Ionospheric Irregularities & Scintillation

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Overview

- Ionospheric irregularities cause deleterious effects on radio wave propagation that can disrupt space-based RF services such as communications and navigation.
- Principal regions affected include high and low latitudes.
- We focus on the equatorial region here (the most severe environment) and the underlying dynamics that give rise to intense irregularities.
- Most existing methods for detecting irregularities utilize dedicated ground-based GNSS and other receivers specialized to measure rapid signal fluctuations.
- From a coverage perspective the number and availability of such sensors is quite limited.
- We present an overview of alternative methods for meaningful near real-time global irregularity characterization with existing sensors and infrastructure; primary contributors are **1. GNSS TEC** data & 2. **GNSS radio occultation** (RO) data.

Ionospheric Irregularities & Scintillation Physics

Time Delay:

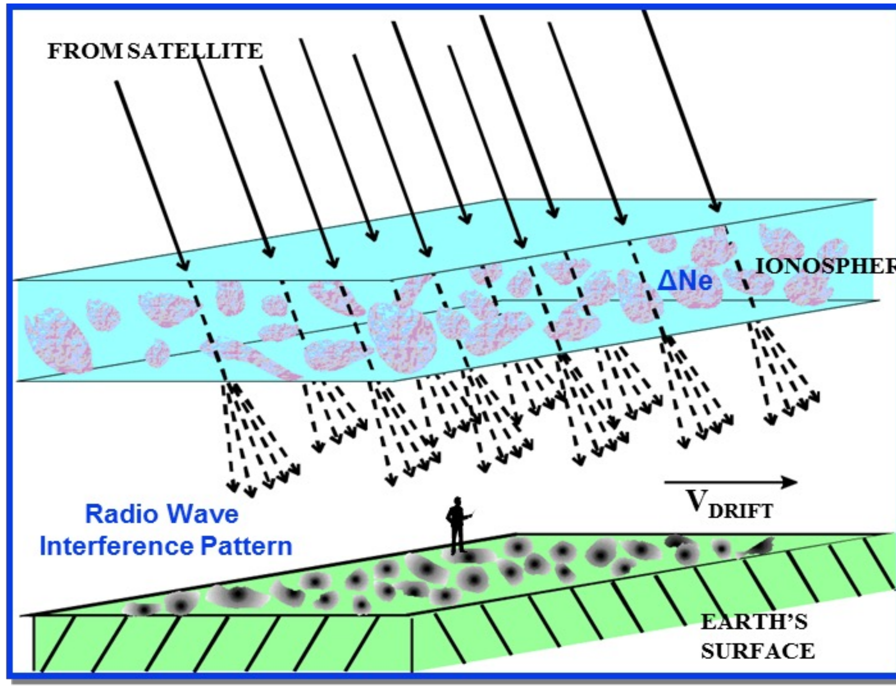
$$\tau_d = R/c + \frac{r_e c}{2\pi}\frac{N_{tot}}{f^2}$$

Phase Perturbation:

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

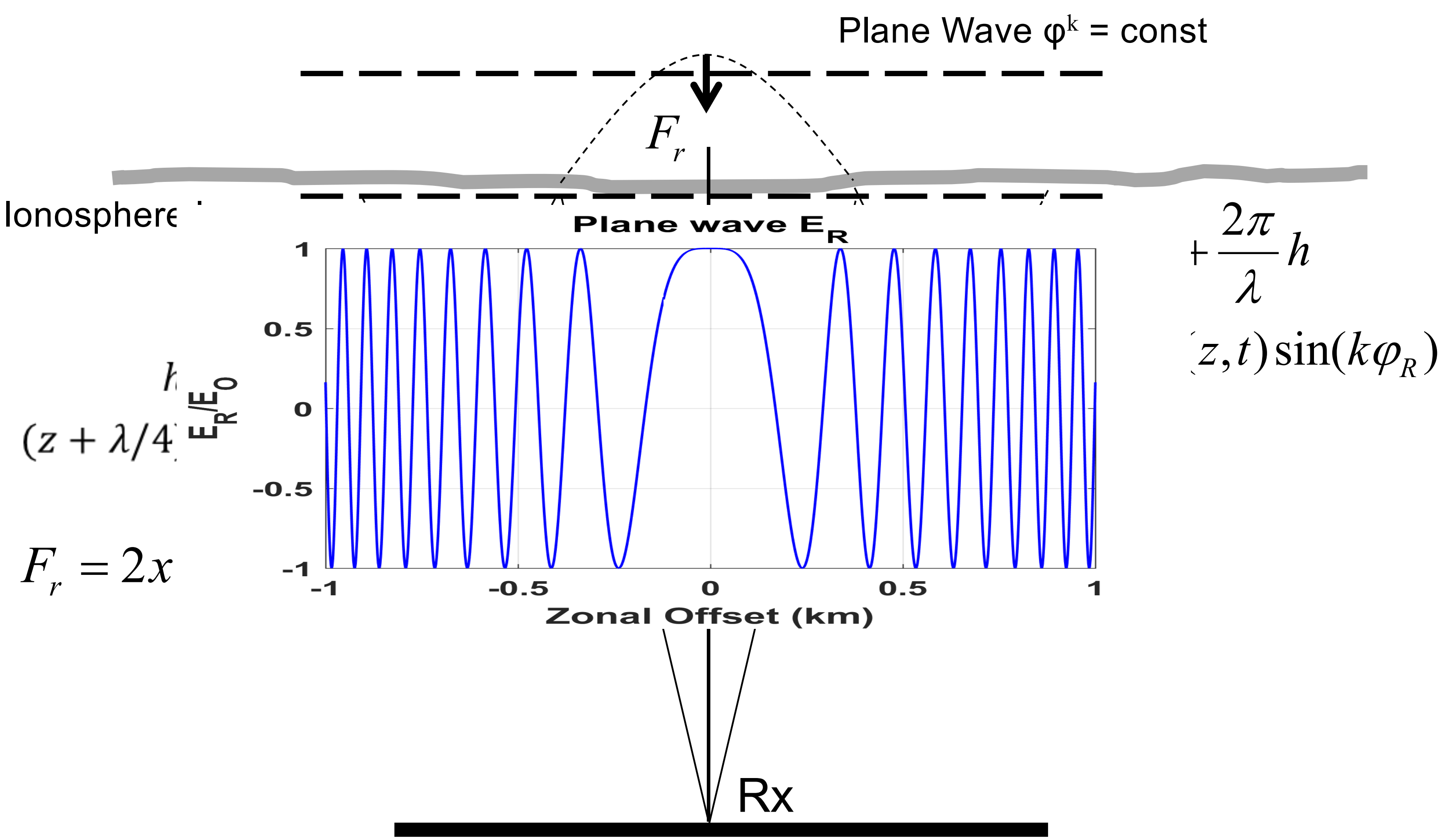
Depends on TEC:

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



- A uniform ionosphere slows transiting radio waves but does not distort amplitude and phase.
- Electron density irregularities introduce phase variations on the wavefront from the satellite causing a diffraction pattern on ground.
- Interference pattern changes in time and space, such that a user observes rapid fluctuations of signal amplitude and phase that degrade system performance.
- For diffraction to occur, the phase changes must occur over a relatively short distance known as the Fresnel scale, $F_r = 2x = \sqrt{2\lambda z}$.

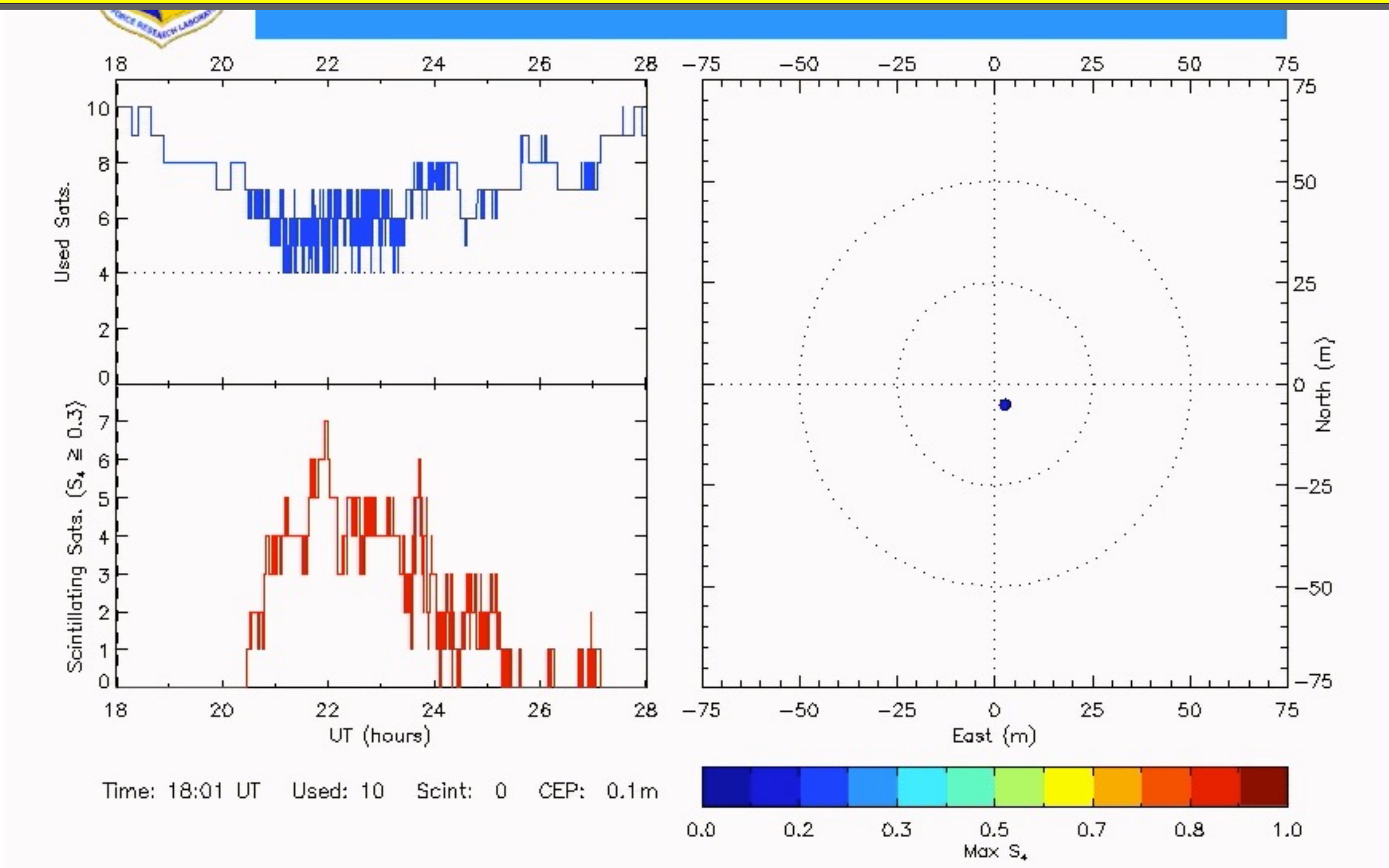
Physical Picture of the Fresnel Scale



- 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.

