African Workshop on GNSS and Space Weather
05 – 06 October 2020

Ionospheric Irregularities and Scintillations

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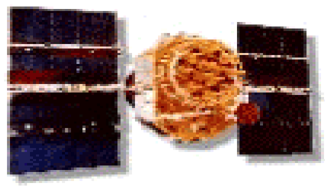
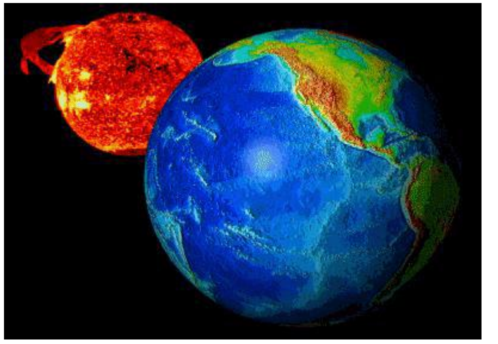
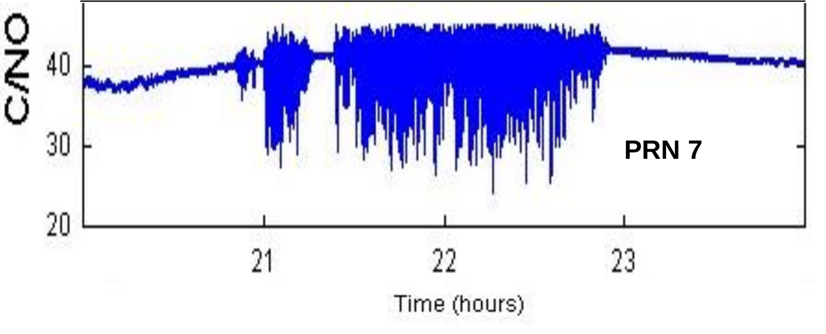
Outline



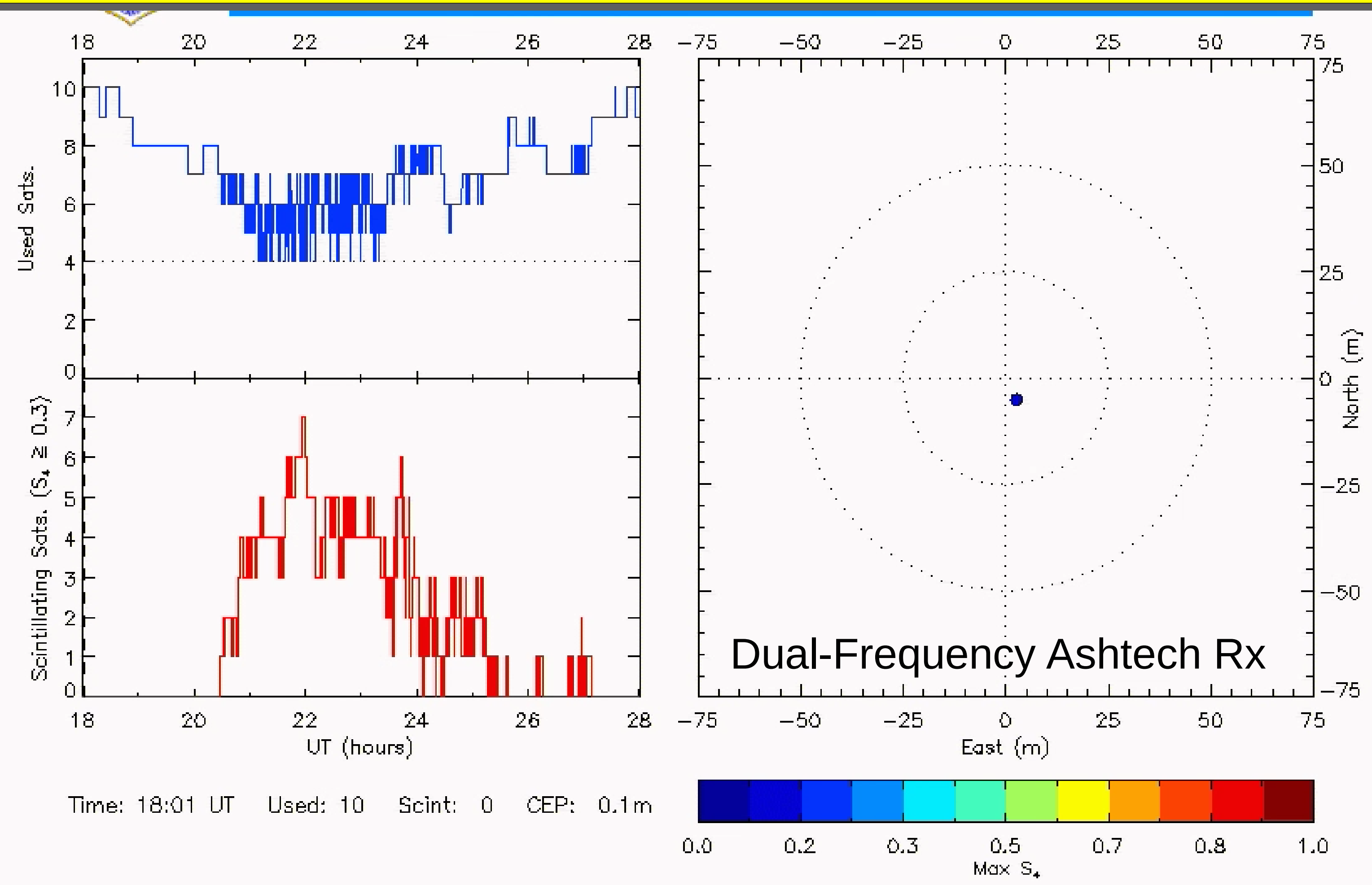


- Motivation
- Irregularities: where and why they form, how we measure them, and other characteristics by region (high, mid- and low lat)
- Ionospheric effects on propagation: scintillation
- Conclusions

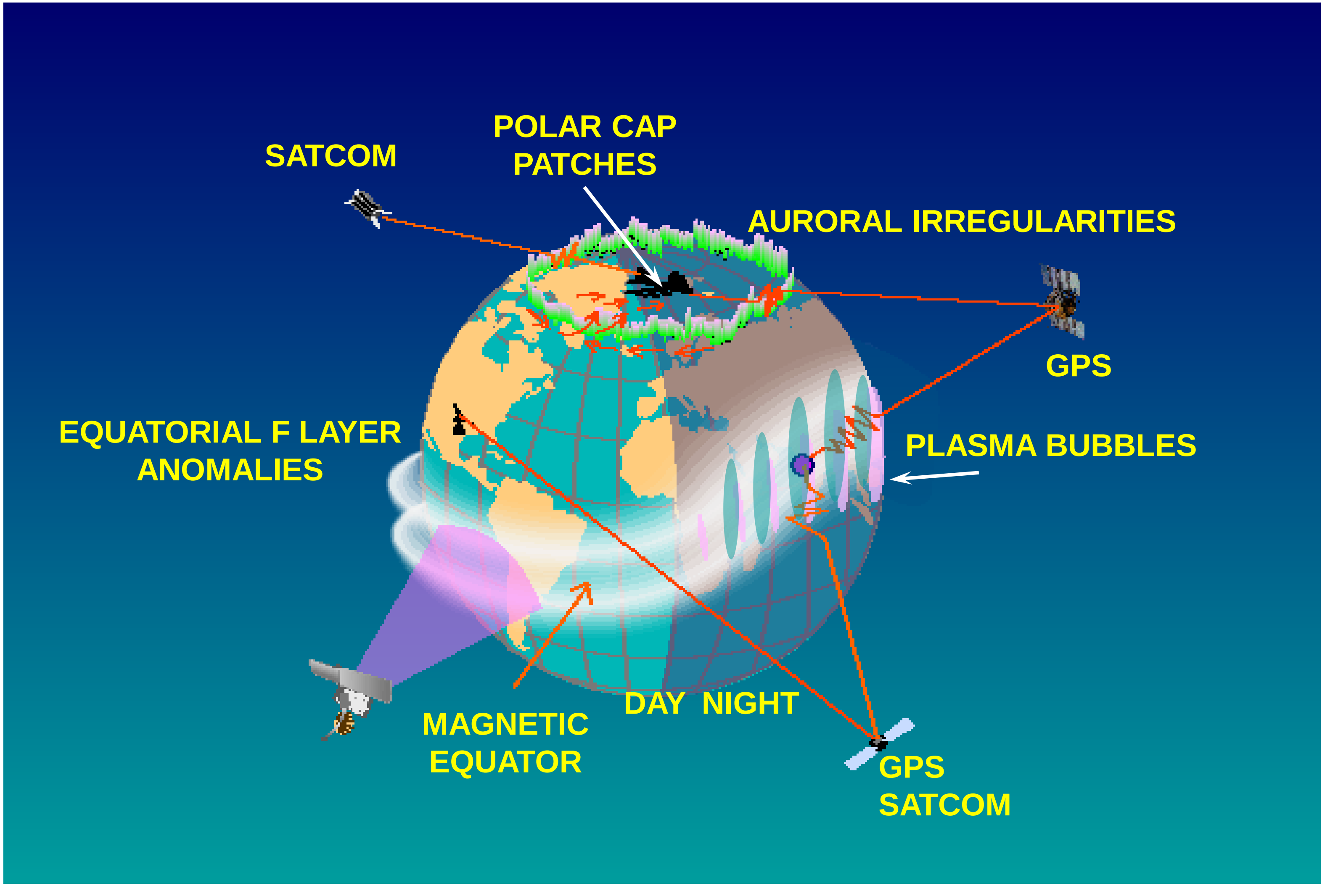


Why do we care?
Irregularities Cause Radio Wave Scintillation

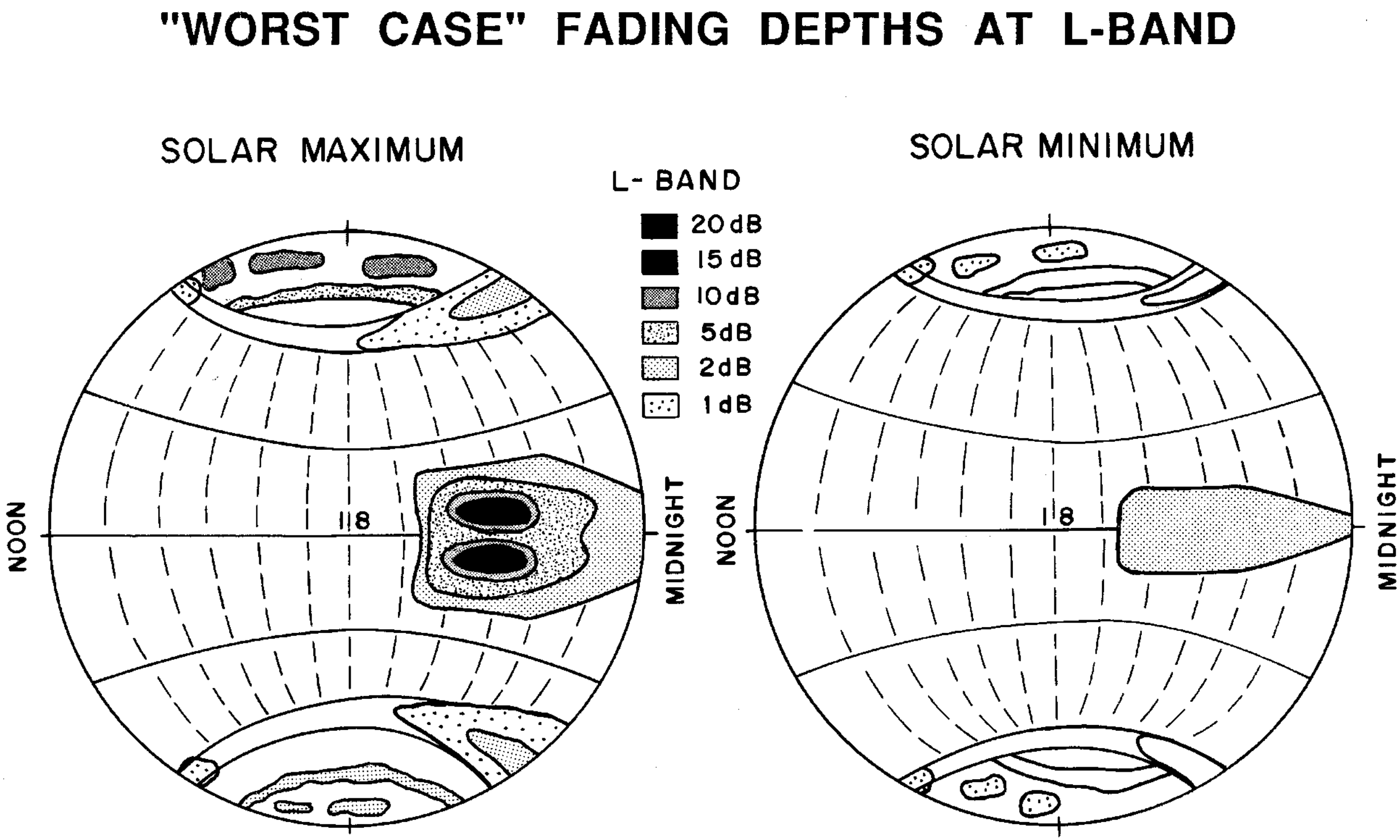
Scintillation can cause rapid fluctuations in GPS positioning
Equatorial scintillation 2002 (Ascension Island)



