Extreme Space Weather During Quiet Solar Conditions: Dynamics of the Low-Latitude Ionosphere

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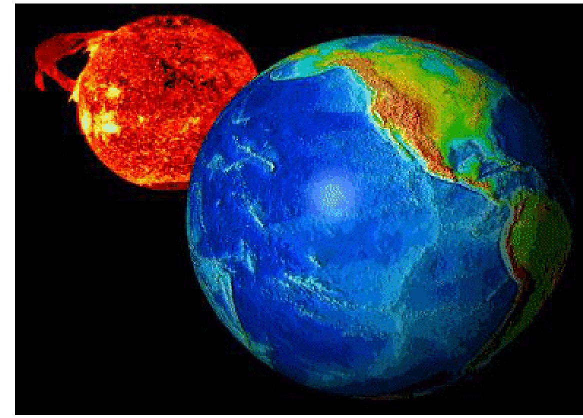
UN-ISWI Workshop on Space Weather: Science and Applications
Vikram Sarabhai Space Centre of the Indian Space Research Organization

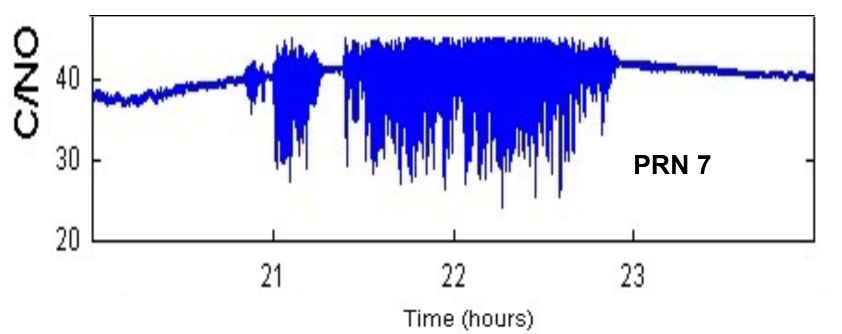
2 - 3 November 2021

Overview

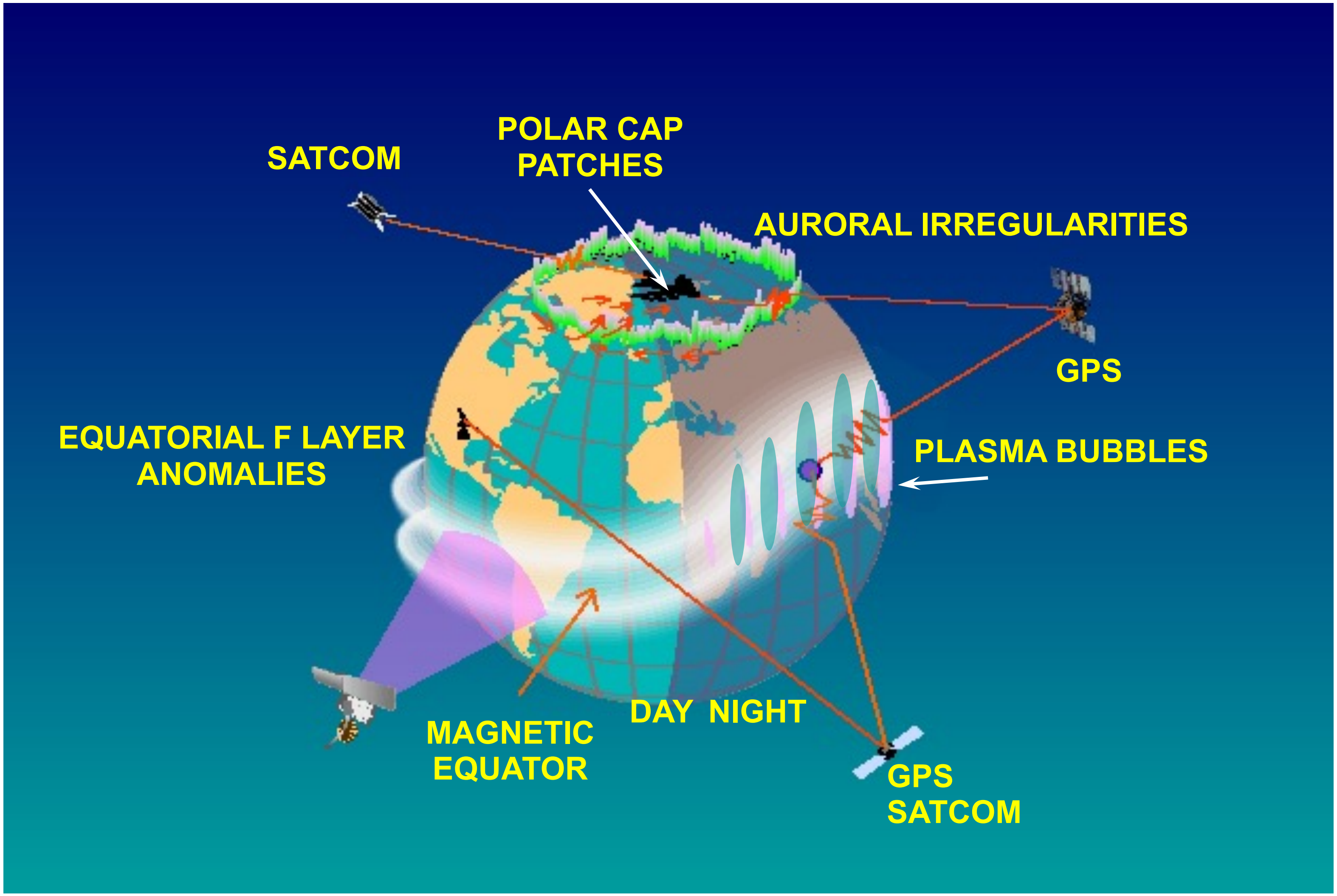
- Most space weather impacts are driven by impulsive energetic events on the sun
- However, at low latitudes, the strongest electron densities irregularities in the ionosphere form routinely due to internal ionosphere-thermosphere coupling with no solar excitation