GPS Positioning Errors During Solar Max

Scintillation can cause rapid fluctuations in GPS position fix;
Typical night from field experiments in 2002



The Ionosphere is a Small Perturbation for GNSS

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

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

$$f_p \sim 10 \ MHz$$

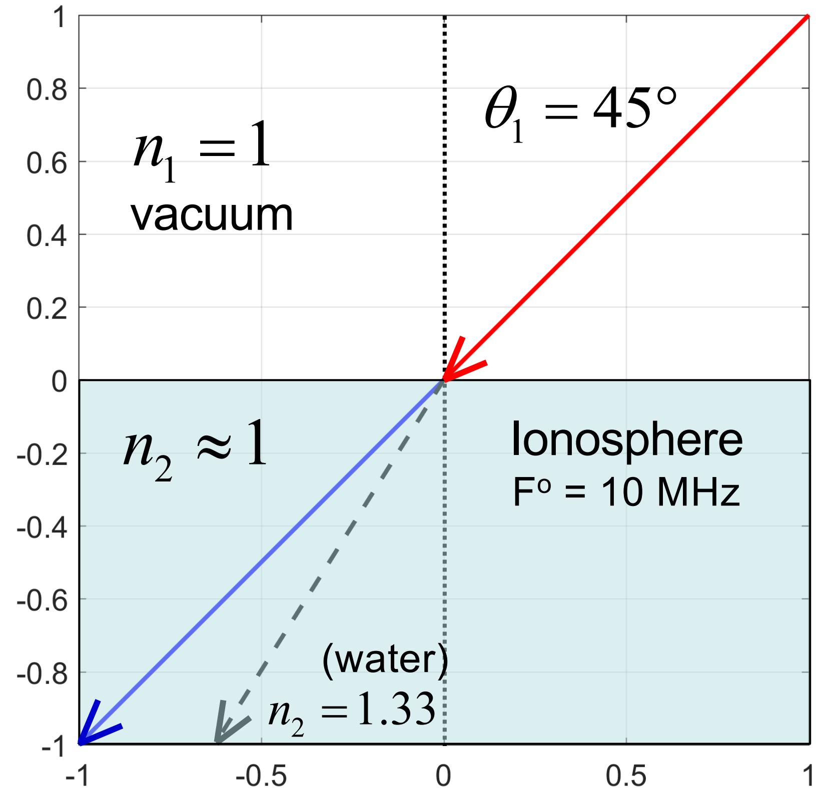
$$f = 1575 MHz$$

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

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!

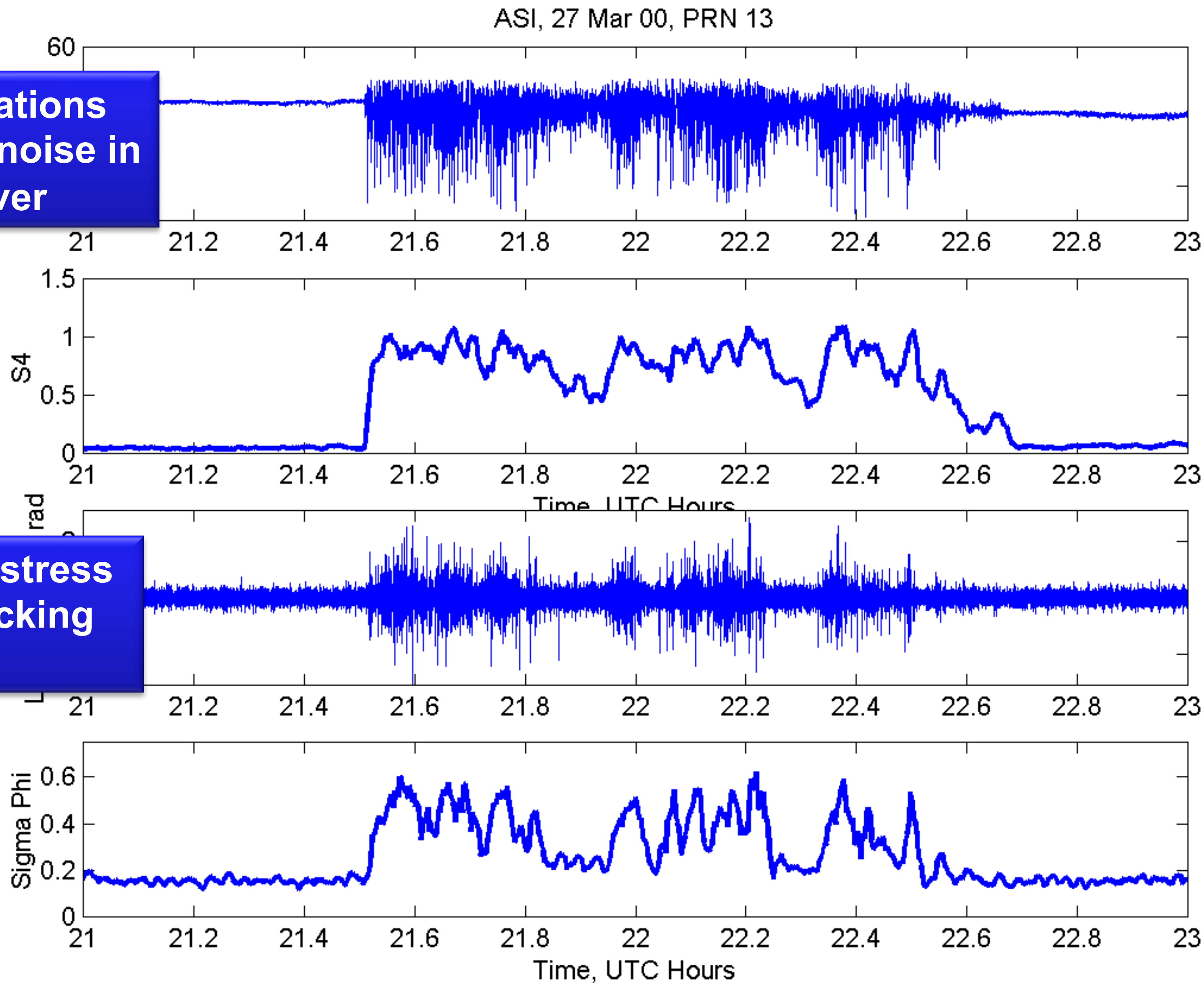
GPS Signal Fluctuations Caused by Ionospheric Scintillation

