Ionospheric Scintillation of GNSS Signals: Impacts and Mitigation

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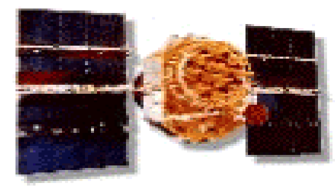
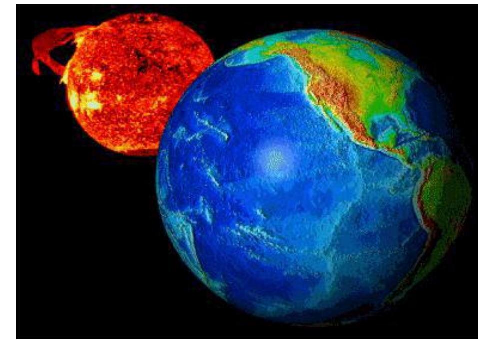
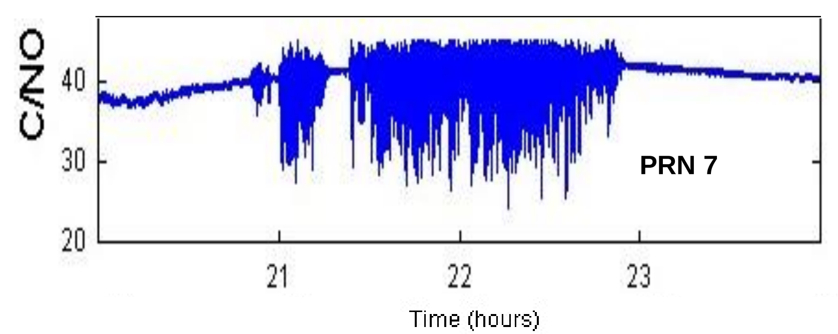
Outline



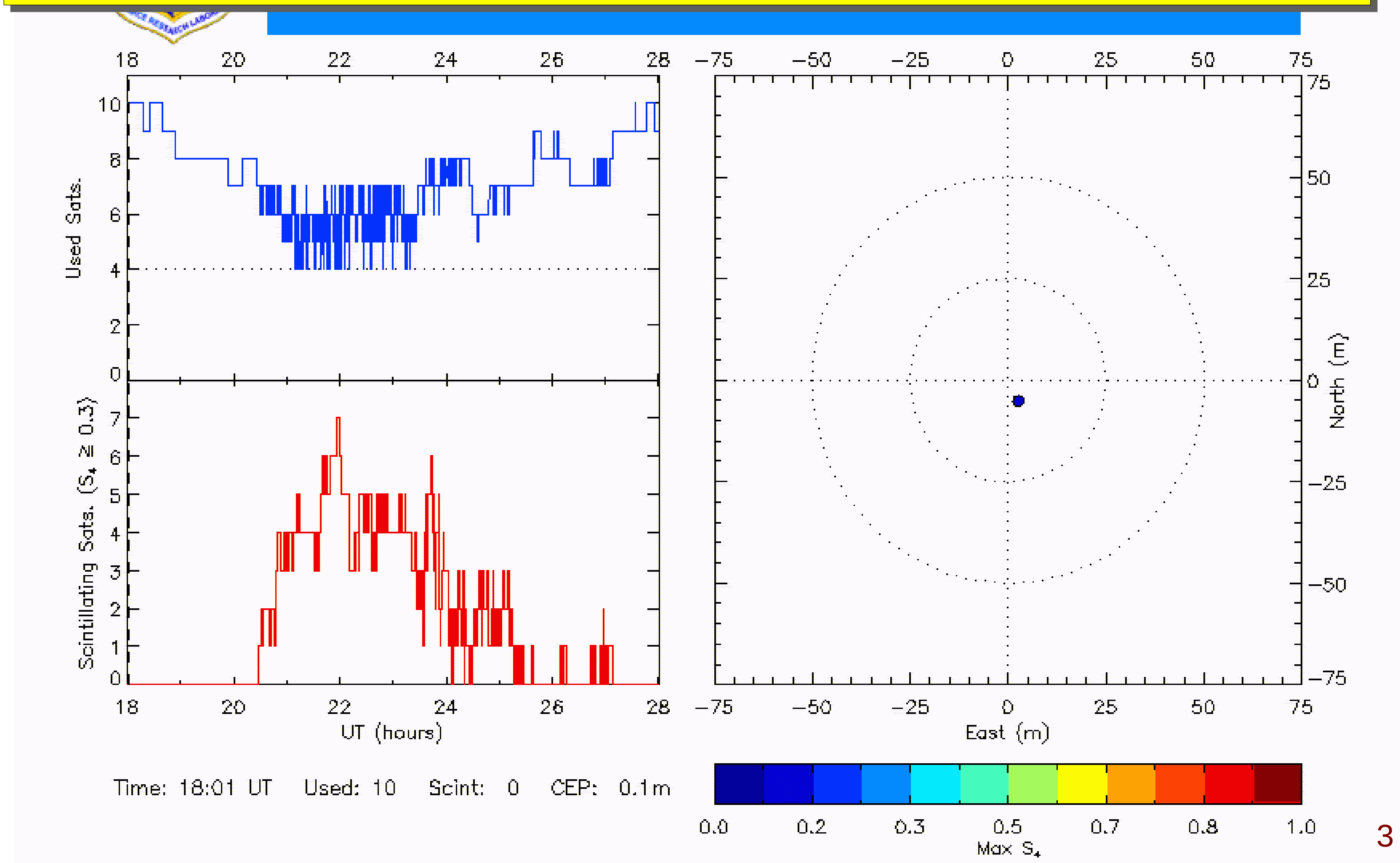
- Motivation
- Ionospheric effects on propagation
- Characteristics of equatorial irregularities
- Mitigation
- Conclusions





GPS Positioning Errors During Solar Max

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



The Ionosphere is a Small Perturbation for GNSS

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

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

$$f_p \approx 10\ MHz$$

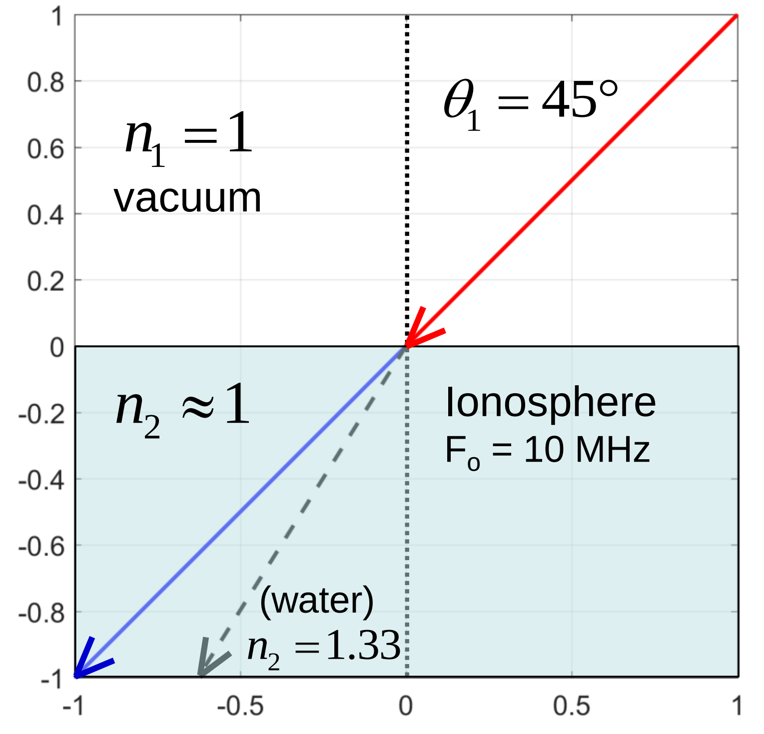
$$f = 1575 MHz$$

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

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!

Scintillation Physics Simple Picture

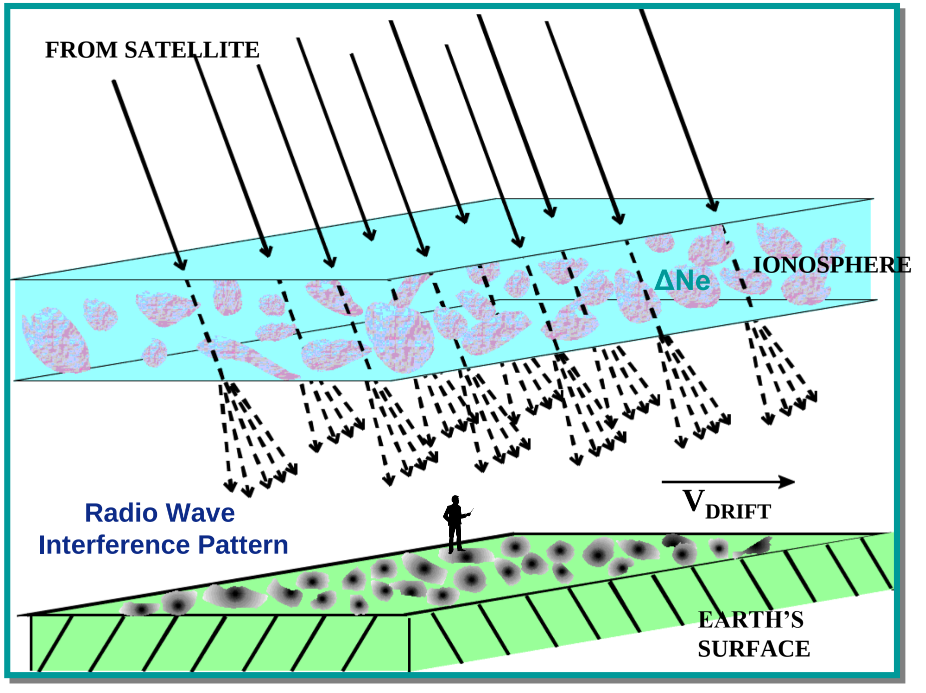
$$\tau_d = R/c + \frac{r_e c}{2\pi}\frac{N_{tot}}{f^2}$$

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

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

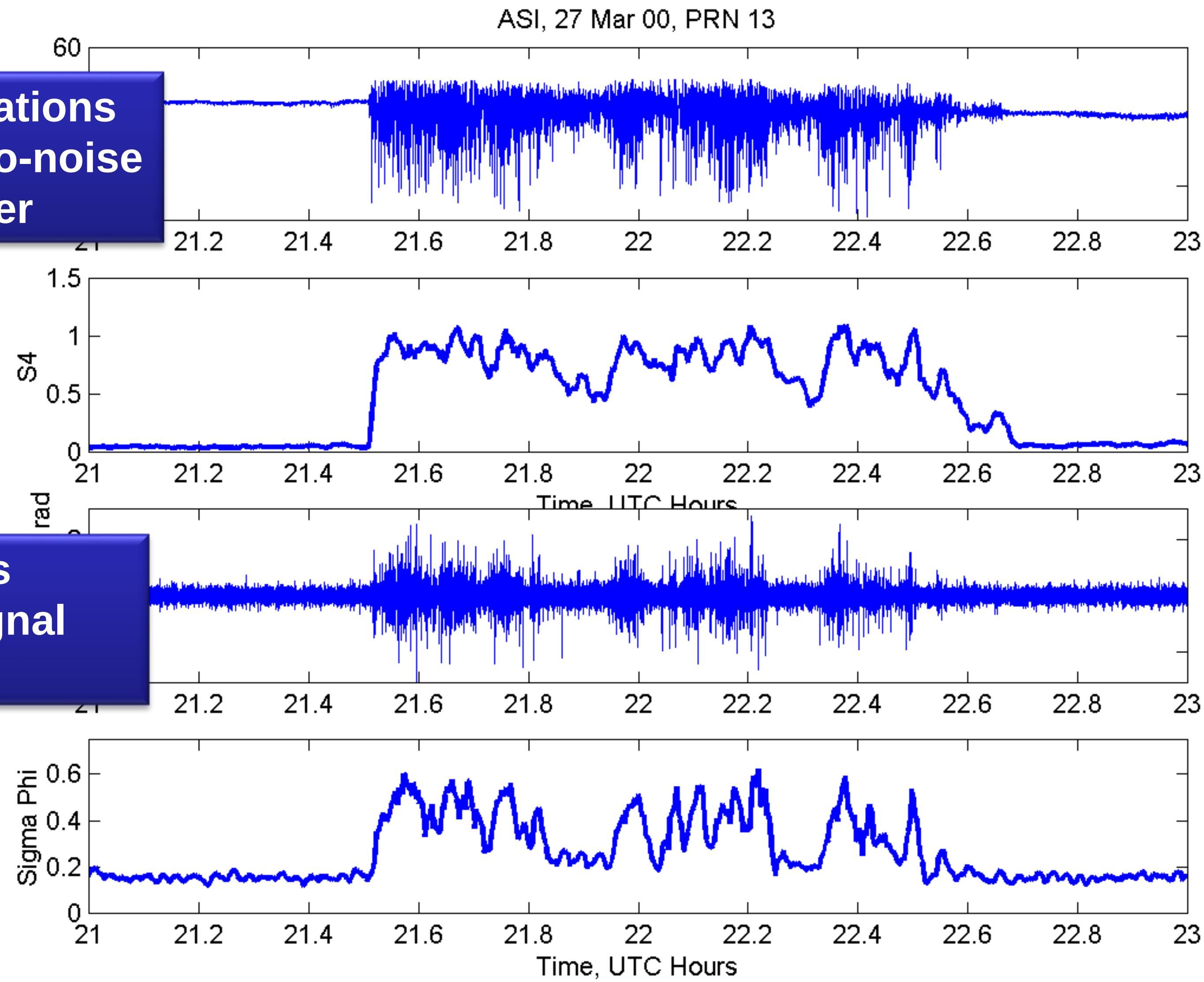
Phase change due to ionized layer

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



- 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, the Fresnel zone, $F_r = \sqrt{2\lambda z}$, ~ 400-500 meters for L1 and typical iono parameters

