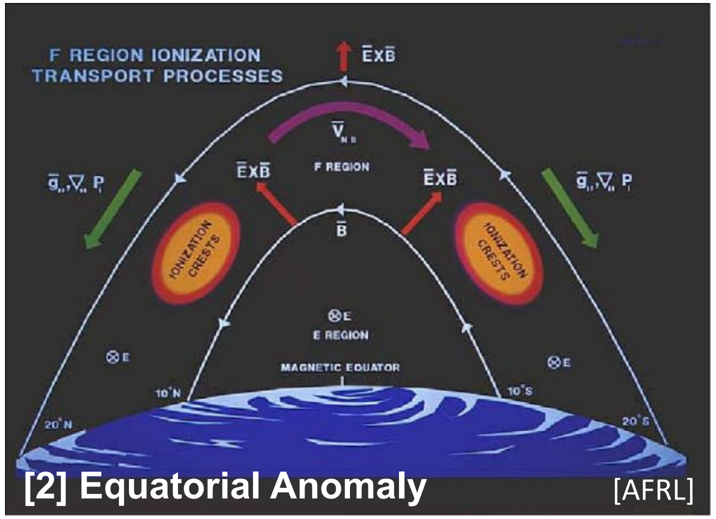
Neutral Dynamics–Acoustic-Gravity Wave TIDs and Turbulence



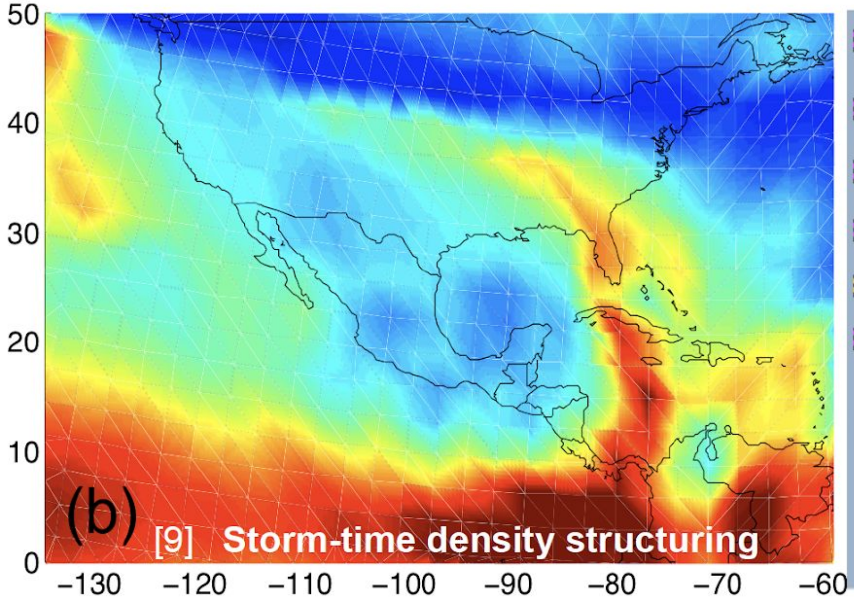
[*Nishioka et al.*, 2013]