Intensity fluctuations reduce signal-to-noise in GNSS receiver

S4: normalized st. dev. of intensity

Phase variations stress GNSS signal tracking loops

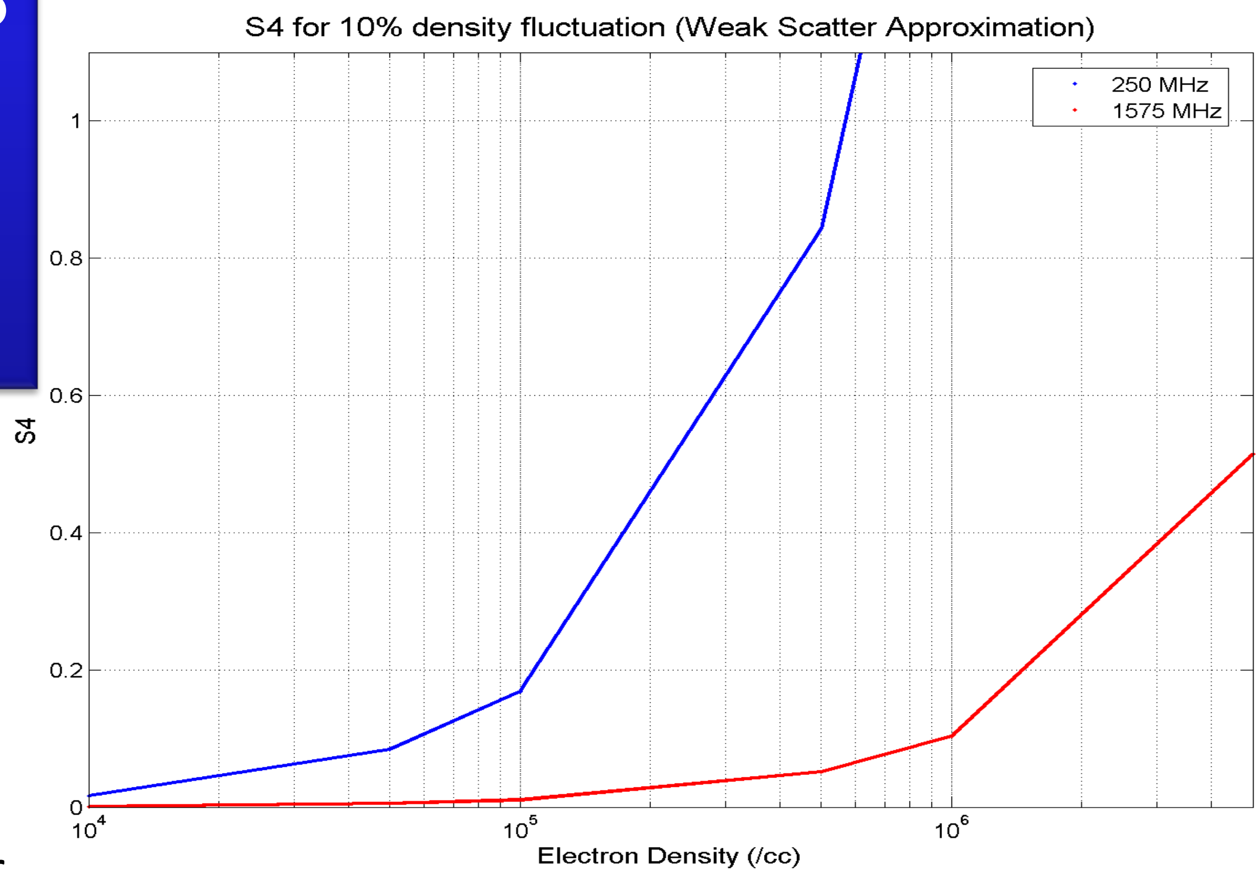
σ^{ϕ} : st. dev. of phase



Effect of Electron Density on S4

Scintillation requires two physical ingredients:

1. **Electron density**
2. **Irregularities**



- Significant relative density fluctuations will not cause scintillation if the background electron density is too low
- NmF2 must exceed ~10^5/cc for VHF scintillation, ~10^6/cc for GNSS (~50 TEC units)

$$N\sigma_{N/\Delta N} = S_4^{thresh}\left\{2\pi r_e^2\lambda^2\, q_0 L \sec\theta \left(\frac{\lambda z_R \sec\theta}{4\pi}\right)\right\}^{-1/2}$$

Weak Scatter Approximation

(assumes fluctuation σ = 10%)

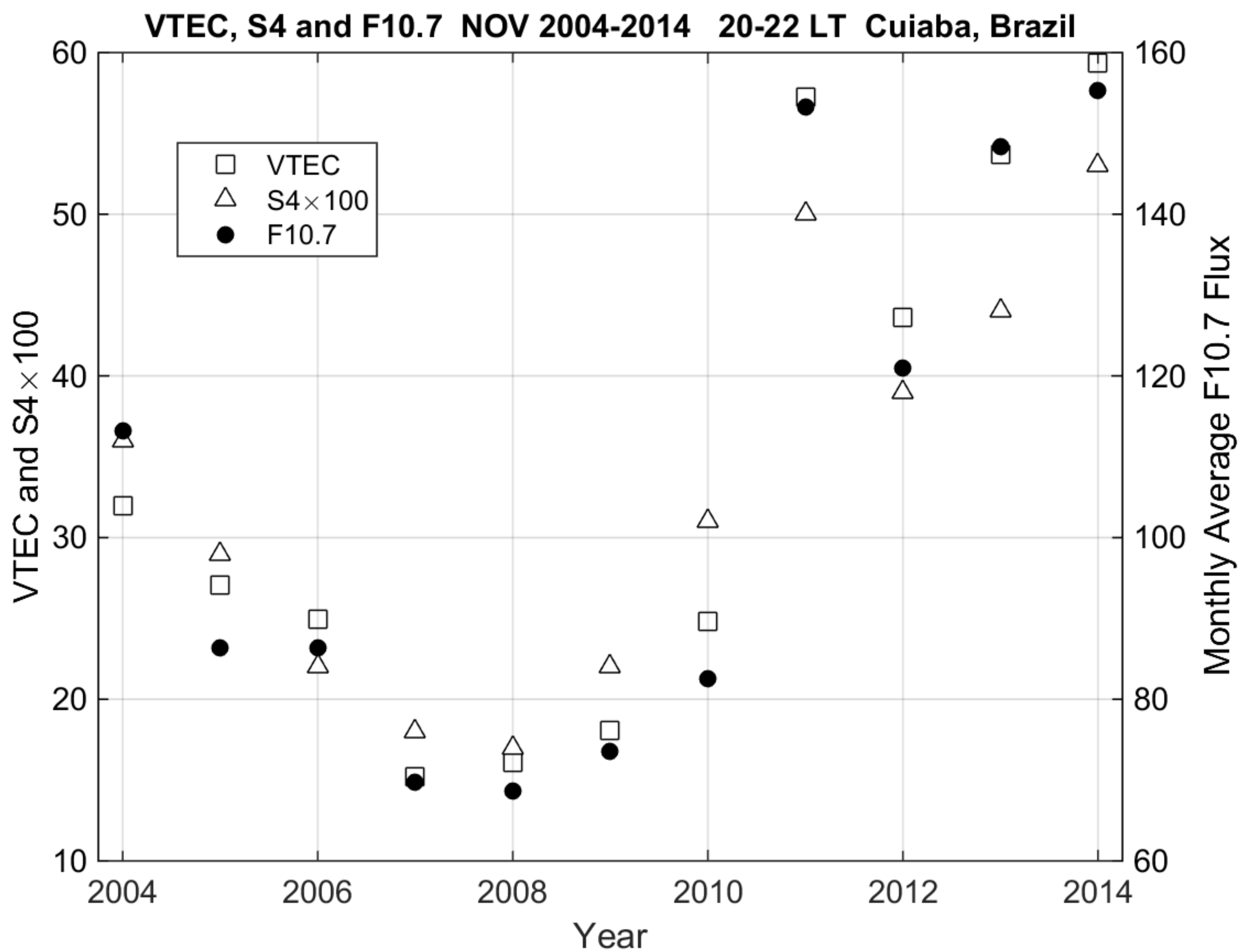
Implications for the Ionosphere & GNSS

Let's run some numbers…

- At L-band, $\delta\varphi \approx 5 \times TEC \text{ radians}$, so a phase changes of ~ π radians (condition for destructive interference) requires $\delta TEC \approx 0.6$ TECu.
- But the variations must occur over limited spatial scale, the Fresnel zone, $F_r = \sqrt{2\lambda z}$, ~ 500 meters for L1 and typical iono parameters

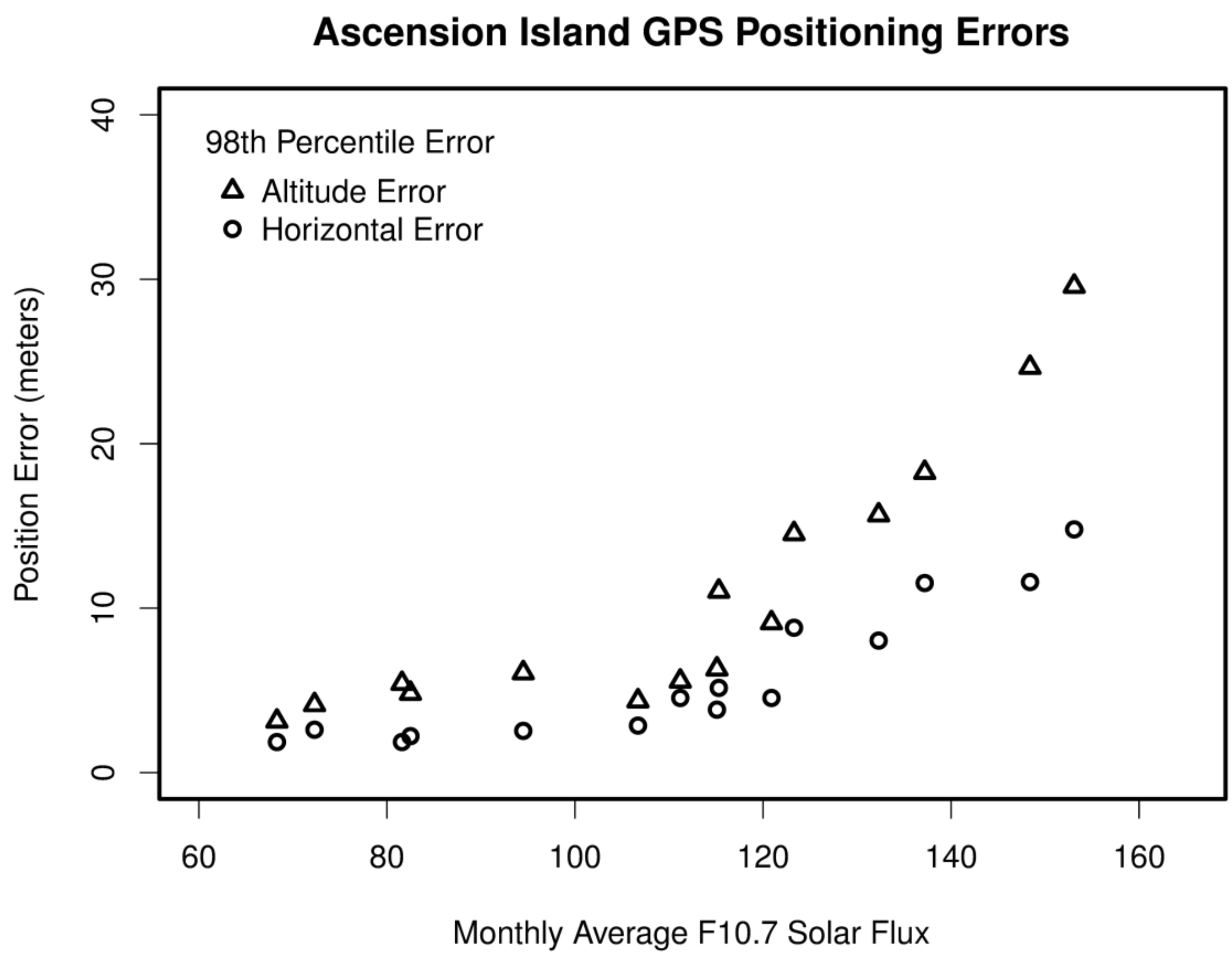
- Solar max TEC ~ 50-100
  - Small relative density fluctuations required (1-2%)
- Solar min TEC ~ 1-5 (nighttime)
  - Large relative density fluctuations required (10-50%)
- Consistent with expectations, GPS scintillations are generally weak during solar minimum
- Scintillation impacts on GPS are limited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