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

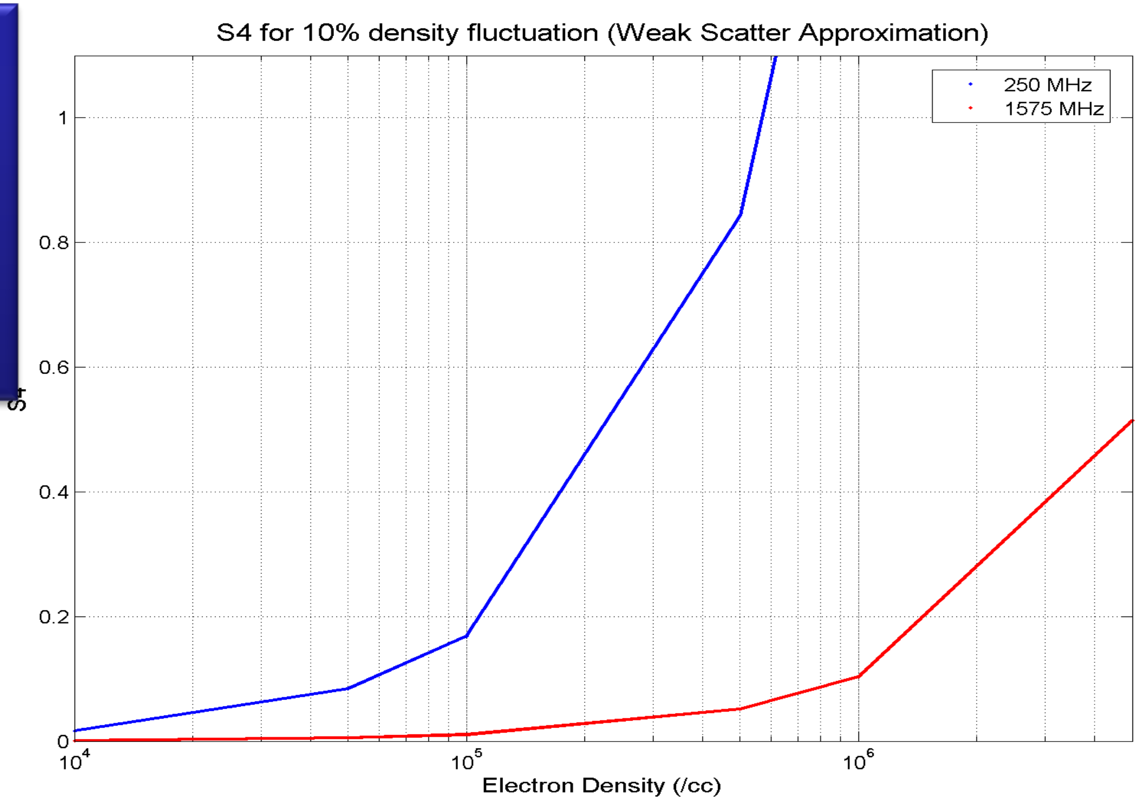
σ_ϕ : st. dev. of phase

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 ~1e5/cc for VHF, ~1e6 for GNSS (~50 TEC units)



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

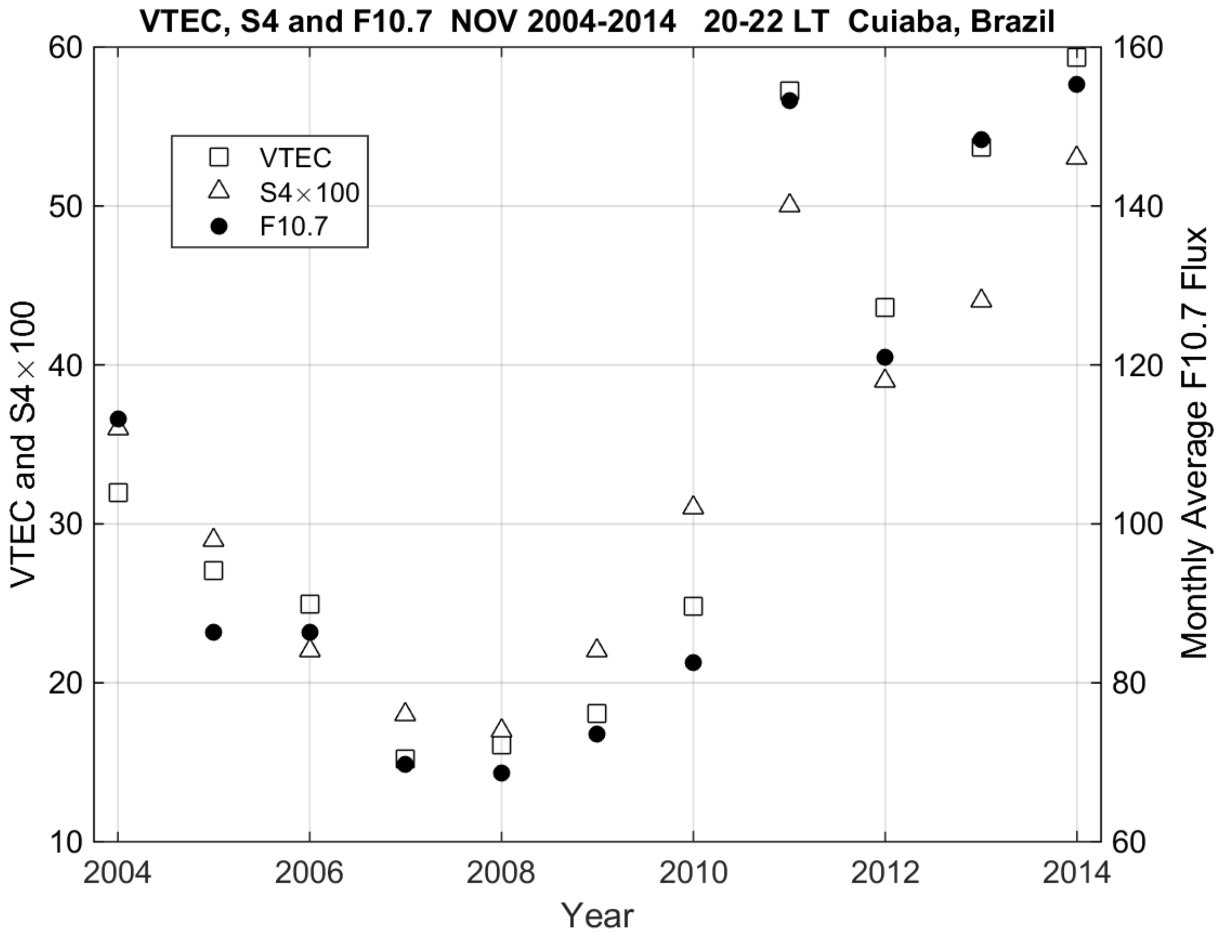
Weak Scatter Approximation

Implications for the Ionosphere

Recall 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

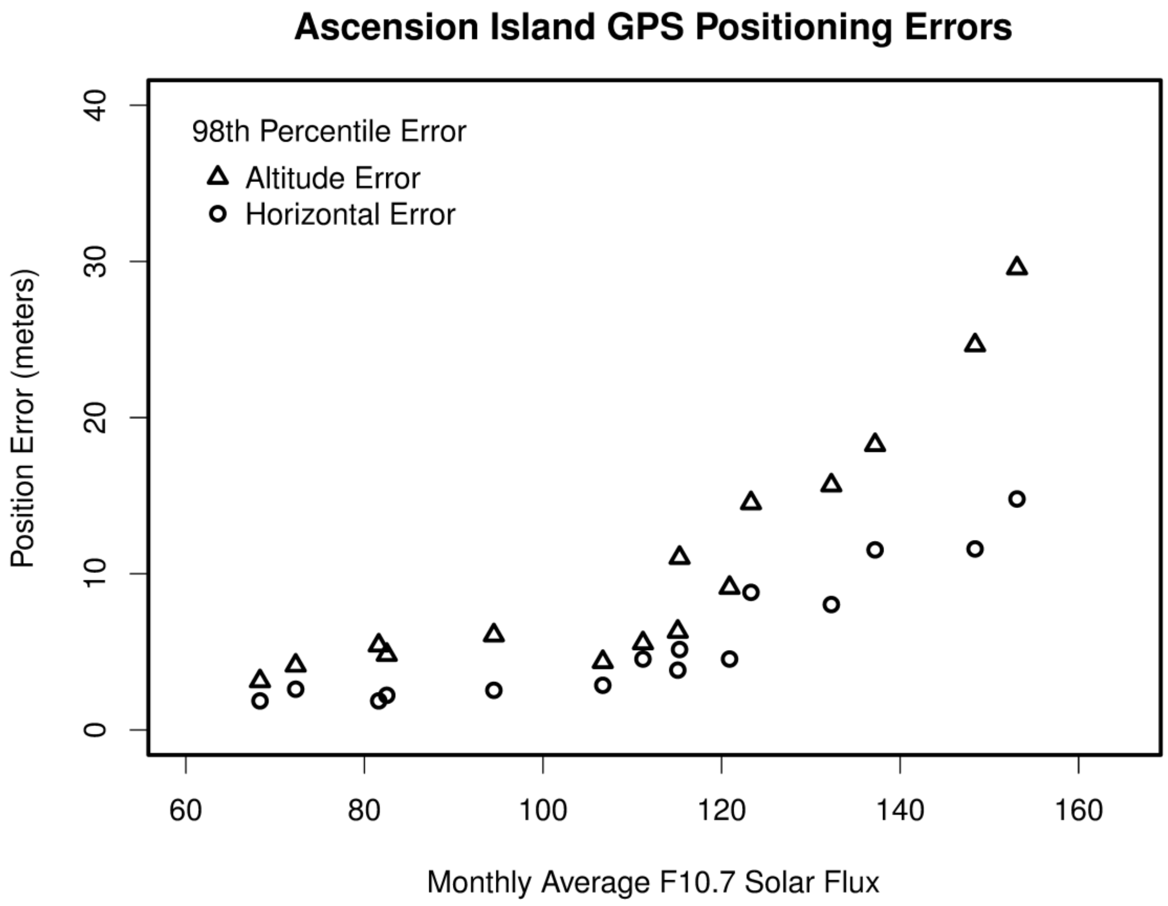
- Solar max TEC ~ 50-100
  - Small relative density fluctuations required (1-2%)
- Solar min TEC ~ 1-5 (nighttime)
  - Large relative density fluctuations required (10-50%)
- Consistent with expectations, GPS scintillations are generally weak during solar minimum
- Scintillation impacts on GPS are limited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