Disturbed Ionospheric Regions and Systems Affected by Scintillation

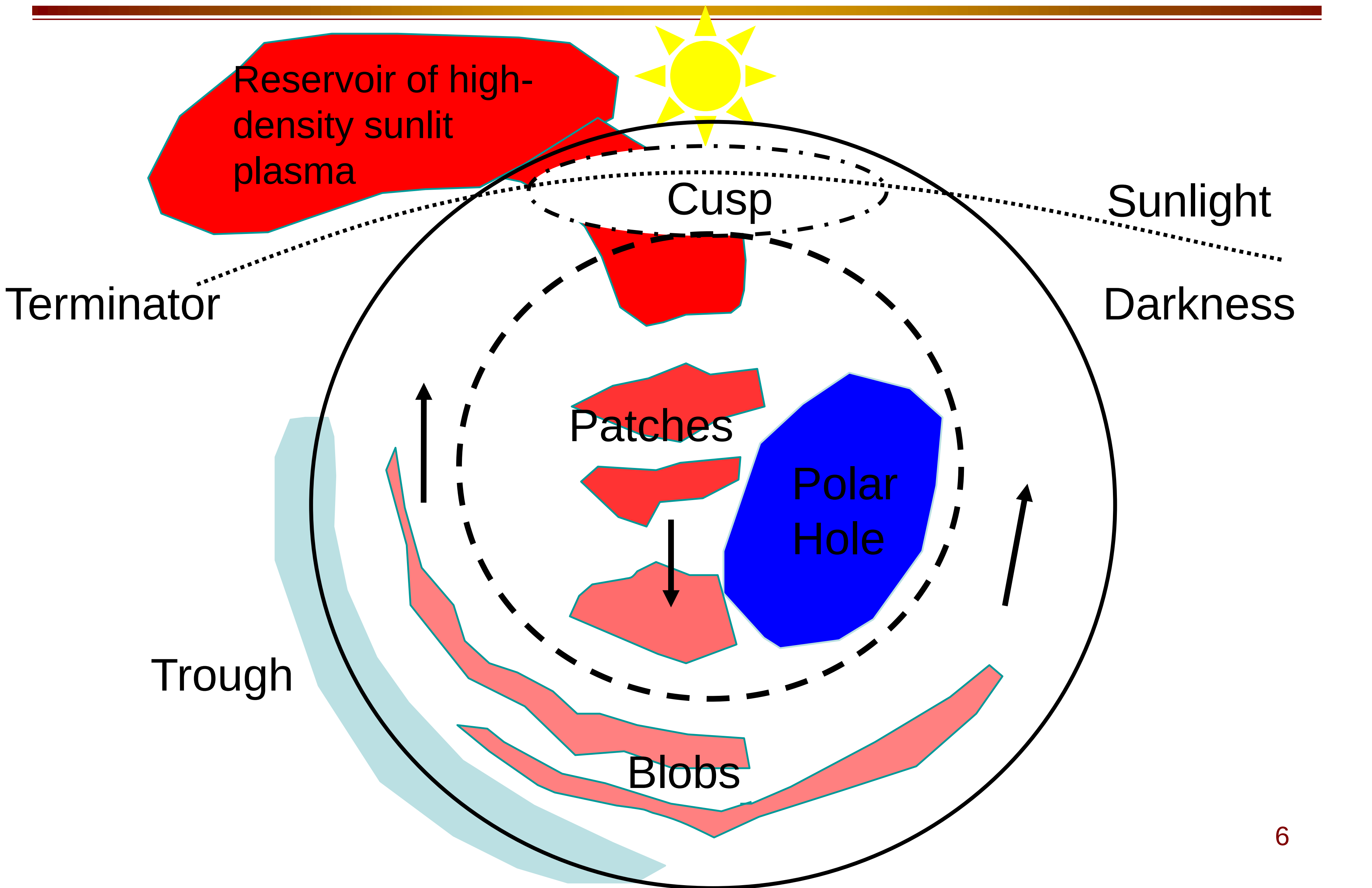


Global Morphology

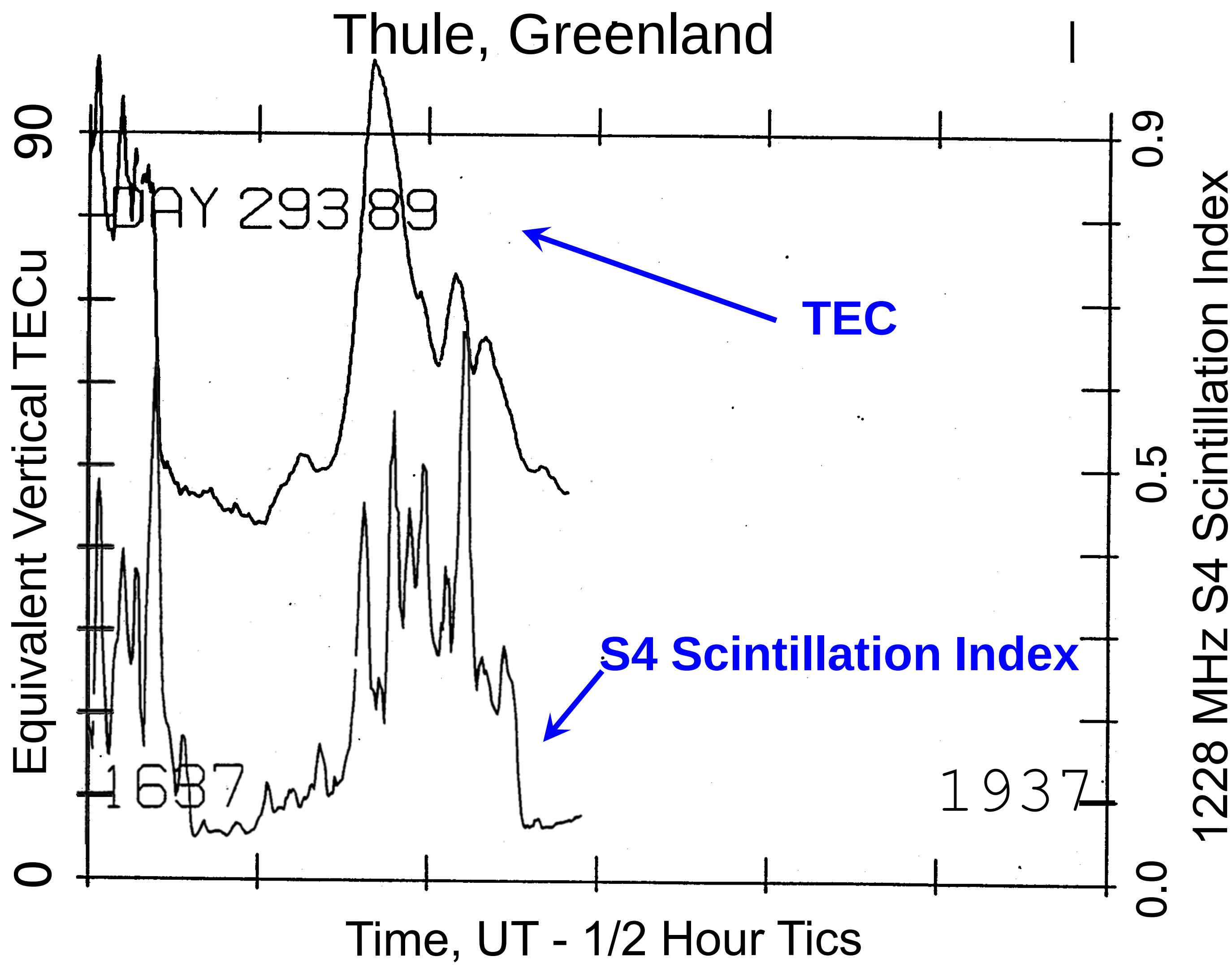


[After Basu, et al.]

Polar Ionosphere Density Regimes
(Winter, Bz < 0)



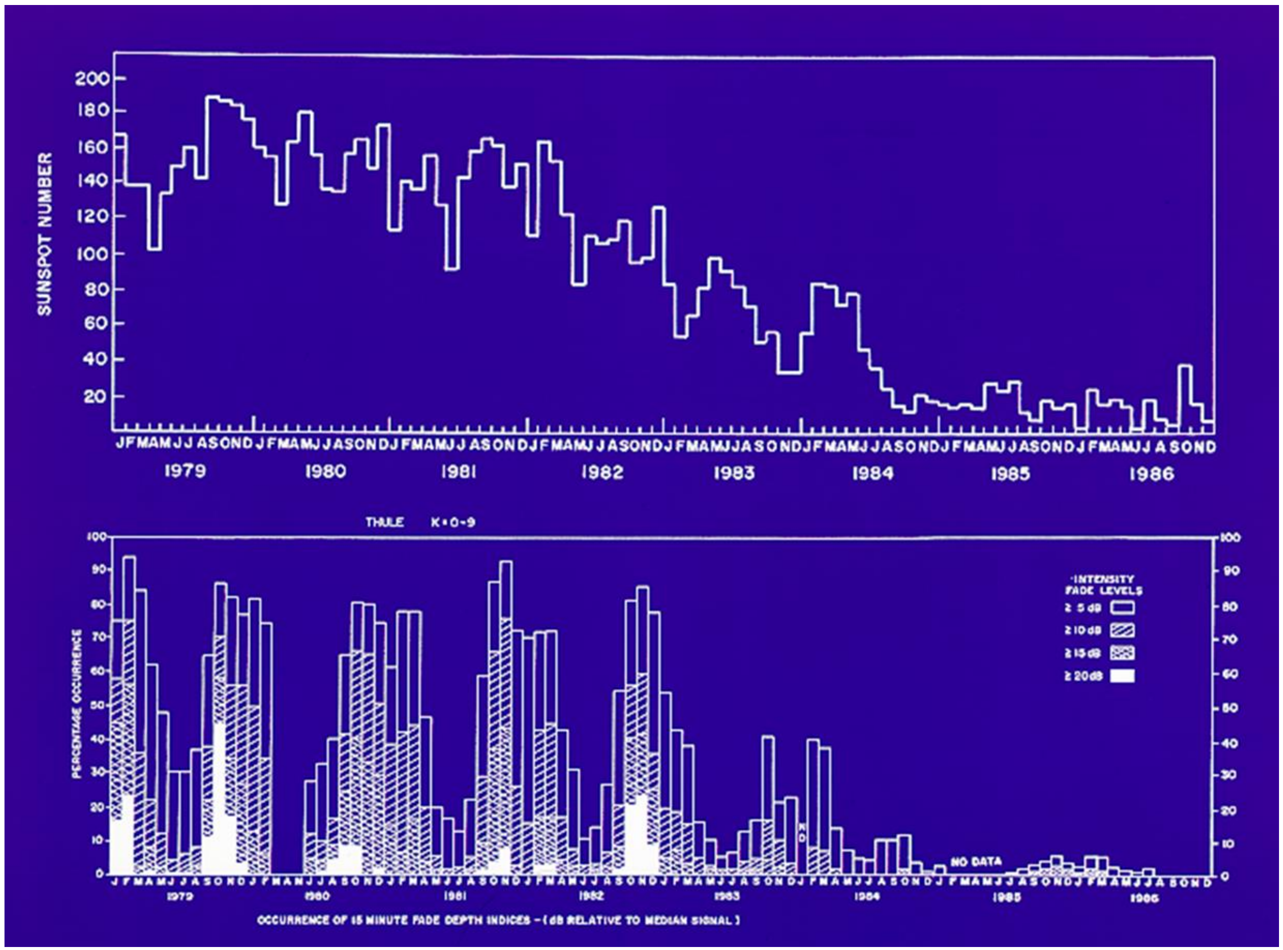
TEC Fluctuations and Scintillation during Patch Events



Bishop, et al.

Polar Cap Scintillation
Thulе, Greenland

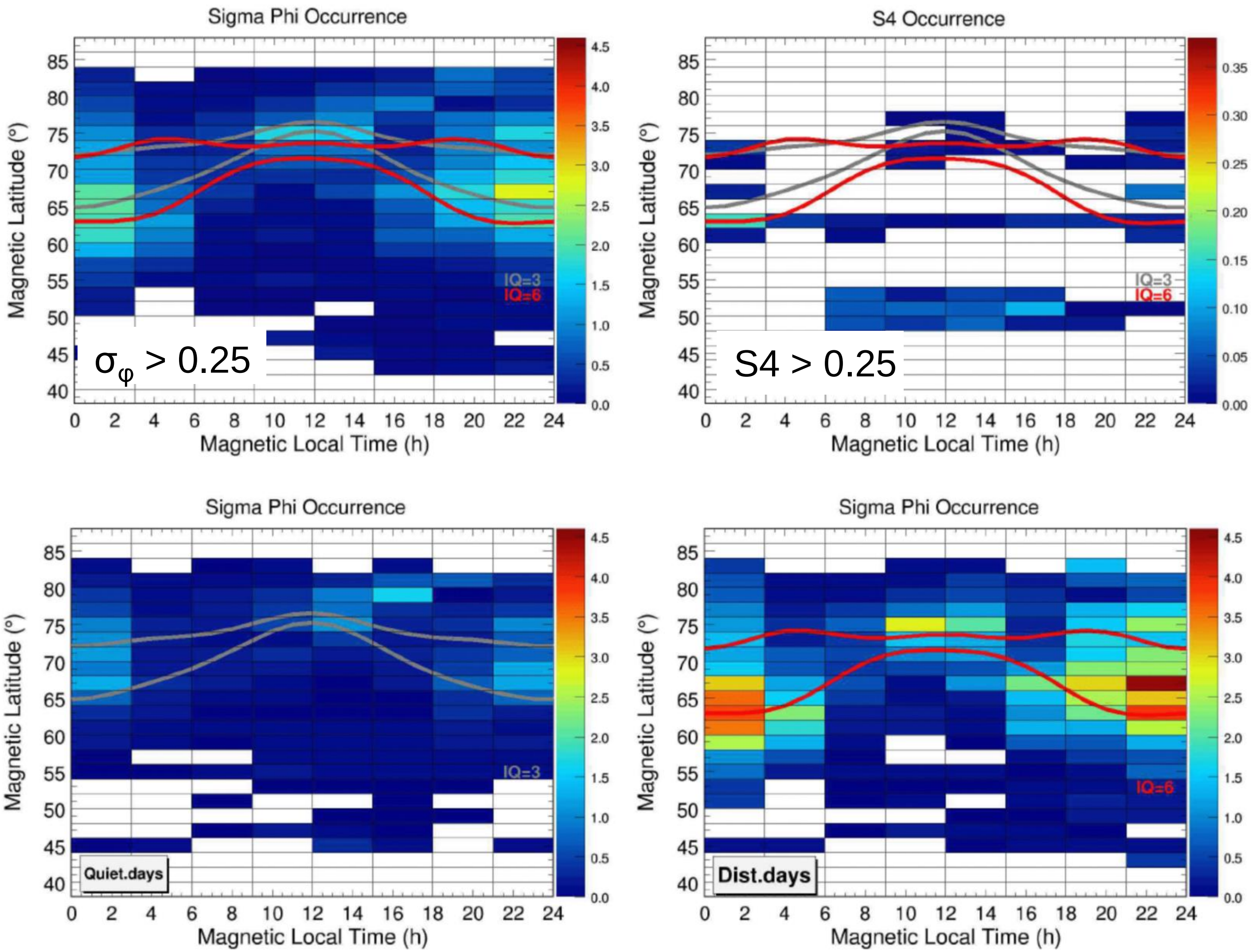
Seasonal and solar cycle dependence of scintillation from polar cap patches



Why doesn't scintillation occur during periods of low solar flux?
Why doesn't it occur during sunlit months?