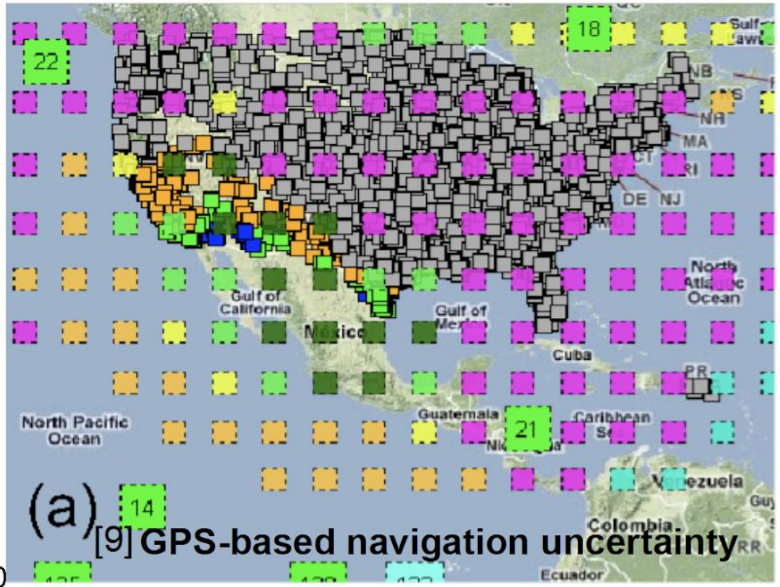


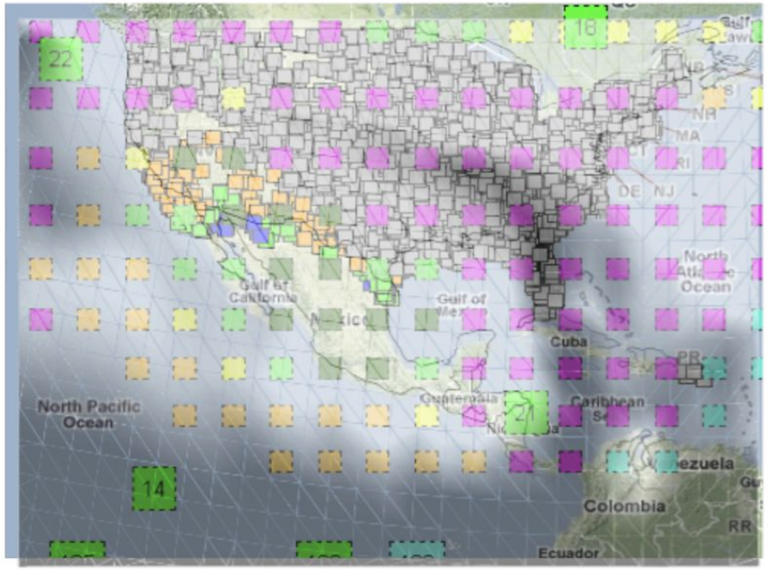
UV image of equatorial anomaly

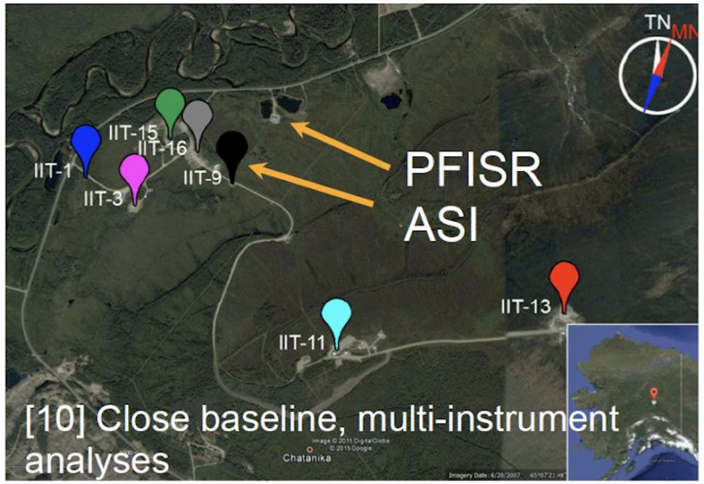


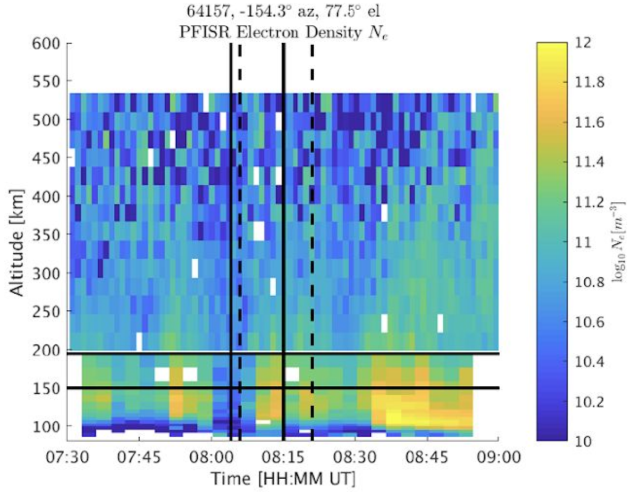
Ionospheric State and Dynamics

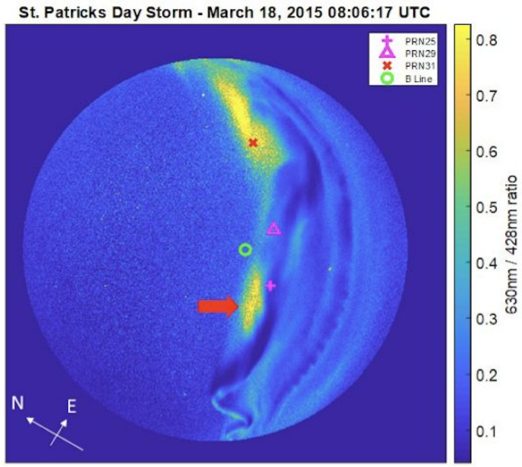












Ionospheric Irregularity Impacts on Safety-Critical Navigation: Research Needs

1. What do we need to understand to enable predictive capability on the state of the ionosphere and its irregularities?

- Forecasting should quantify not only the estimate (for accuracy) but uncertainty (for integrity), to be useful to safety-critical applications. (Also helpful for assimilation and ensemble approaches)
- Deterministic answers to triggering of instabilities or stochastic approaches for forecasting storms / scintillation to improve continuity of service.
- Forecast updates over scales ~minutes-to-hours rather than ~daily. Global scale storm effects, with estimates of impacts that may extend to ~10s of meter scale.