Solar Flux, Density & S4



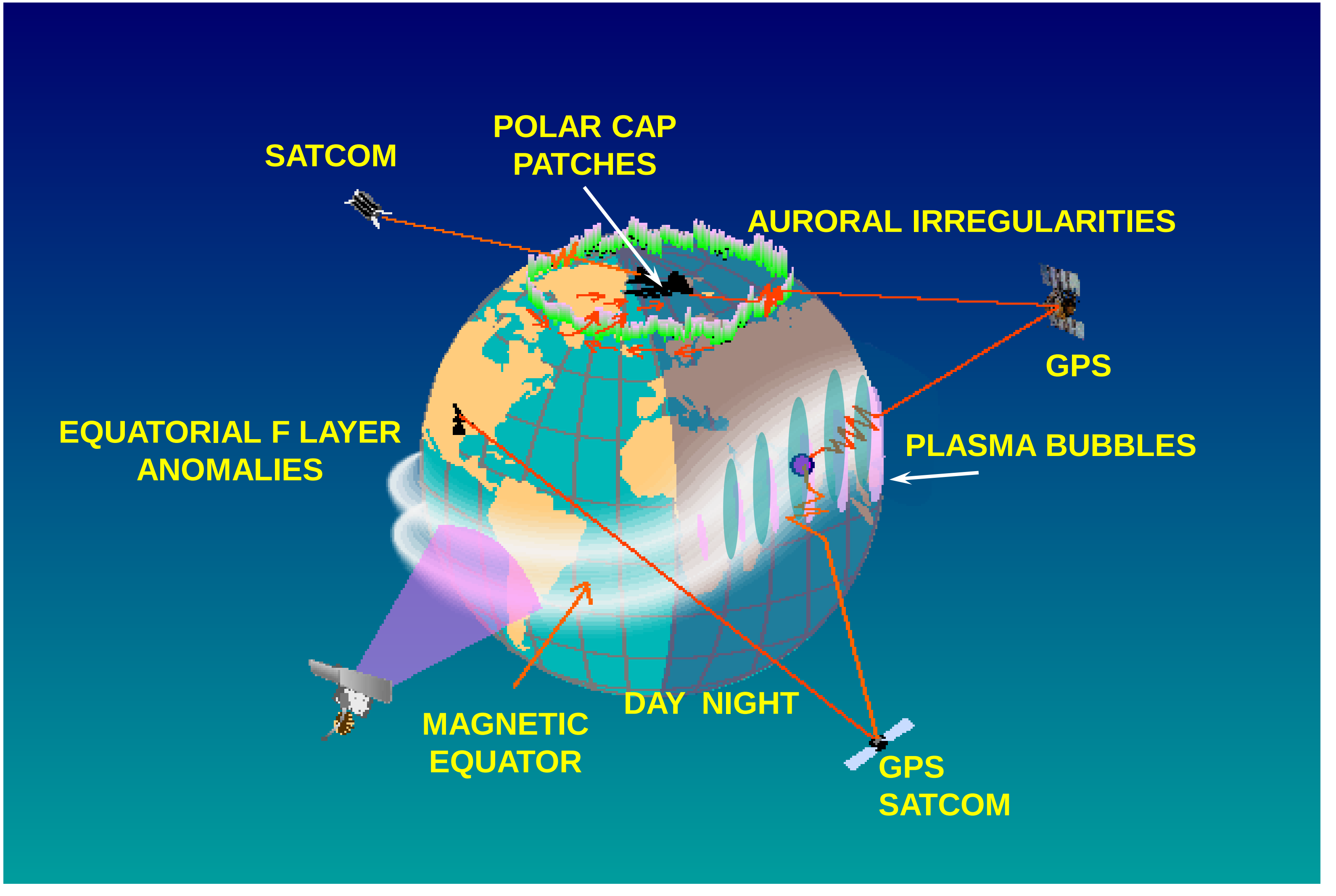
Solar flux determines electron density which determines S4

Solar Flux & Positioning Errors



Solar flux controls S4 which controls impact on GNSS performance

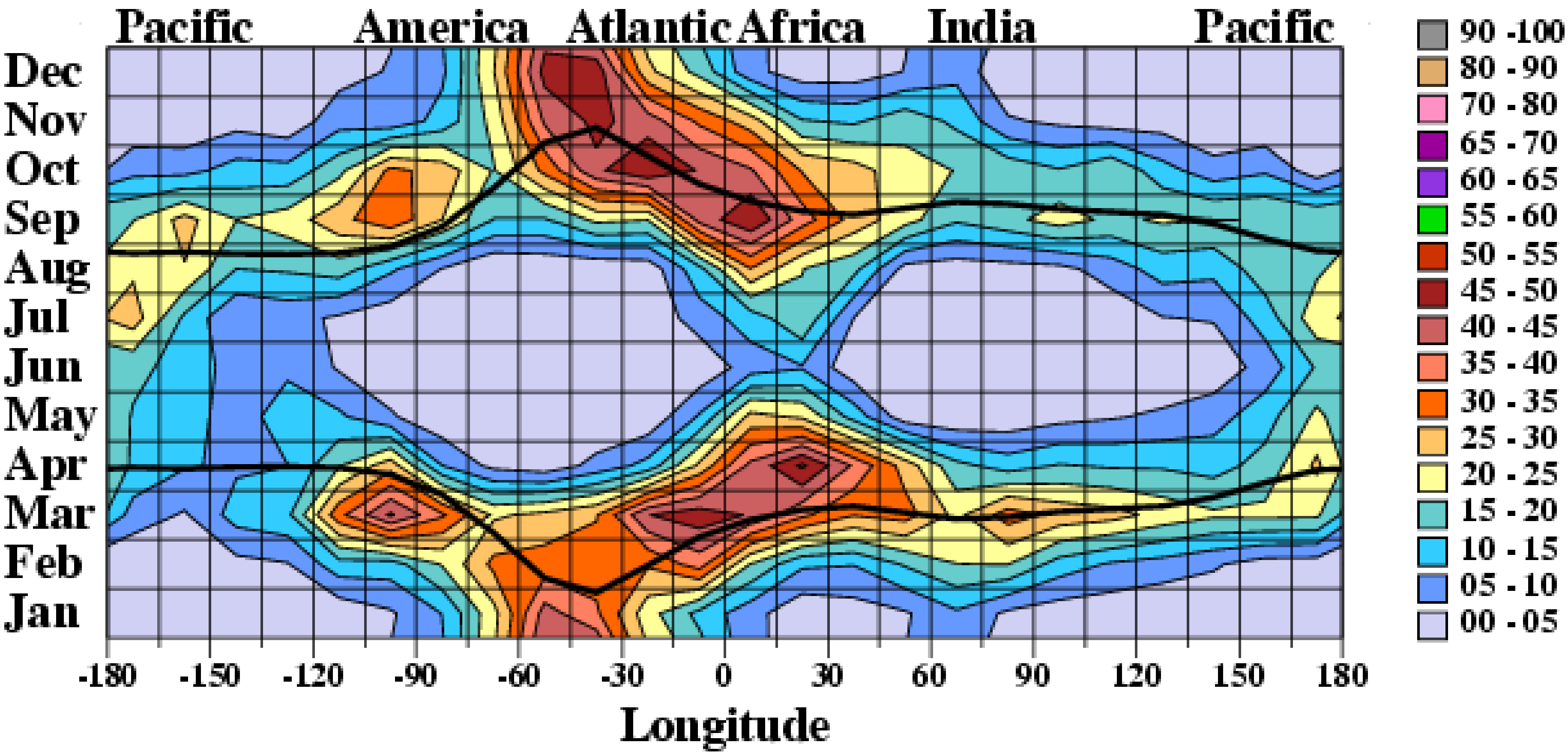
Disturbed Ionospheric Regions and Systems Affected by Scintillation



DMSP Satellite Observations:
Bubble Detection 1999 - 2002

In situ irregularities detection statistics
800 km circular polar orbit

800 km Occurrence Climatology

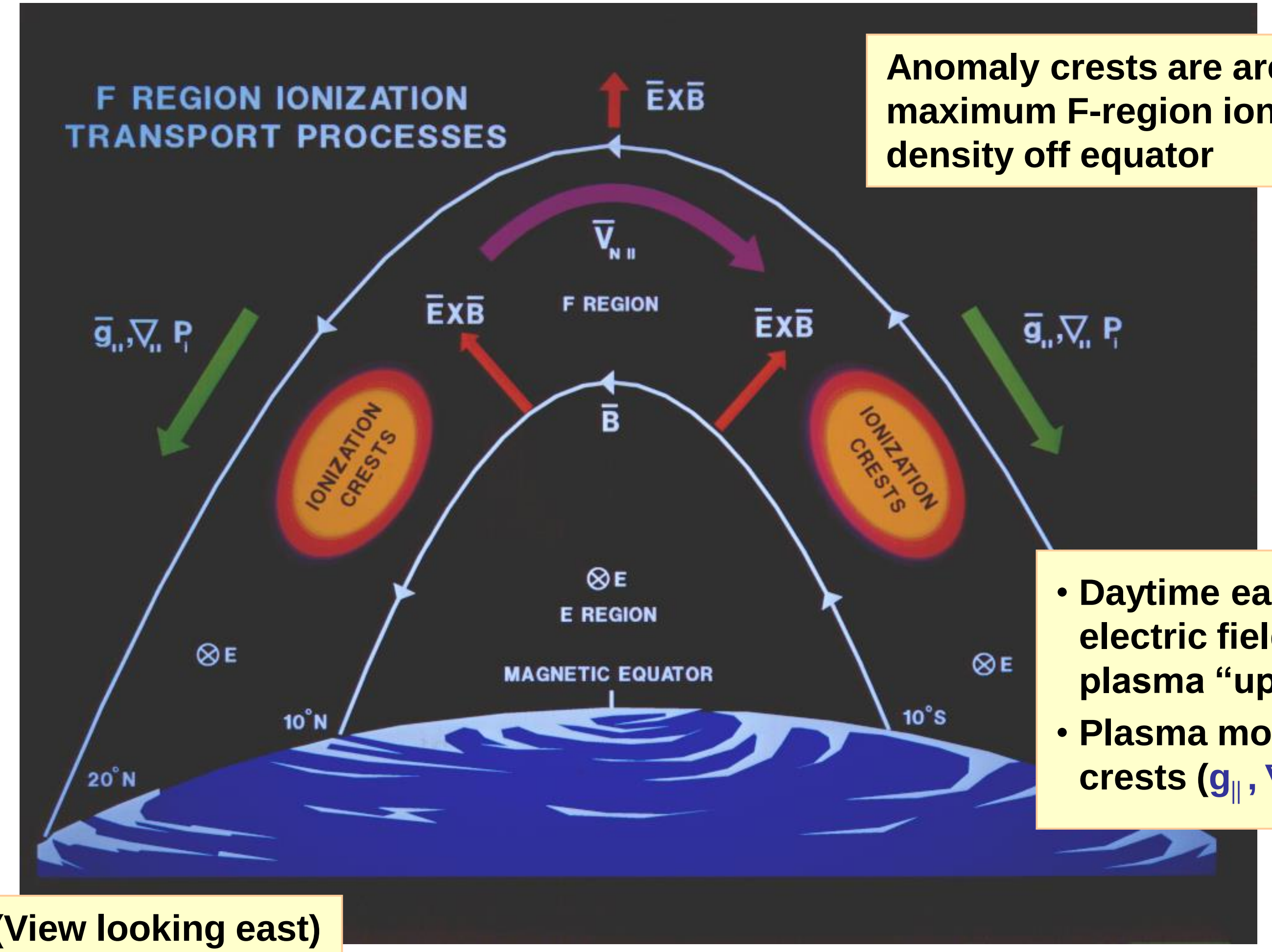


From Burke & Huang [2004]