Auroral GNSS Scintillation: Mostly Phase

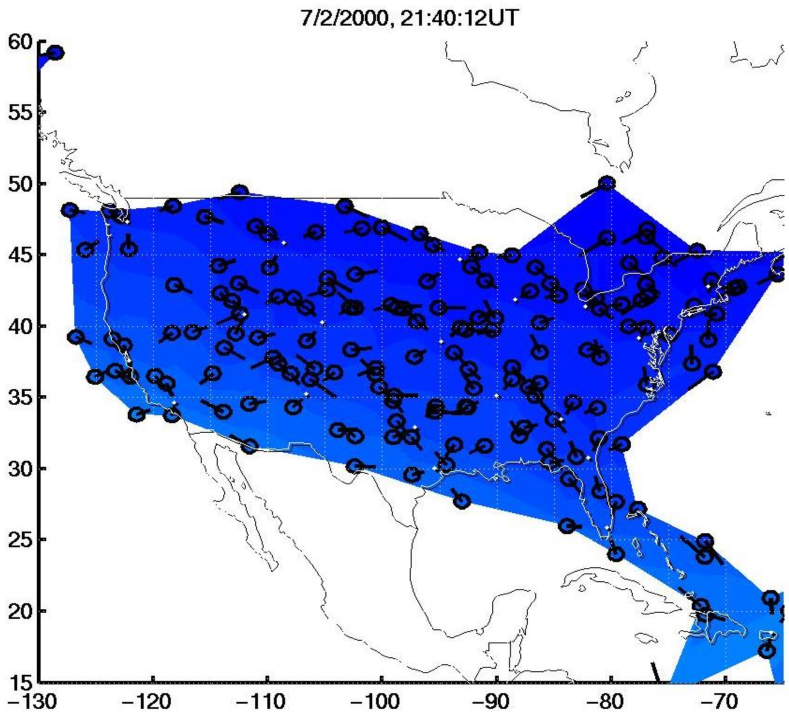
Spogli, et al., Annales Geophys, 2009

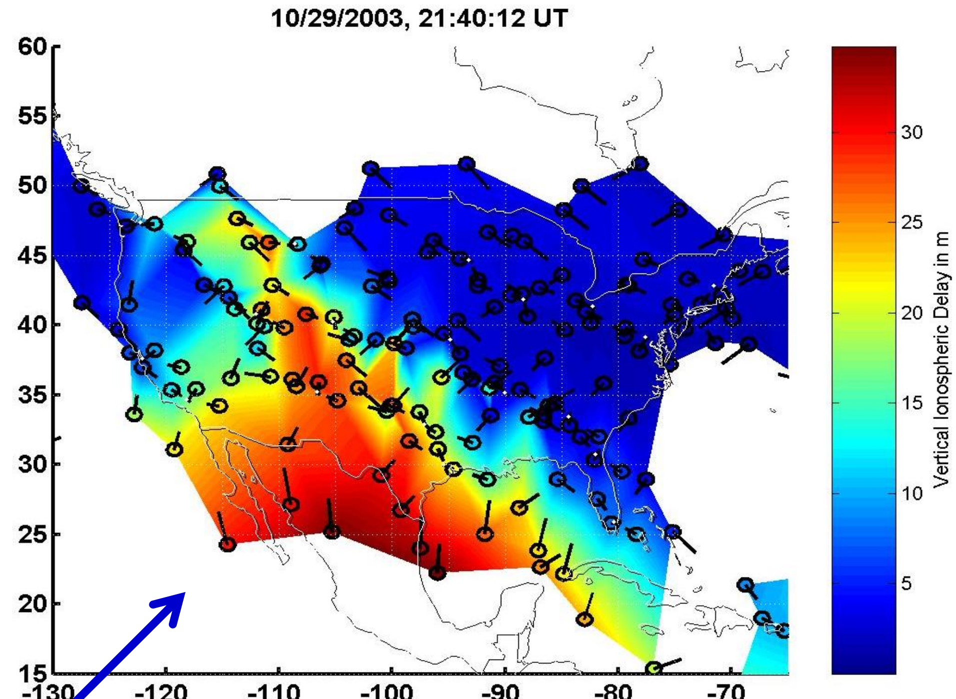


High latitudes dominated by phase scintillation

Quiet versus Disturbed Ionosphere: Storm-time Enhanced Density Events

WAAS Reference Station Measurements





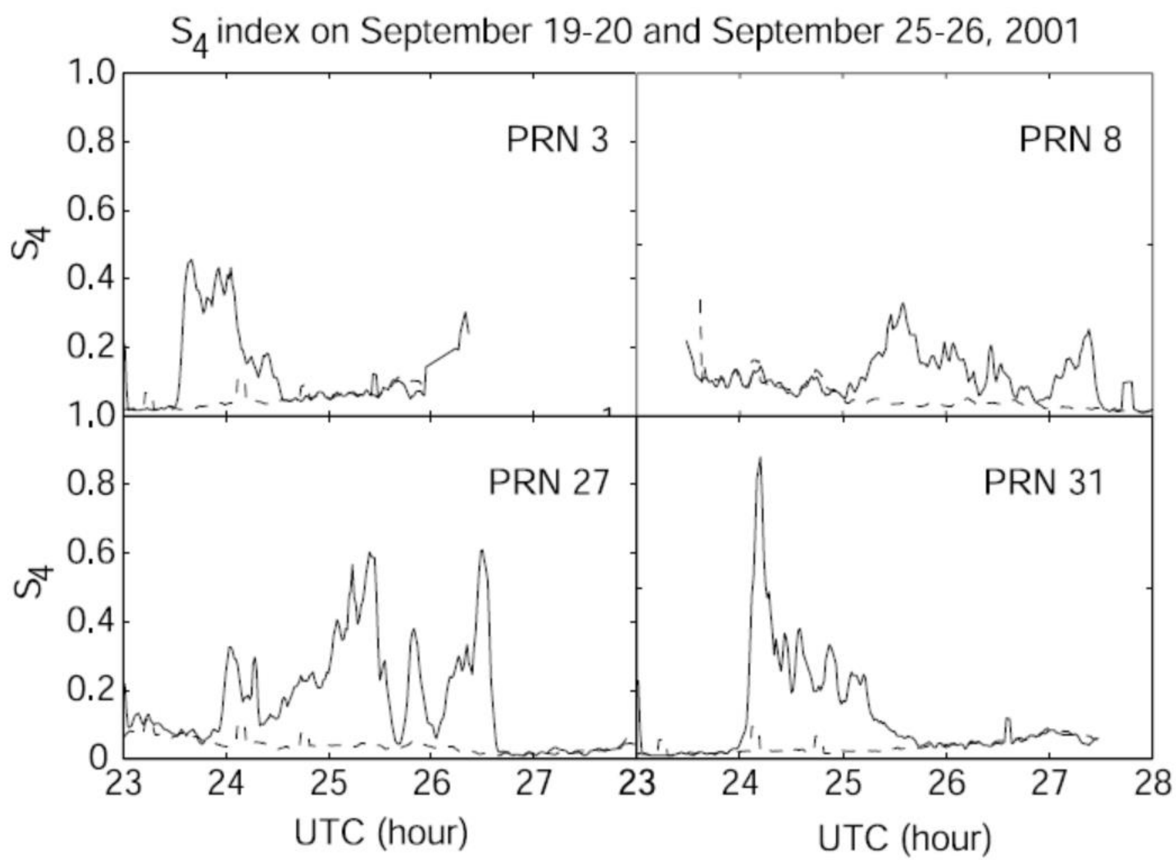
Storm-time Enhanced Density (SED) [Foster 1993, Foster et al., 2002]

Results in loss of vertical guidance availability

Figures courtesy of Seebany Datta-Barua

Mid-Latitude GPS Scintillation

- Mid-latitude scintillations are associated with storm-time processes
- Specific features remain to be conclusively identified
- SEDs provide necessary density for scintillation, but are not necessarily associated with strong gradients and irregularities
- Low density regions of high speed flow (SAID, SAPS) may cause phase “scintillations” more frequently
- Active research area!

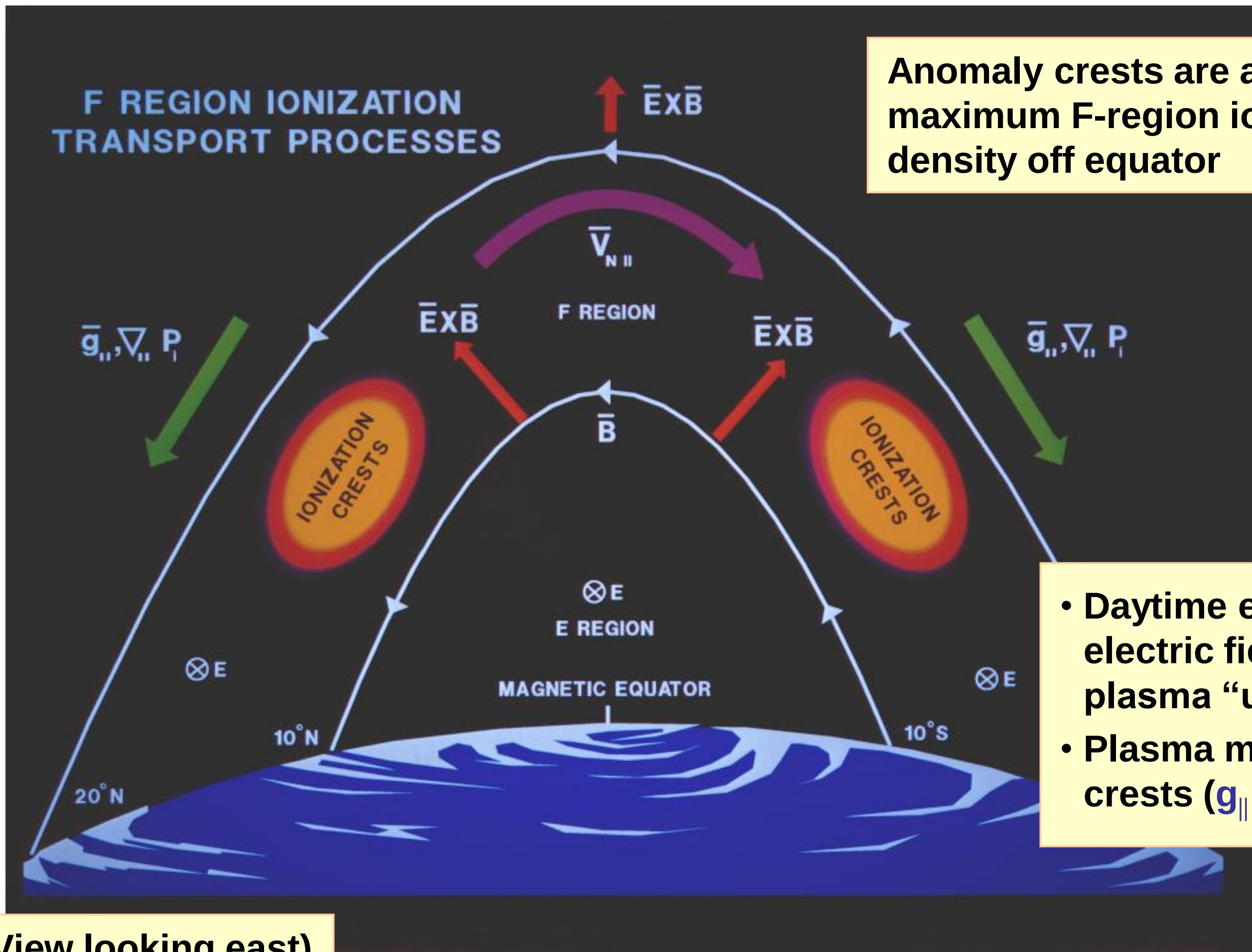


L1 S4 observations from Ithaca, NY
(Ledvina et al., 2002)

What Are Equatorial Dynamics?

Formation of Anomaly Region

- **Presence of anomaly crests strengthens off-equator scintillations**
- **State of anomaly formation is indicative of equatorial dynamics**



Anomaly crests are areas of maximum F-region ionization density off equator

- **Daytime eastward electric field (E) drives plasma "up" (E × B)**
- **Plasma moves toward crests ($g_{\|}$, $\nabla_{\|}P_{\|}$)**

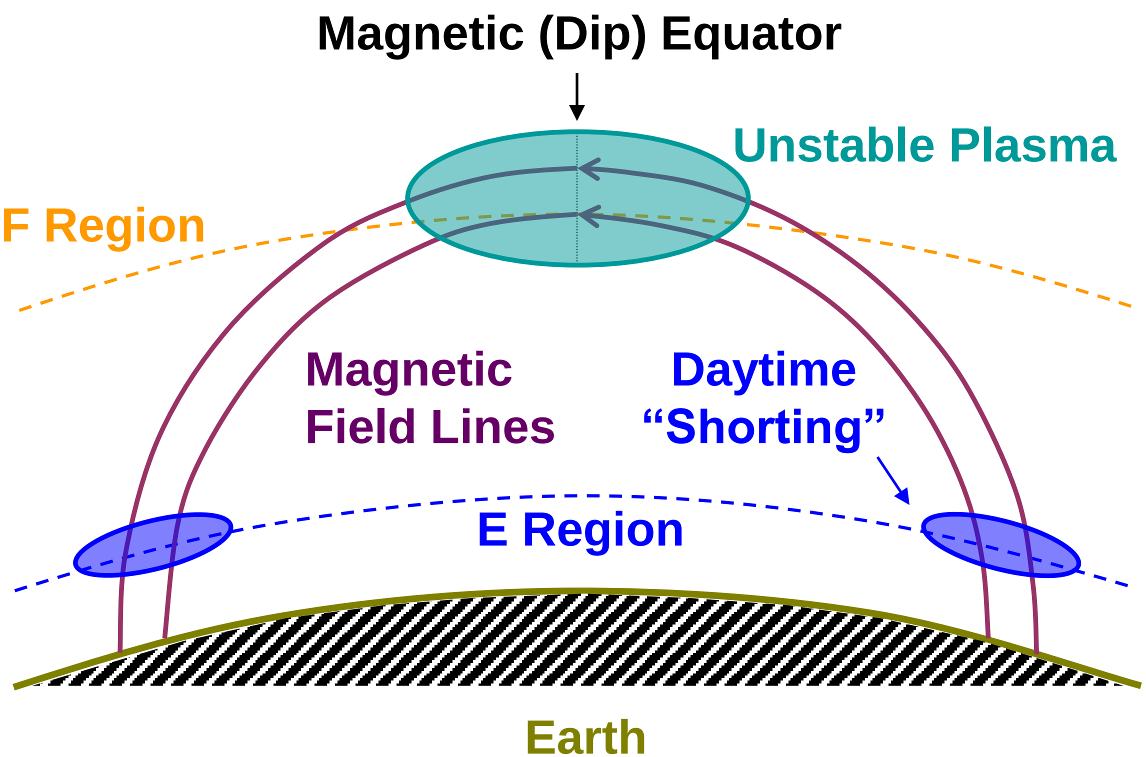
(View looking east)

Why Do Disturbances Form?