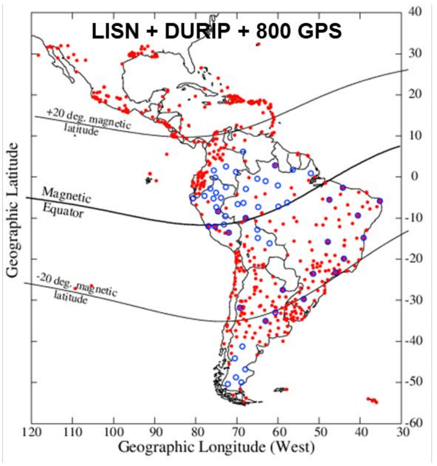
2. What are the research needs to make progress on that understanding?

- Geodetic GNSS networks have been leveraged in the past. Continuous support for these, and expand and upgrade them to multi-frequency, multi-GNSS, scintillation-capable networks for long-term records.
- Statistical approaches can be more widely leveraged (for detection, for alerting).
- Cloud storage infrastructure for open access, findability, usability for large heterogeneous data sets.
- Wrapper packages to minimize the re-creation of I/O routines for researchers.
- Crowd-sourced data, "signals of opportunity," or other aggregated data could be used for research but then quality control (e.g., uncertainty, long-term maintenance) is even more challenging.
- Sampling irregularity structuring vertically via satellite missions offer an alternate perspective than ground systems.

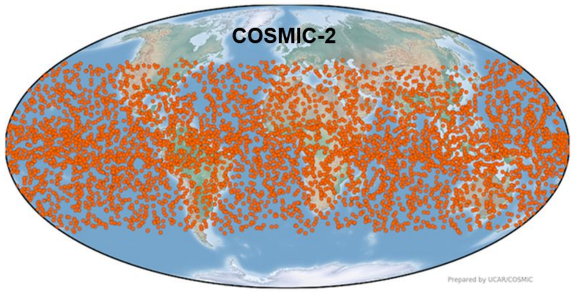
Scintillation & System Impacts

- Ionospheric irregularities cause scintillation of radio waves, which can impact performance of technological systems which society depends upon including

  Satellite communication, global navigation satellite systems (GNSS), space radars used to conduct cloud-free, day-and-night observations of the Earth's surface, Space Surveillance Network
- These same effects may be leveraged for remote sensing: inferring the location, motion, strength, and spectral properties of irregularities from the scintillations they produce.
- Satellite to satellite transmissions (e.g. radio occultations) enable continuous irregularity monitoring with global coverage, but with limited "revisit time" over a given region compared with ground-based receivers. Both sources provide *complementary* information.
- Scintillation observations are required at sufficiently fast temporal cadence to resolve irregularity scale sizes of interest (Fresnel scale sizes produce scintillation)
- What do we need to understand to enable the predictive capability?
  - Real-time specification and forecasting of irregularity regions across the globe
  - Collaboration between communities operating regional networks of ground-based scintillation monitoring sensors; fusion of ground- and space-based data sources
  - Ability to leverage existing sensors and receiver networks originally intended for other purposes (radio occultations, geodetic receiver networks)
  - Forecasting requires an understanding of the ionospheric state and driving mechanisms (e.g. electric fields) leading to instabilities that cause irregularities to develop

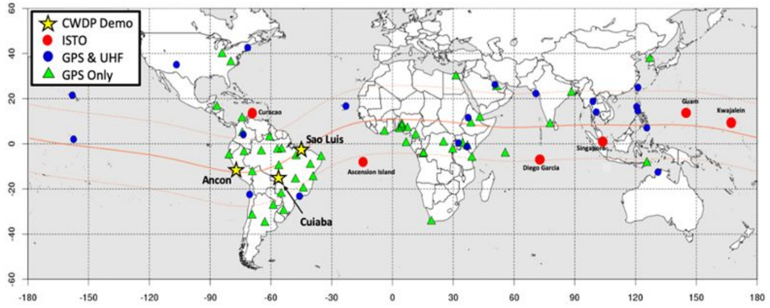


[From: *Cesar Valladares; LISN Network*]



[*UCAR/COSMIC-2*]

SCINDA and ISTO Sensor Locations



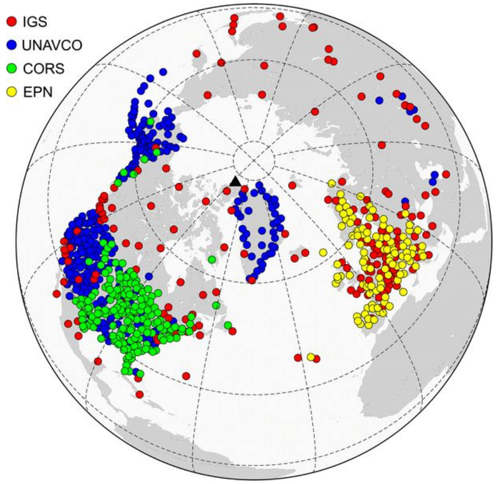
Scintillation & System Impacts: Research Needs

What are the research needs to make progress on the understanding necessary to improve predictive capability?