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

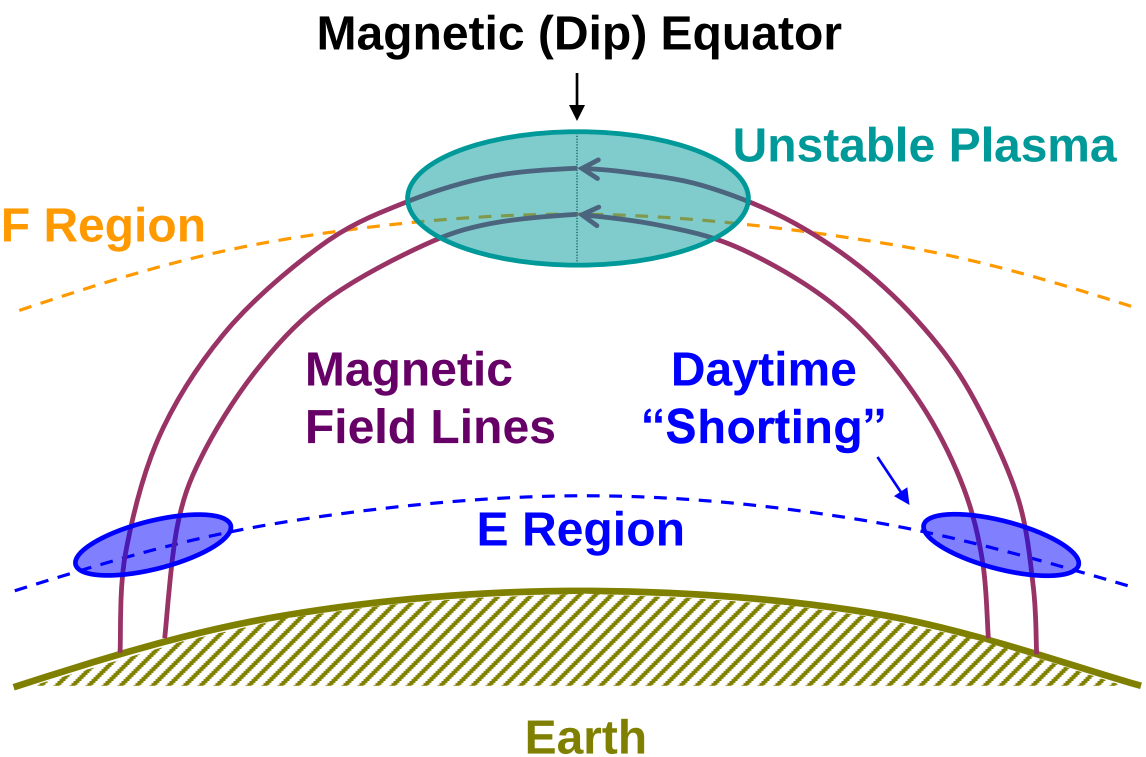
- **Daytime eastward electric field (E) drives plasma "up" (E × B)**
- **Plasma moves toward crests ($g_{\|}$, $\nabla_{\|}P_{\|}$)**

(View looking east)

Why Do Disturbances Form?

Unique Equatorial Magnetic Field Geometry

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

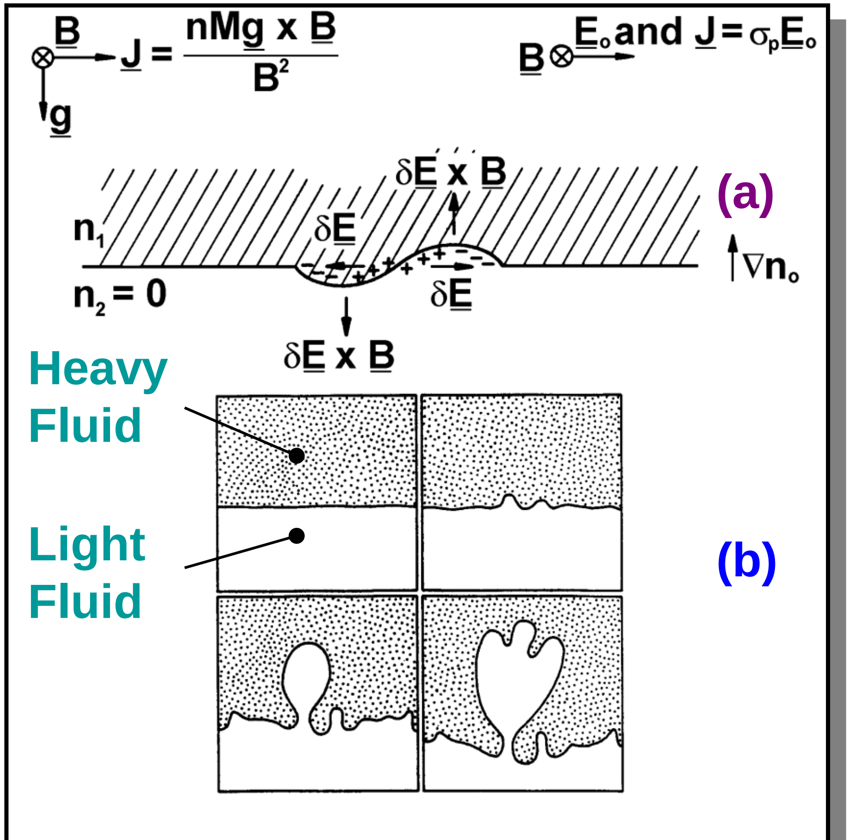


- Plasma moves easily along field lines, which act as conductors
- Horizontal field lines support plasma against gravity– unstable configuration
- E-region "shorts out" electrodynamic instability during the day

What Is Instability Process?

Basic Plasma Instability

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



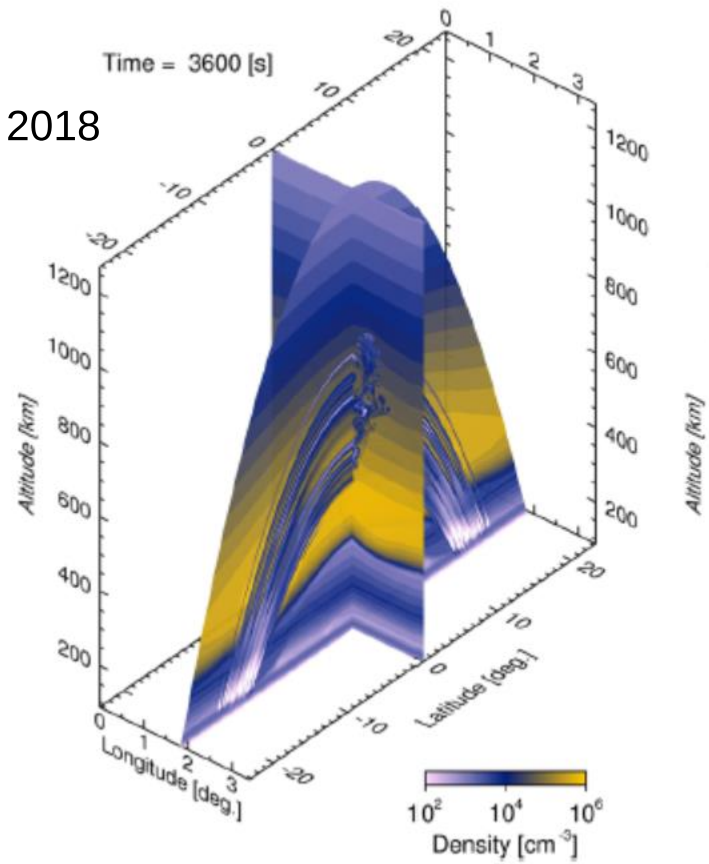
from *Kelley* [1989]

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

Rino, et al., 2018



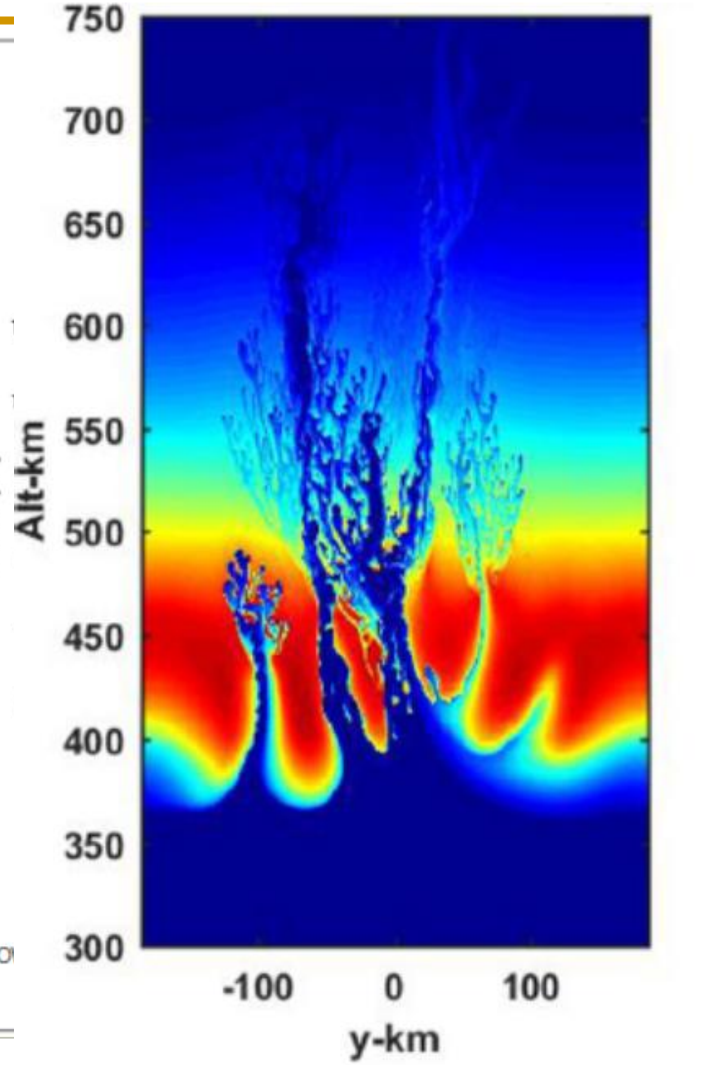


Fig. 1 Perspective view of the EPB simulation environment. The left frame sho ... ructure in two orthogonal slice planes

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

Determining Satellite Availability with S4

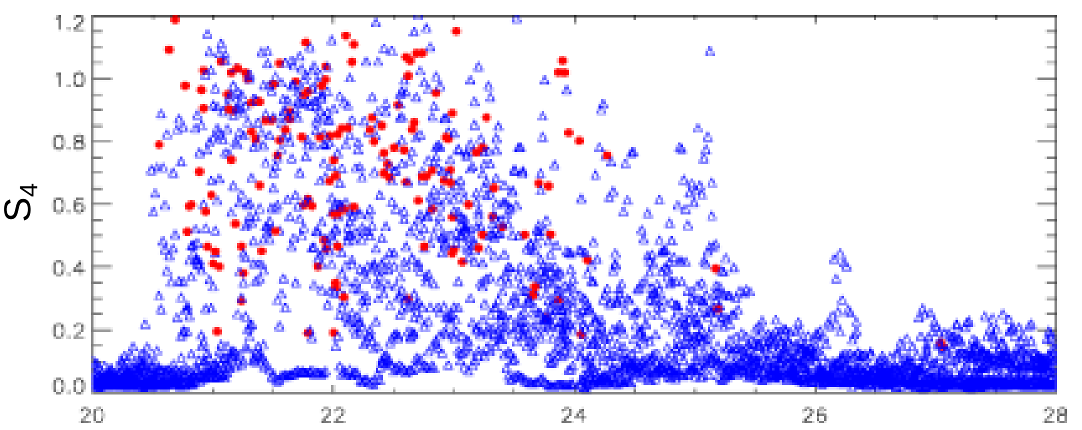
Performance will be receiver dependent

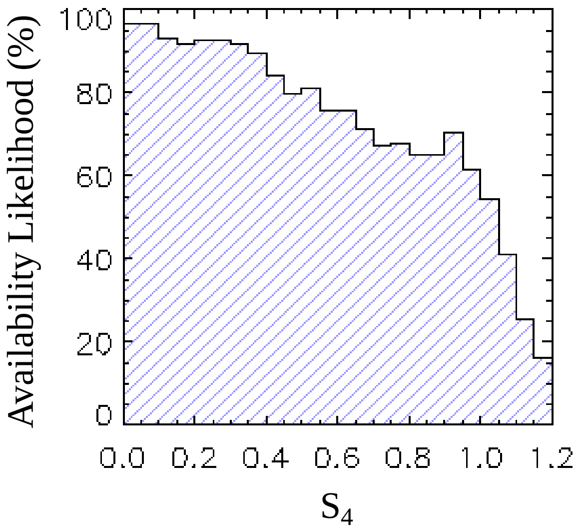
Example:

blue = used in NAV

red = not available (corresponds to spike in DOP)