Unique Equatorial Magnetic Field Geometry

Equatorial scintillation occurs because plasma disturbances readily form with horizontal magnetic field

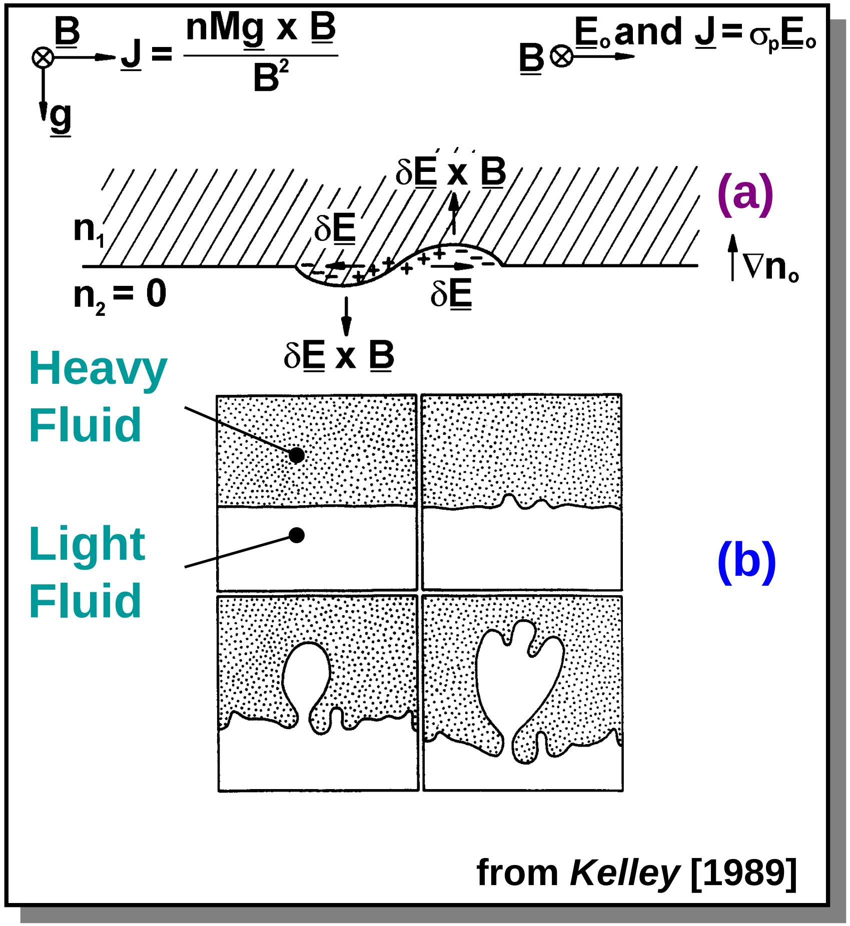
- Plasma moves easily along field lines, which act as conductors
- Horizontal field lines support plasma against gravity– unstable configuration
- E-region "shorts out" electrodynamic instability during the day



What Is the Instability Process?

Basic Plasma Instability

View along bottomside of ionosphere (E-W section, looking N from equator)



from *Kelley* [1989]

Plasma supported by horizontal field lines against gravity is unstable

- (a) Bottomside unstable to perturbations (density gradient against gravity)
- (b) Analogy with fluid Rayleigh-Taylor instability
- Perturbations start at large scales (100s km)
- Cascade to smaller scales (200 km to 30 cm)

3D Model Realizations of Bubbles

Yokoyama, 2014
Rino, et al., 2018

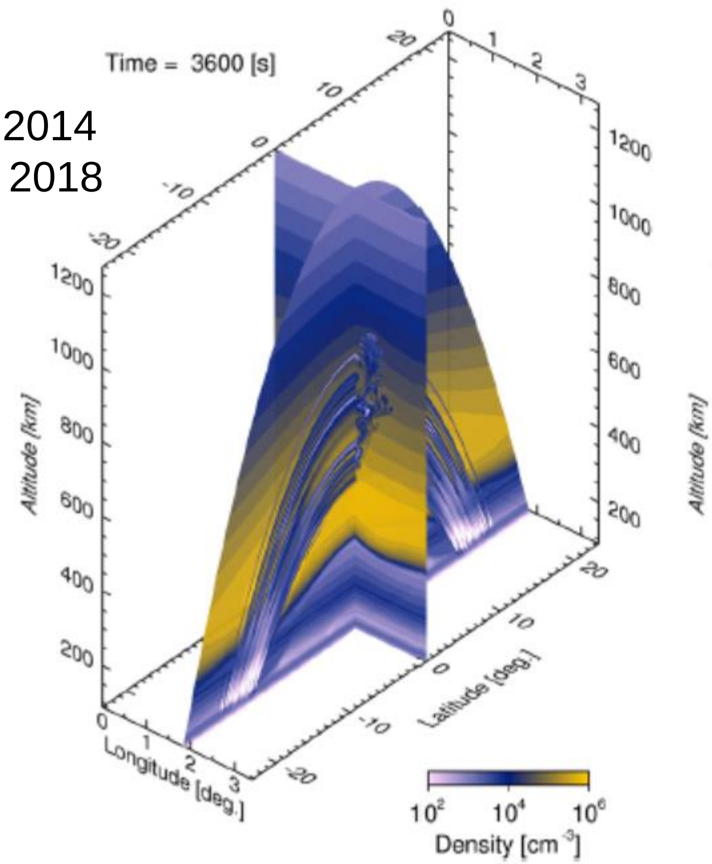
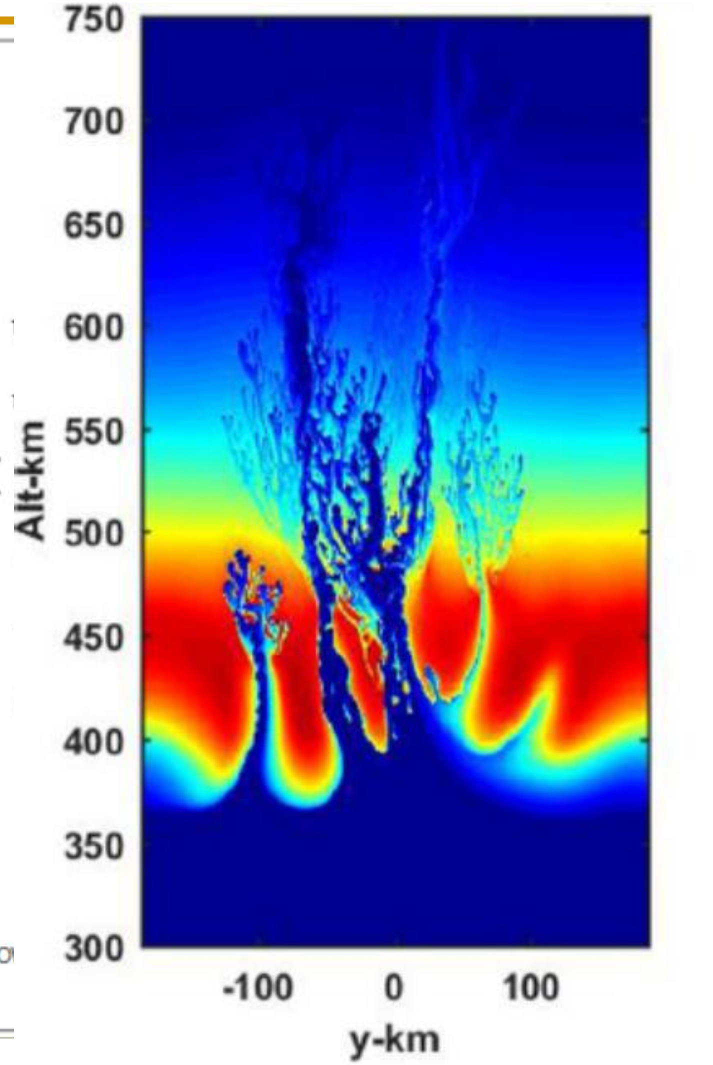


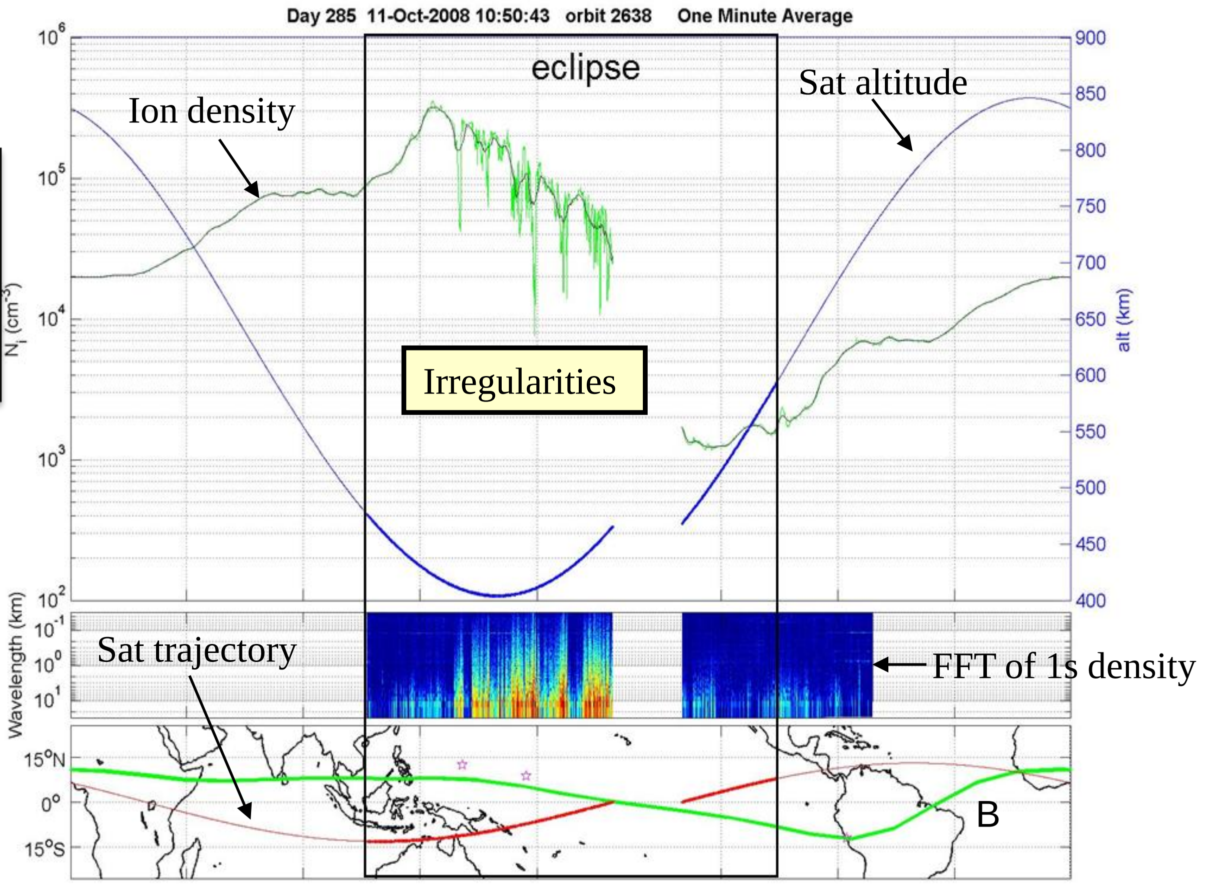
Fig. 1 Perspective view of the EPB simulation environment. The left frame sho ... ructure in two orthogonal slice planes



- Full fluid treatment simulations at scintillation-scale spatial resolution (~500 m)

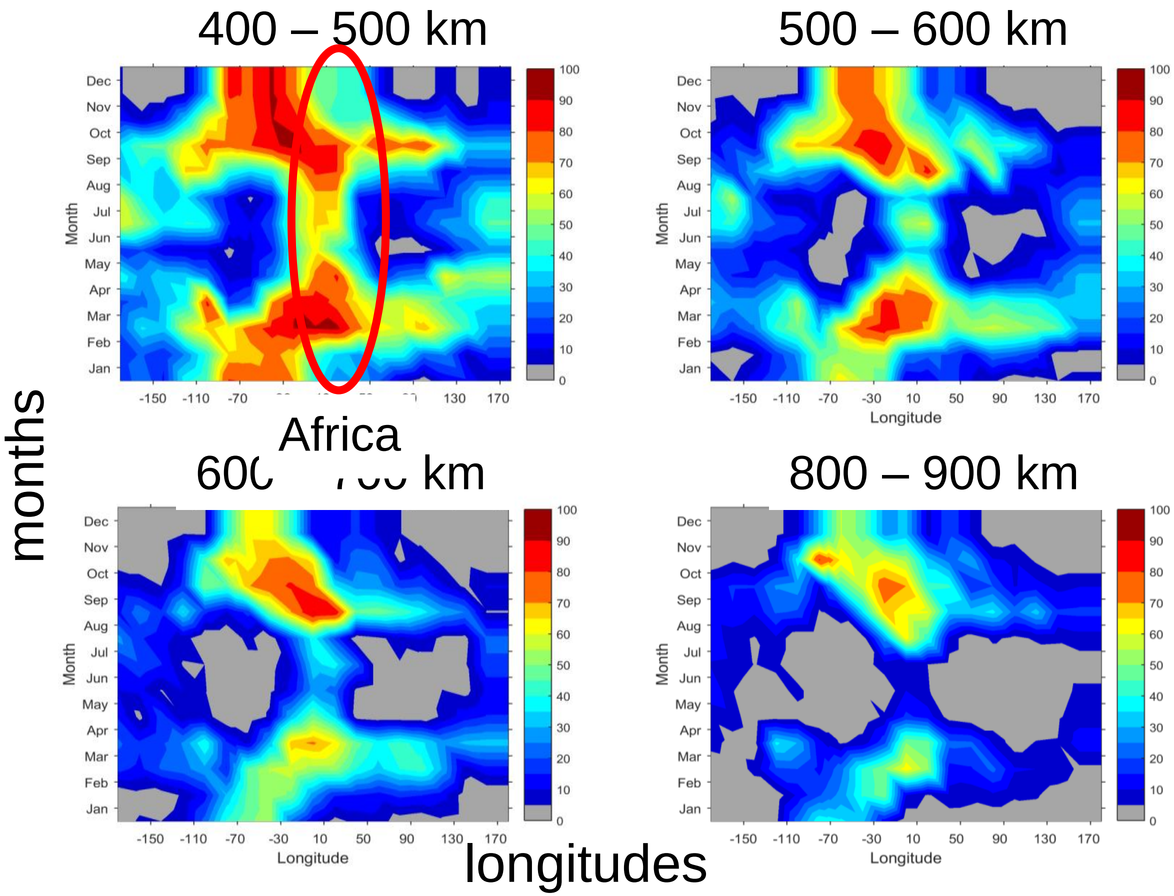
How Do We Observe Irregularities? In Situ Satellite Observations

C/NOFS satellite: low inclination, highly elliptical orbit (400 – 850 km)



GLON	045.4	087.3	129.5	171.6	238.0	279.9	321.9	003.6
GLAT	-03.6	-11.5	-12.6	-06.4	+03.5	+11.4	+12.6	+06.5
GALT	724	555	431	411	515	684	817	837
MLON	116.4	157.0	200.8	244.0	307.5	349.9	039.3	075.4
MLAT	-13.4	-22.5	-22.1	-10.8	+08.9	+23.3	+13.4	-06.8
UT	11:45	11:57	12:08	12:20	10:54	11:06	11:19	11:32
LT	15:00	18:00	21:00	00:00	03:00	06:00	09:00	12:00