- Sensors and Networks
  - Regional networks of scintillation monitors with *support to collect, disseminate & archive long-term records*
  - Radio occultation satellite systems that provide high rate (50Hz) data while ray-path lies within ionosphere (e.g. like COSMIC-2), not just while ray-path lies within the lower troposphere (like COSMIC-1)
  - Networks of standard GNSS receivers capable of providing 1 Hz total electron content observations
  - Networks of spaced-antenna systems to measure the zonal irregularity drift at low latitudes

- Modeling Efforts
  - Theoretical work to derive *quantitative* scintillation metrics from TEC rate of change (ROTI) and/or under-sampled C/No fluctuations would enable utilization of vast data resources from existing networks
  - Recent work relating ROTI to scintillation metrics stresses the relevance of irregularity drift; global modeling efforts (WAM-IPE) need drift data to assimilate (COSMIC2-IVM, DMSP, spaced-antenna)
  - Improved algorithms for geolocation and characterization of irregularities from RO observations, better techniques for fusing space-based and ground-based scintillation observations.

- System Impact Models for Emerging Technologies & Applications
  - GNSS applications (e.g. precision agriculture, precise takeoff and landing) have exploded during the last two solar cycles, which were unusually weak by historical standards.
  - New GNSS signals (GPS L2C, L5, etc.) & tracking technologies remain untested under extreme conditions
  - Updated models are needed to predict impacts on new & emerging technologies during intense solar activity



Cherniak, et al. (2018)

Plasma Drifts 800 km 15UT March 17th 2015

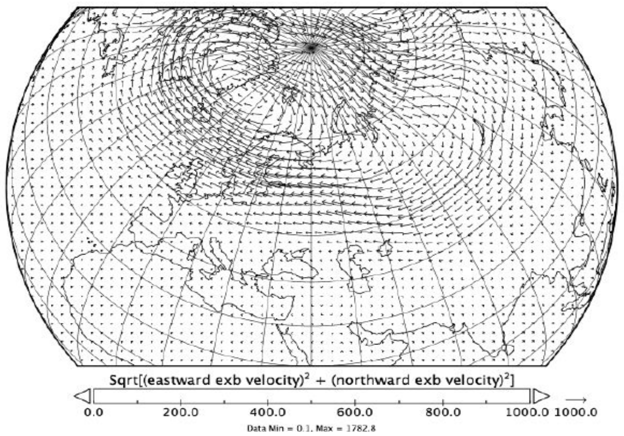
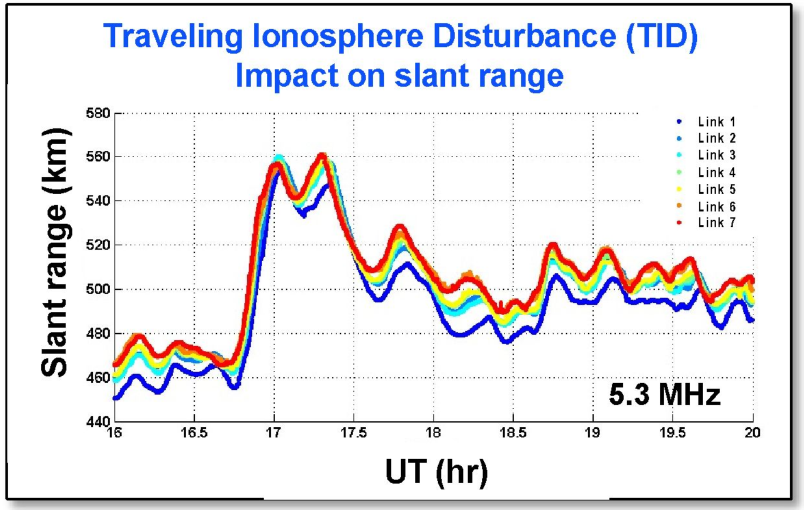
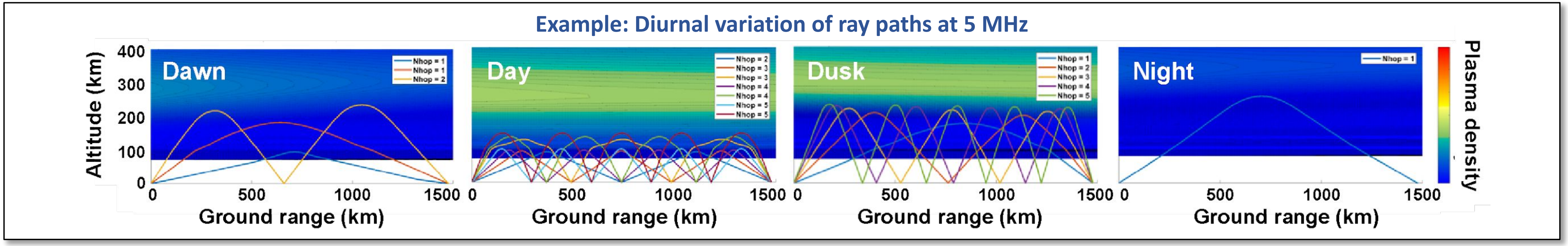