16 Mar 2002, ASI



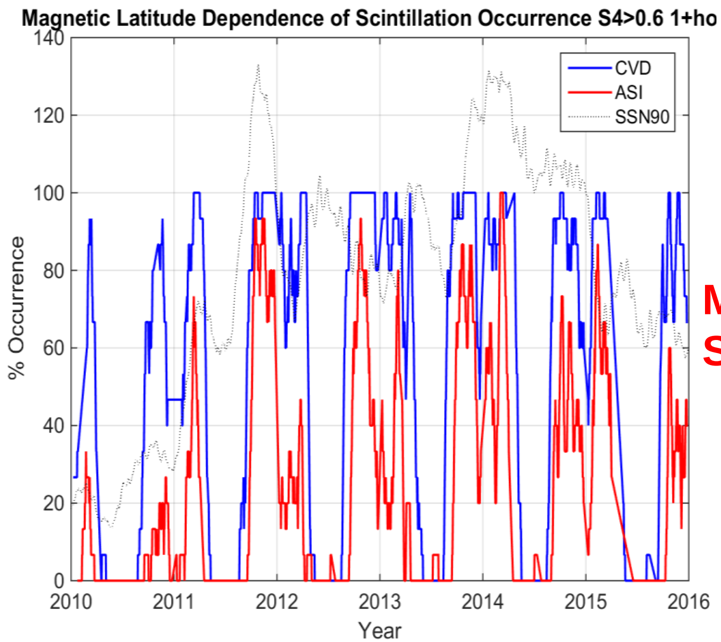


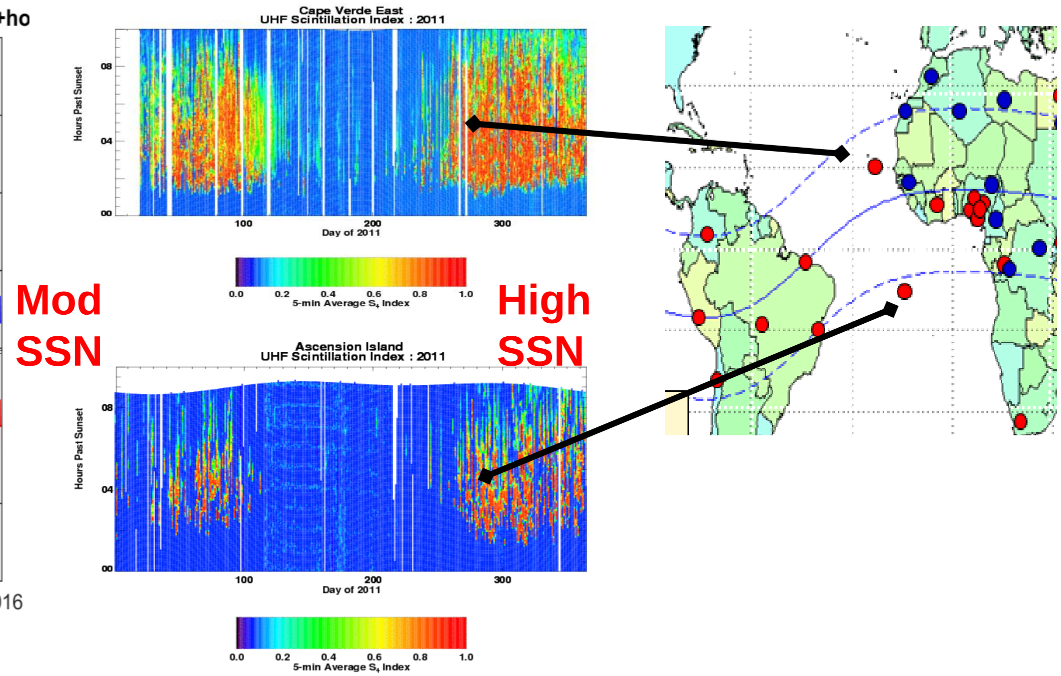
As expected, the probability that a satellite will be available decreases as scintillation intensity increases, but there is no simple S4 threshold for losing lock

Best metric might depend on receiver's “failure mode”

- If phase fluctuations tend to break the phase lock loop (PLL), use σ_φ
- Other parameters (e.g., decorrelation time) should also be considered

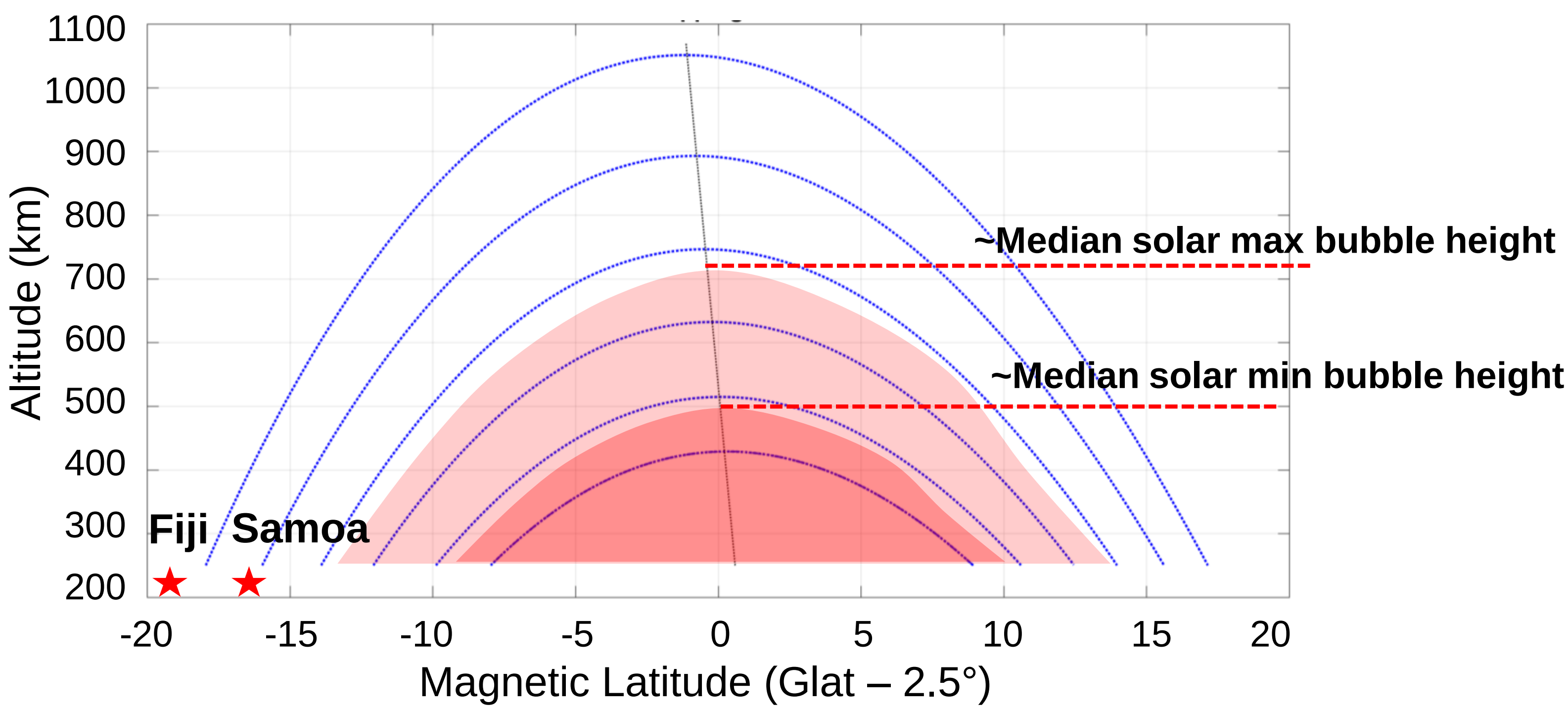
Scintillation Occurrence & Apex Altitude





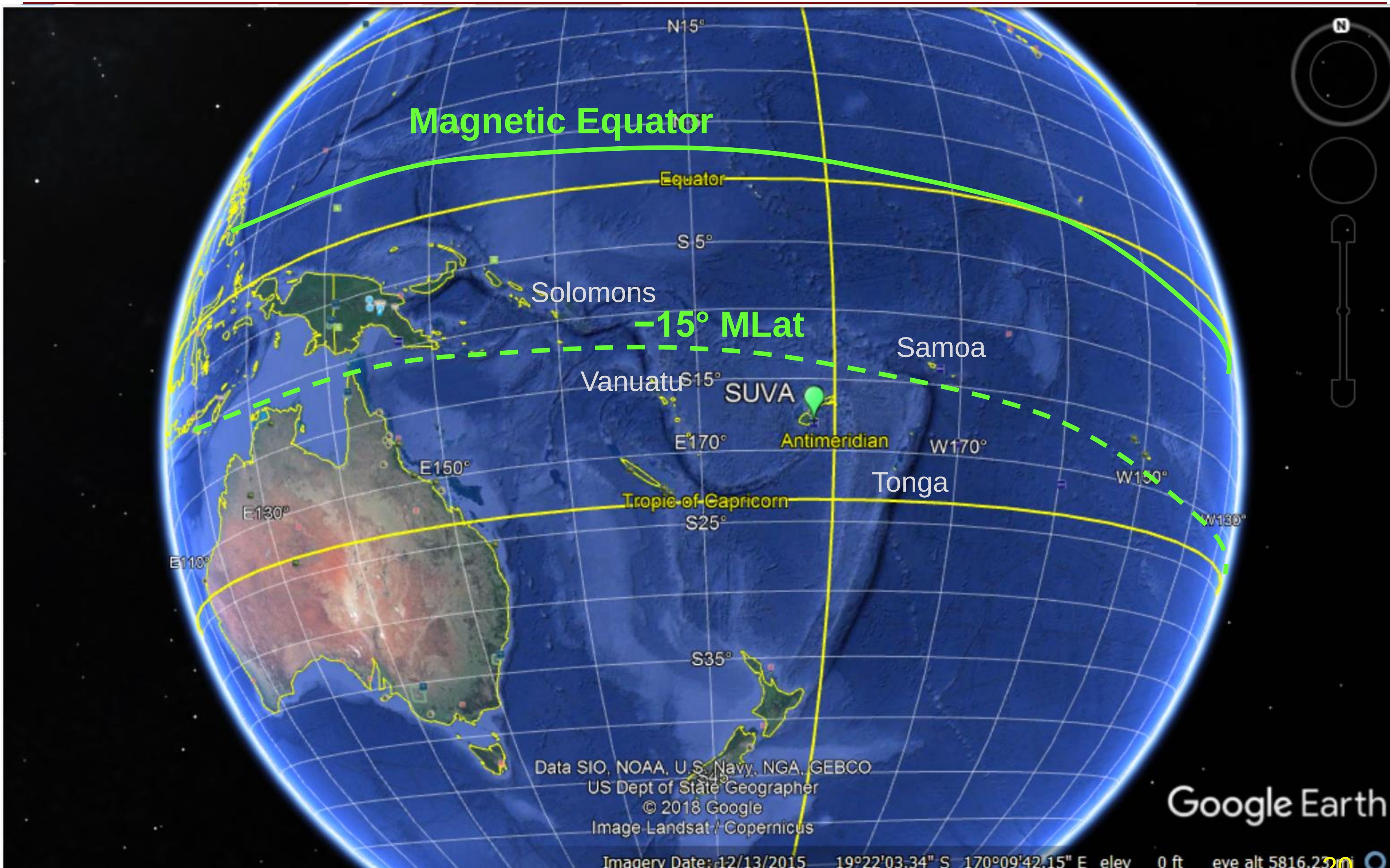
- Ground-based VHF measurements show that scintillation occurrence at Ascension Island (18°S maglat) reached 50-80% during the peak seasons between 2011-2015
- Assuming bubble height determines meridional extent, structures must rise to over 1000 km to reach Ascension, but only about 400 km to reach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