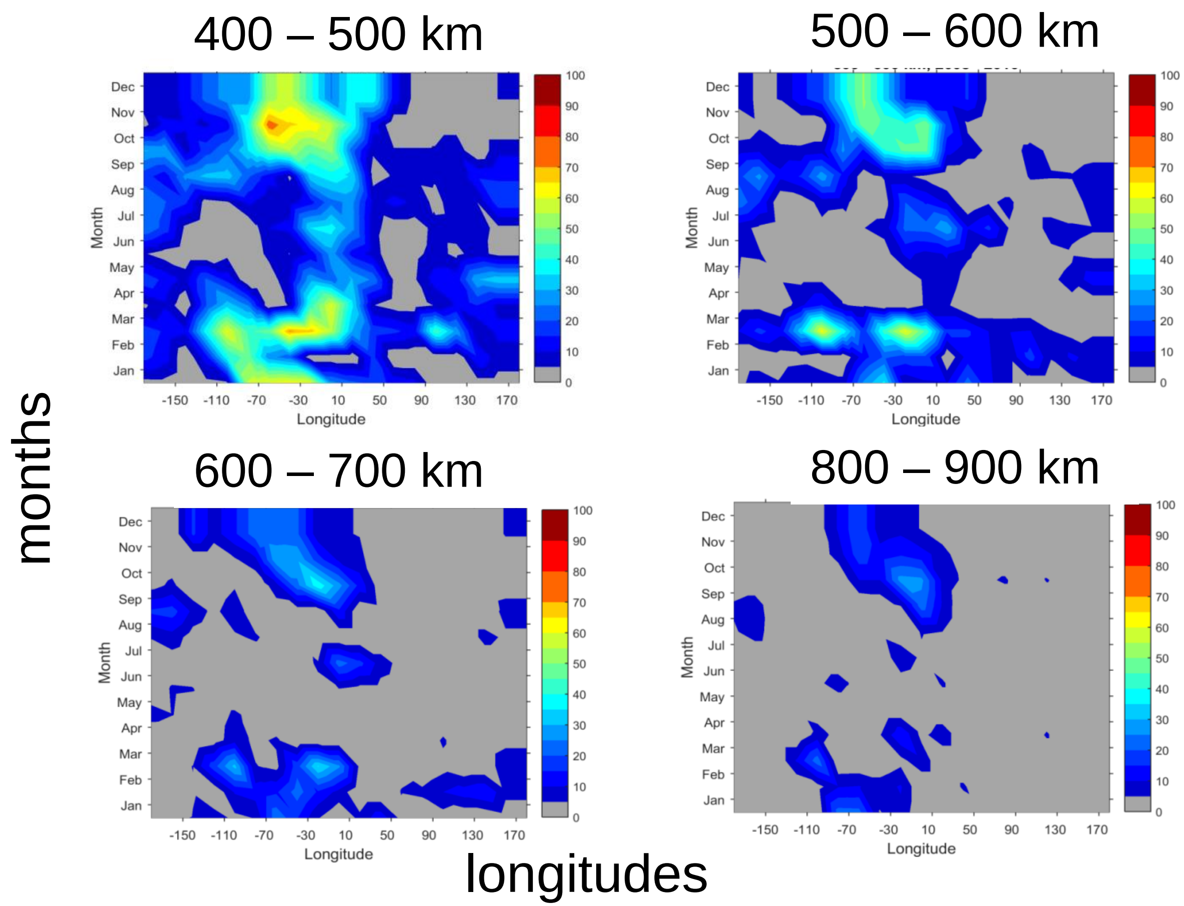
C/NOFS Observations : 2011 - 2014



Dev Joshi, BC
PhD thesis, 2019

- The occurrence probability is generally high in equinoctial months and low around June solstice, maximizes in the longitude sector from 280°E to 30°E
- Peak occurrence rates above 700 km are ≥ 50% , similar to that observed with DMSP in the previous solar cycle

C/NOFS Observations : 2008 - 2010

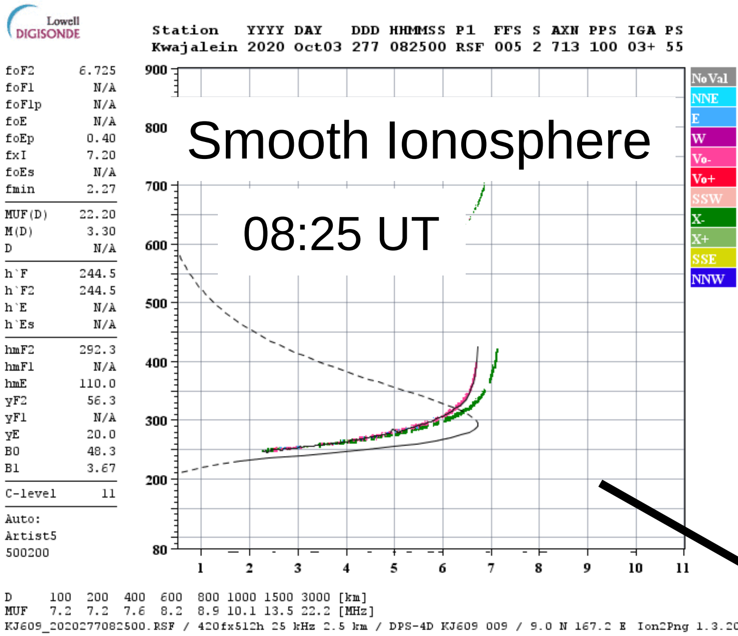


Dev Joshi, BC
PhD thesis, 2019

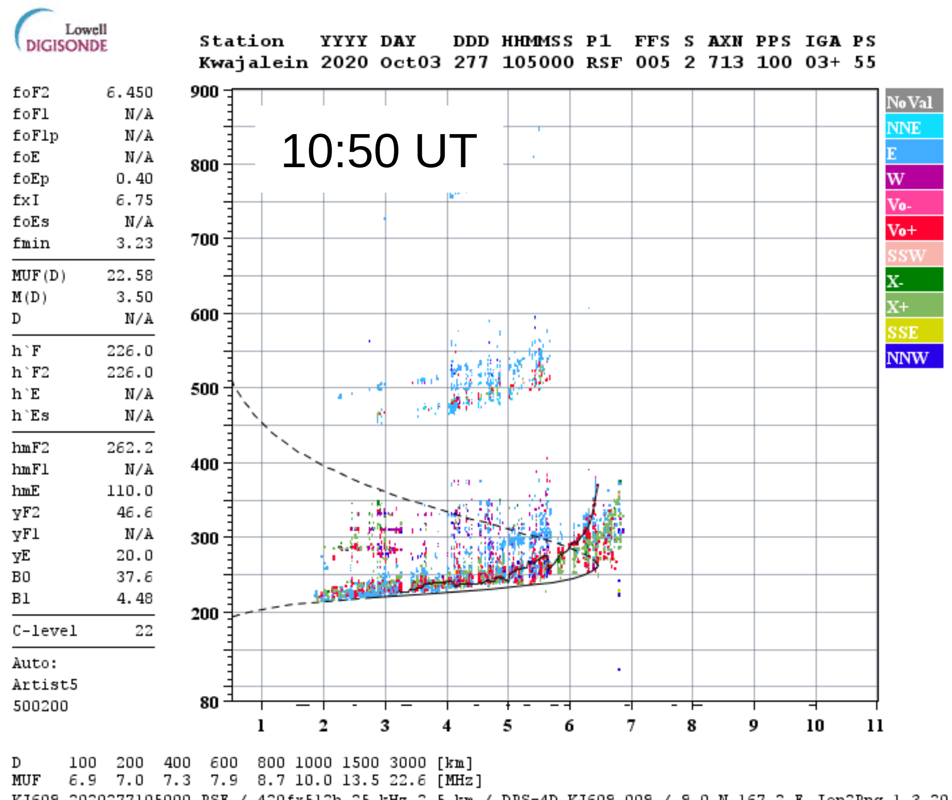
- The plots show less activity at higher apex altitudes during low solar activity years
- Results are consistent with DMSP observations at higher apex-altitudes

HF Ionosonde "Spread-F"

Kwajalein Atoll, 03 October 2020



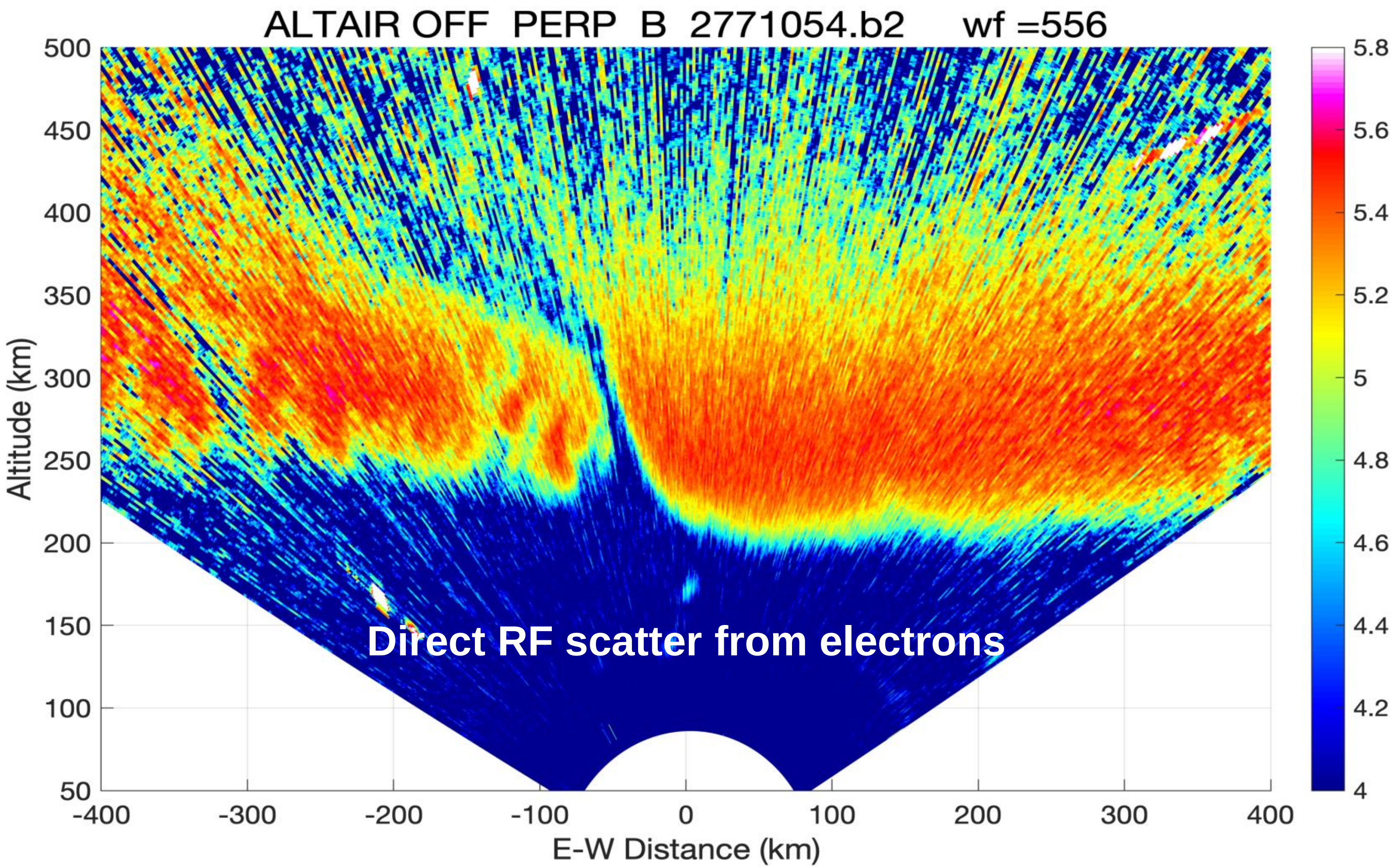
- Equatorial irregularities were originally discovered with swept HF sounding of the upper atmosphere and named 'Spread-F'.



- The clean trace reflected by a smooth ionosphere "spreads" as the reflecting surface becomes irregular, like light scattering off a rough ocean surface.

Incoherent Scatter Radar Observations

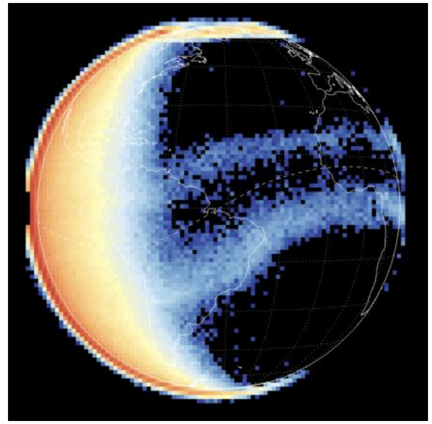
Kwajalein Atoll, 03 October 2020 10:54 UT

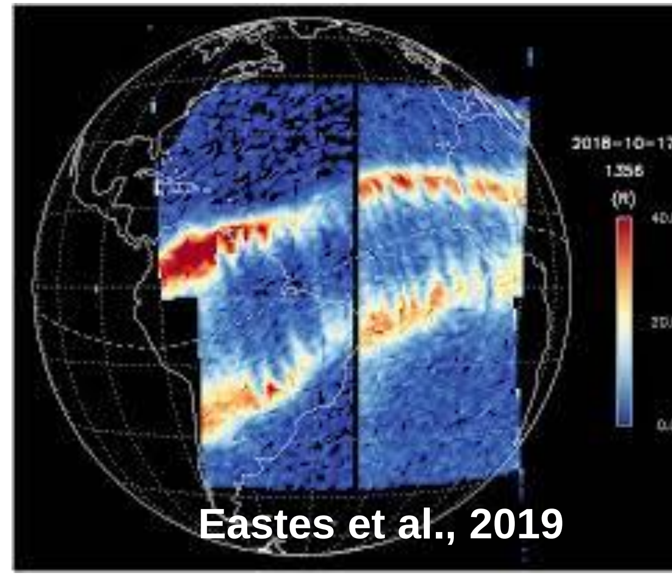


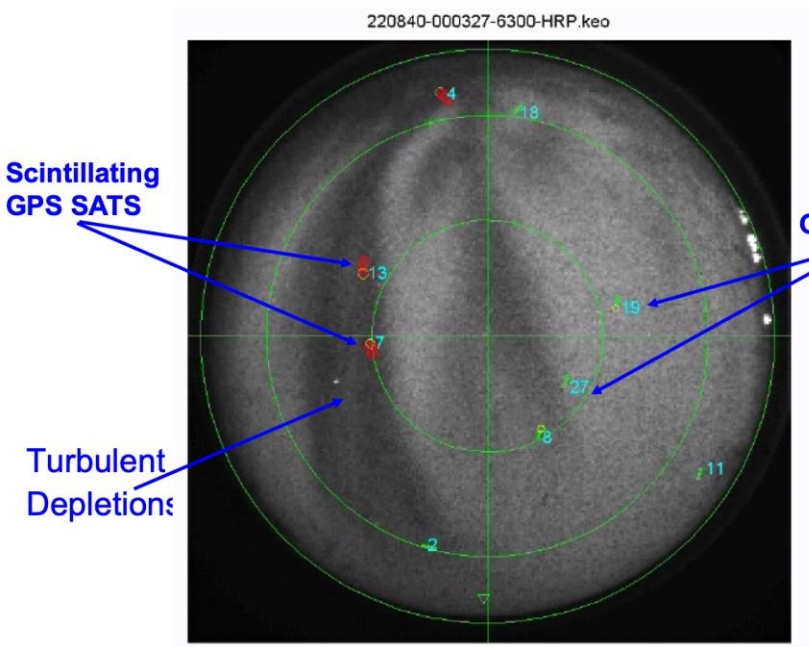
E-W Zonal Scan Mapping Ionospheric Structure

Optical Signatures

- GOLD satellite UV images
  - Geostationary UV imager clearly shows equatorial anomaly and post-sunset depletions