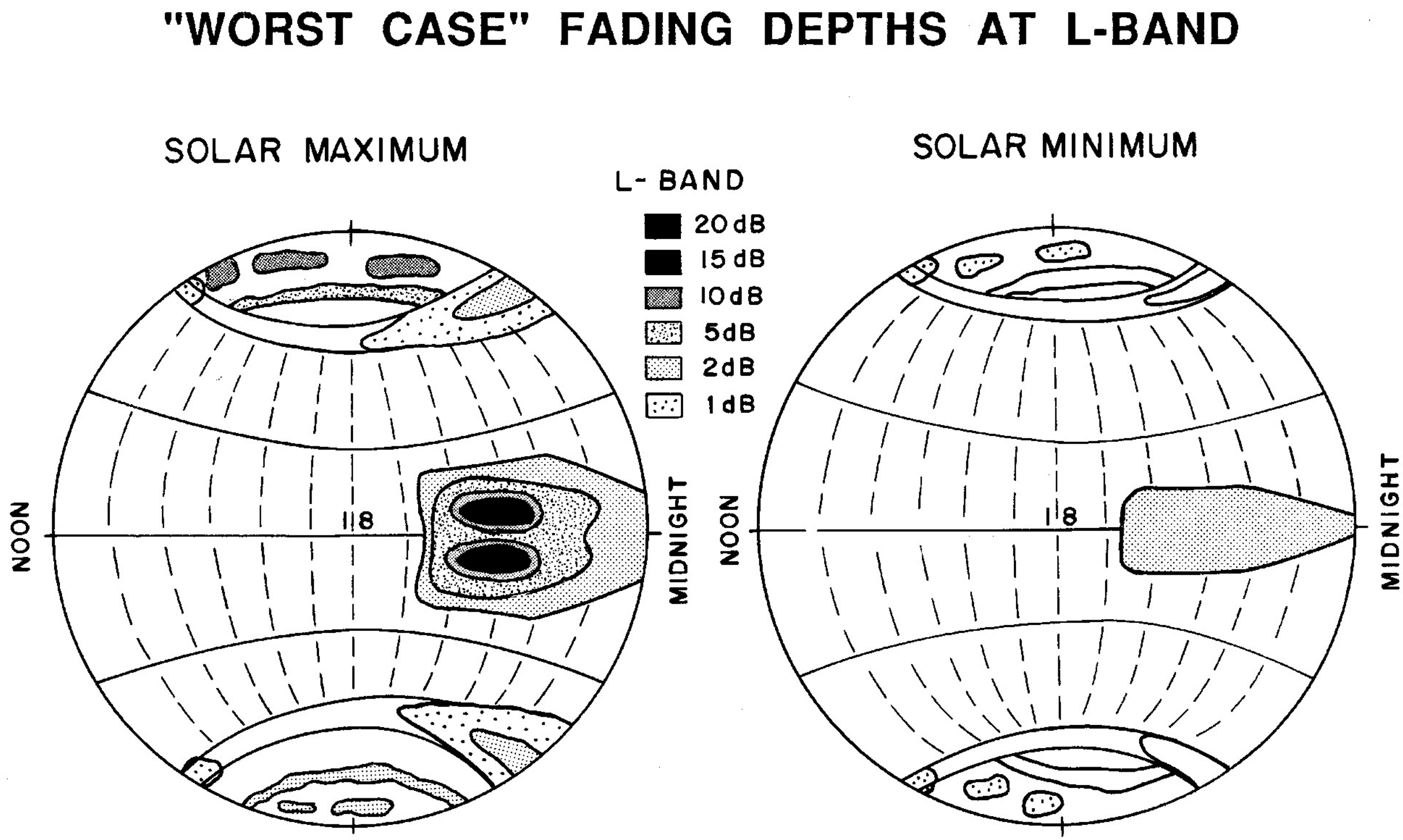
- Instabilities are driven by the action of the neutral wind, electron density gradients at sunset and the horizontal magnetic field at the equator
- The processes are actually suppressed during magnetic storms
- We care because the irregularities cause strong scintillation of radio waves critical to space-based communications and navigation systems