Solar Flux, Density & S4



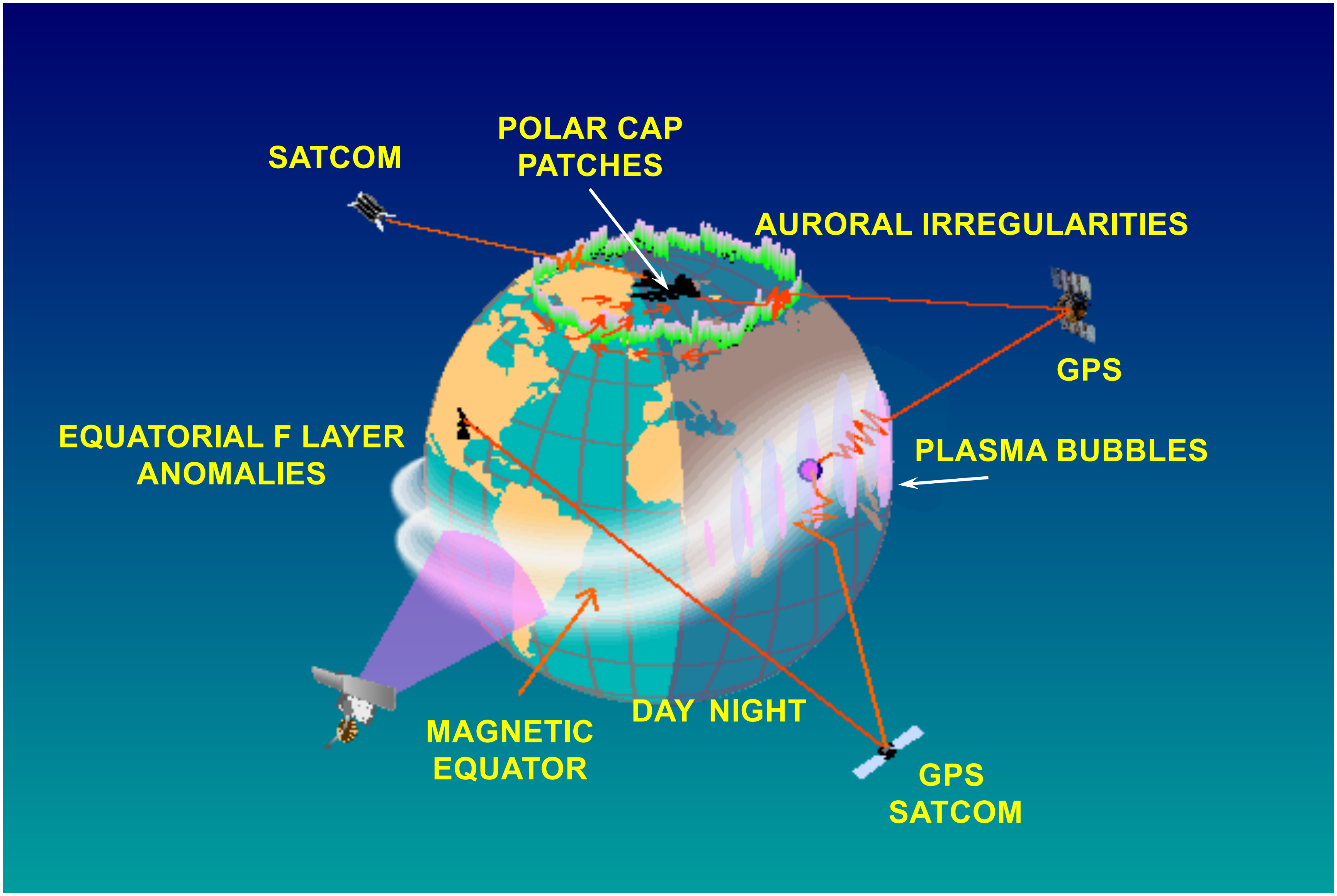
Solar flux determines electron density which determines S4

Solar Flux & Positioning Errors



Solar flux controls S4 which controls impact on GNSS performance

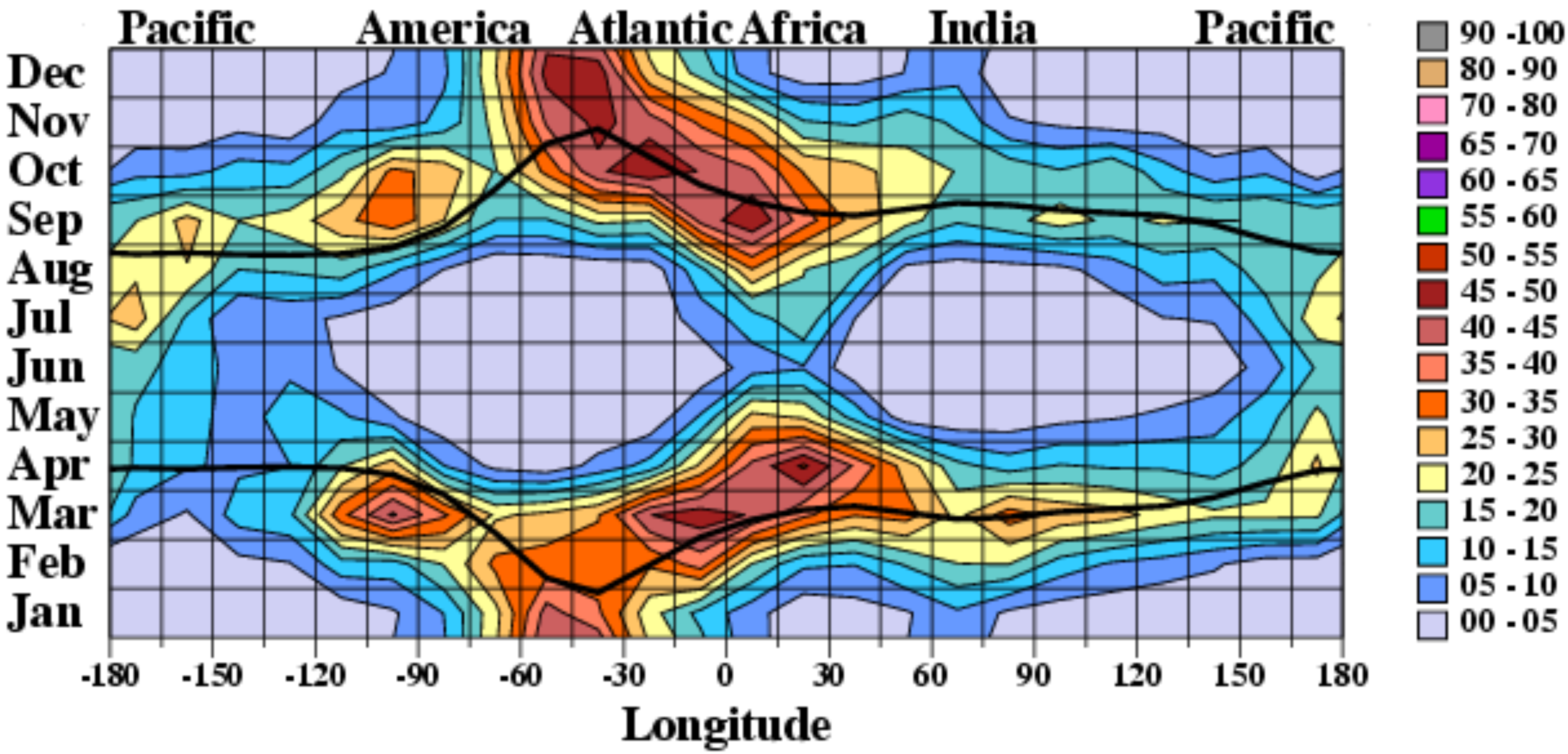
Disturbed Ionospheric Regions



DMSP Satellite Observations: Irregularity Detection Over the Equator (1999 – 2002)