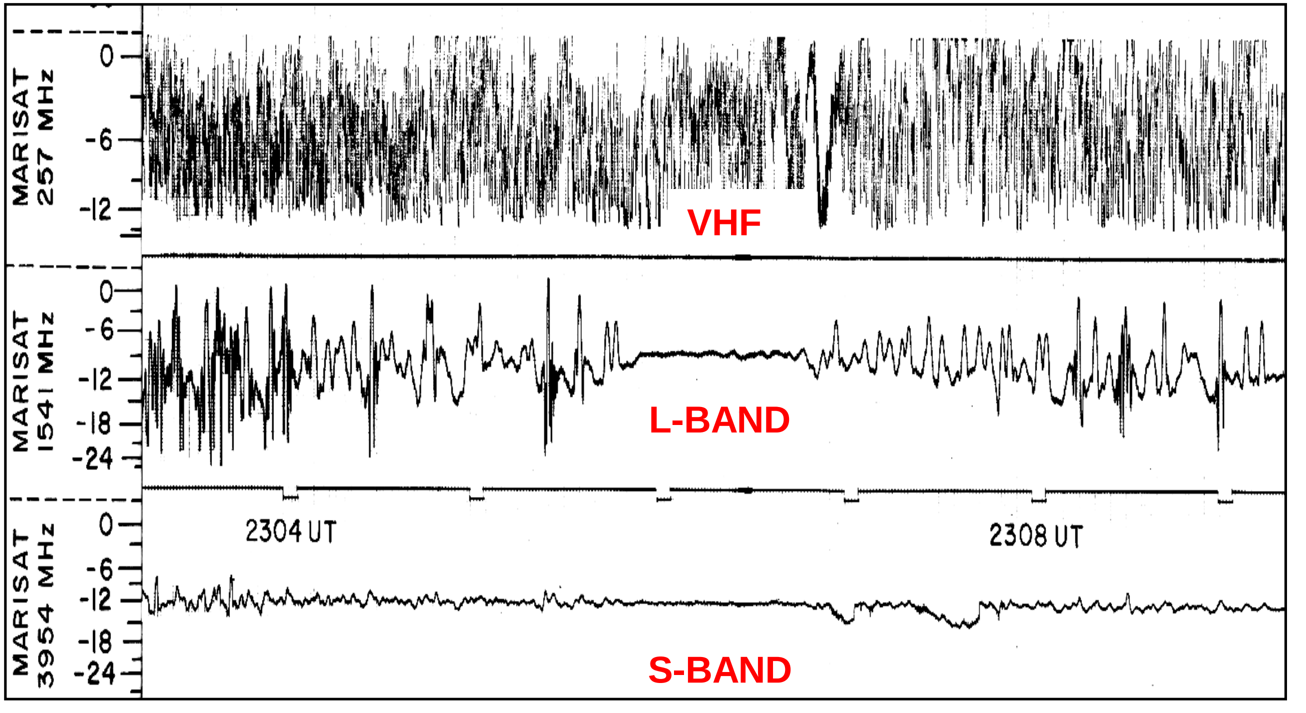




- Ground-based all-sky imagers
  - Detection of faint red-line emissions (630 nm) from electron recombination with oxygen ions also show depletions associated with bubbles.

Mostly We Use Radio Wave Scintillations

Signals at three different frequencies broadcast from the same satellite



- The severity of scintillation effects decreases with increasing frequency, though no simple scaling law describes the changes accurately.

The Ionosphere is a Small Perturbation for GNSS

$$v_\varphi = \frac{\omega}{k} = \frac{c}{n}$$

$$n = \sqrt{1 - \frac{f_p^2}{f^2}}$$

$$f_p \sim 10\ MHz$$

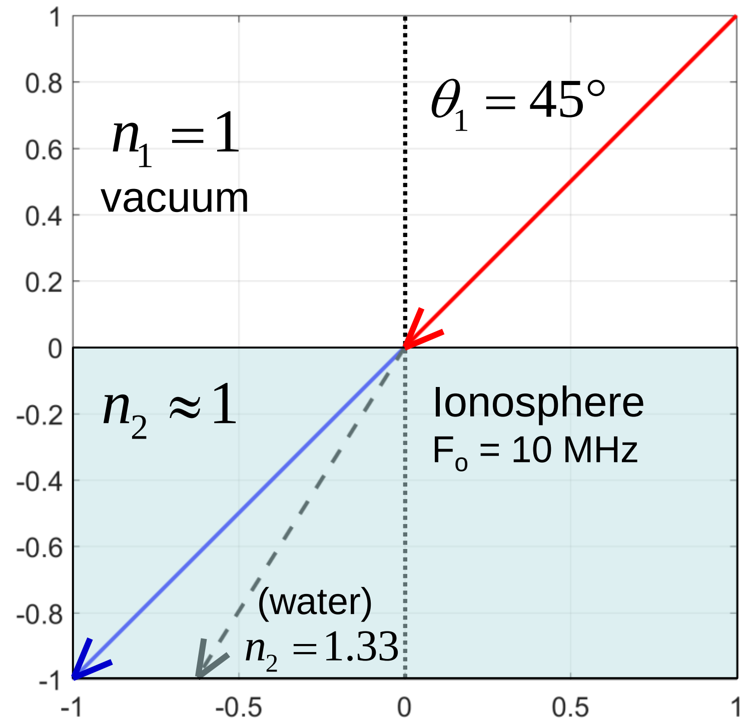
$$f = 1575 MHz$$

$$\boxed{f_p^2 / f^2 \approx 4 \times 10^{-5} !!}$$

Snell's Law:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

For the parameters shown at right, the change in angle is 0.001° (20 µrad)! Can you see it?



Perturbation to index of refraction is very small, yet it is enough to cause serious propagation effects!

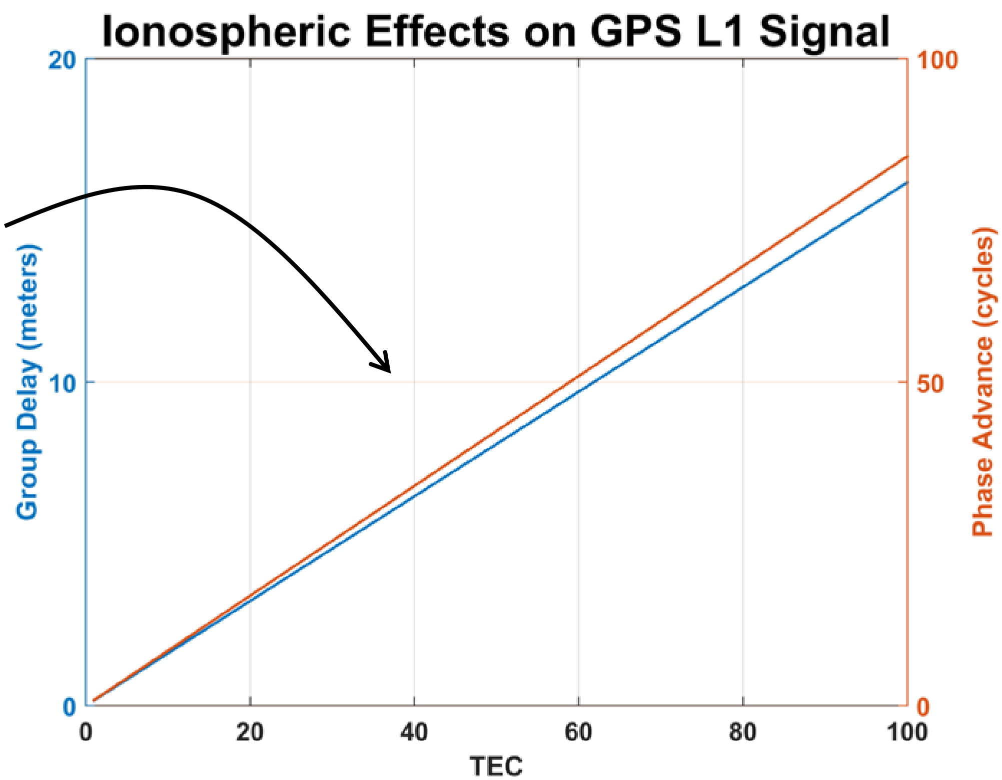
Basic Ionospheric Propagation Effects

$$\tau_d = R/c + \frac{r_e c}{2\pi}\frac{N_{tot}}{f^2}$$

Ionospheric Contribution

$$\delta\varphi = 2\pi f R/c - r_e c\frac{N_{tot}}{f}$$

$$N_{tot} = \int N_e(z)\,dz$$



- These modest refraction effects are dispersive (function of f), so they can be removed by differencing signals at two frequencies
- How do these modest propagation effects cause disruptive fluctuations to the signal amplitude and phase (i.e., scintillation)?

Scintillation Physics Simple Picture

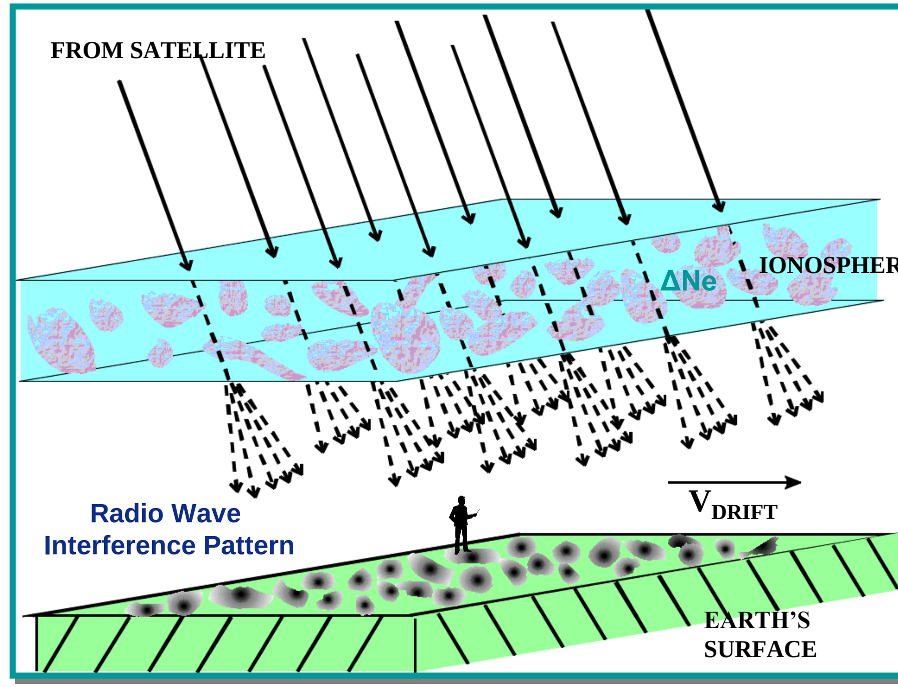
$$\tau_d = R/c + \frac{r_e c}{2\pi}\frac{N_{tot}}{f^2}$$

$$N_{tot} = \int N_e(z)dz$$

$$\varphi = 2\pi f R/c - \underbrace{r_e c \frac{N_{tot}}{f}}_{\delta\varphi}$$

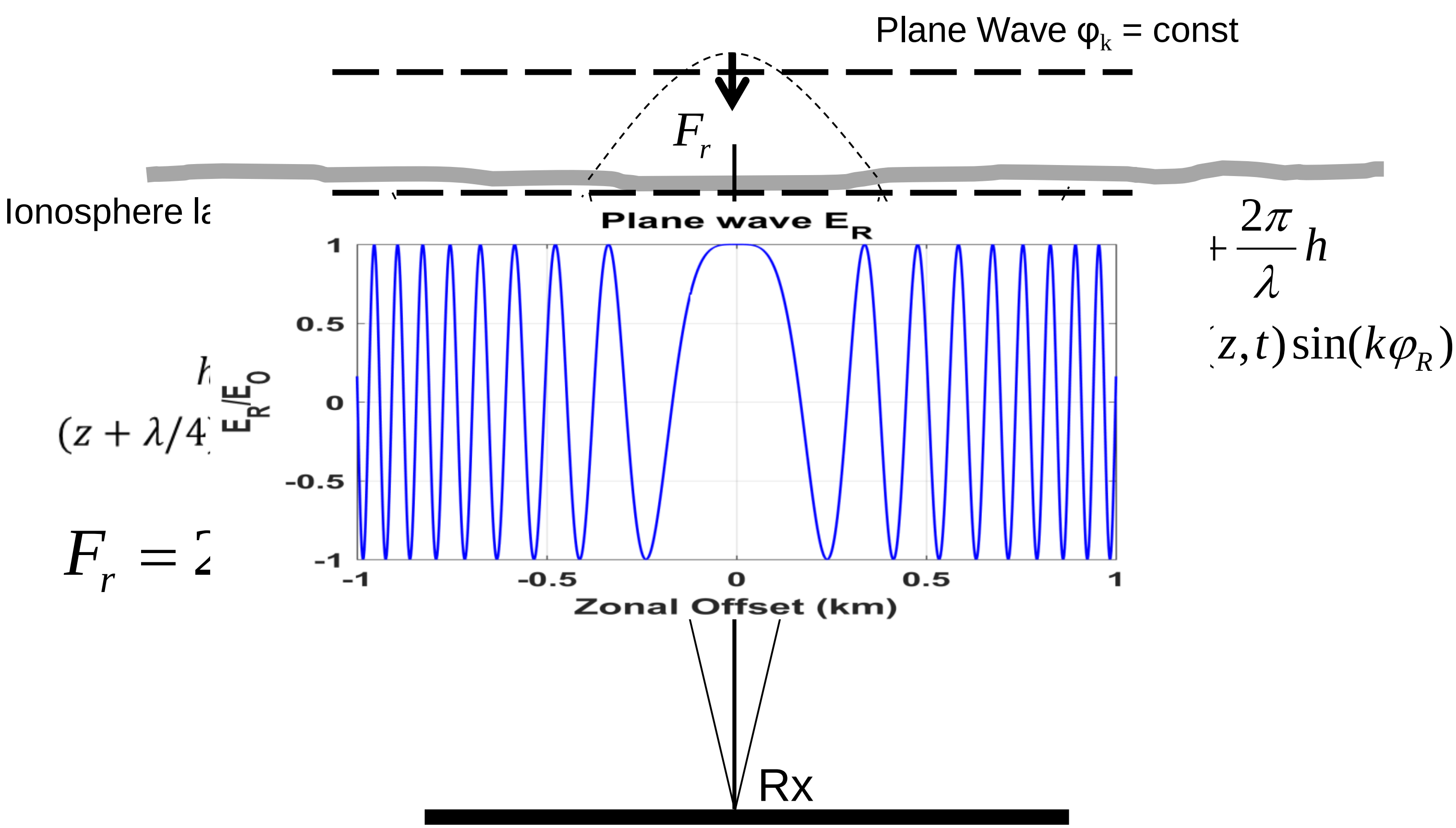
Phase change due
to ionized layer

$$\delta\varphi \approx 5 \times TEC \text{ radians}$$



- Phase variations on wavefront cause diffraction pattern on ground
- A phase changes of ~ π radians (i.e., 0.6 TEC units) required for total destructive interference
- But the variations must occur over limited spatial scale (Fresnel zone)

