# Ionospheric Irregularities and their Impacts on GNSS Systems

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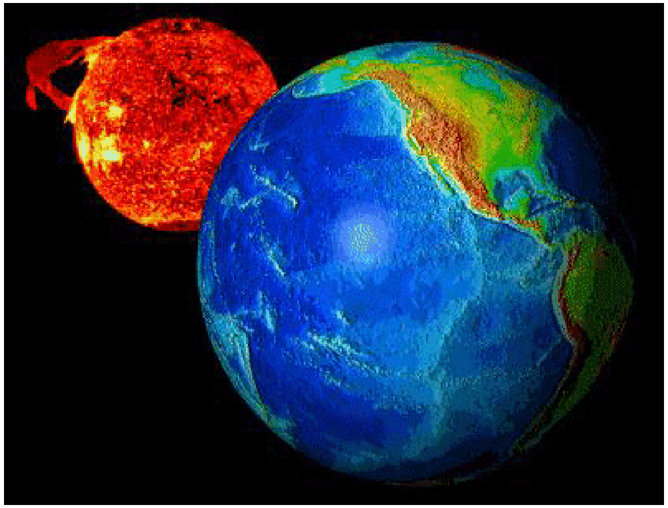
# The Scintillation Environment & Impacts on GNSS

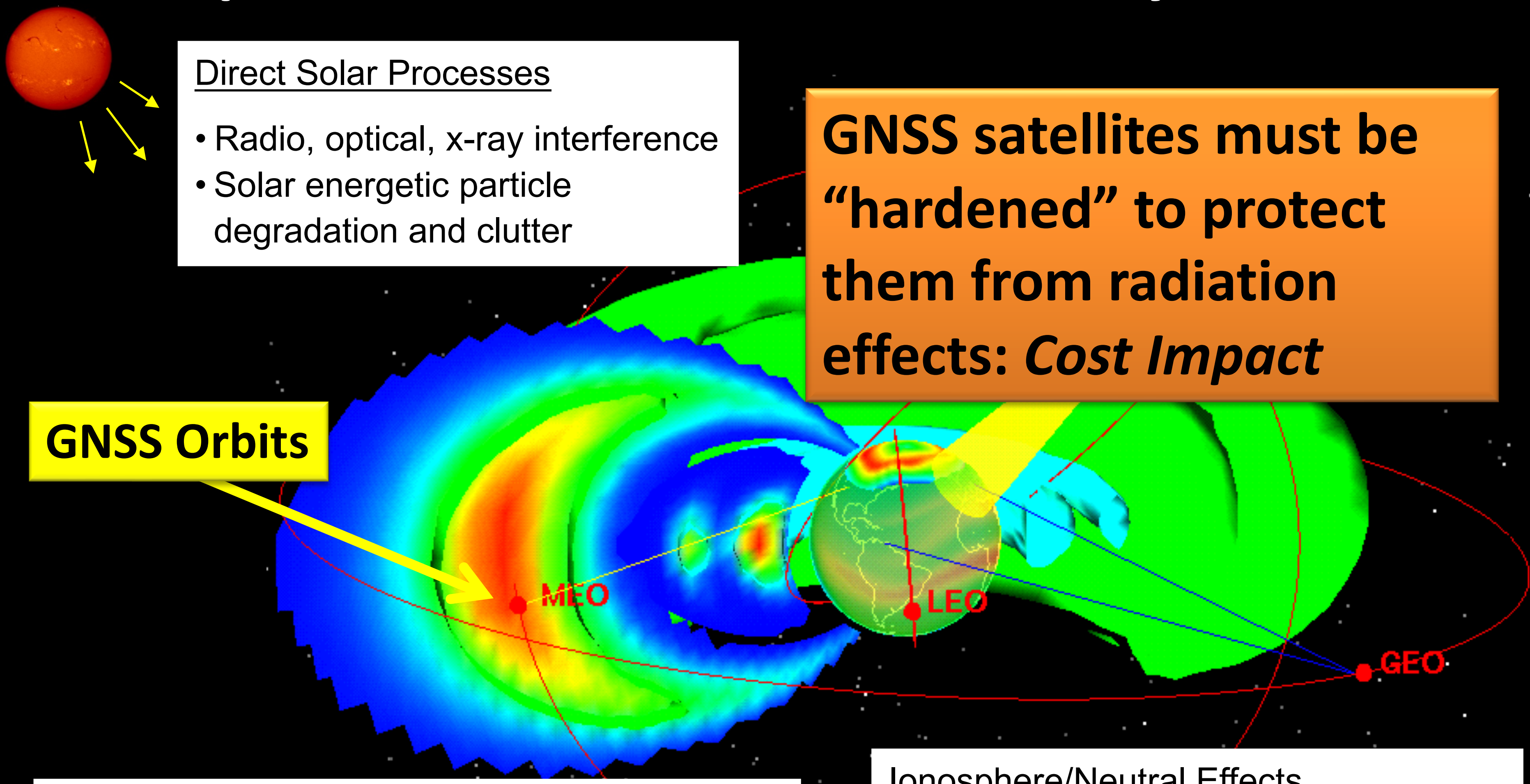
- Overview of Environment
- Scintillation Basics
- "Quiet Time" Space Weather: Equatorial irregularities
- Position, Navigation & Timing Impacts
- Summary



# The Miracle of GNSS

- Inexpensive positioning knowledge anywhere, anytime
- The principles of GNSS navigation: time and distance

# Space Weather Effects on GNSS Systems




<u>Direct Solar Processes</u>

- Radio, optical, x-ray interference
- Solar energetic particle degradation and clutter

**GNSS satellites must be "hardened" to protect them from radiation effects: *Cost Impact***

**GNSS Orbits**

<u>Space Particle  Hazards</u>

- Radiation degradation & electronics upsets
- Surface and internal charging / discharging
- Increased hazard for humans at high altitudes

<u>Ionosphere/Neutral Effects</u>

- Comm/Nav link degradation/outage
- Satellite Drag
- Variations in HF communications (black-outs and modified channels)

# Ionospheric Irregularities & Scintillation Physics

Time Delay:

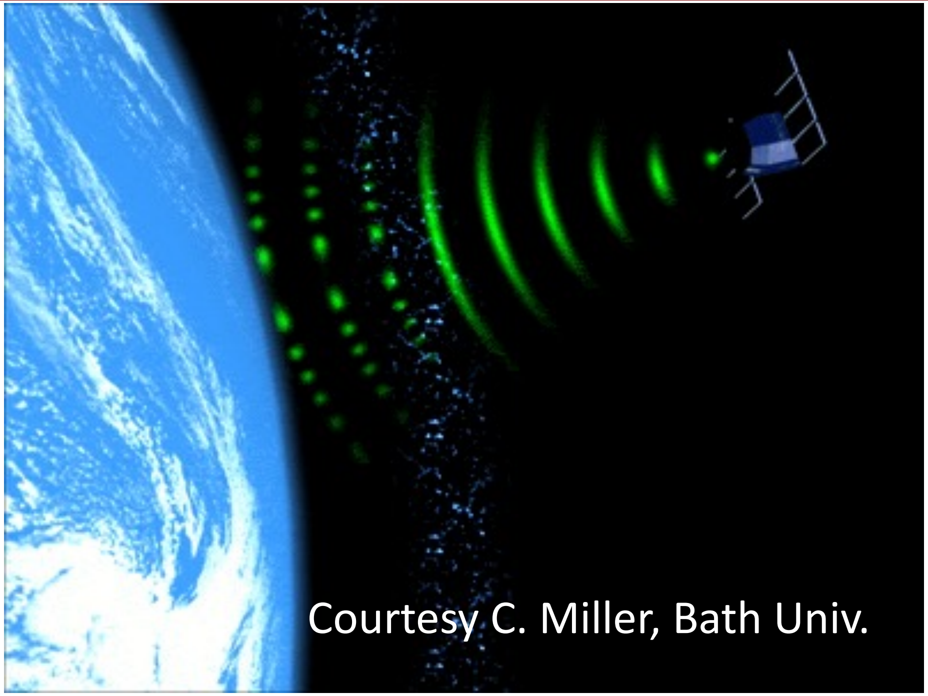
$$\tau_d = R/c + \frac{r_e c}{2\pi}\frac{N_{tot}}{f^2}$$

Phase Perturbation:

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

Depends on TEC:

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



Courtesy C. Miller, Bath Univ.

- 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, $F_r = 2x = \sqrt{2\lambda z}$ .

# The Ionosphere is a Small Perturbation for GNSS

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

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

$$f_p \sim 10\ MHz$$

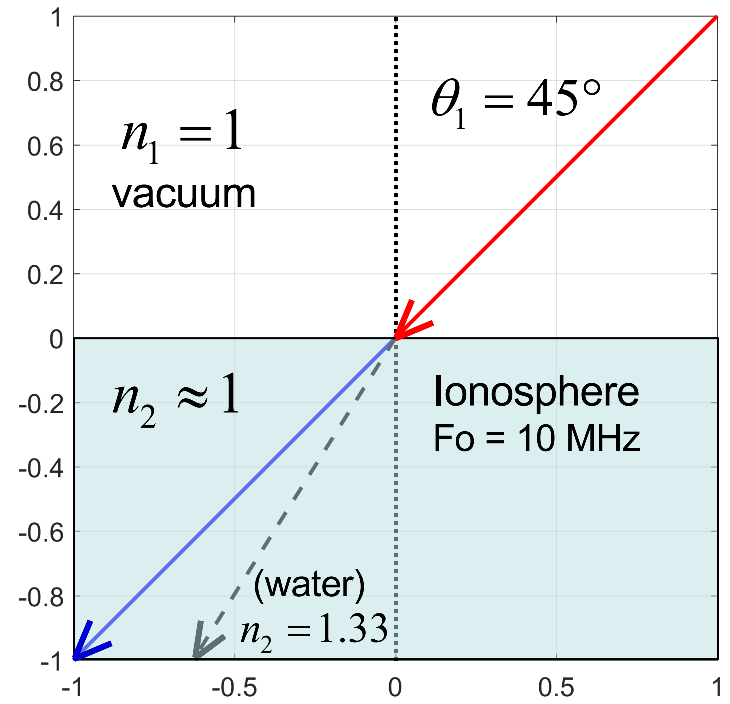
$$f = 1575 MHz$$

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

Snell's Law:

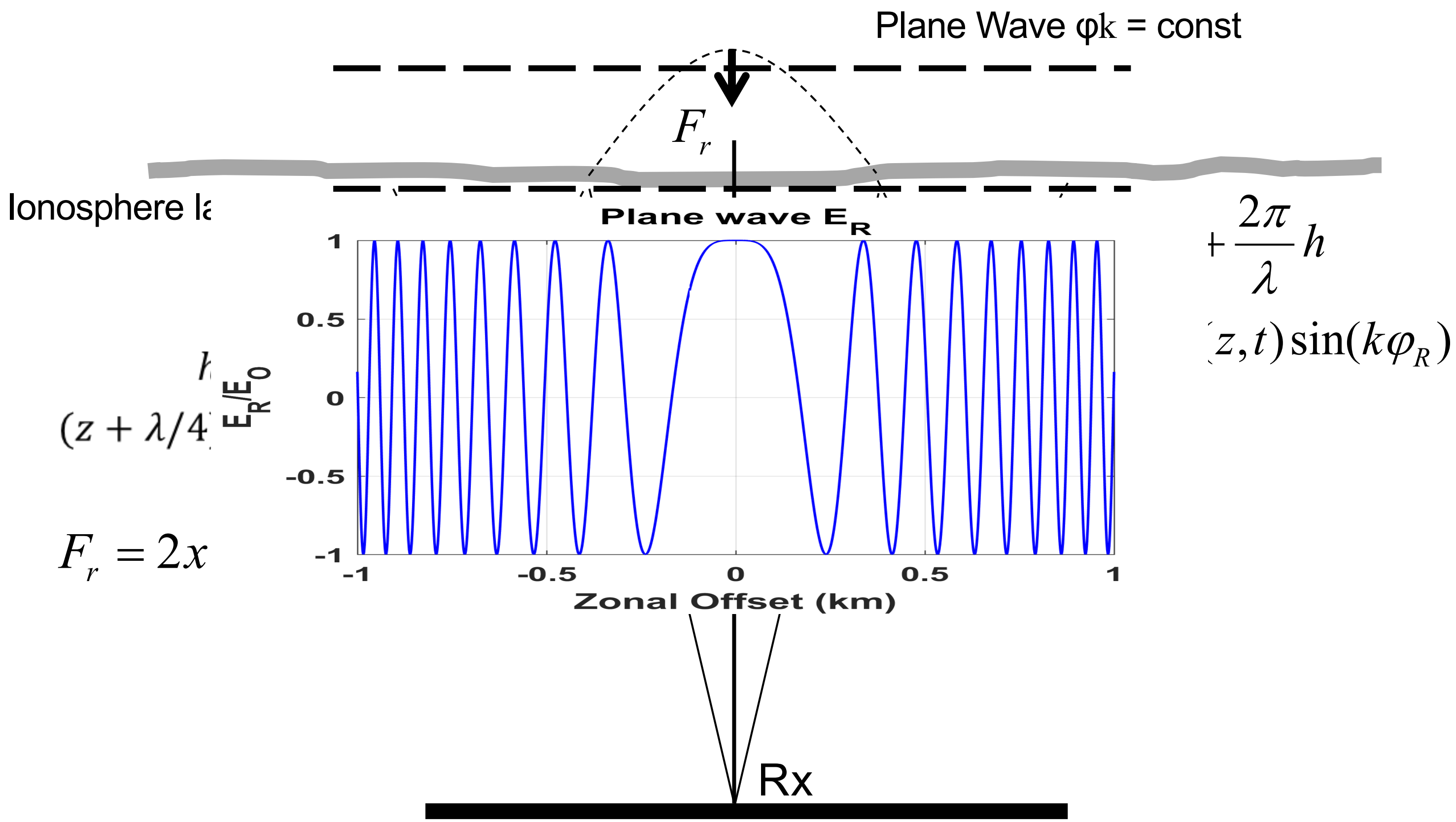
$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

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!**

# 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.

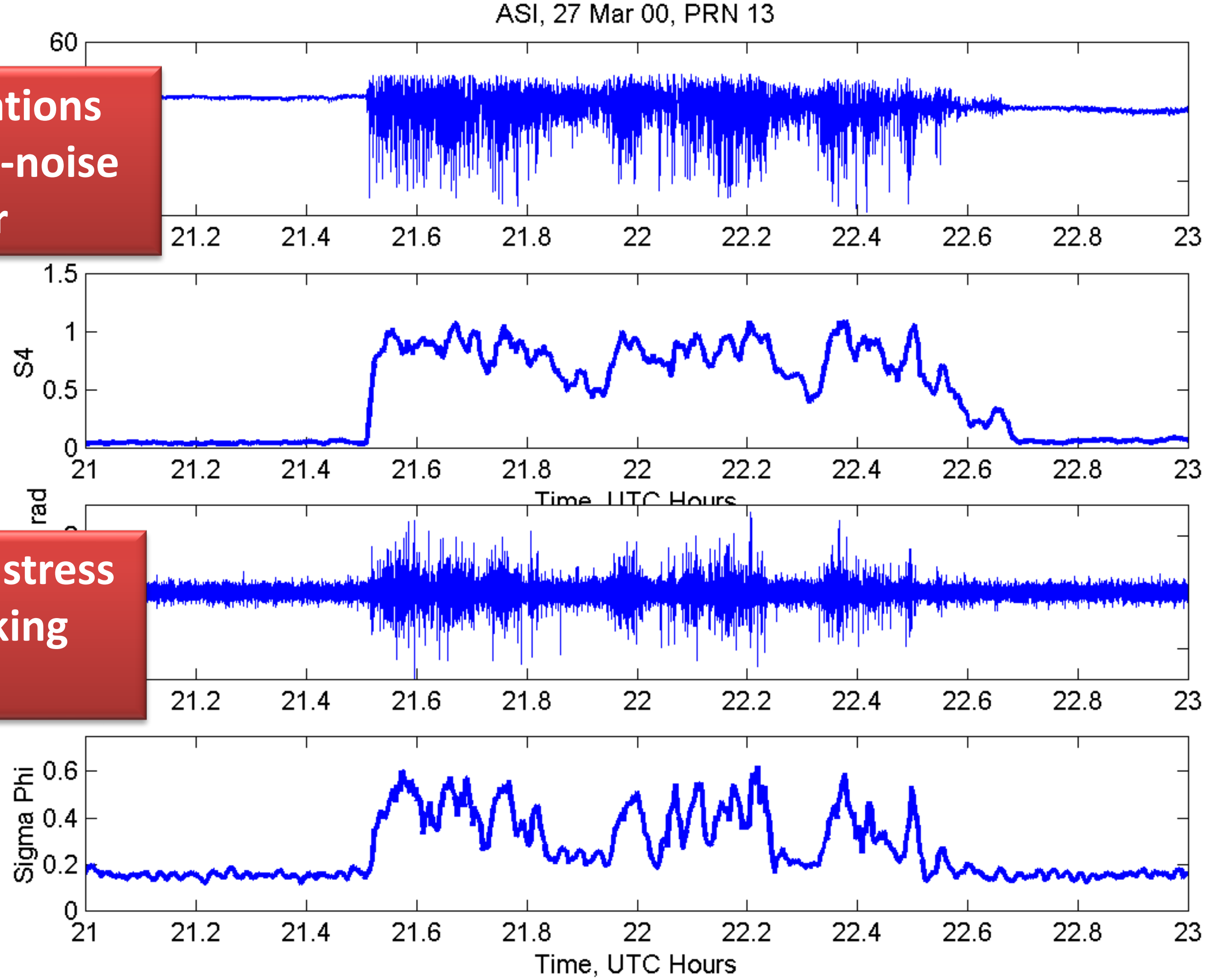
# GPS Signal Fluctuations Caused by Ionospheric Scintillation

**Intensity fluctuations reduce signal-to-noise in GNSS receiver**

**S4**: Normalized Stand. Dev. Of Intensity

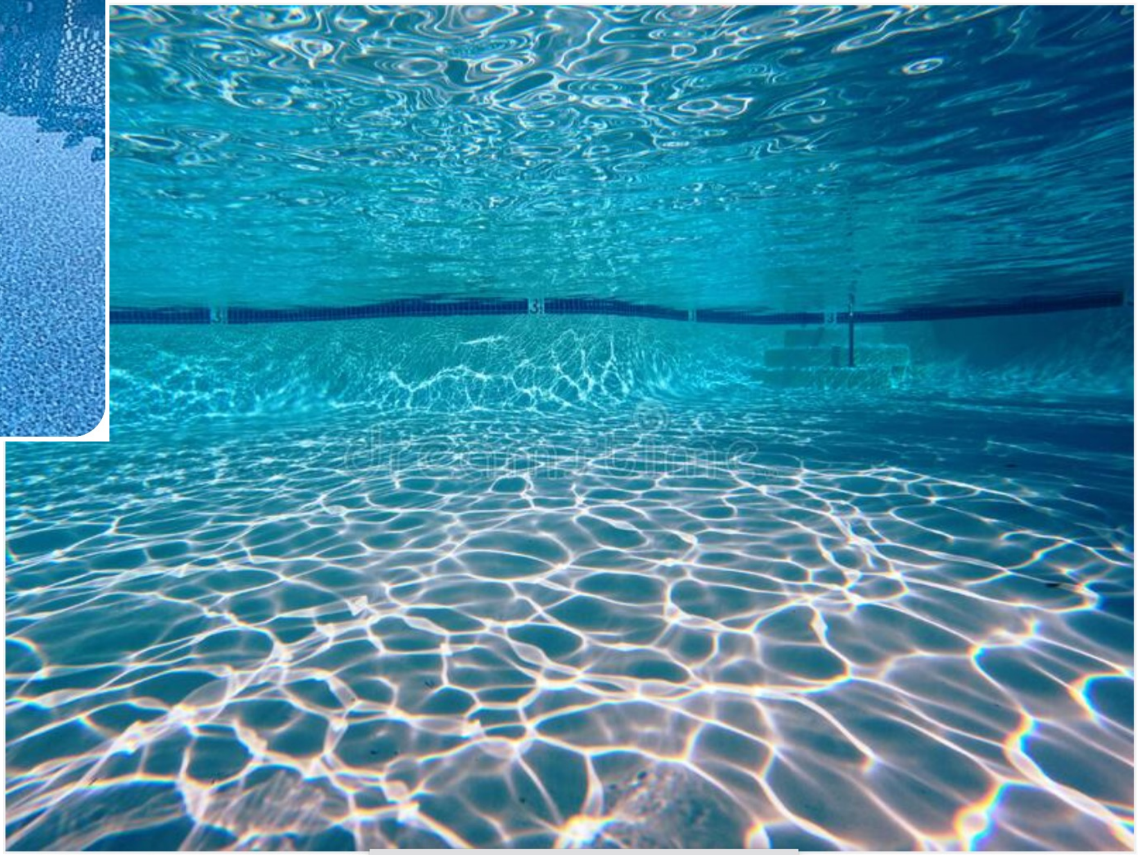
**Phase variations stress GNSS signal tracking loops**

**$\sigma_\phi$** : Stand. Dev. of Phase



# A Familiar Example

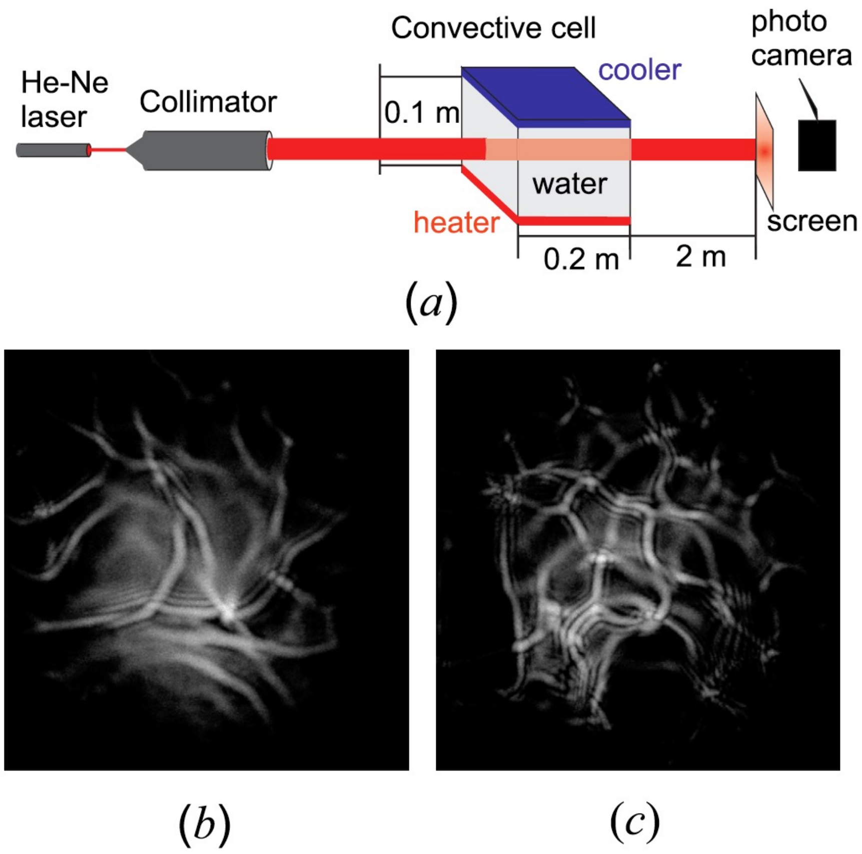
**One can see clearly in a calm swimming pool**