In situ irregularities detection statistics
800 km circular polar orbit

800 km Occurrence Climatology



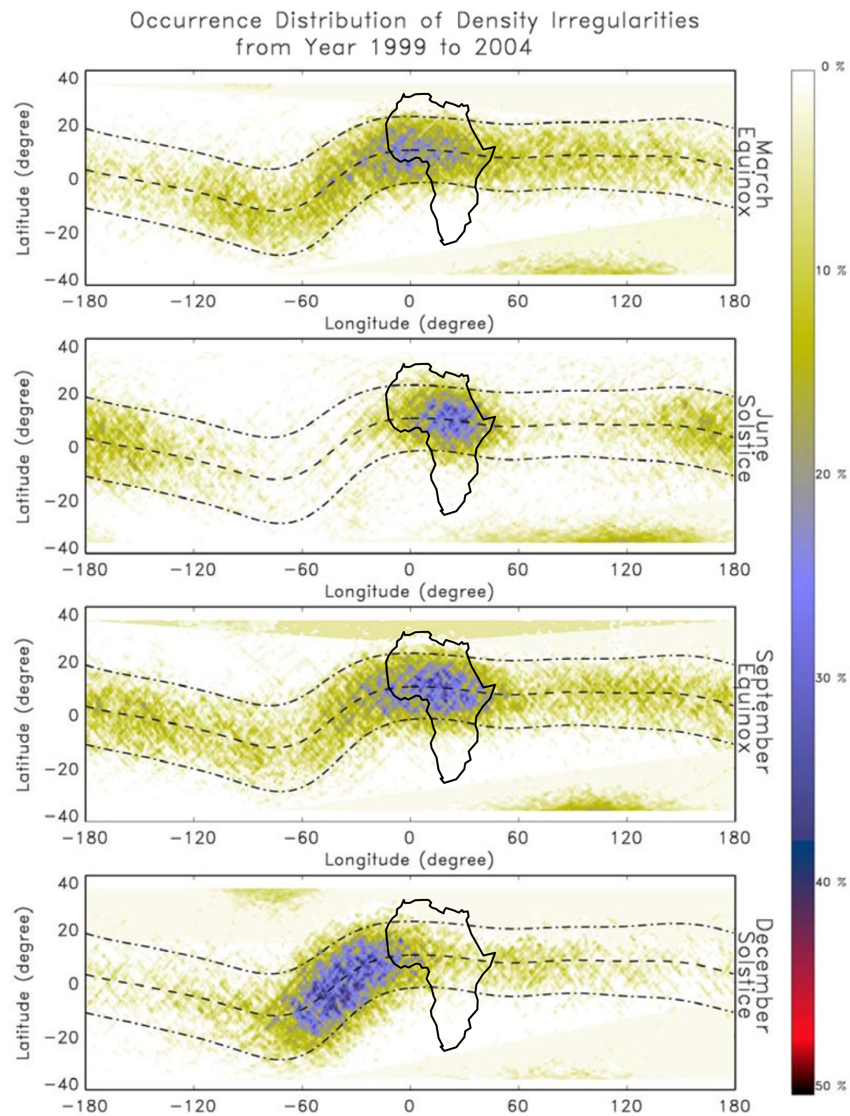
From Burke & Huang [2004]

Scintillation Activity over Africa

Low-latitude scintillation affects nearly 50% of the earth's surface.

- ROCSAT observed irregularities above Africa virtually year round.
- C/NOFS saw a similar integrated maximum in activity over Africa.
- The reasons for this are still under investigation.
- The takeaway is that post-sunset scintillation is a regular feature of the low-latitude ionosphere over Africa and space-based radio frequency systems must be prepared to deal with it.

ROCSAT (600 km)

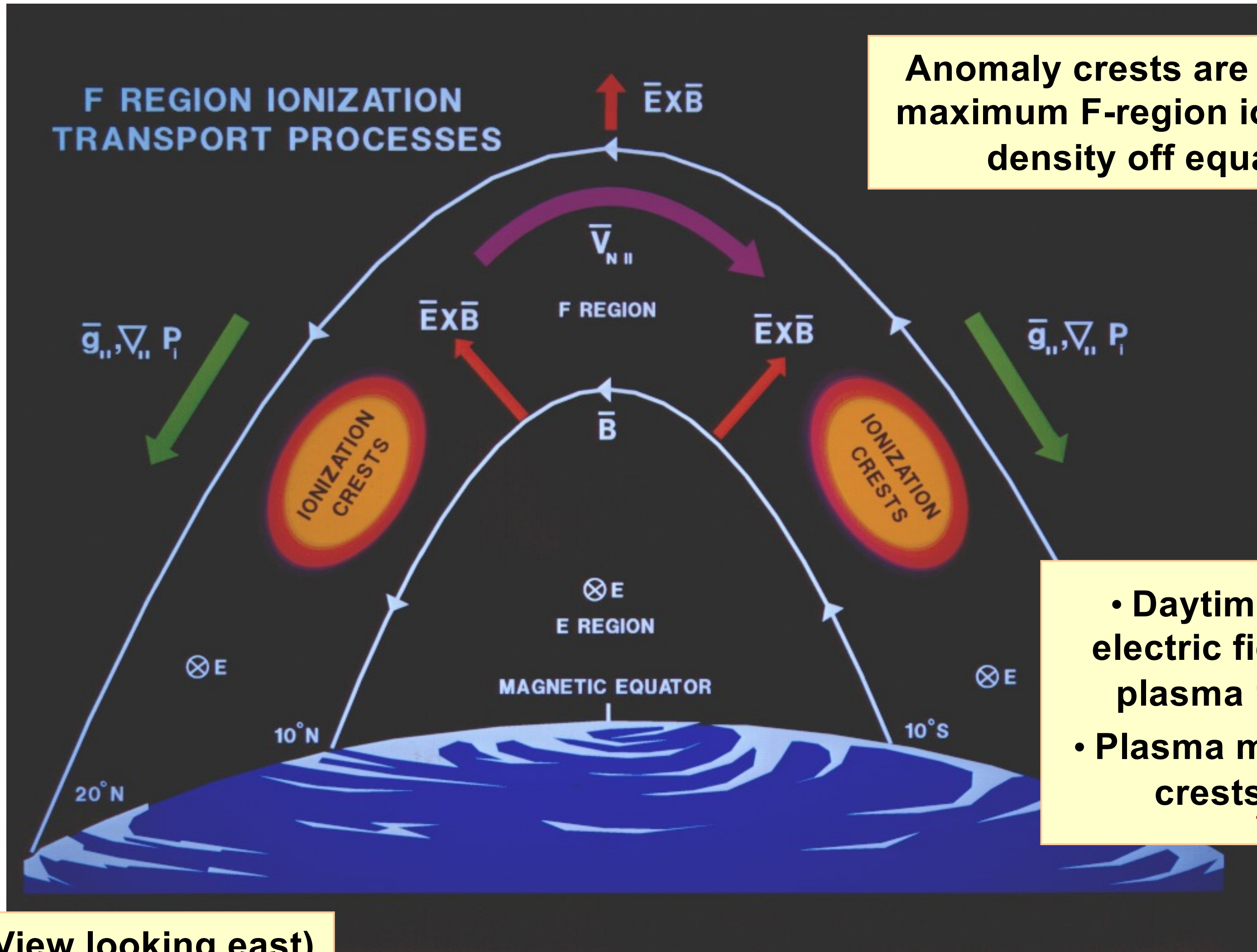


Adapted from S.Y Su, 2005

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 ($g^{\|}$, $\nabla^{\|}P^{\|}$)

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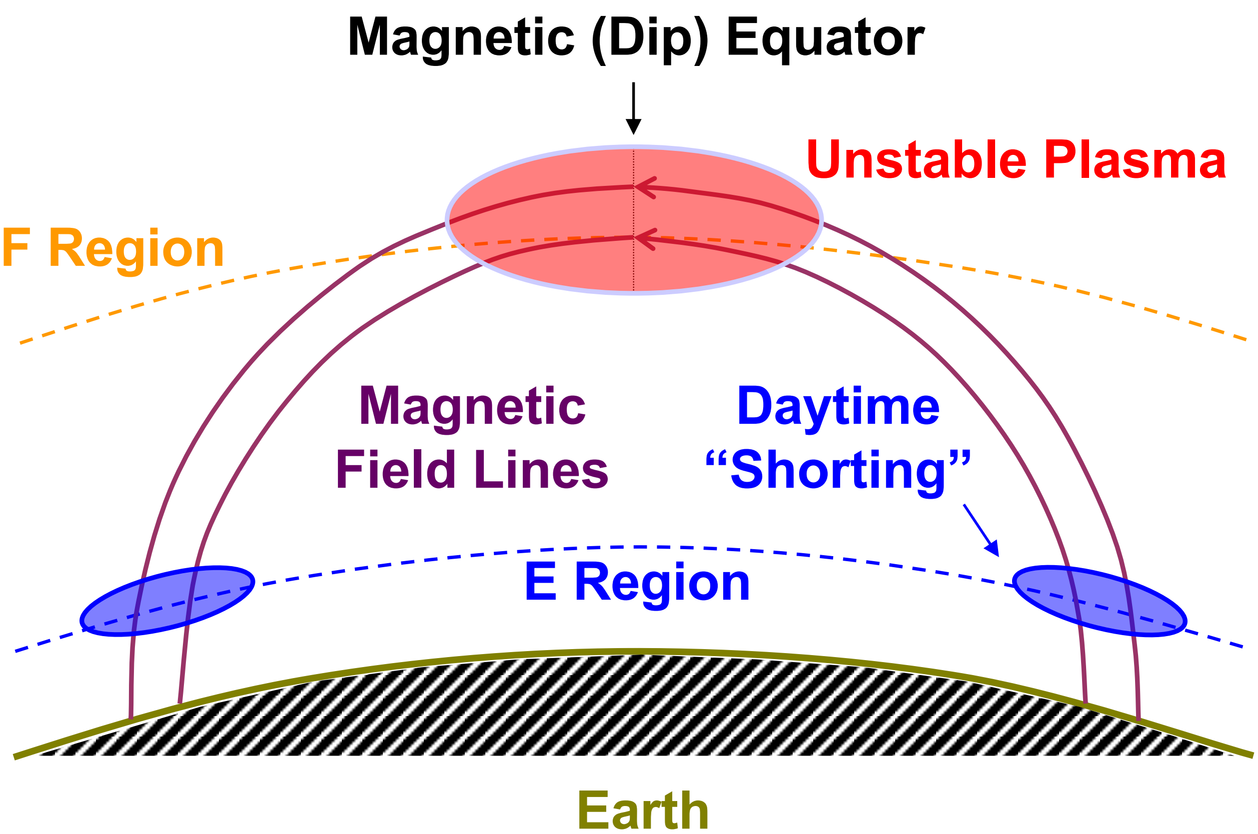
(View looking east)

Why Do Disturbances Form?