Physical Picture of the Fresnel Scale



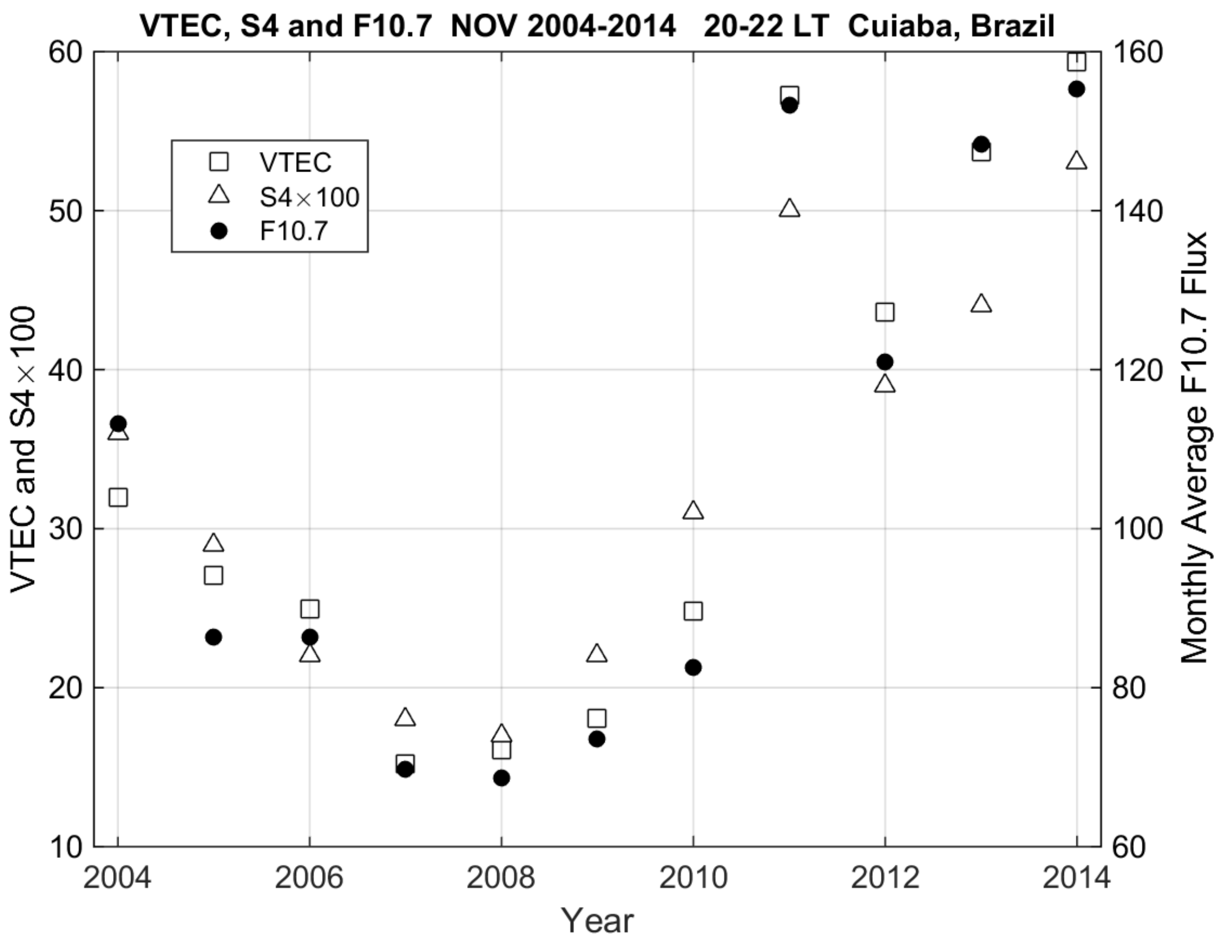
- The distance over which scattering contributions contribute “in phase” at the receiver
- For GPS L1 frequency, Fr is typically 400-500 meters; density fluctuations larger than this scale size will not cause GPS amplitude scintillations.

Implications for the Ionosphere

At L1 we need ~0.6 TEC unit variations over spatial scales of a few 100 meters to achieve strong scintillation; lesser variations will cause correspondingly weaker intensity fluctuations

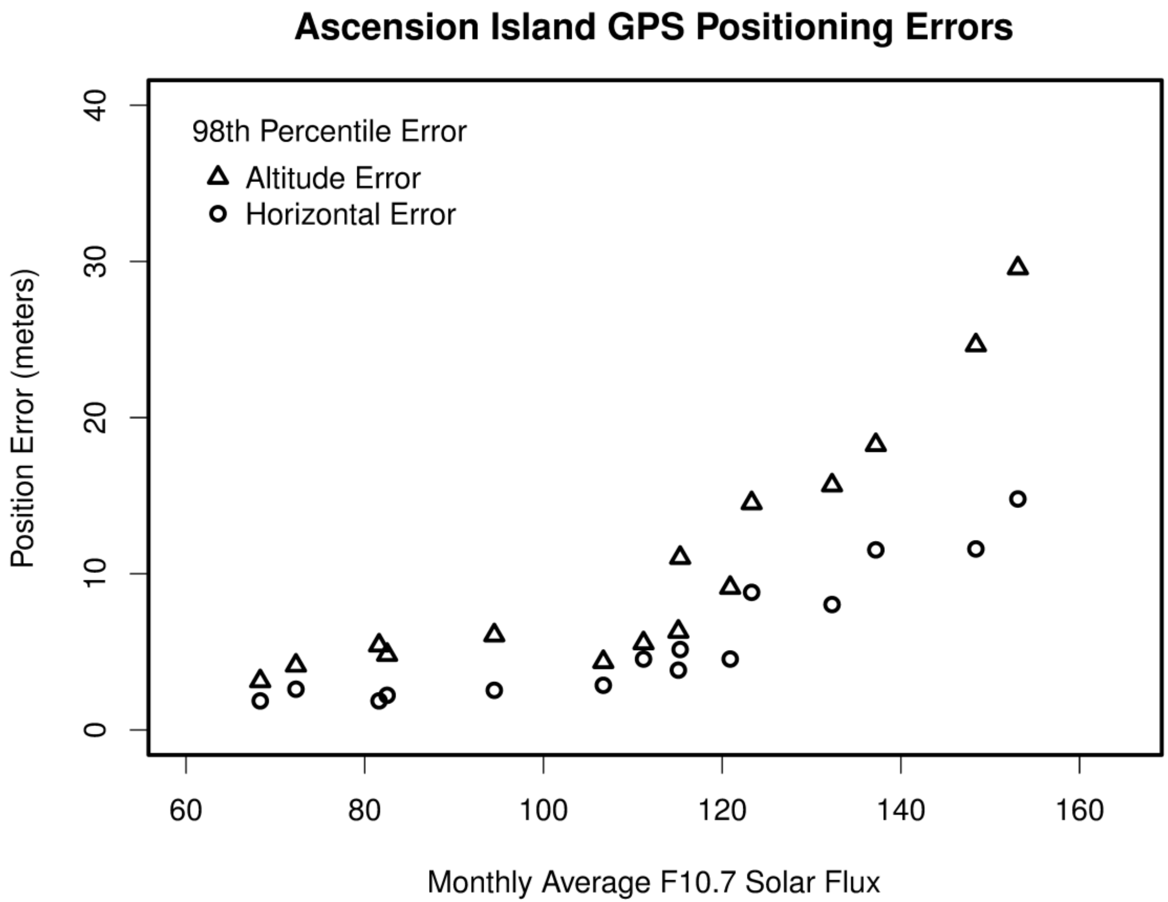
- Solar max TEC ~ 50-100
  - Small relative density fluctuations required (1-2%)
- Solar min TEC ~ 1-5 (nighttime)
  - Large relative density fluctuations required (10-50%)
- Consistent with expectations, GNSS scintillations are generally weak during solar minimum
- Scintillation impacts on GNSS are limited to solar max periods (3-4 years around peak)

Solar Flux, Density & S4



Solar flux determines electron density which determines S4

Solar Flux & Positioning Errors

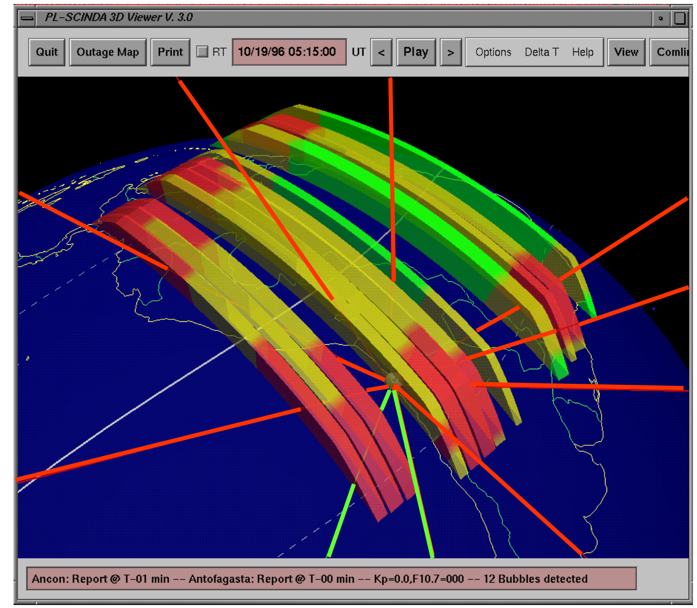


Solar flux controls S4 which controls impact on GNSS performance

Assessing Impacts on GNSS Performance

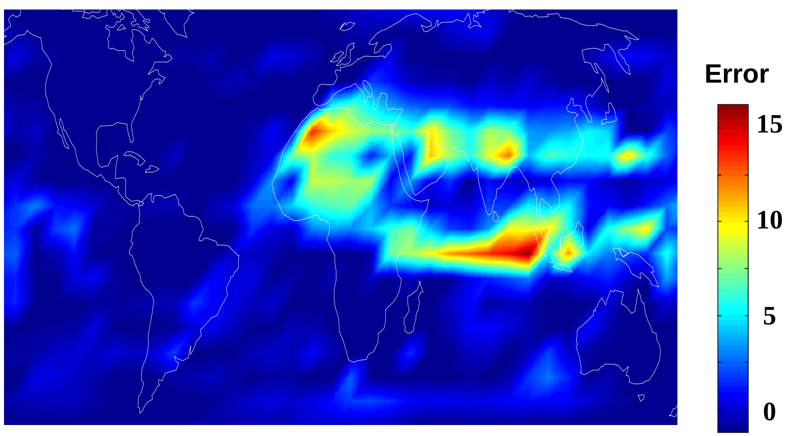
L-Band Impacts at Solar Maximum

Multiple GNSS-ground links will be affected simultaneously



Ionospheric Disturbance Visualization

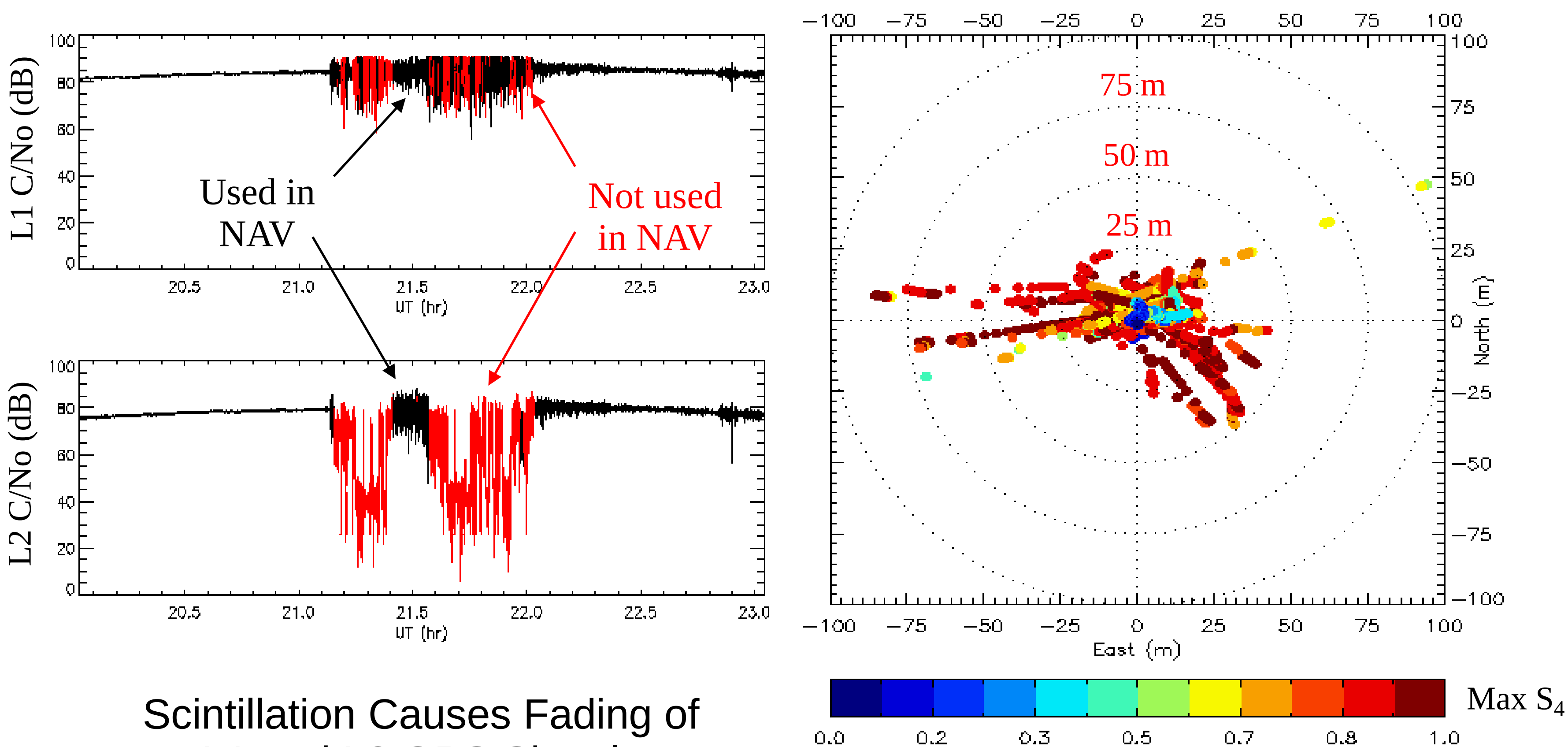
Objective to produce multi-frequency GNSS position error maps



Equatorial scintillation structures may routinely degrade optimal navigation solution geometry; potential impacts under investigation

Effects on GNSS Positioning Accuracy

16 Mar 2002, ASI



Scintillation Causes Fading of L1 and L2 GPS Signals

Resulting Positioning Error

Some Take-aways

- Irregularities at mid- and high-latitudes are highly dependent on magnetic storm activity; low-latitude irregularities are not.
- Strong irregularities can only be sustained at night.
- Relatively weak ionospheric interaction with L-band signals produces surprisingly strong radio wave propagation effects.
- Scintillation strength is proportional to irregularity strength which is related to the background electron density and thus strongly dependent on solar cycle.
- The occurrence and spatial extent (apex altitude) of low-lat irregularities are also functions of solar flux.
- Irregularities at high latitudes often occur in low densities and high drifts, causing rapid phase variations on the ground; not true scintillation (diffraction), but GNSS receivers may not know the difference!
- Numerous scintillation-induced GNSS performance impacts have been observed and documented during solar max.