Apex Height vs Latitude: South Pacific



- Site (magnetic) latitude determines what activity will be visible as a function of solar flux
- Implications for South Pacific Island Nations:
  - Further from the equator: Less frequent activity but intense
  - Closer to the equator: More frequent and more moderate

South Pacific Magnetic Latitude Geography

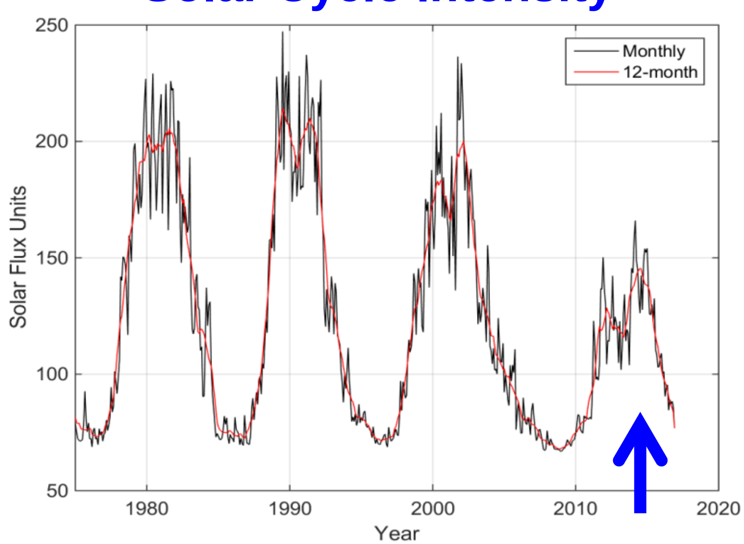


GPS Positioning Errors from Space Weather

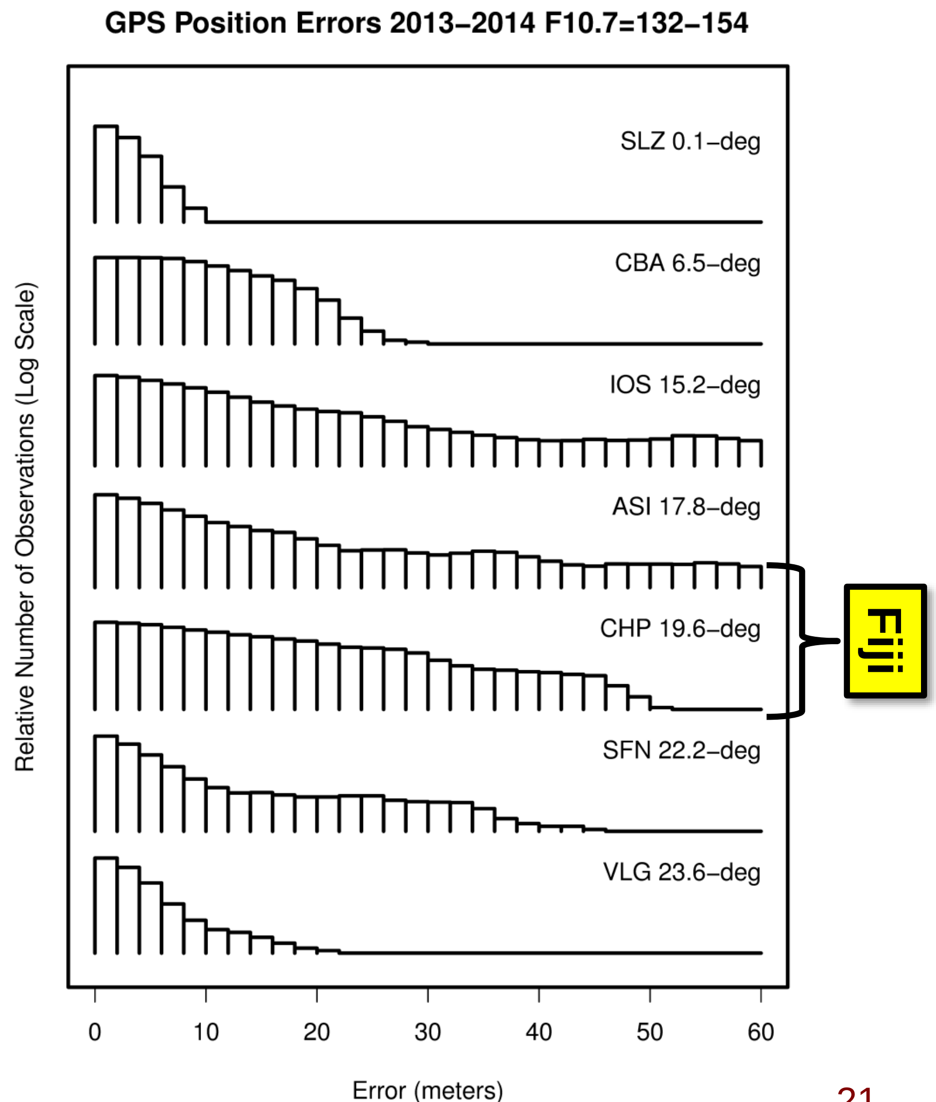
Magnetic Latitude Dependence

- Night time positioning errors from 2013-2014 in South America
- Largest errors occur 15-20 degrees from magnetic equator (~Fiji / Samoa)

Solar Cycle Intensity



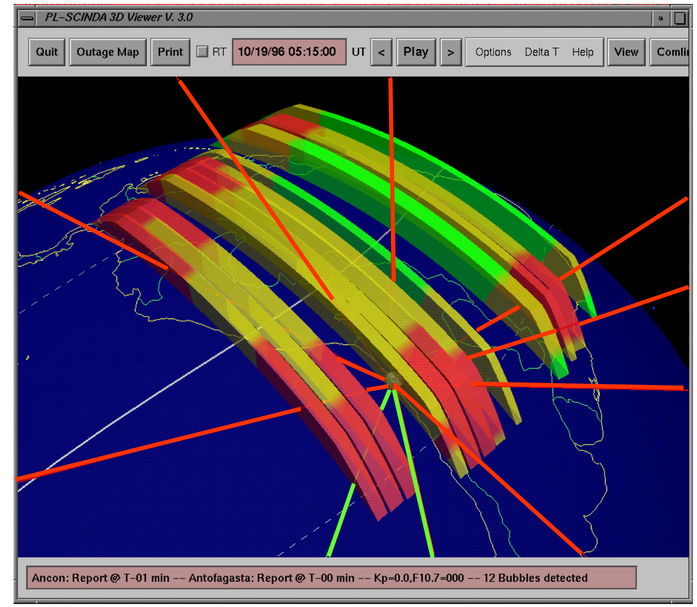
Data Collection Period



Assessing Impacts on GNSS Performance

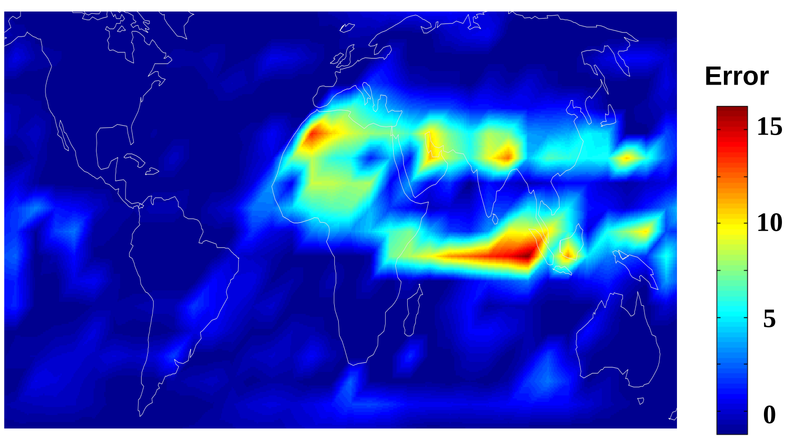
L-Band Impacts at Solar Maximum

Multiple GNSS-ground links will be affected simultaneously



Ionospheric Disturbance Visualization

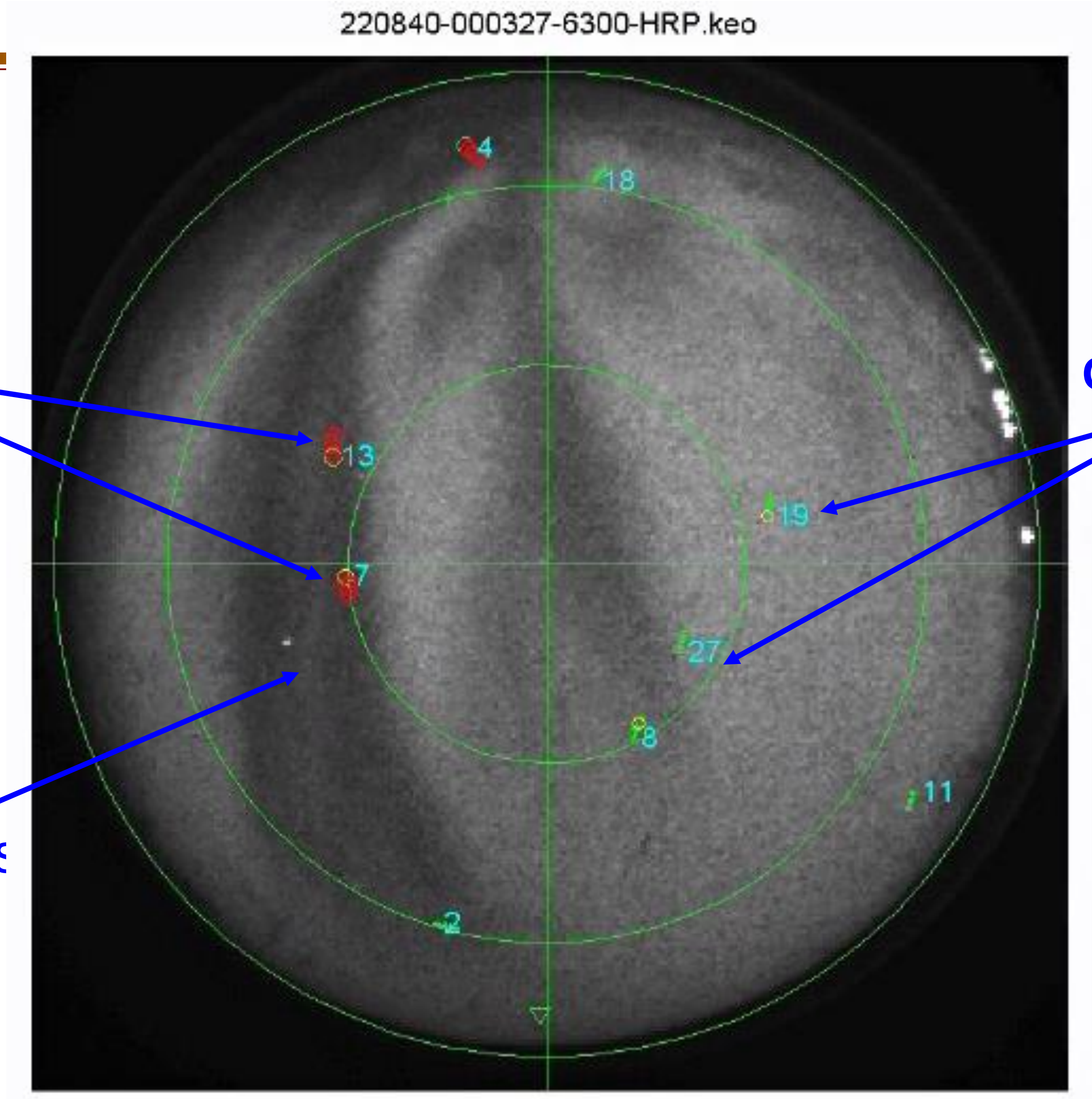
Objective to produce multi-frequency GNSS position error maps