Figure Credit: NOAA

Impacts on HF Propagation

- High Frequency (HF, 3-30 MHz) radio waves can reflect off the bottom of the ionosphere enabling long-distance propagation (>> line of sight)
- Applications include:
  - HF communications
  - Over-The-Horizon-Radar (OTHR)
- Performance is limited by knowledge of the ionospheric state
  - Variability of ray paths and path loss are major concerns
- **What do we need to understand to enable the predictive capability?**
  - Bottom-side electron density profiles and parameters over the entire planet
  - Sporadic E-layer maps
  - Validated models using operationally relevant metrics (e.g. path loss, group delay, angle-of-arrival)



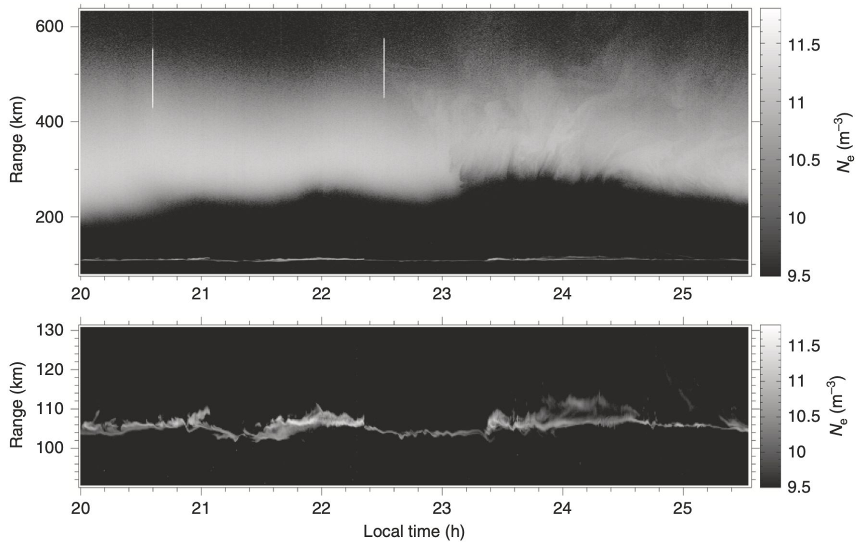


Impacts on HF Propagation: Research Needs

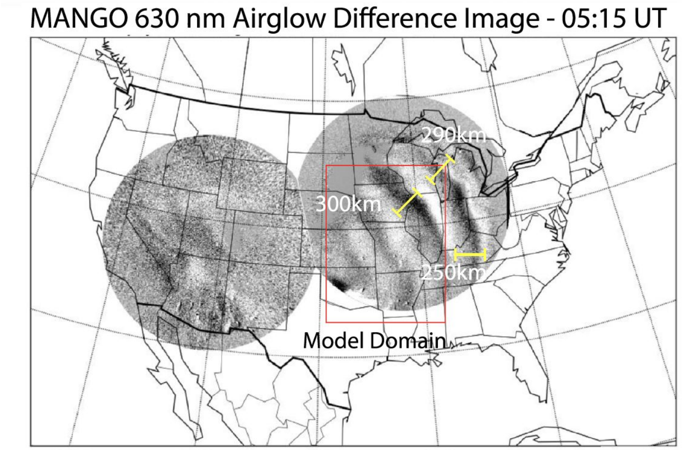
- **What are the research needs to make progress on the understanding necessary to improve predictive capability?**
  - A global network for measuring bottom-side electron density profiles
    - GNSS ground-based and remote occultation TEC sensing
      - Will this have high enough spatial and temporal resolution to provide the necessary accuracy for bottom side propagation applications when ingested into data assimilation models?
      - Is it a good sporadic E detector?
    - Sounding network
      - How can standard and low-power sounders be proliferated and networked across the globe?
      - Can oblique networks be set up?
    - Signals of opportunity
      - Oceanographic HF radars used for ocean wave and current characterization operate in frequency bands useful for ionospheric characterization
      - Can waveform parameters be standardized and and a network of ionospheric monitoring links established using passive receivers?
  - Systematic validation of ionospheric models with operationally relevant metrics, e.g. path loss, group delay, angle-of-arrival
    - For specific applications, estimates of operational metrics can vary widely between models (e.g. path loss varying by 10’s dB)
    - An HF multi-range link network operating over the long-term is needed to assess model performance and build an applications metric database
      - Well-calibrated transmitter-receiver systems at several frequencies and different waveforms
      - 24/7 operation over at least a solar cycle
      - Low-power systems operating autonomously with low bandwidth data transfers
    - Data integration and distribution centers need to be set up or integrated into existing organizations