Reflection

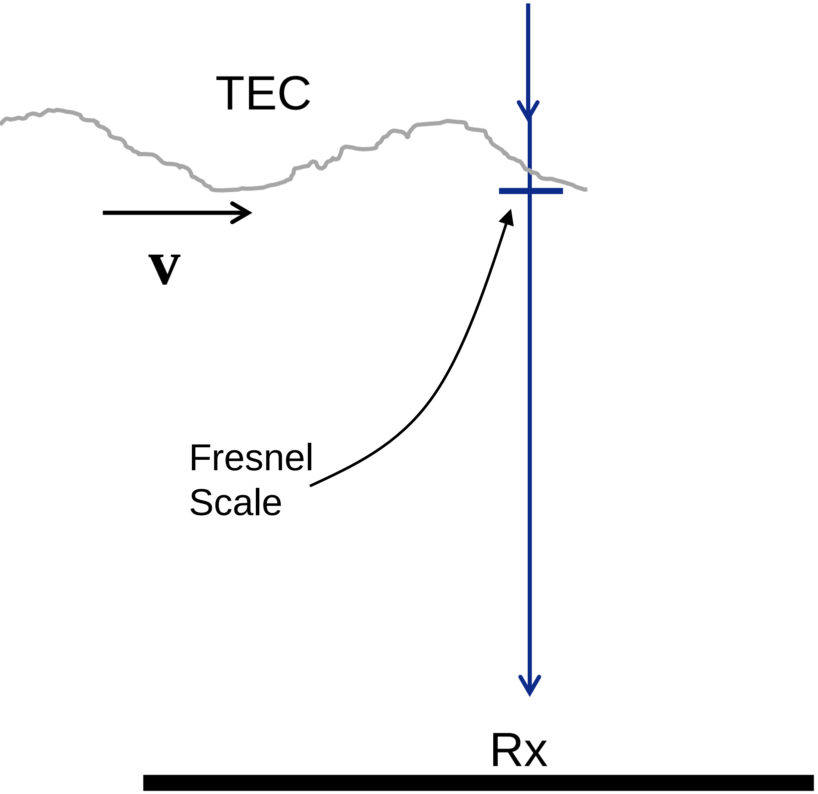
I am very sorry that we cannot meet to discuss these topics together in person and hope that will change soon. Until then, stay safe and continue to grow and learn.

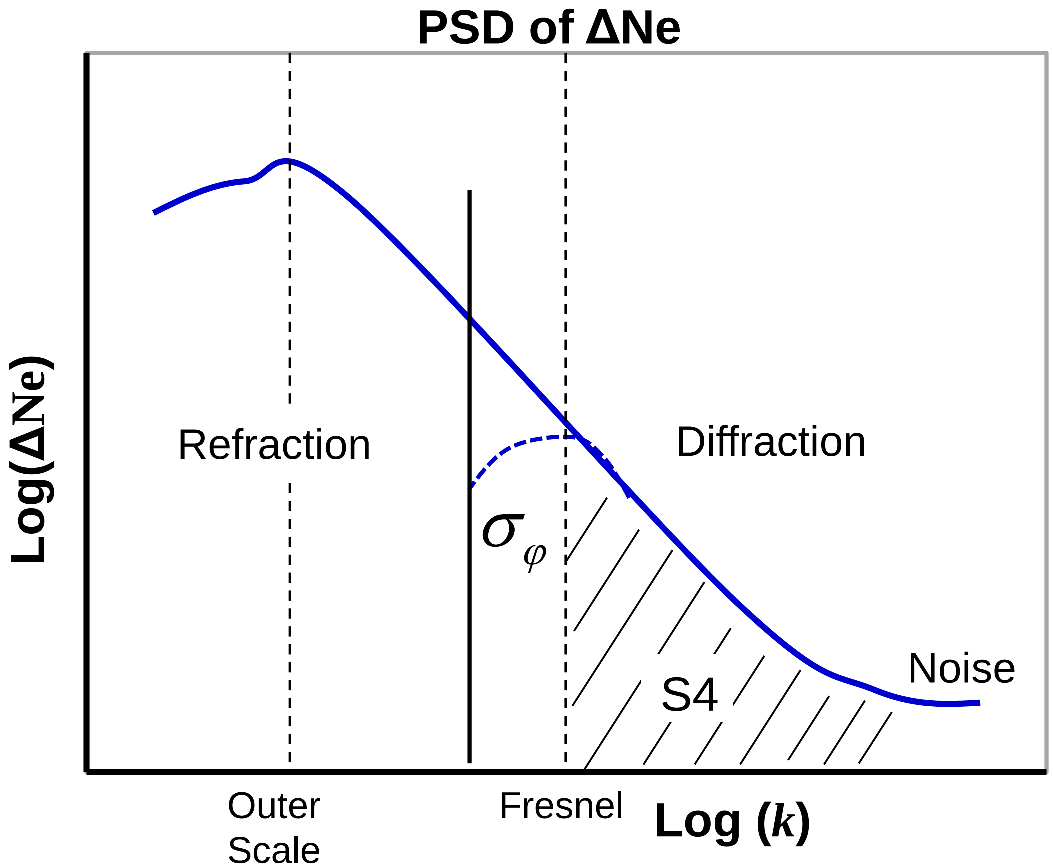
Thank You!

Group Photo, GNSS Workshop, ICTP, Trieste Italy 2019

Back Up Slides

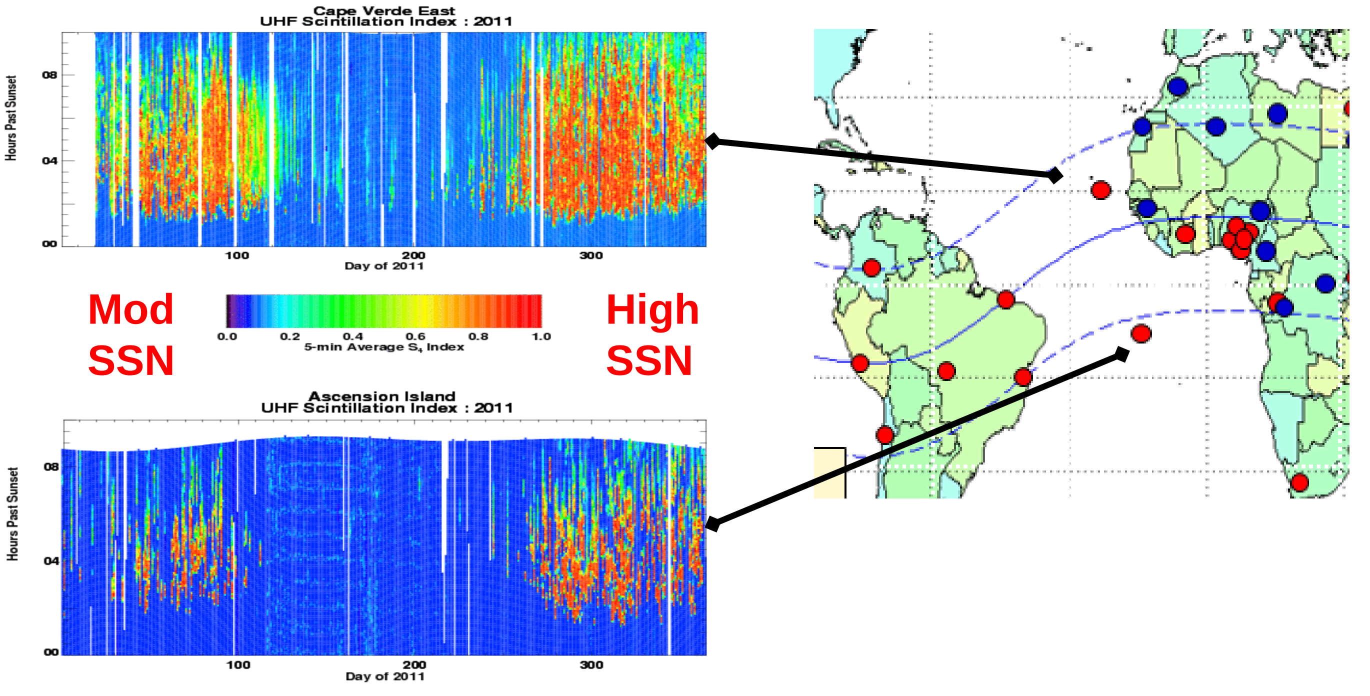
High Latitude Phase Scintillations: Fast Variations Driven by High Drift Speeds





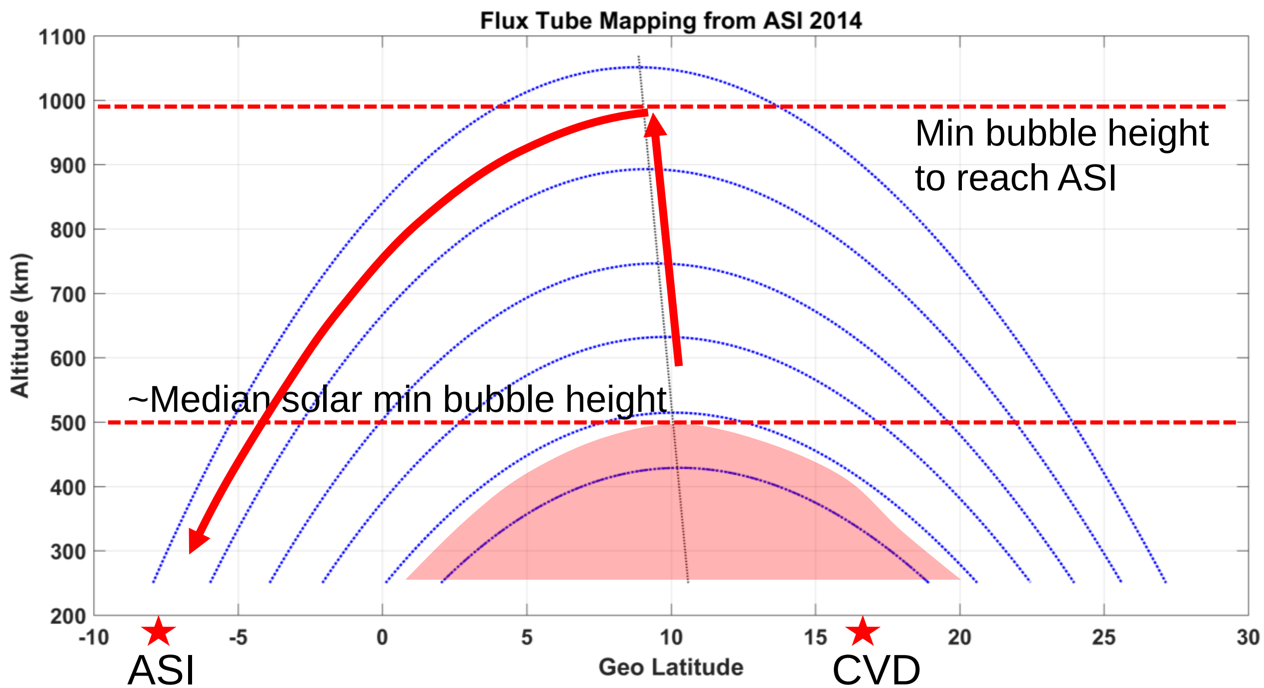
- S4 is limited by the Fresnel scale, regardless of drift velocity; it is constrained by a physical dimension
- Phase fluctuations are limited only by the outer scale; the faster the ionosphere drifts overhead the more phase variation there will be in a given sampling period

Irregularity Occurrence & Magnetic Lat



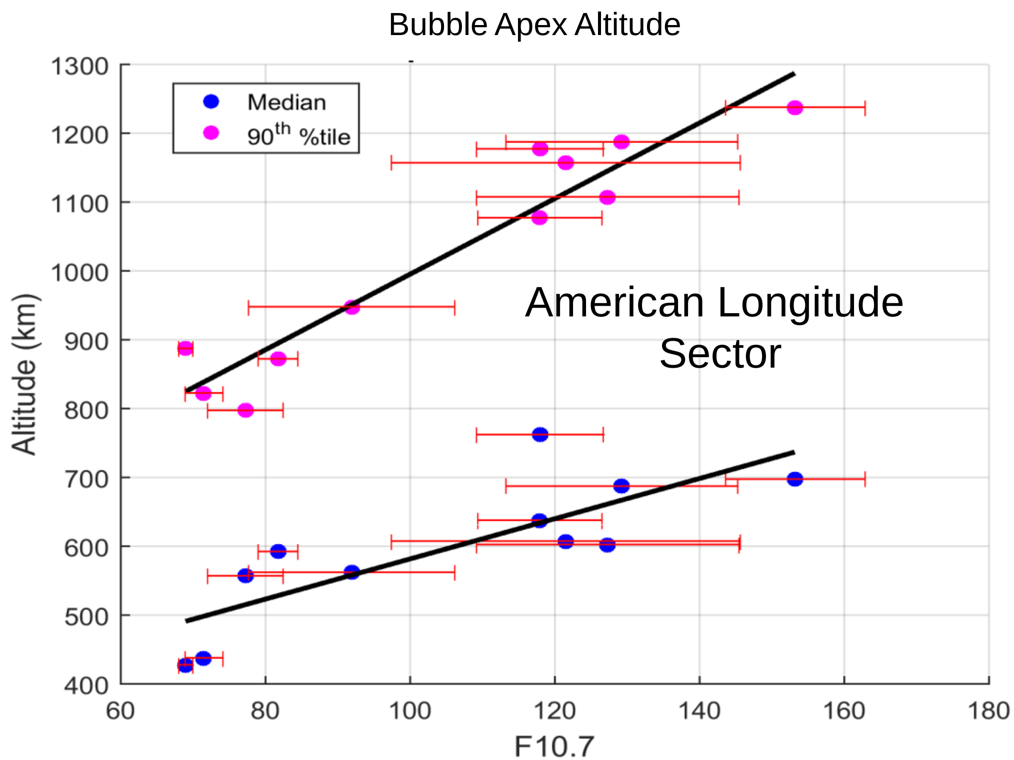
- Ground-based VHF measurements show that scintillation occurrence at Ascension Island (18°S maglat) reached 50-80% during the peak seasons between 2011-2015.
- Assuming bubble height determines meridional extent, structures must rise to over 1000 km to reach Ascension, but only about 400 km to reach Cape Verde.

Apex Height vs Latitude



- Irregularities occur over Cape Verde throughout the solar cycle, whereas activity at Ascension Island is restricted to solar maximum periods when bubbles rise higher.

Apex Altitude vs Solar Flux



Dev Joshi, BC
PhD thesis, 2019

Data from C/NOFS satellite in situ planar Langmuir probe (PLP); courtesy P. Roddy, AFRL

- The evolution of the median peak apex altitudes from mid-2008 through 2014 is plotted above as a function of solar flux (F10.7).
- Both the occurrence frequency and latitudinal coverage decrease during solar min as median bubble heights decrease to less than 500 km