**But surface waves cause self-interference of the light reaching the bottom (refraction & diffraction)**

# More Physically Representative Example

- A laser shining through ”clear” water encounters turbulence due to convection in the water due to an imposed temperature difference of (b) 10° C & (c) 20° C
- The authors used phase screen theory (neutral gas) to estimate turbulence parameters
- Relatively simple experiment and analysis—published in 2016!
- The main difference in the ionosphere is that the turbulence is organized along the magnetic field and the index of refraction perturbations are much smaller



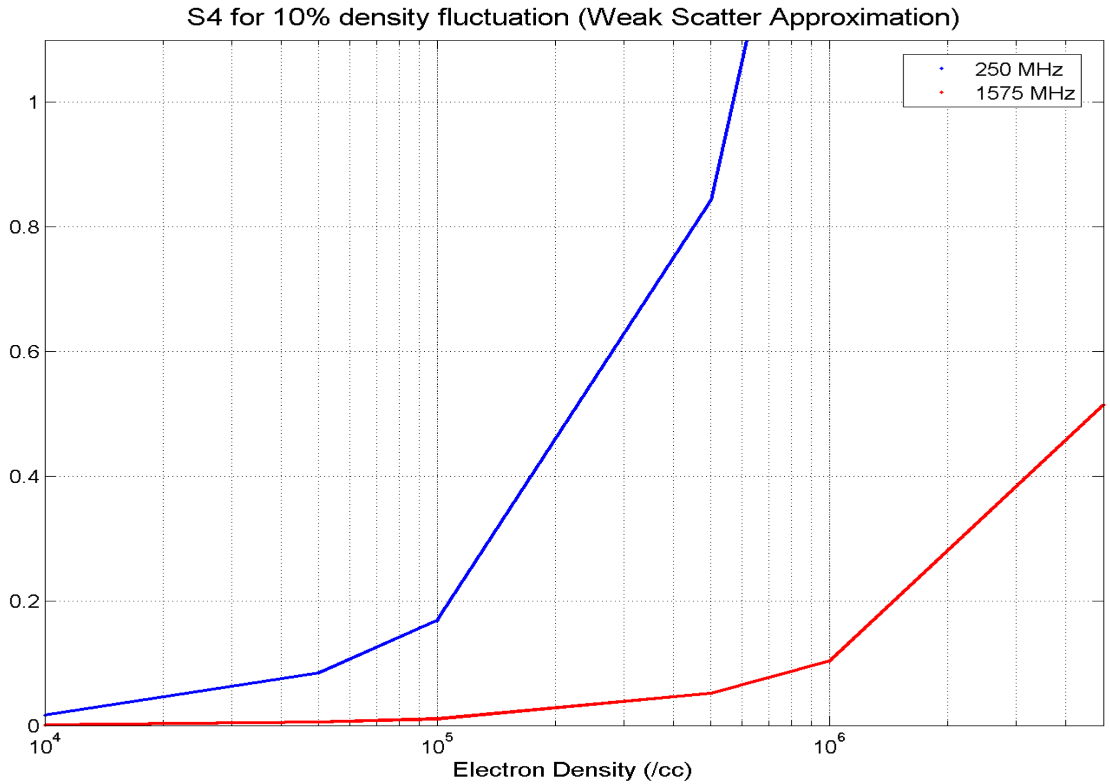

V. A. Kulikov; *Journal of Applied Physics* **119,** 123103 (2016)

# Effect of Electron Density on S4

**Scintillation requires two ingredients:**

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

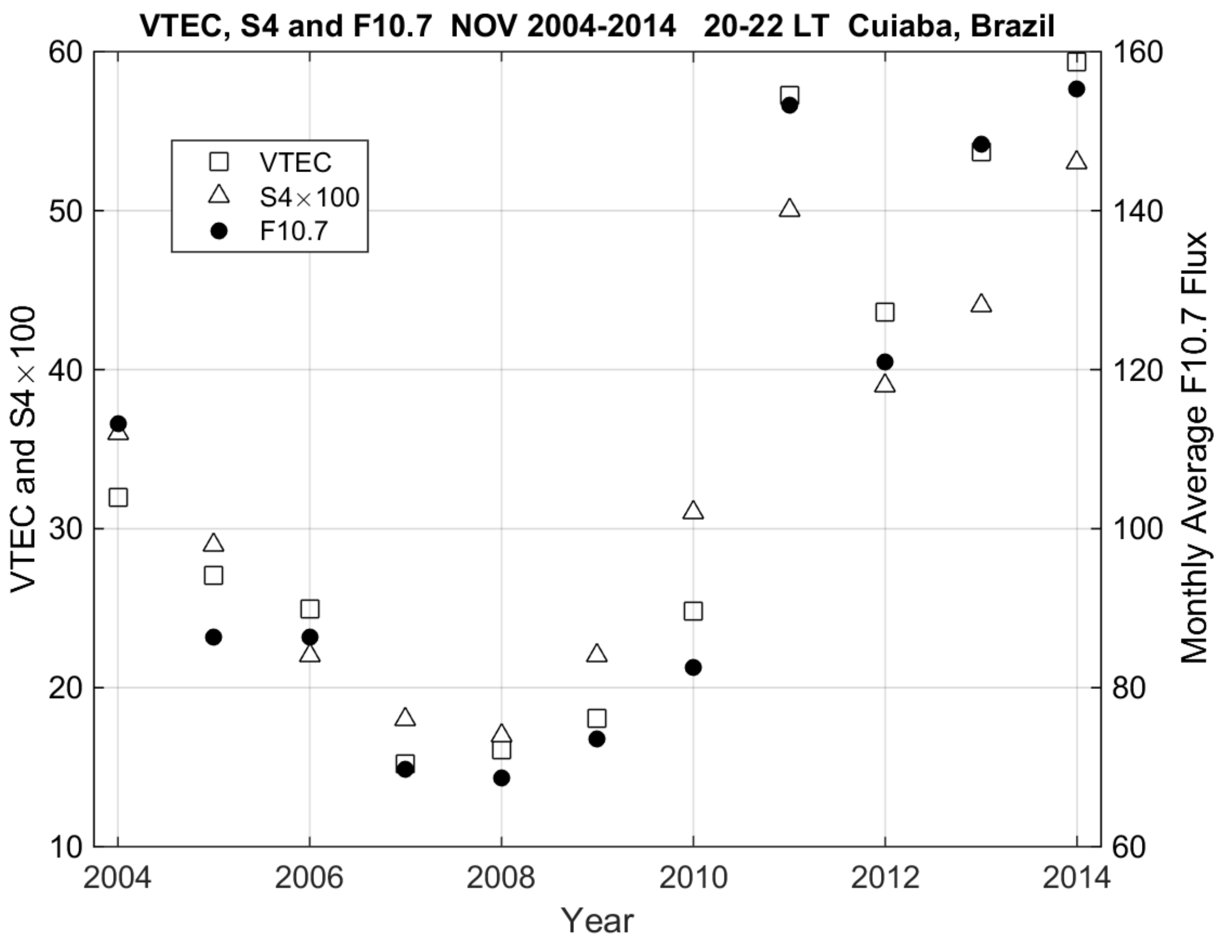
- Significant relative density fluctuations will not cause scintillation if the background electron density is too low
- Must exceed ~1e5/cc for VHF, ~1e6 for GPS (~50 TEC units)