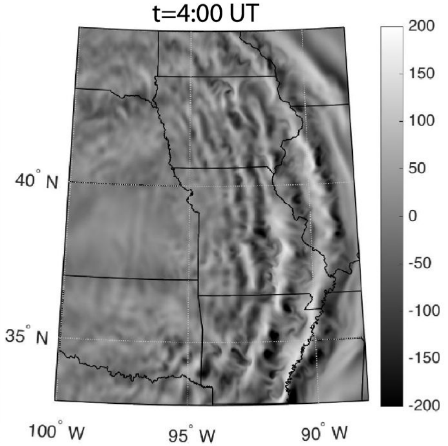
Thermosphere-Ionosphere Small-Scale Dynamics

- **Understanding atmospheric inputs to the bottom-side ionosphere from below**:
  - **Preconditioning of the ionospheric state** through density and compositional fluctuations, strong and variable shears, at a wide range of scales.
  - Lower-thermosphere (LT) **modulation of the E- and F-region by neutral waves**, including TIDs at 10s-1000 km spatial scales, and neutral instabilities at ≤1-10s km spatial scales.
    - Acoustic-gravity waves (AGWs), which may include neutral fluctuations ~100 m/s and ~10s of % densities, drive MSTIDs with similar ionospheric flow & density fluctuations.
    - Instability and nonlinear dissipation of AGWs in the LT contribute to transport, modulate sheared flows, and drive vigorous turbulence – also in ionospheric species.
    - IT-driven E-F region dynamo effects map small-scale fluctuations along field lines.
- As well as providing ionospheric remote sensing, **GNSS TEC and HF measurements have equal utility in studying underlying thermospheric dynamics**.
- Reiterates value/need for **multi-scale, <u>multi-system</u>, physics-based modeling**.

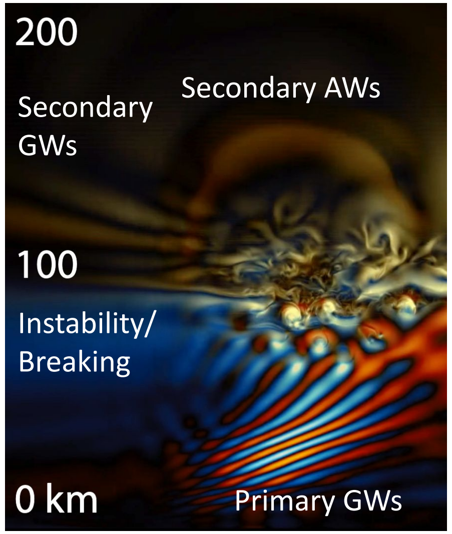


Neutral dynamics in the E-region, via coupling along field lines, cause significant structuring of the E- through F-region [Figure from: *Hysell et al*., 2018; 10.1038/s41467-018-05809-x]





Neutral dynamics underlying meteorological wave-driven MSTIDs are often <u>quite</u> strong – note 630 nm wave imagery of waves vs. numerical simulations of underlying / preceding lower-thermospheric AGW dynamics in temperature (K) [Figure from: *Heale et al.*, 2019; 10.1029/2019GL085934].



Neutral AGW (Acoustic-Gravity Wave) dynamics vigorously disturb the lower thermosphere / ionosphere, and launch secondary waves that propagate throughout the thermosphere [*Snively & Calhoun*; *Sabatini & Snively;* AGU FM, 2021]

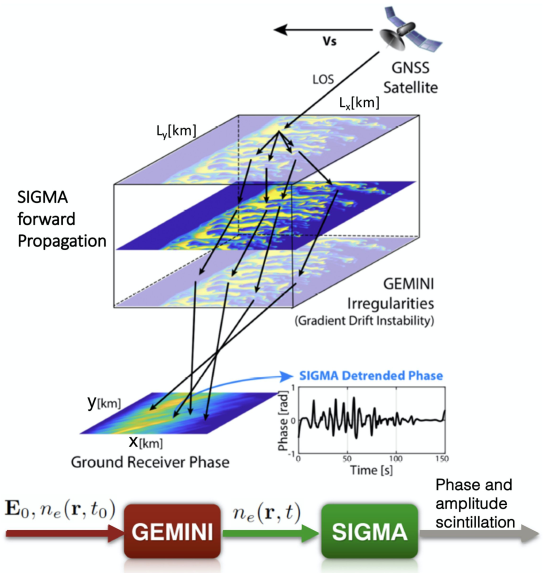
Thermosphere-Ionosphere Small-Scale Dynamics: Research Needs

What do we need to understand to enable predictive capability of the state of the ionosphere and its irregularities?