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

At present, we don't know threshold of pain for most GNSS receivers

6300 Å All-sky Imagery



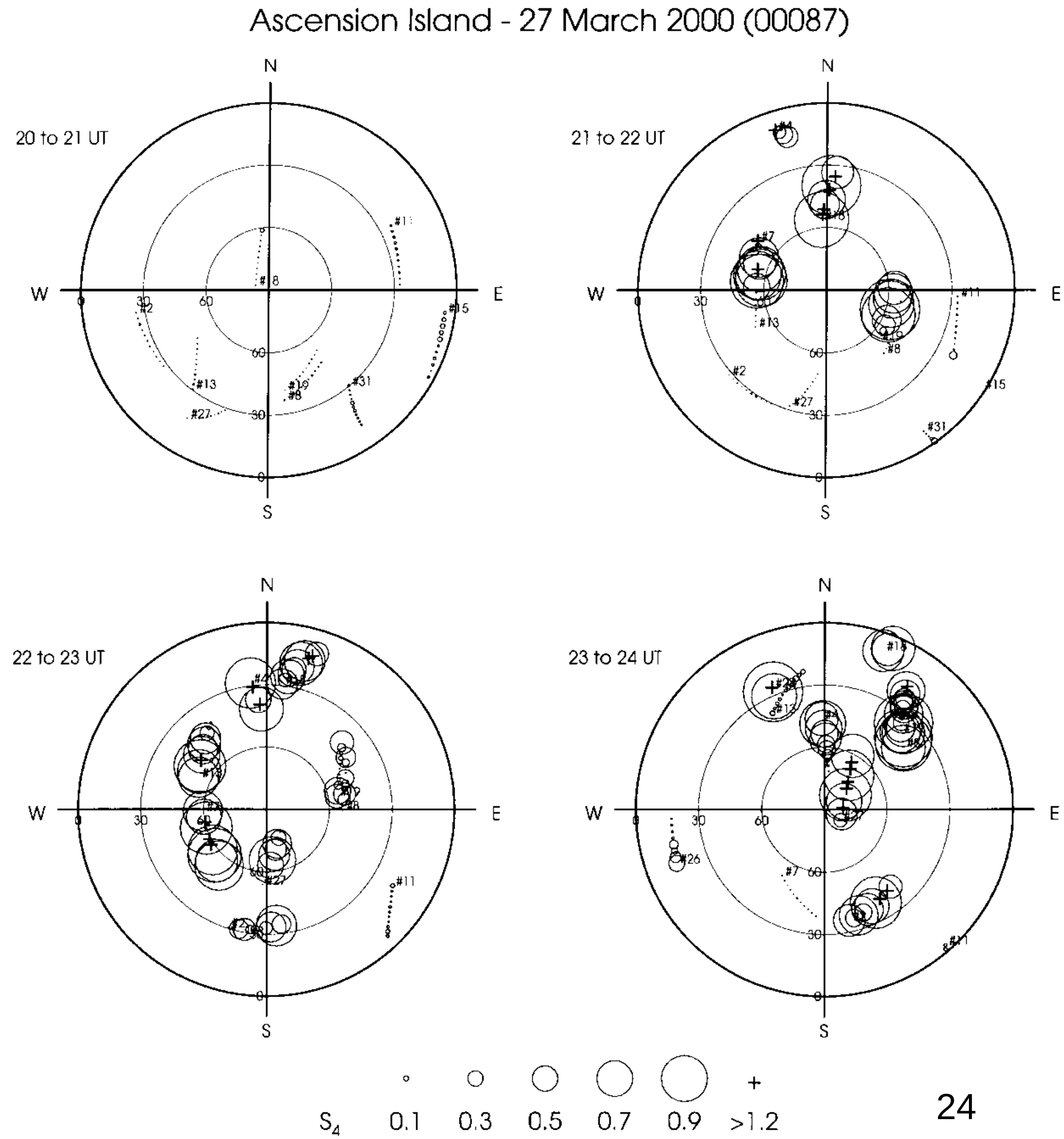
Scintillating GPS SATS

GPS SATS

Turbulent Depletions

GNSS as a Mitigation Strategy

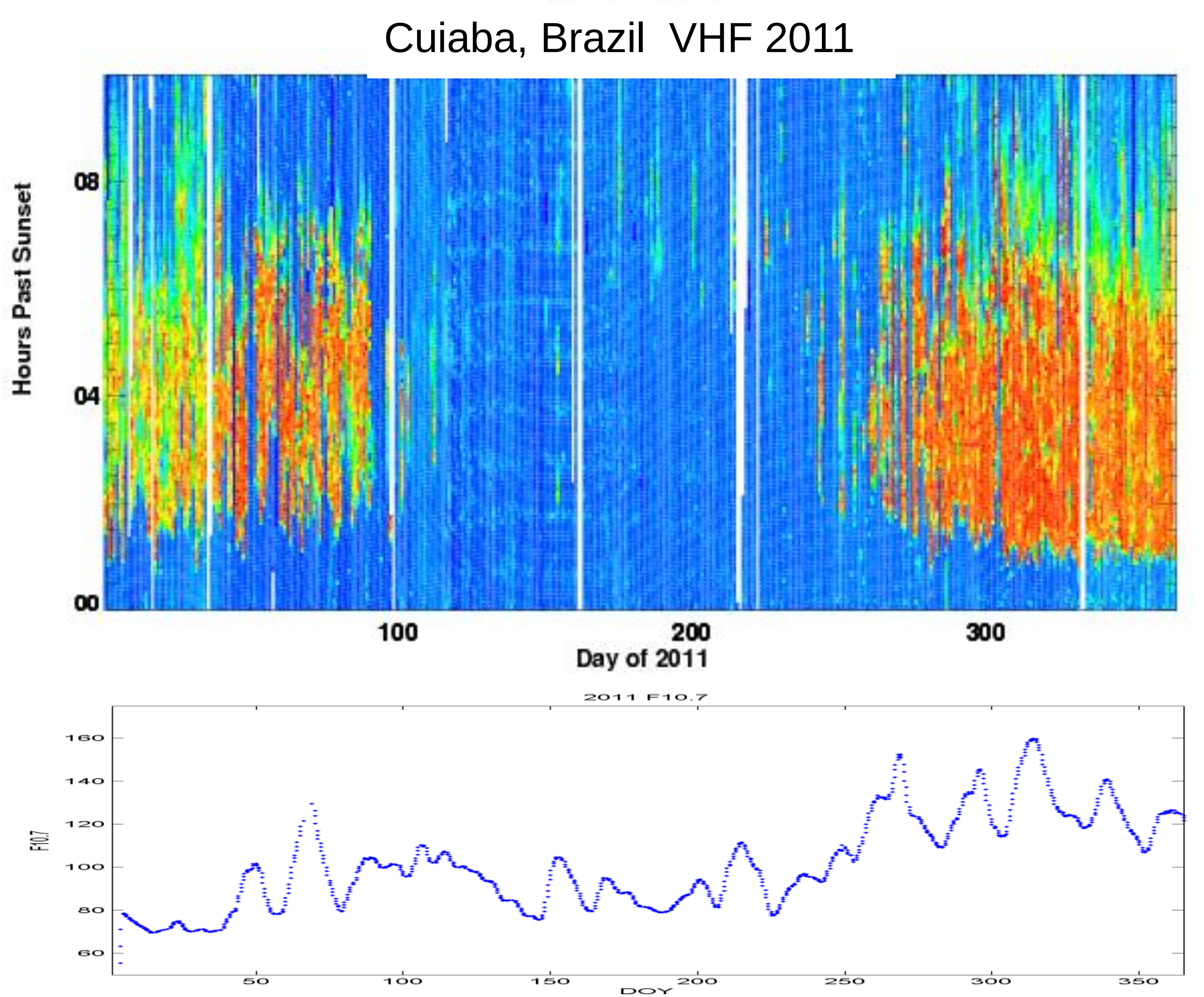
- Transition to true GNSS will improve performance, but maybe not in a linear way
- Large sectors of the sky are often blocked, so DOP will still be impacted
- Fewer periods when less than four satellites are available (inability to navigate)



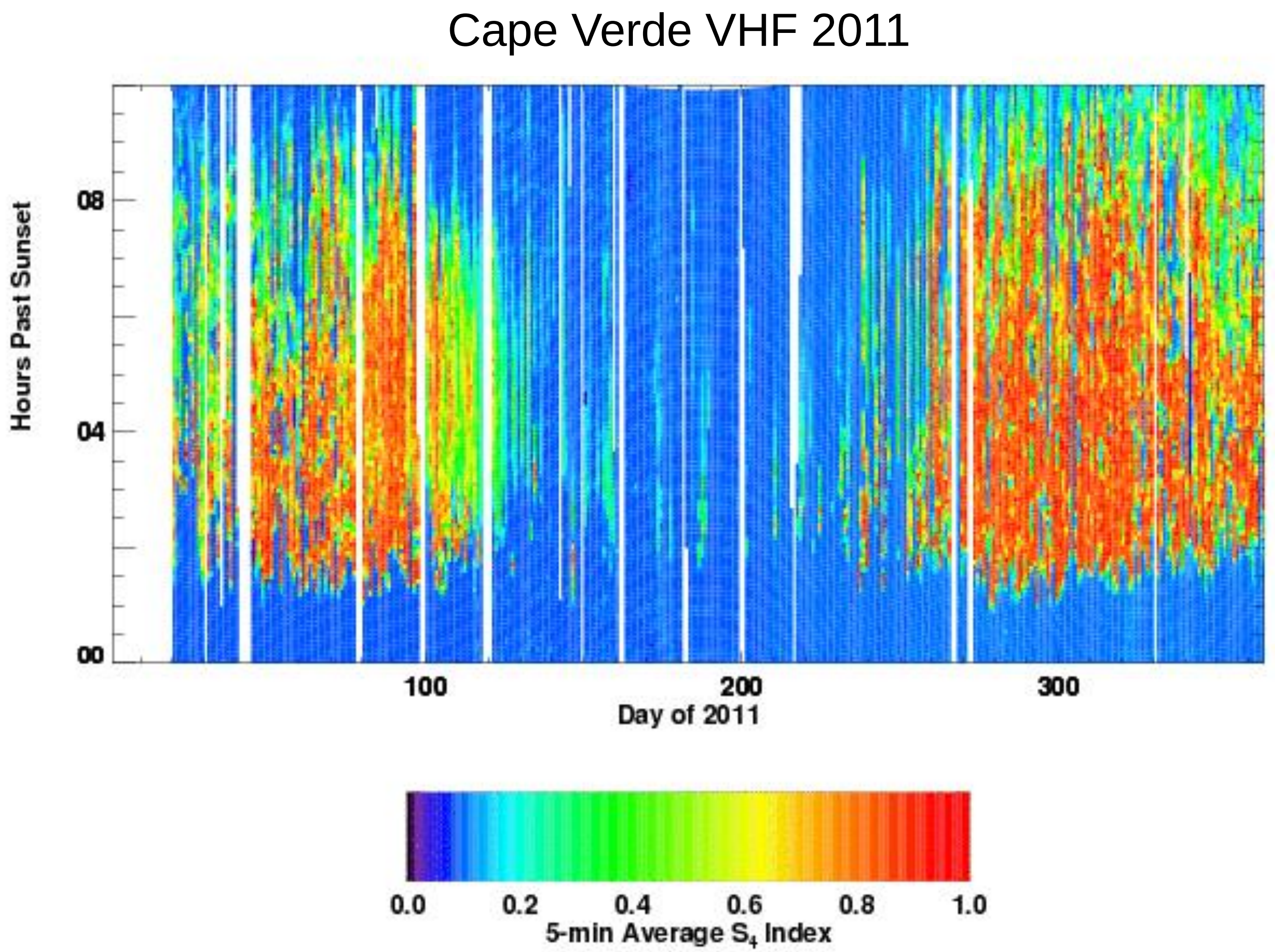
Longitudinal Variability

Examine 250 MHz scintillation observations from three separate longitude sectors in 2011

Extreme Day-to-Day Variability ?