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

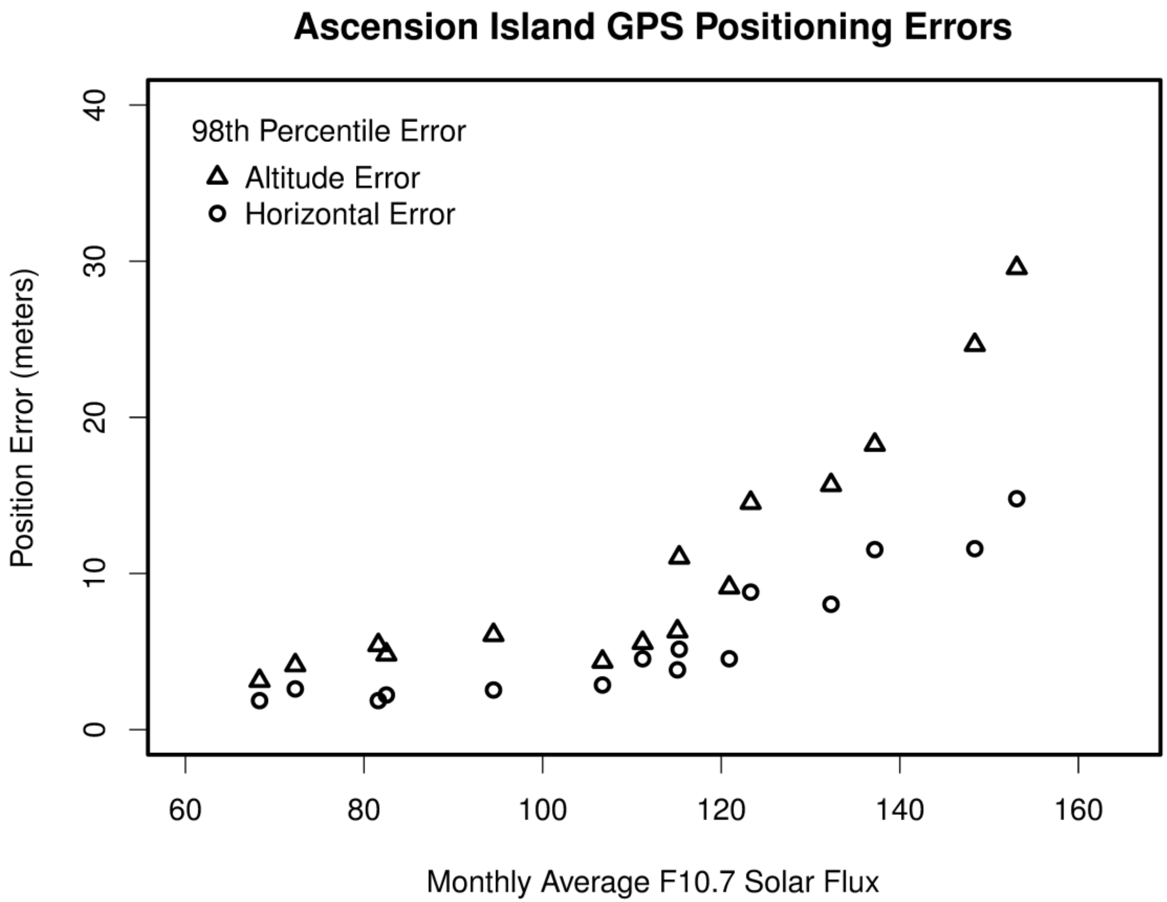
Weak Scatter Approximation

# Solar Flux, Density & S4



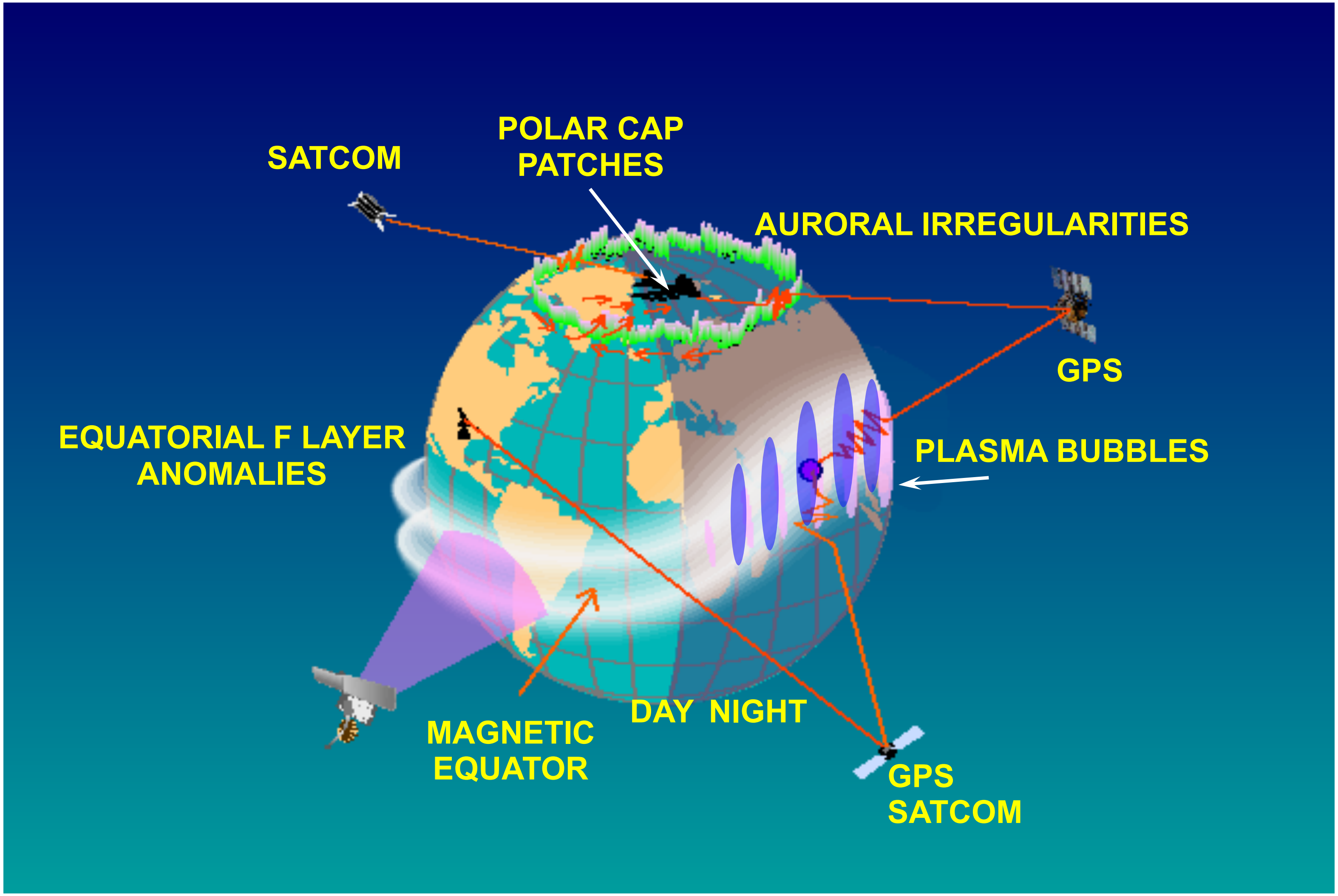

Solar flux determines electron density which determines S4

# Solar Flux & Positioning Errors




Solar flux controls S4 which controls impact on GNSS performance

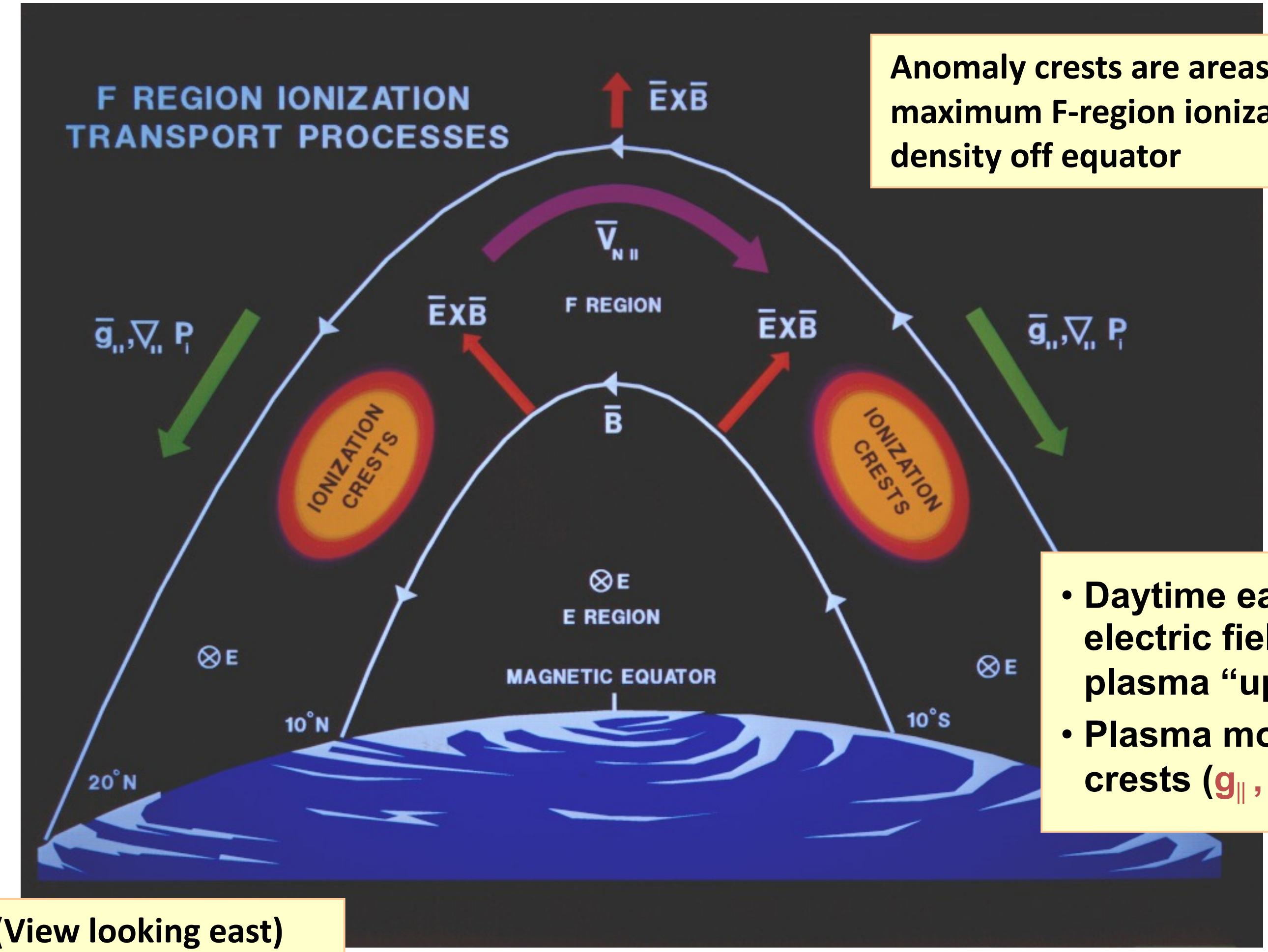
# Disturbed Ionospheric Regions and Systems Affected by Scintillation



# Low Latitude Quiet Time 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" ($\mathbf{E} \times \mathbf{B}$)
- Plasma moves toward crests ($g_{\parallel}$ , $\nabla_{\parallel} P_{\parallel}$)

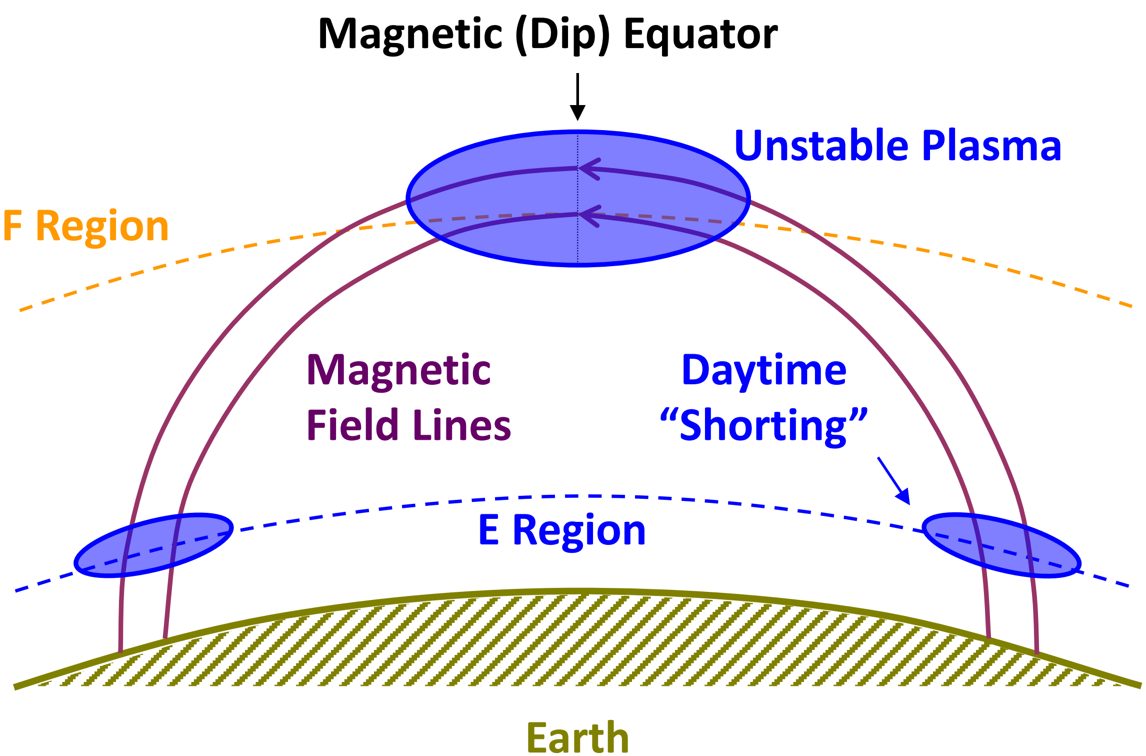
(View looking east)

# Why Do Disturbances Form?

## Unique Equatorial Magnetic Field Geometry

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

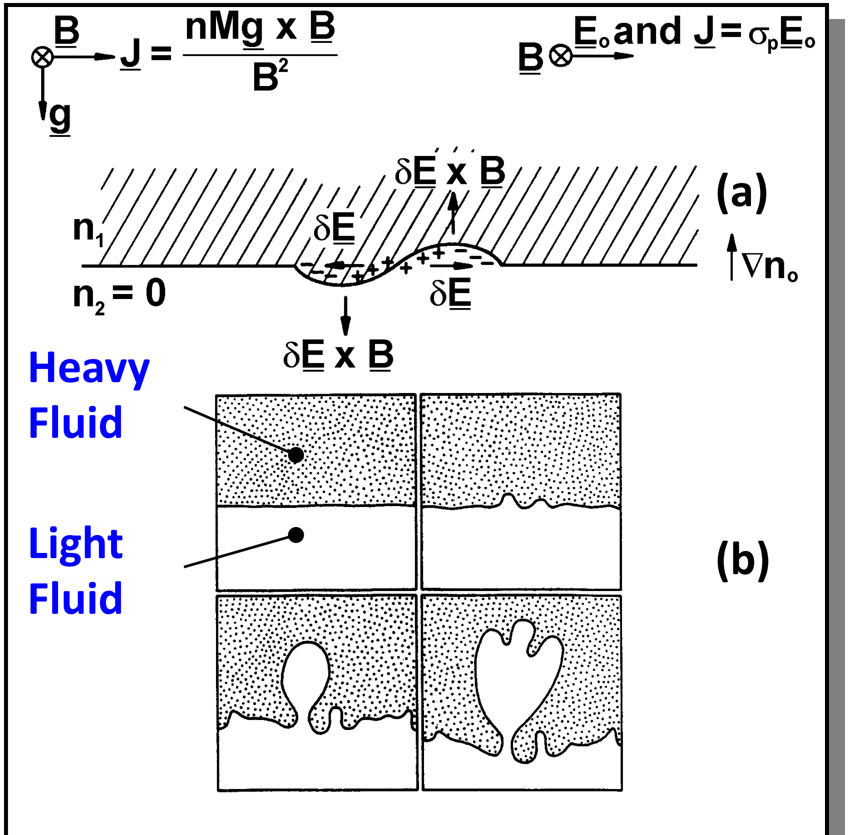
- Plasma moves easily along field lines, which act as conductors
- Horizontal field lines support plasma against gravity– unstable configuration
- E-region "shorts out" electrodynamic instability during the day