- **The underlying physics, to know how (best) to model/simulate across scales and systems**, e.g., from large-scale inputs from above and below, to small-scale evolutions, to measurement of process manifestations in signals.
- **Fundamental strategies to connect local-scale process models to predictive models** (including the roles of neutral variability).
- **ITM system dynamics, and measurement strategies** that sufficiently-capture the most-relevant parameters.

What are the research needs to make progress on that understanding?

- Observations of key ITM parameters with sufficient coverage, resolution, and cadence (4D, ideally), e.g.:
  - *Composition* — High-res composition of lower-thermosphere (including well-resolved layers in the ITM);
  - *Flows* — Winds, with shears and wave structuring, throughout lower thermosphere (~100-200 km);
  - *Dynamics* — Quantification of processes that modulate the bottom-side ionosphere, globally and locally.
- Physics-based modeling capabilities for neutral-ionosphere coupling and plasma evolutions across relevant scales, and associated impacts on propagation, to understand the underlying processes.
- Large-scale data-constrained forecast model capabilities that ”mesh” well (literally and figuratively, in terms of capturing relevant physics) with local-scale physics-based models and, next, signal propagation.
- Recognize value / address complications of high-resolution datasets, which may be feasible to collect but unwieldy to manage in volume, or that may require partnerships across disciplines (i.e., networked GNSS of broad utility beyond heliophysics).



Physics-based models can provide input to propagation models, towards numerical-experimental assessments of impacts. [e.g., Deshpande et al., 2019; 10.1029/2019GL082576]

Thermosphere-Ionosphere Large-Scale State

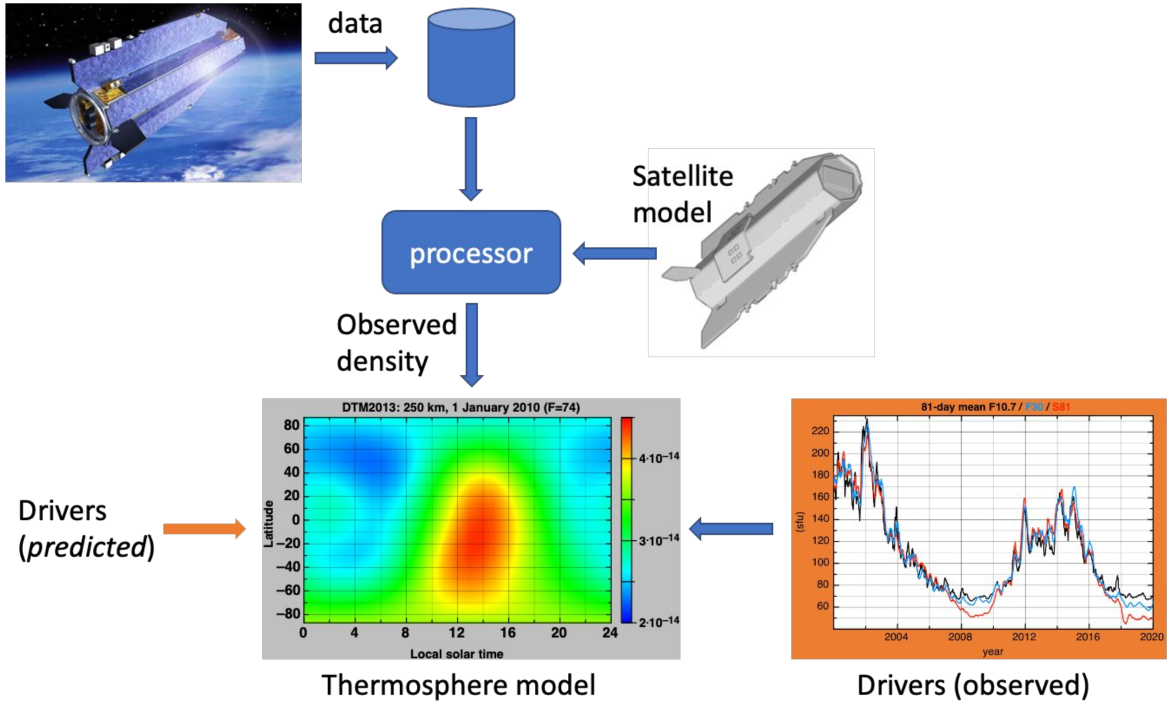
- Thermosphere density is proportional to the atmospheric drag force, which causes spacecraft to decay and ultimately re-enter the lower atmosphere – *it is by far the dominant error source in orbit computation*
- Models are required for (besides science objectives):
  - Precision orbit determination, conjunction analysis
  - Satellite lifetime estimation, mission analysis
- Orbit calculations are limited by current performance of the thermosphere specification and forecast
  - Inconsistent quality and sparse distribution of the data
  - Simple empirical models used in orbit calculations, first principles models cannot be used *yet*
  - Proxy use
- Modeling of the ionospheric state requires an accurate description of the neutral composition