Unique Equatorial Magnetic Field Geometry

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

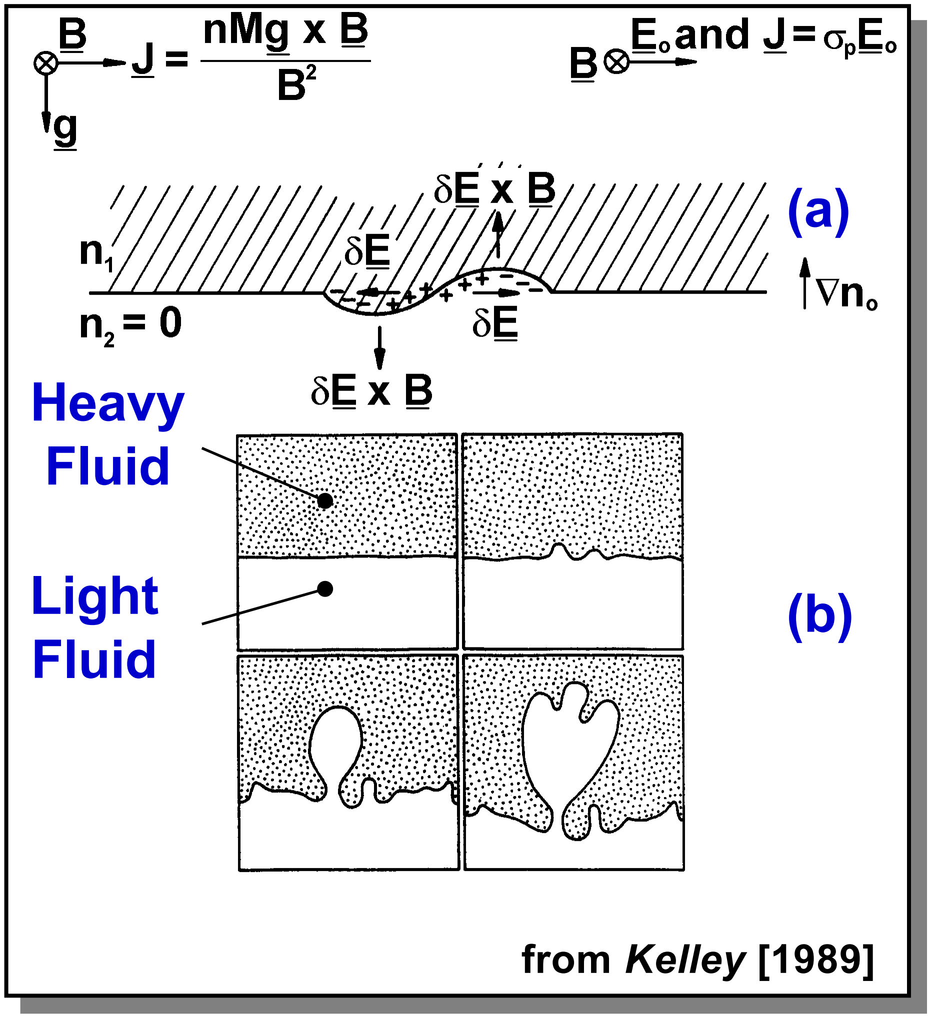
- Plasma moves easily along field lines, which act as conductors
- Horizontal field lines support plasma against gravity– unstable configuration
- E-region "shorts out" electrodynamic instability during the day



What Is Instability Process?

Basic Plasma Instability

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

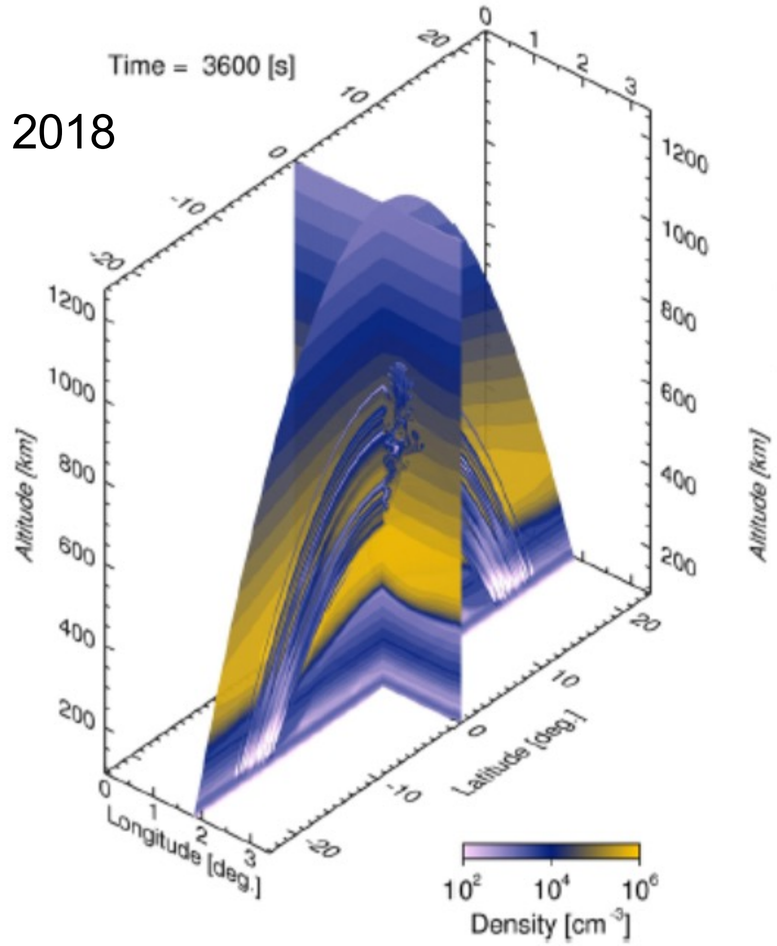


Plasma supported by horizontal field lines against gravity is unstable

- (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

Rino, et al., 2018



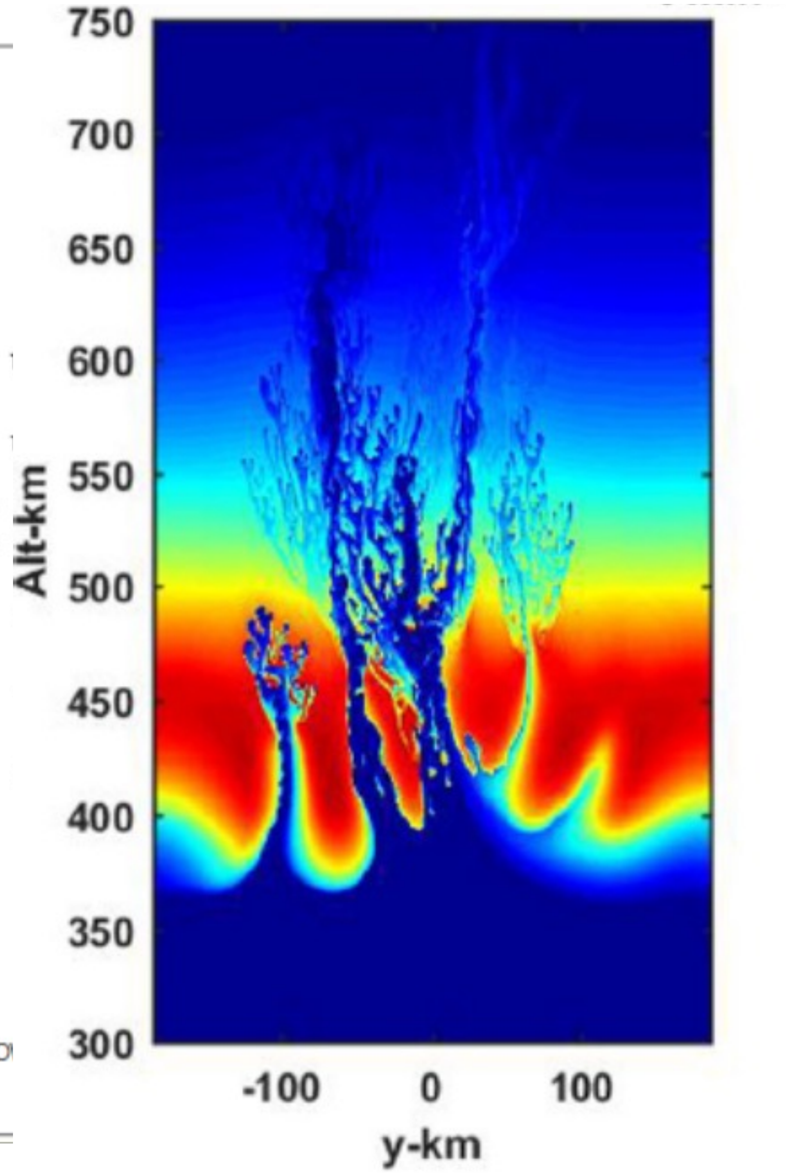


Fig. 1 Perspective view of the EPB simulation environment. The left frame sho ... ructure in two orthogonal slice planes

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

"Observables": S_4, σ_φ and ROTI

- S_4 is the standard deviation of detrended and normalized intensity fluctuations:

$$S_4^2 = \frac{<I^2> - <I>^2}{<I>^2} = \frac{1}{2\pi}\int_{-\infty}^{\infty} \Phi_I(k)dk$$

- It depends on irregularity strength and propagation geometry. Time constant of detrending filter should be long compared to Fresnel time-scale.