# What Is Instability Process?

## Gravitational plasma instability with horizontal B field

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



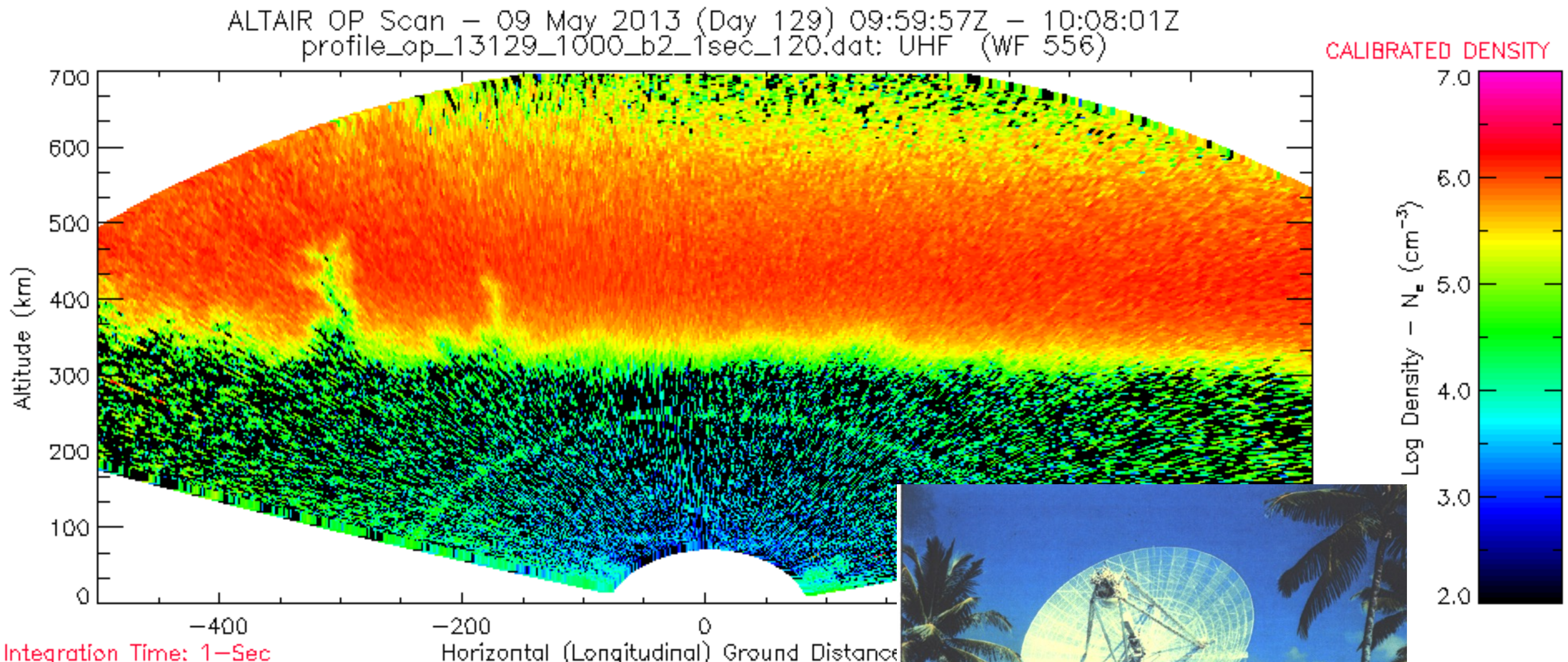

from *Kelley* [1989]