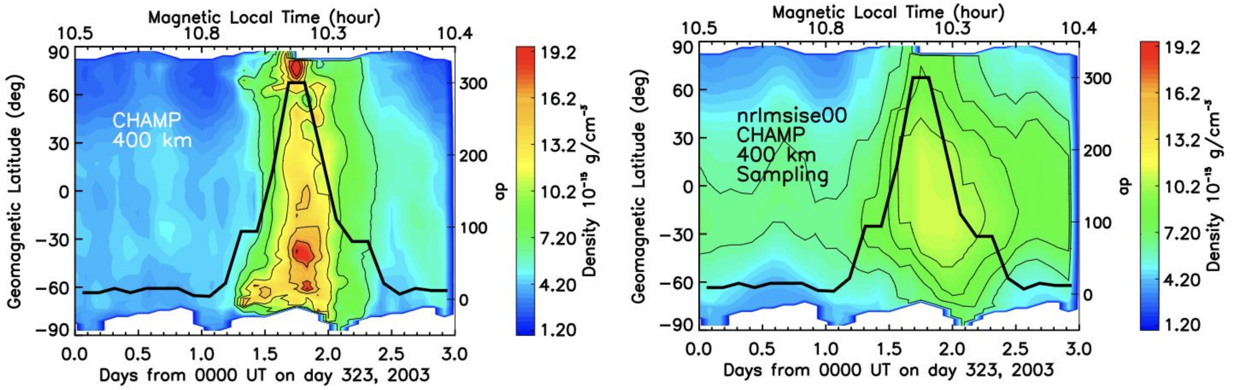
- **What do we need to understand to enable the predictive capability?**
  - Improve models in the LTI region (transition region, 100-200 km), which affect the entire TI system
  - Interaction of the solar wind with magnetosphere, ionosphere, thermosphere (net energy input?)
  - More accurate drivers (e.g., proxies are employed, calibration issues), improve temporal distribution
  - More accurate forecasts of solar and geomagnetic activity, solar wind, Bz

Thermosphere-Ionosphere Large-Scale State: Research Needs

What are the research needs to make progress on the understanding necessary to improve predictive capability?

- An observing system (example: WMO)
  - Composition and total density observations
    - Spatial and temporal resolution
    - Quality (calibration, processing standards)
    - Miniaturized mass spectrometer
  - Solar activity
    - Sustained, calibrated measurements in EUV (notably He II)
    - Observations from L1, L5
  - Geomagnetic activity
    - Solar wind measurements, magnetic observatories
- Model and near real time data assimilation
  - Develop and test data assimilation schemes, combine models and near-real-time observations
  - Ensemble modeling
- Systematic assessment of models (CCMC action)
- People





doi:10.1029/2005JA011284

Ionospheric State and Irregularities: Summary/Conclusions

1. What do we need to understand to enable predictive capability on the state of the ionosphere and its irregularities?
    1. The state of the ionosphere and its impacts both ”from above” and “from below”, to include magnetospheric and atmospheric drivers of ionospheric composition, dynamics, and energetics
    2. Physical mechanisms, supported by models and data to understand chains of processes, e.g.,:
        1. how the state of the ionosphere evolves to produce irregularities,
        2. how irregularities modulate signals (e.g., scintillation or impacts on propagation paths or absorption),
        3. and how signal fluctuations ultimately impact system performance.
    3. How to guide forecasts of processes across scales, with timely update cycles and quantifiable uncertainties.
2. What are the research needs to make progress on that understanding?
    1. Global instrument network datasets that are collected routinely and kept readily available for research.
    2. Validated data products for key parameters, that can be used reliably for research and/or operations.
    3. Coordination and collaboration across communities that share data (e.g., GNSS, for Earth Sciences and Heliophysics), to optimize (maximize?) the value of cross-disciplinary datasets for multiple users.
    4. Flexible data and model interfaces that can be readily used for new applications.
    5. Models (of varied fidelity) that enable simulations of chains of processes across scales and systems.
    6. Model assessments, with community-adopted metrics and objective validations.