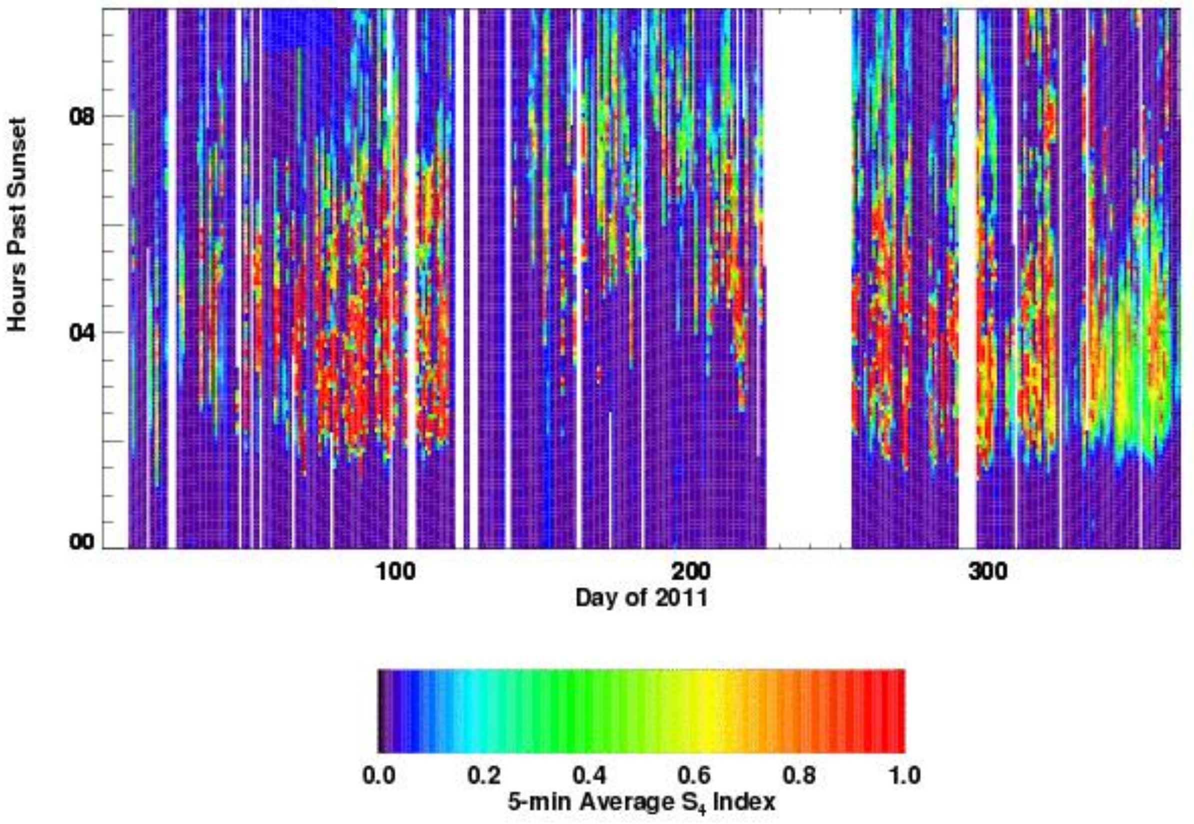
Scintillation Occurrence in W. Africa



- Response looks pretty similar to Cuiaba
- Wet and Dry seasons

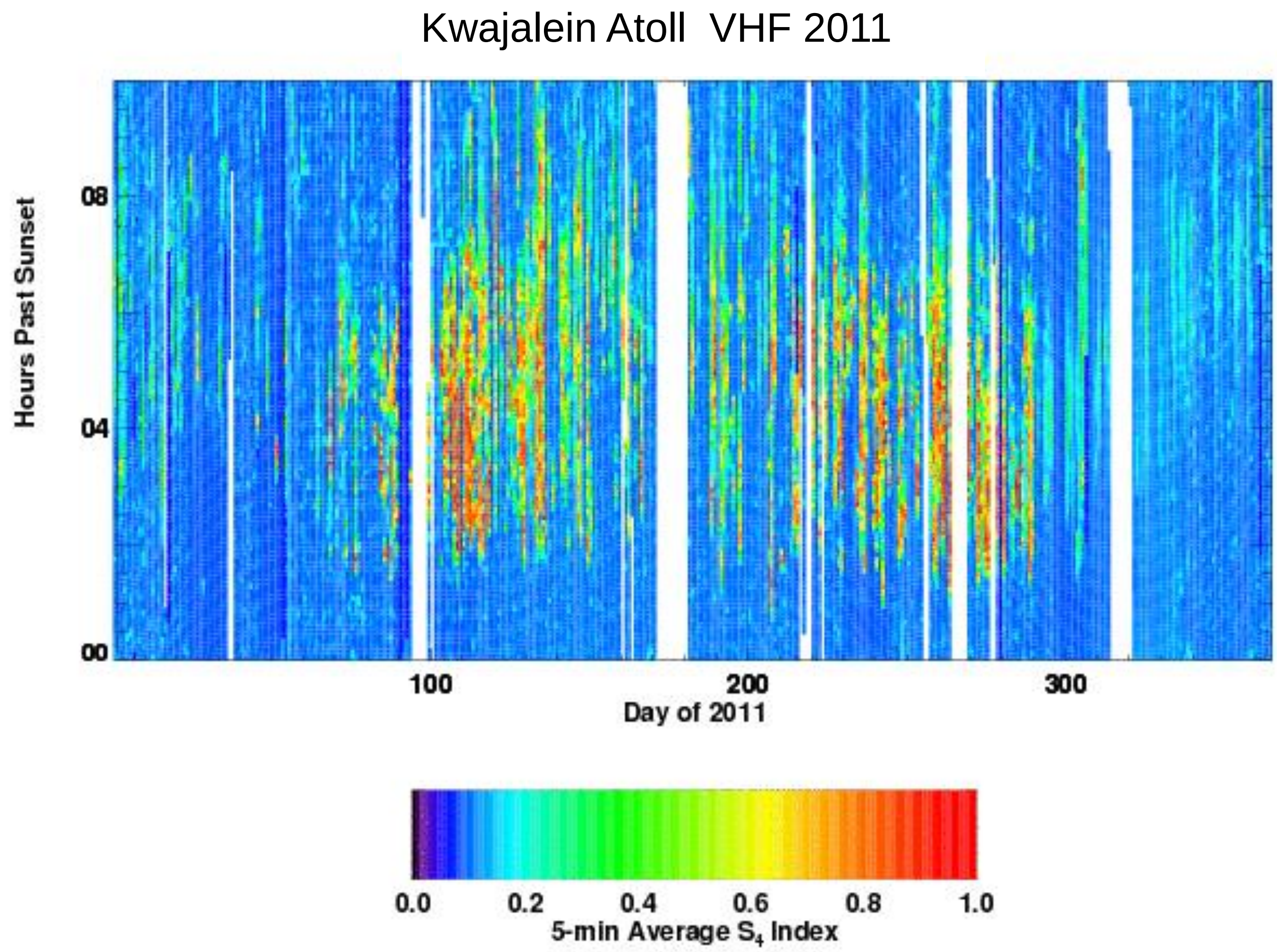
Scintillation Occurrence in E. Africa

Nairobi, Kenya, VHF 2011



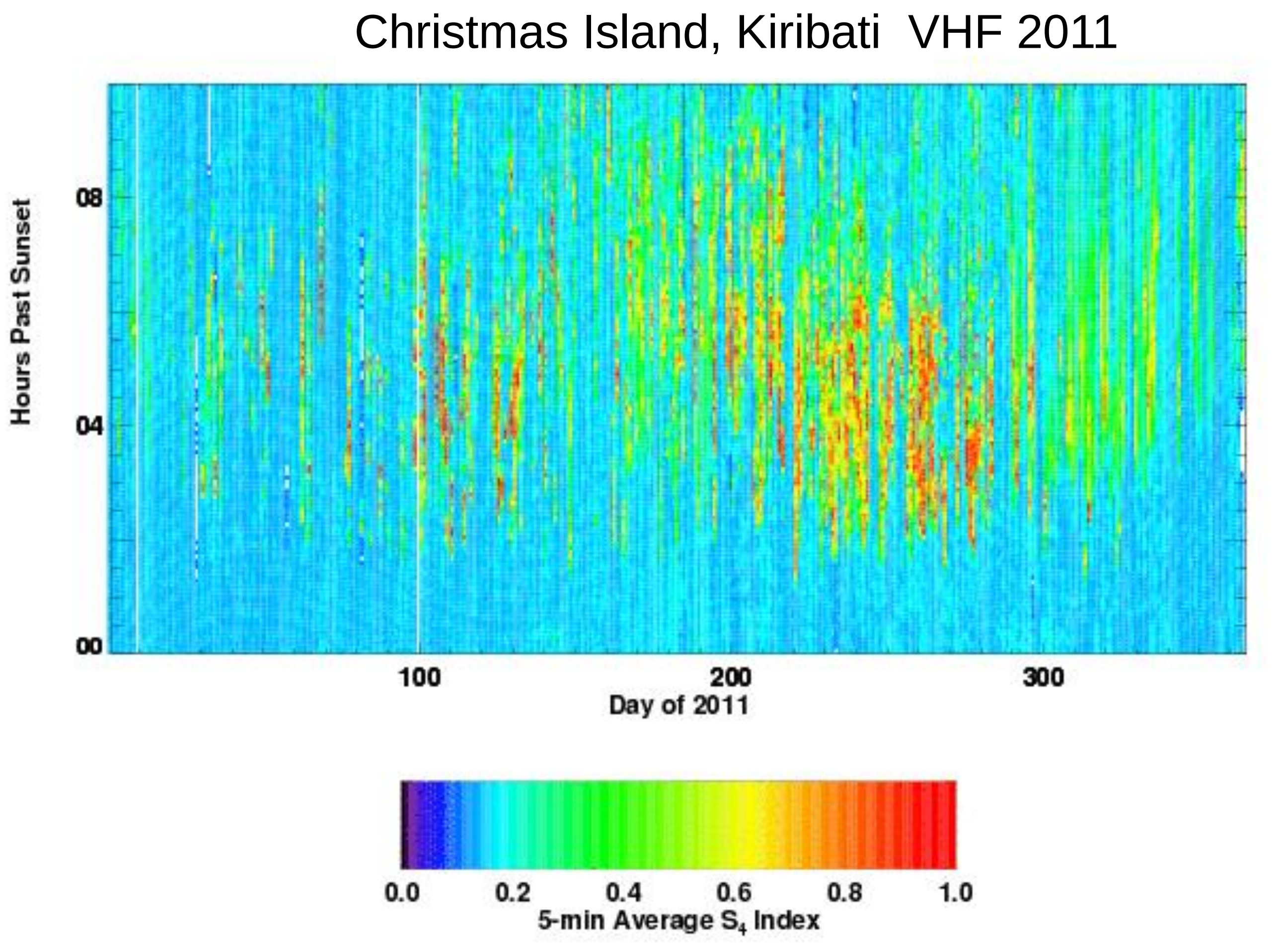
- Region shows a lot of activity, much of it severe
- Fundamental shift in local time of onset during June/July
- Data appears to show more variability than American sector

Kwajalein, R.M.I.



- Variability exists throughout the year, but average severity is markedly less than in Nairobi
- Part of the difference in severity may be attributable to mag lat

Christmas Island (Kiritimati)



- Overall pattern similar to Kwajalein
- Decrease in severity may be magnetic latitude effect (1° vs 4°)

Summary

- Relatively weak ionospheric interaction with L-band signals produces surprisingly strong propagation effects
- Numerous scintillation-induced GPS performance impacts have been observed and documented during solar maximum periods
- Strong scintillation requires the presence of small-scale irregularities and relatively high background densities
- Post-sunset cintillation occurrence at low-latitudes is common and more than 90% of the activity occurs during quiet solar periods
- Severity is greatest near the equatorial anomaly regions, but occurrence frequency maximizes near the magnetic equator
- S4 and sigma_phi are useful indices, but do not fully characterize the propagation environment and are *inadequate to predict impacts on GNSS receivers*
- Multi-constellation observations represent one of the best mitigation strategies for navigation outages but large-scale scintillation structures will still increase positioning errors, primarily through impacts on DOP

- **High-rate GNSS observations from South Pacific Island Nations could dramatically improve our understanding of scintillation and equatorial anomaly dynamics in this longitude sector.**

Bula Vinaka!

Questions?