**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)

# Incoherent Scatter Radar Observations

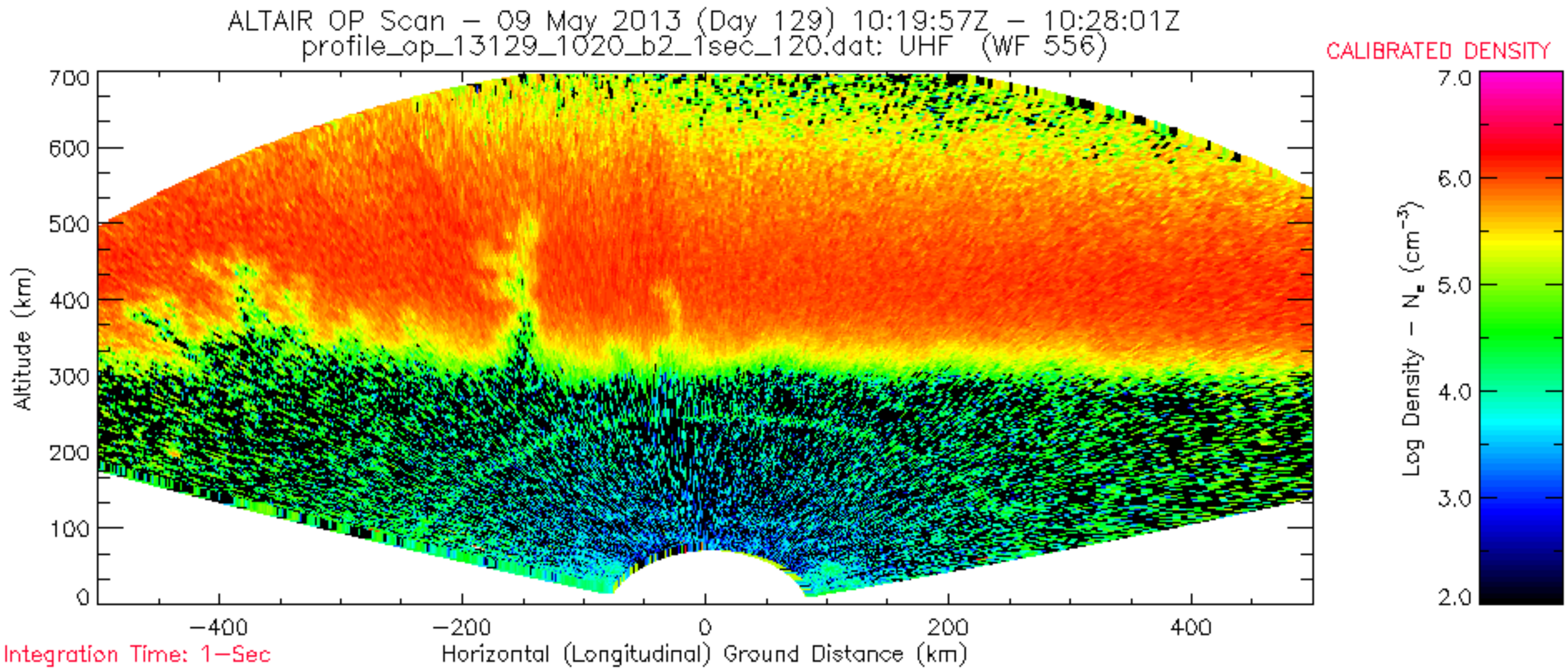
10:00 UT to 10:08 UT




ALTAIR VHF/UHF Radar

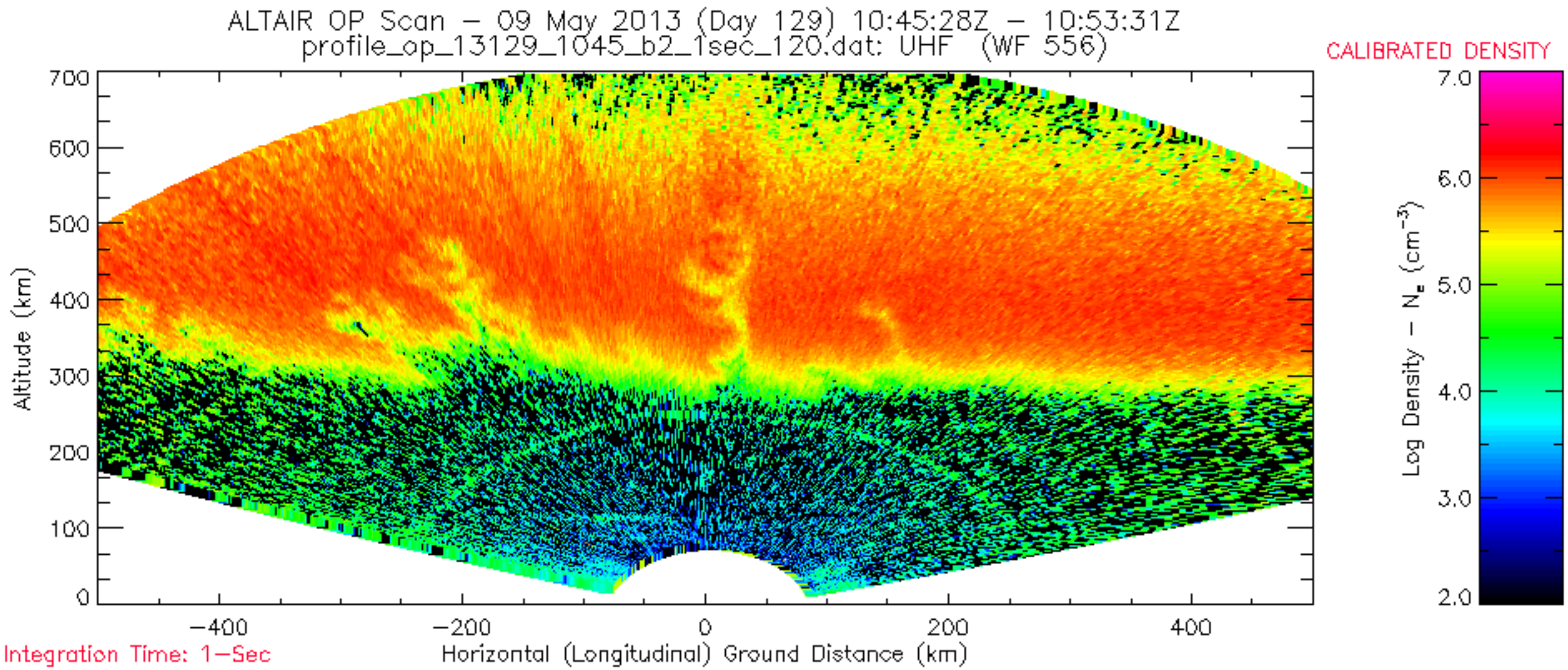
# Off-Perp Incoherent Scatter Scans

10:20 UT to 10:28 UT



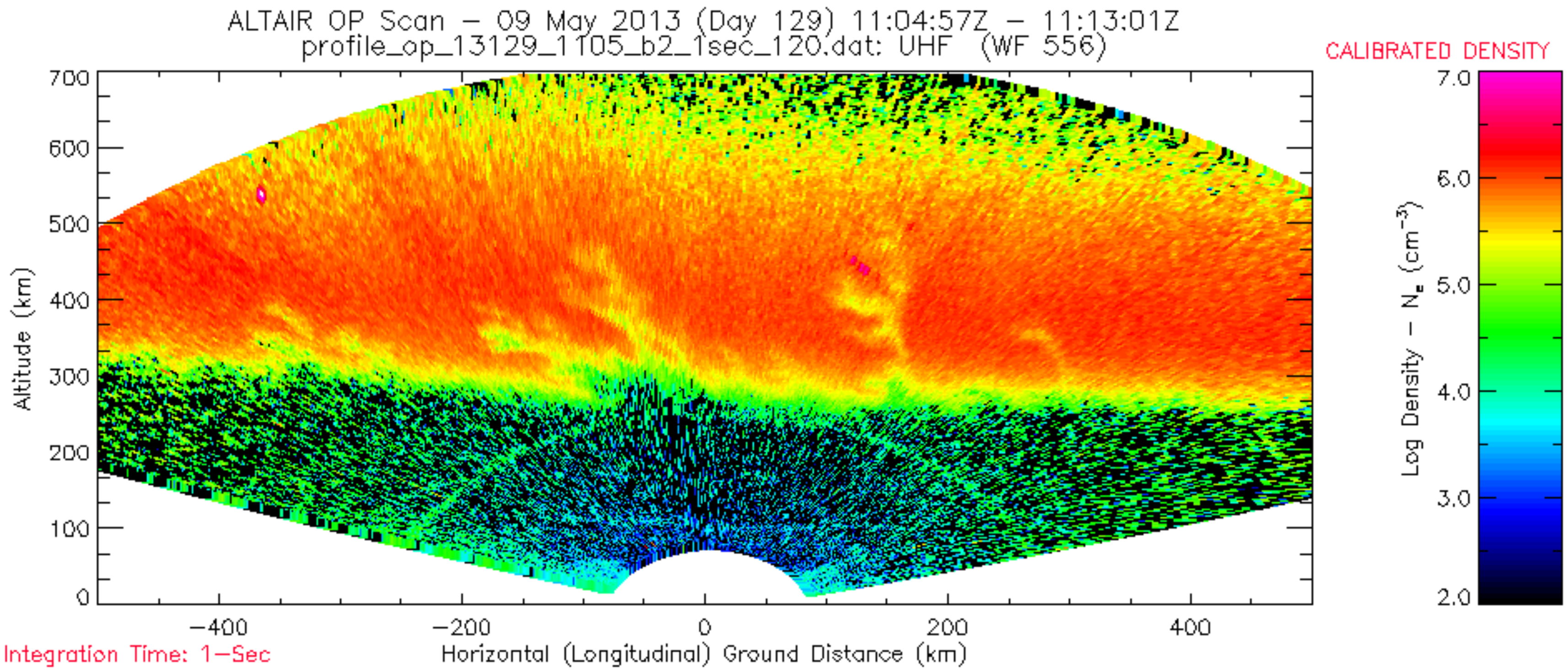
# Off-Perp Incoherent Scatter Scans

10:45 UT to 10:53 UT



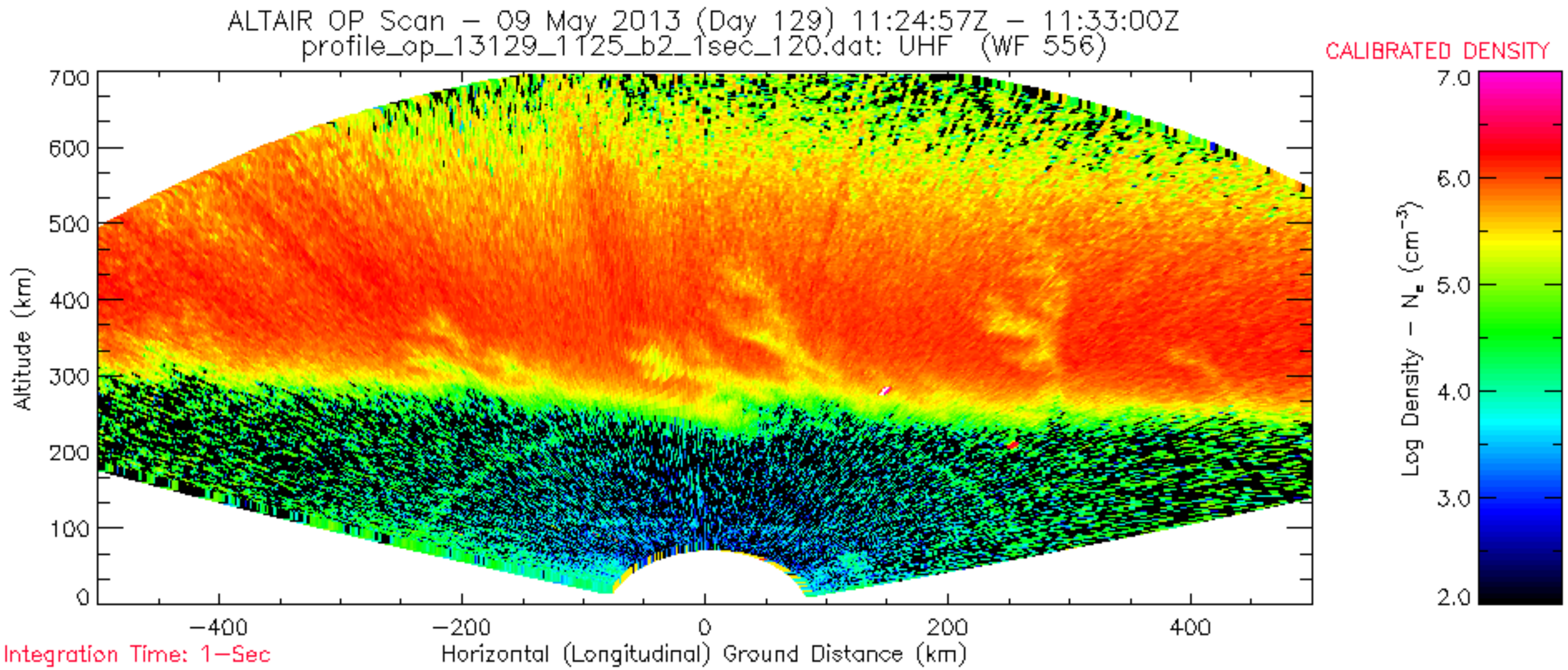
# Off-Perp Incoherent Scatter Scans

11:05 UT to 11:13 UT



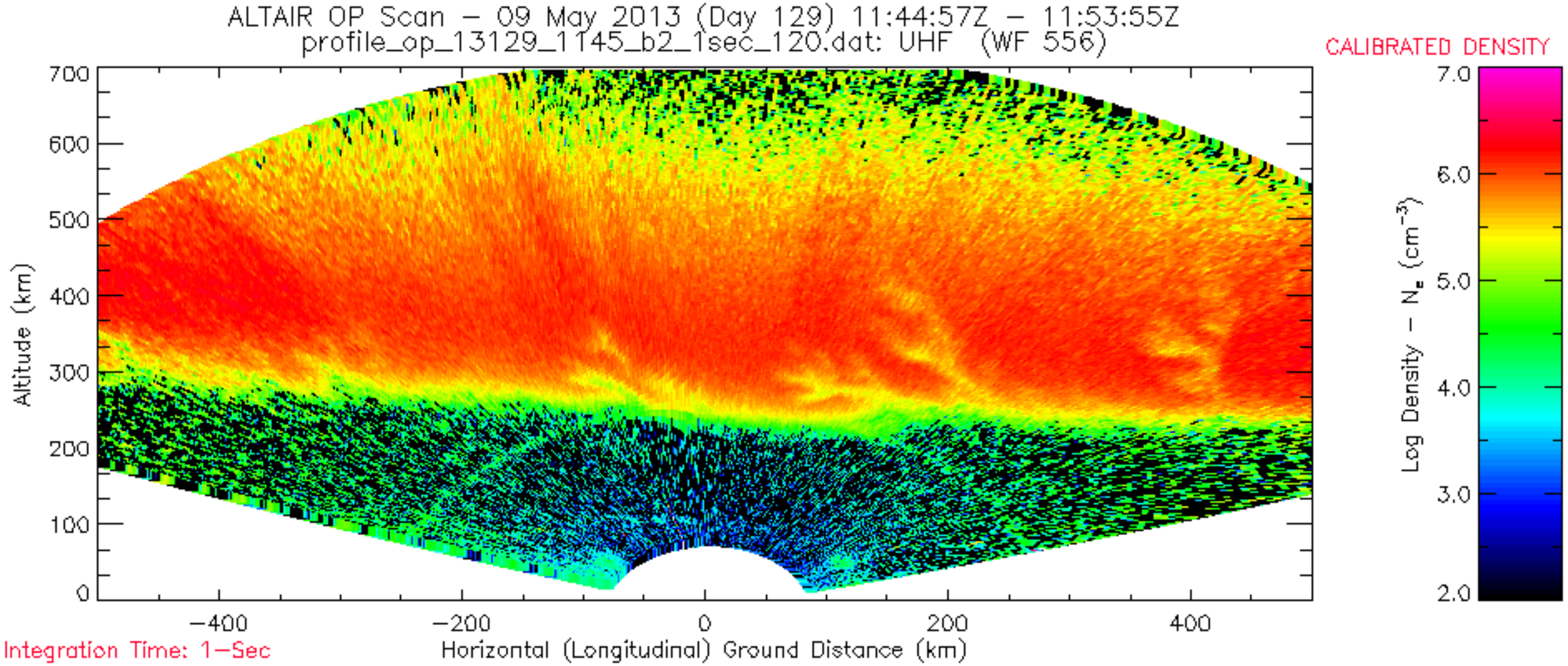
# Off-Perp Incoherent Scatter Scans

11:25 UT to 11:33 UT

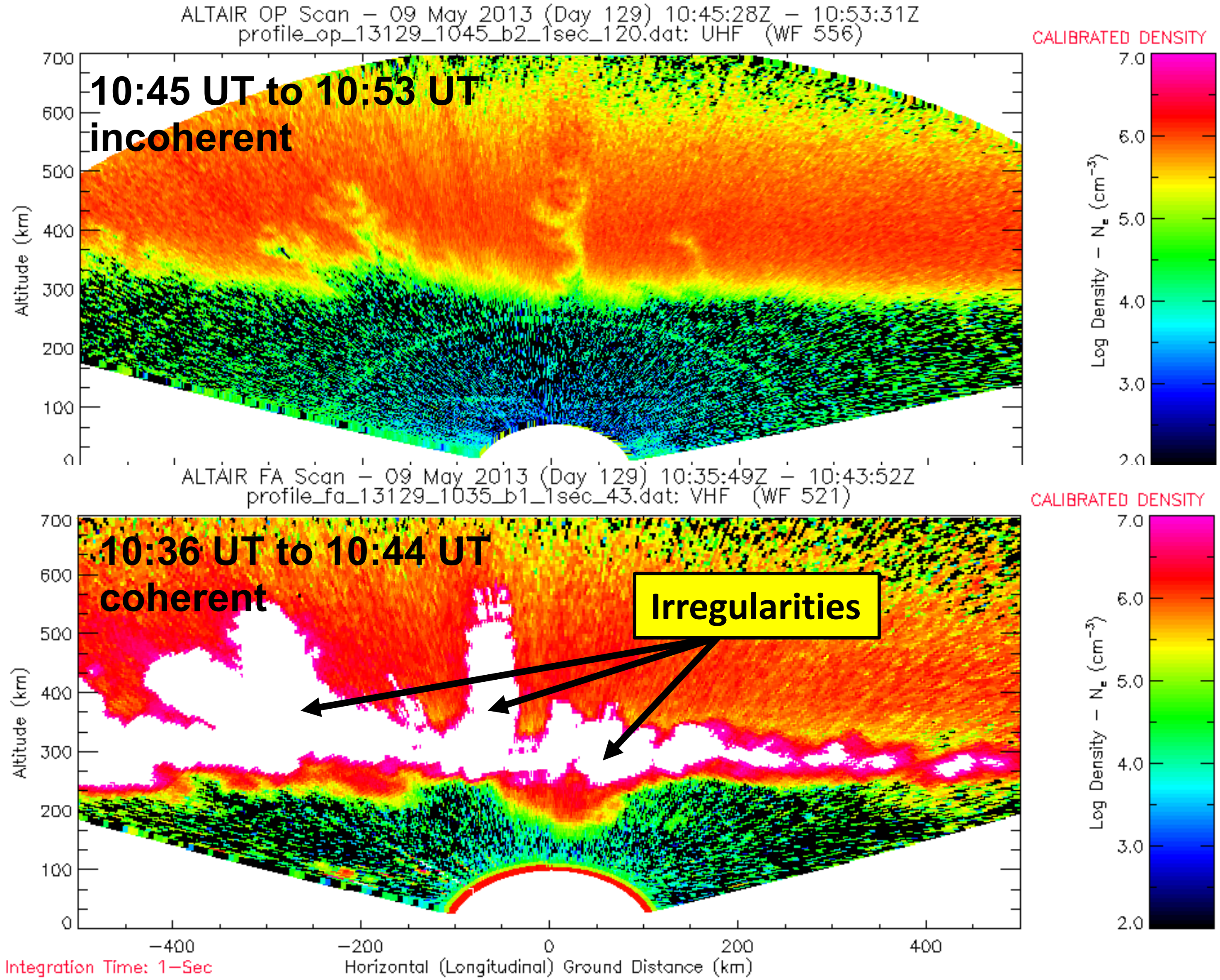


# Off-Perp Incoherent Scatter Scans

11:45 UT to 11:53 UT