- σ_φ is the standard deviation of detrended and normalized phase fluctuations:

$$\sigma_\varphi^2 = <\varphi^2> - <\varphi>^2 = \frac{1}{2\pi}\int_{-\infty}^{\infty} \Phi_\varphi(k)dk$$

- Depends on irregularity strength, but also on effective scan velocity and time constant (τ_c) of the detrend filter.

- ROTI is the standard deviation of the TEC rate of change:

$$ROTI^2(\delta t) \equiv \left\langle \frac{|TEC(t+\delta t) - TEC(\delta t)|^2}{\delta t^2} \right\rangle$$

- Sampling rate (δt) and averaging interval for computing ROTI varies, but 30 sec samples averaged over 5 min is typical.

Relating Observables Through a Unified Theory

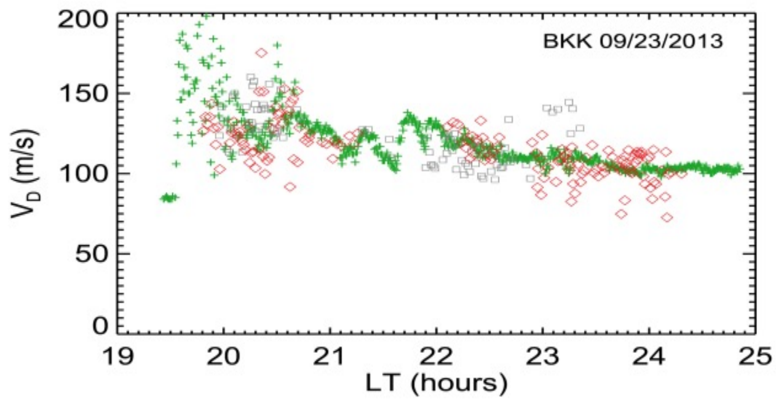
Amplitude Parameters		Phase Parameters	
Amplitude scintillation	$S_4^2 = C_p F_S(p) \wp(p) \rho_F^{p-1}$	**Phase scintillation**	$\sigma_\varphi^2 = C_p G F_\sigma(p) \left[V_{eff} \tau_c\right]^{p-1}$
Decor-relation time	$\tau_I \sim \rho_F / V_{eff}$ (weak) $\tau_I = [C_p G F_\tau(p)]^{-1(p-1)} / V_{eff}$ (strong)	**TEC rate of change index**	$ROTI^2 = C_p G F_R(p) \frac{c^2}{\delta t^2} \left[V_{eff} \delta t\right]^{p-1}$

- Phase perturbation C_p depends on irregularity strength as $C_p = r_e^2 \lambda^2 \sec\theta \left(2\pi / 1000\right)^{p+1} C_k L$
- S_4, σ_φ, and *ROTI* share same dependence on irregularity strength, any of them can measure $C_k L$.
- S_4 depends on the distance to the irregularities through the Fresnel parameter. It scales with wavelength as $S_4 \propto \lambda^{(p+3)/4}$. It saturates in very strong scatter.
- σ_φ and *ROTI* depend on the irregularity drift through the effective scan velocity. In weak scatter they are proportional to wavelength $\sigma_\varphi \propto \lambda$, and $ROTI \propto \lambda$ (and simply related to each other!)
- τ_I depends on V_{eff} in weak scatter, decreases with increasing irregularity strength in strong scatter.

Carrano et al. (2019), On the Relationship between the Rate of Change of Total Electron Content Index (ROTI), Irregularity Strength (CkL) and the Scintillation Index (S4), JGR Space Physics, doi:10.1029/2018JA026353.

Experimental Confirmation: S4 from ROTI

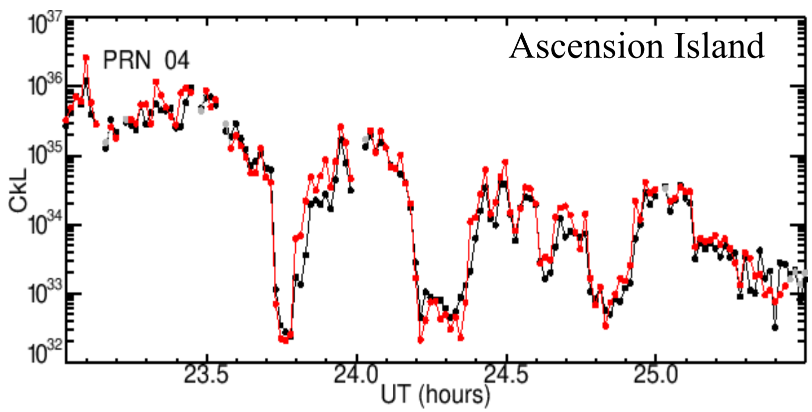
- Taking appropriate theoretical ratios of the propagation indices allows us to infer physical parameters such as drift velocity or one index can be used to deduce another.
- Measuring drift from S4 and sigma-phi (Carrano et al, 2016):



$$\frac{\sigma_\varphi^2(\delta t)}{S_4^2} = \frac{GF_3(p)}{\wp(\nu)} \cdot \left| \frac{V_{eff}}{\rho_F} \tau_c \right|^{p-1}$$

Zonal drift measured by spaced VHF antennas (green) and a single-station GPS receiver (red and gray diamonds) inferred from S4 and σ_φ measurements.

- Measuring S4 and CkL from ROTI (Carrano et al, 2019):



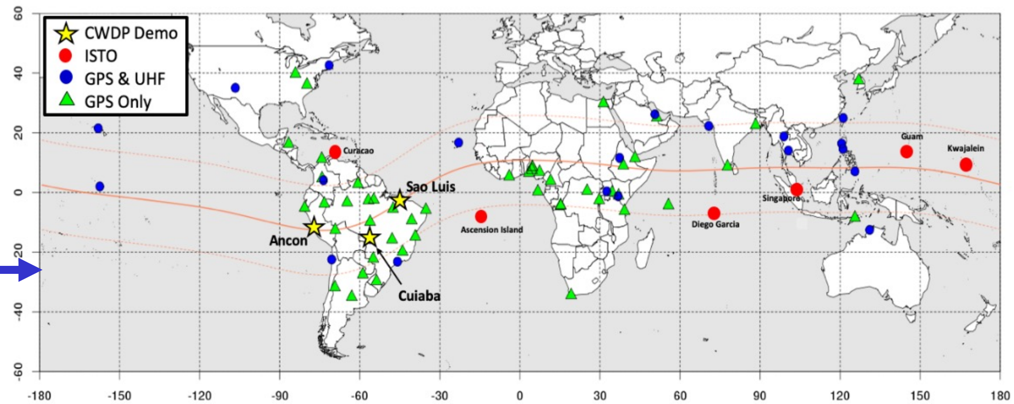
$$\frac{ROTI^2(\delta t)}{S_4^2} = \frac{c^2}{\delta t^2} \frac{GF_1(p)}{\wp(\nu)} \cdot \left| \frac{V_{eff}}{\rho_F} \delta t \right|^{p-1}$$

C_kL directly measured from 20-Hz intensity samples (black) and inferred from 1-Hz TEC data (red).

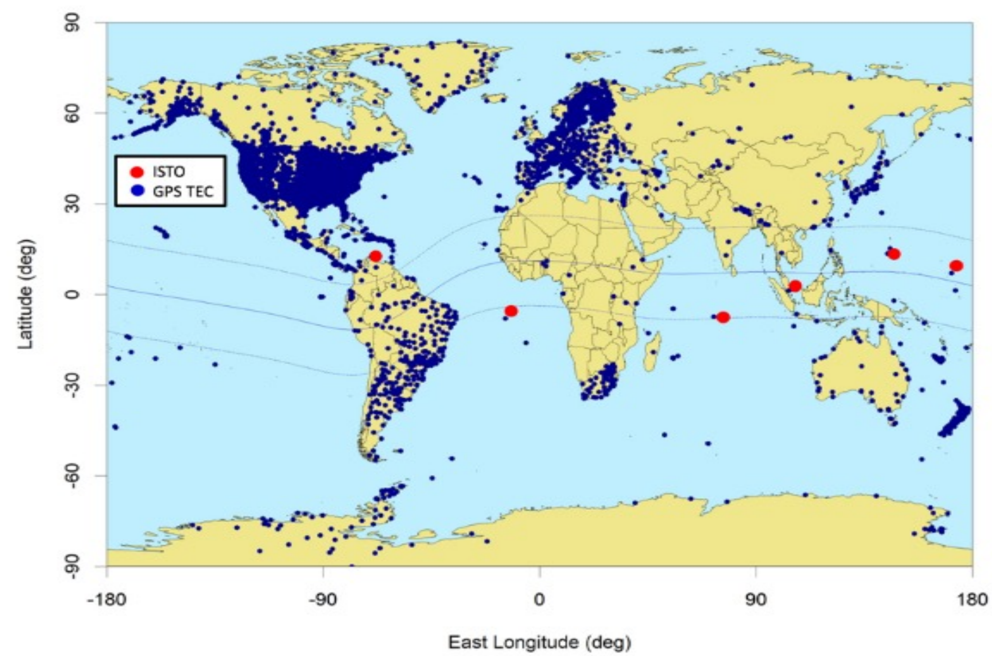
Carrano, C. S., K. M. Groves, C. L. Rino, and P. H. Doherty (2016), A Technique for Inferring Zonal Irregularity Drift from Single-Station GNSS Measurements of Intensity (S4) and Phase (σϕ) Scintillations, Radio Sci., 51, 8, 1263-1277, doi:10.1002/2015RS005864

Global Modeling Efforts

- The international research community operates a small number of specialized GNSS scintillation monitors worldwide; UHF spaced antenna drift measurements available at yellow stars, red and blue dots on the map
- Computing scintillation metrics from TEC would provide vastly more data.
- We are currently working with NOAA to leverage this idea globally, extracting quantitative estimates of S4 at latitudes and σ_φ at high latitudes from sites providing high-rate TEC.
- A reasonably good global assimilative model of the plasma drift will be needed to make this possible.
- More demonstrations on a local scale, particularly at high-latitudes, are required before implementing such an approach globally.