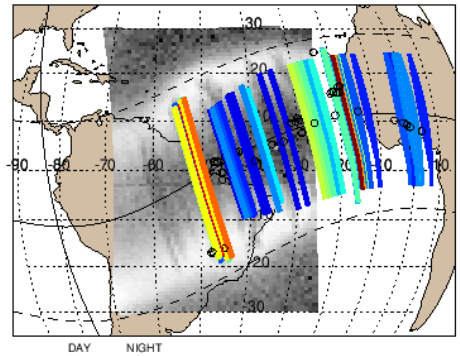


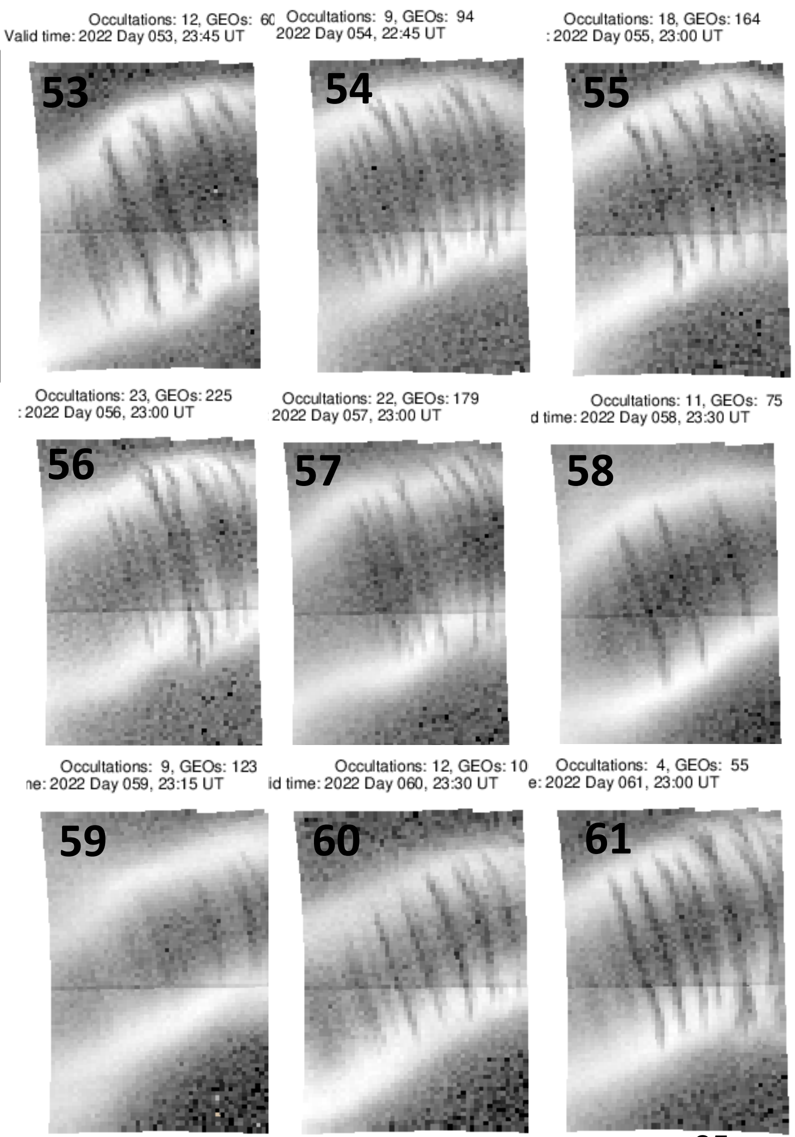
# Off-Perp Incoherent and Perp-B Coherent Scatter Scans



# The Anomaly & Depletions in GOLD UV Imagery, days 53-61 2022

Anomaly structure in GOLD imagery and bubbles mapped from COSMIC-2 radio occultation data

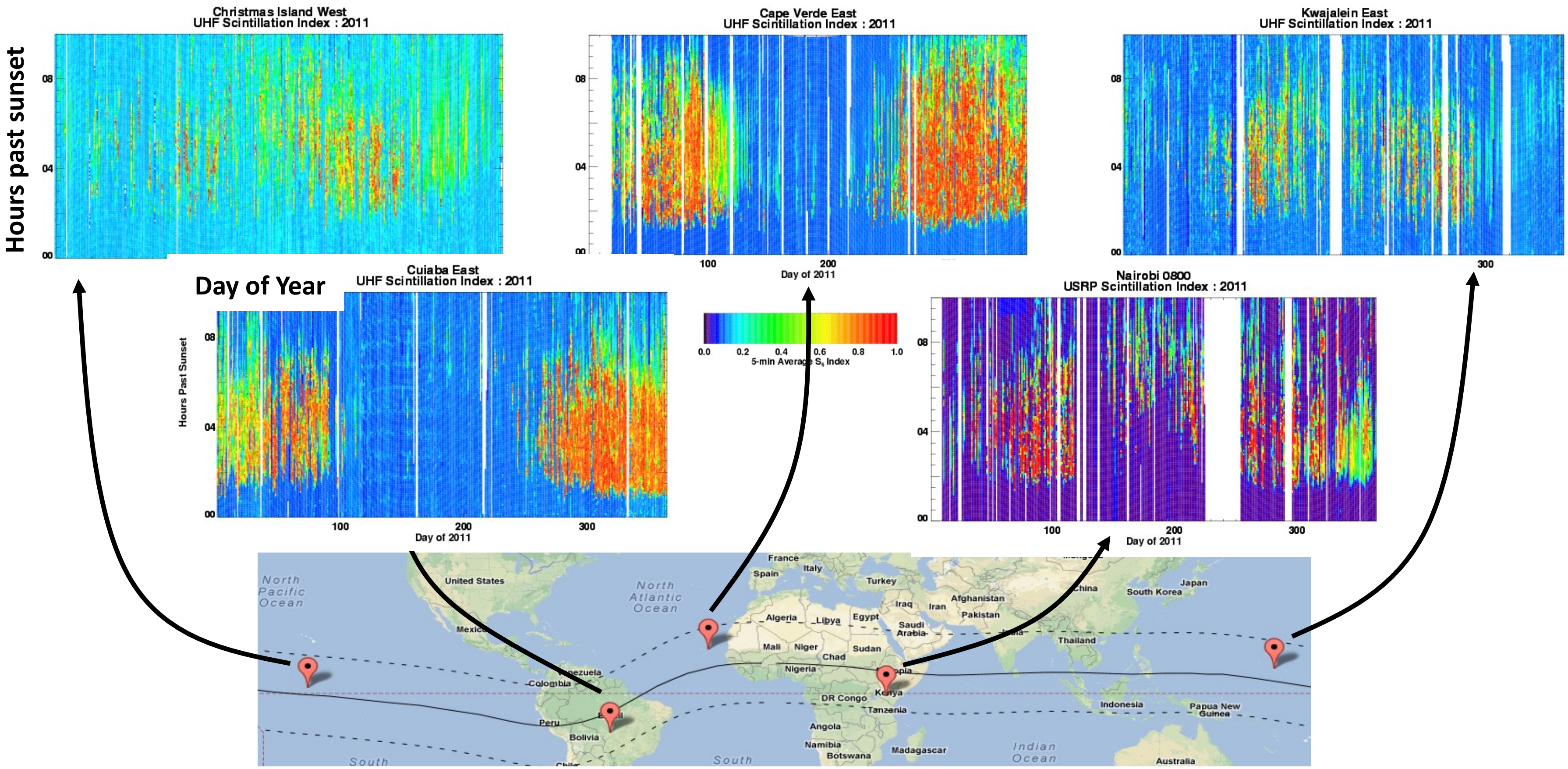



- There is a tremendous amount of variability in the anomaly from day to day; for the first time with GOLD we can routinely image the anomaly as well as the post-sunset depletions (bubbles) associated with equatorial spread F
- These studies are just getting underway; the data is available on-line at: https://gold.cs.ucf.edu/data/gold-data-usage/

# Scintillation Occurrence & Longitudinal Variability

**250 MHz scintillation observations from five sites in 2011**

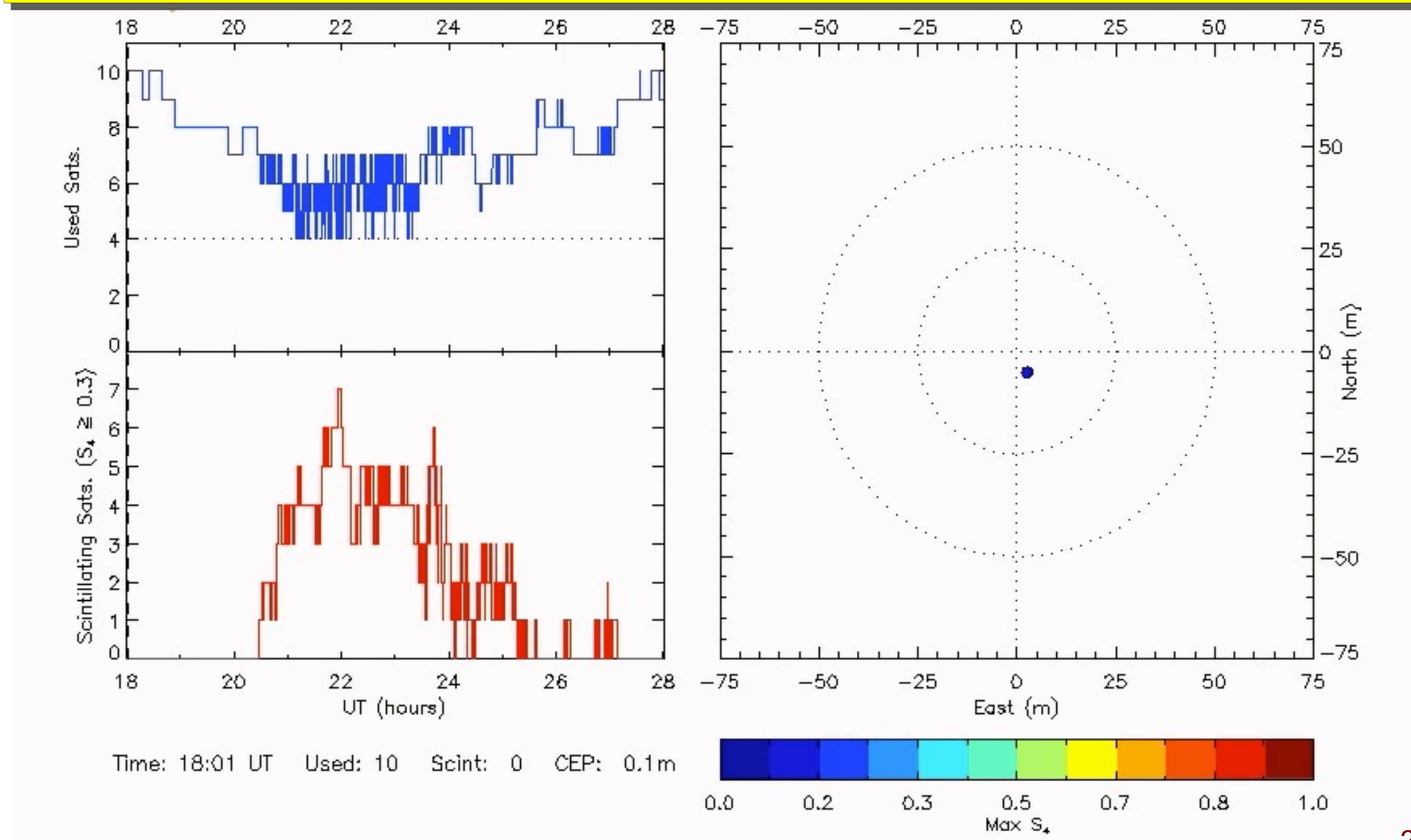



**Frequent activity with a strong seasonal dependence that does not depend on magnetic activity**

# GPS Positioning Errors from Space Weather

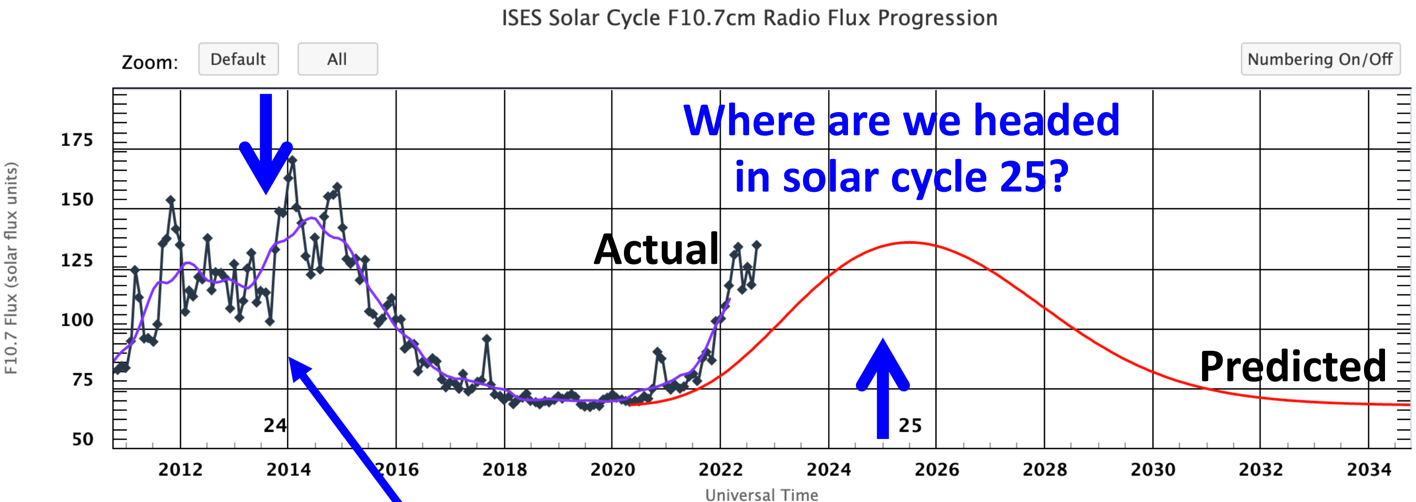
## Dual Frequency GPS Positioning Errors

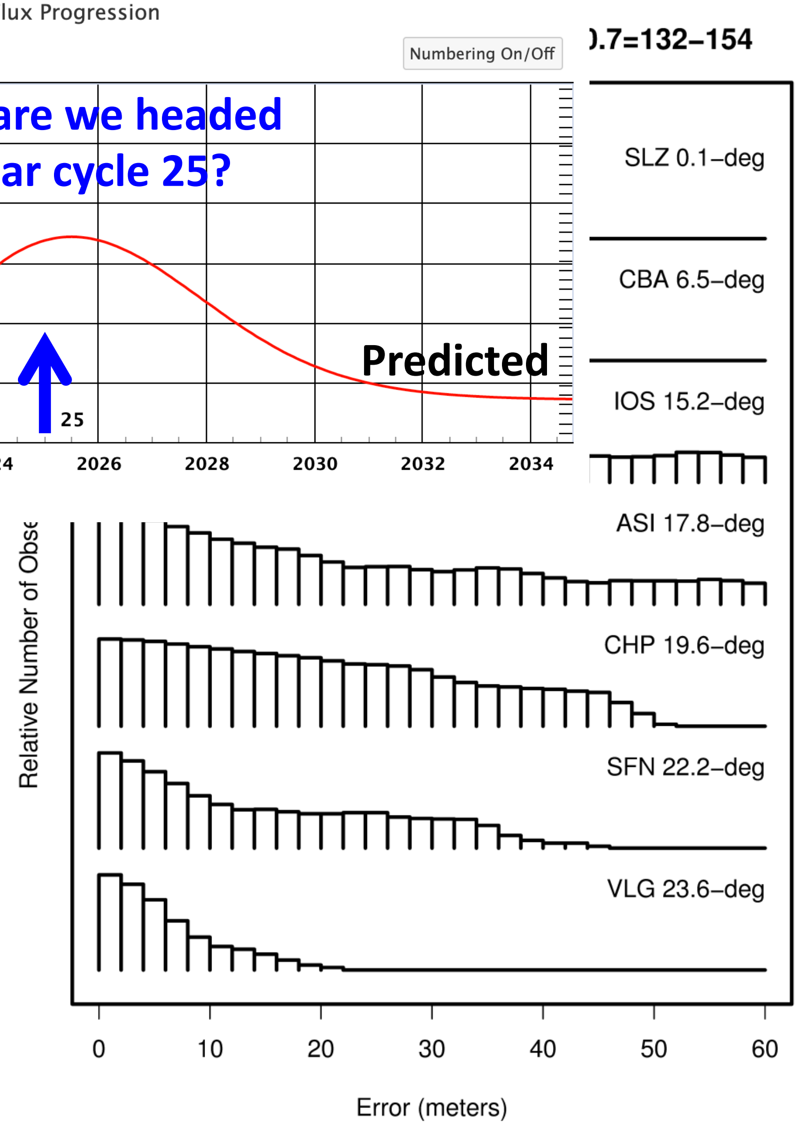
Scintillation causes rapid fluctuations in GPS position fix
Typical night from solar maximum at Ascension Island

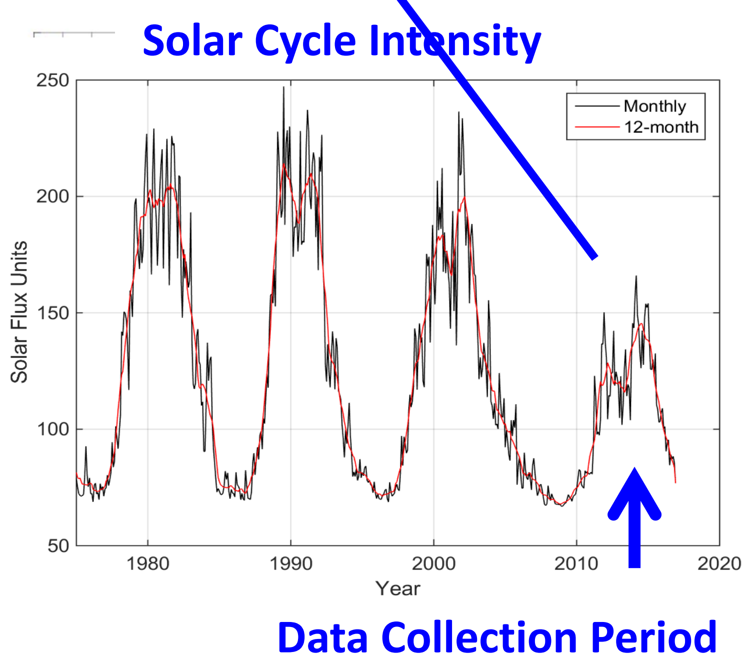


# GPS Positioning Errors from Solar Cycle 24

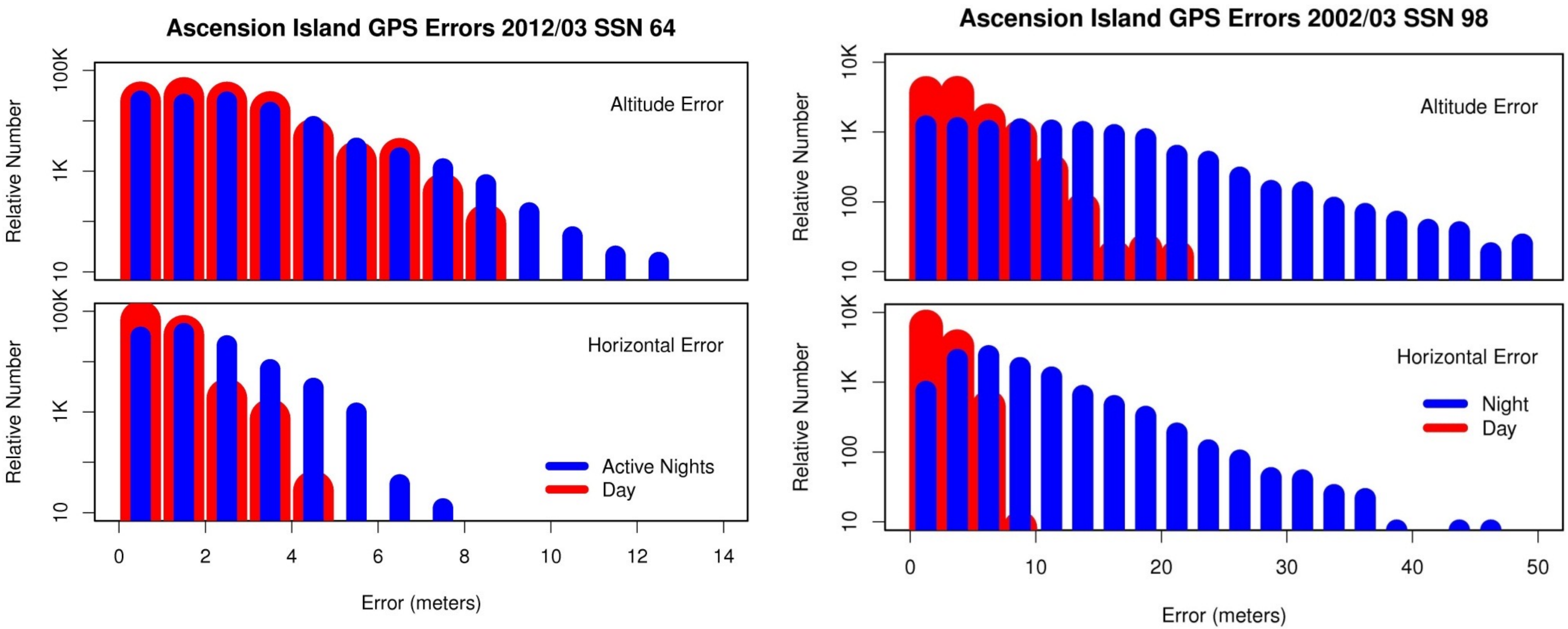
## Magnetic Latitude Dependence



# Position Errors at Ascension Island
## A Solar Cycle Perspective




- Equinox 2012 (SSN ~ ***64***) errors increased significantly during nighttime periods
- Equinox 2002 (SSN ~ ***96***) illustrates results from last solar maximum

# Where is the "GNSS"?

- Results presented here were all GPS, but in principle similar propagation effects will impact all L-band GNSS systems
  - CDMA L-band systems include GLONASS, Galileo and Beidou
  - NAVIC uses S-band and L-band—potentially less vulnerable to impact
- Two different GPS receivers will experience different performance impacts in detail, so feel confident that the different GNSS systems will respond differently to scintillated signals
- Research on other constellations is needed

# Summary

- Scintillation impacts the performance of both single and dual-frequency GNSS receivers
- Depends on two essential ingredients:  electron density and irregularities
- Prevalent in the post-sunset equatorial region and at high latitudes, but may have greatest impact at mid-latitudes during storm periods
- Fortunately, where scintillation is the most severe (low latitudes) it may also be the most predictable
- Results presented here were all GPS, but similar propagation effects will impact all L-band GNSS systems

# Thank you for your attention