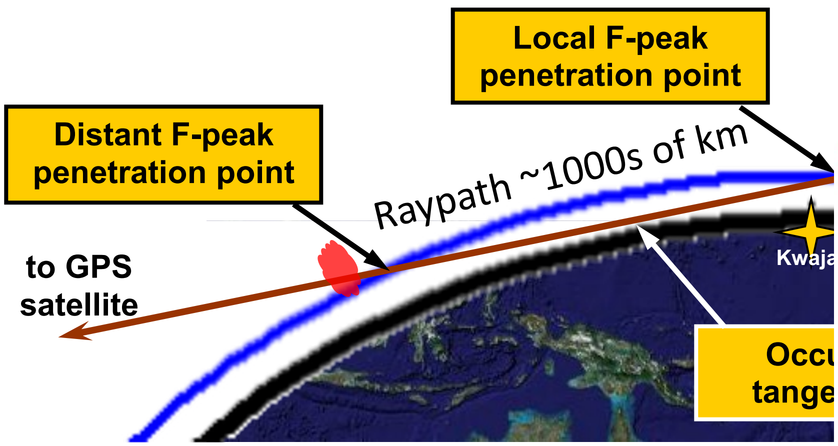
ISTO and TEC Sensor Locations

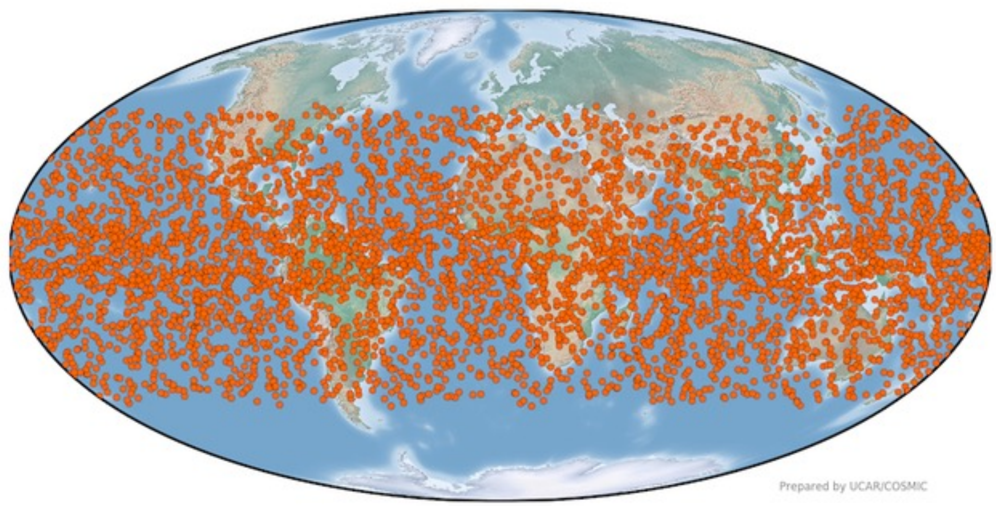


Downloadable GPS TEC sites (6000+ blue dots) and existing ISTO sites (6 red dots).

Scintillation Monitoring from Space via Radio Occultations

- Observed signal is integrated over long slant paths (1000-5000 km). Scintillation can be generated by irregularities located anywhere along the path (in principle).
- Quantitative use of data requires geolocation: determination of the location and spatial extent of the irregularities from the scintillations they produce.
- COSMIC-2 generates ~ 4,000 occultations per day covering mid- to low latitudes



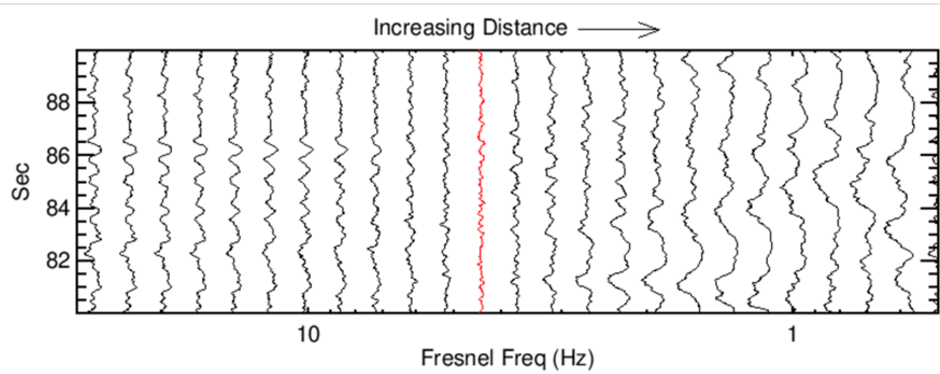


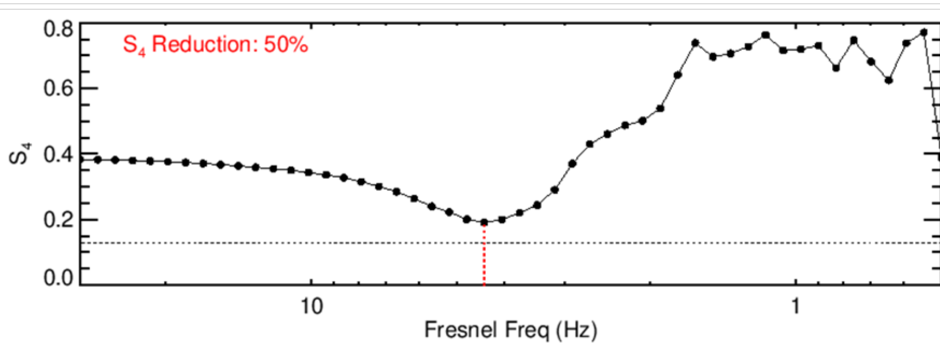
Bubble Geolocation via Back-Propagation

Unlike traditional BP algorithms, we perform back-propagation in the time domain, with Fresnel frequency as the independent variable to be measured. We use the Rino scintillation model (1979), generalized to the RO geometry, to relate Fresnel frequency to Fresnel scale, and then to distance along the ray-path to the irregularity region.

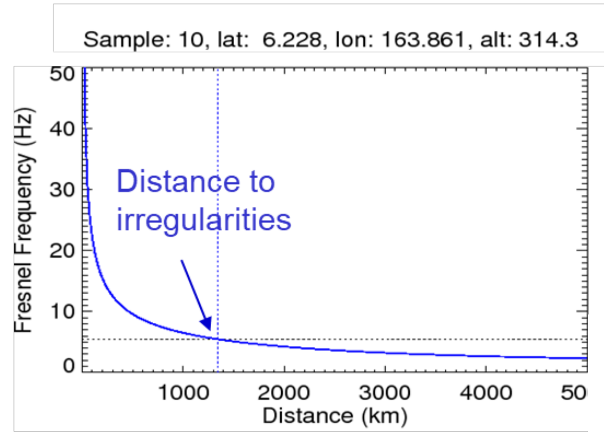
$$U_s(t) = F^{-1}\left\{\exp\left[-\tfrac{1}{2} i (2\pi f / f_F)^2\right] F\left[U_{RX}(t)\right](f)\right\}$$

1. Back-propagate complex signal in 10-sec segments to measure Fresnel frequency of the scattering.

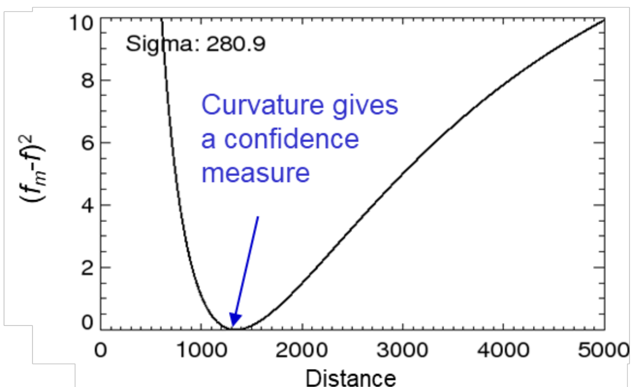




2. Geometric model provides Fresnel frequency vs distance. Intersection with measurement gives distance to irregularities.



Measured f_F



Summary

- Ionospheric irregularities are a pervasive problem in the nighttime equatorial ionosphere.
- Irregularity strength is modulated by the background density which is, in turn, controlled by the solar flux…the solar cycle determines scintillation strength!
- Scintillation intensity depends on the amplitude of the integrated density fluctuations near the Fresnel scale along the path and frequency of the radio wave (decreases with increasing frequency).
- Global irregularity knowledge facilitates specification of propagation effects on any system at any time anywhere in the world; at present we are not able to forecast the instabilities that generate irregularities, but we understand their morphology and climatology.
- The potential to exploit available ROTI observations as a quantitative proxy for scintillation indices promises to greatly expand coverage for characterizing ionospheric irregularities—*1 Hz TEC data are particularly desirable*.
- Similarly, the ability to characterize irregularities from space-based radio occultation platforms offers global 24/7 coverage; preliminary results for validating this approach appear very promising (< 200 km errors).

References

Carrano et al. (2019), On the Relationship between the Rate of Change of Total Electron Content Index (ROTI), Irregularity Strength (CkL) and the Scintillation Index (S4), JGR Space Physics, doi:10.1029/2018JA026353.

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