Disturbed Ionospheric Regions and Systems Affected by Scintillation



Global Morphology

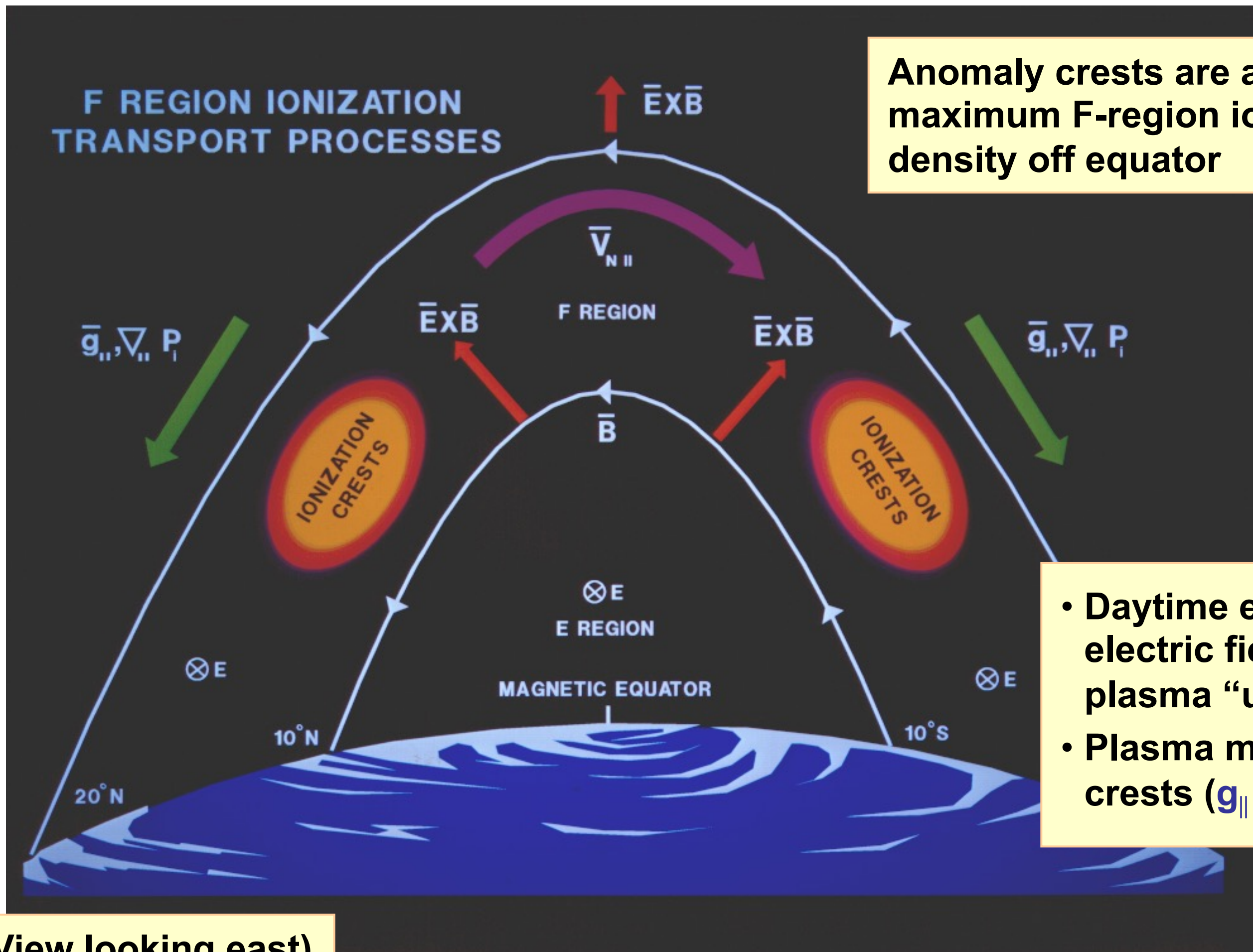


[After Basu, et al., 2005]

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 ($g_{\parallel}$, $\nabla_{\parallel} P_{\parallel}$)**

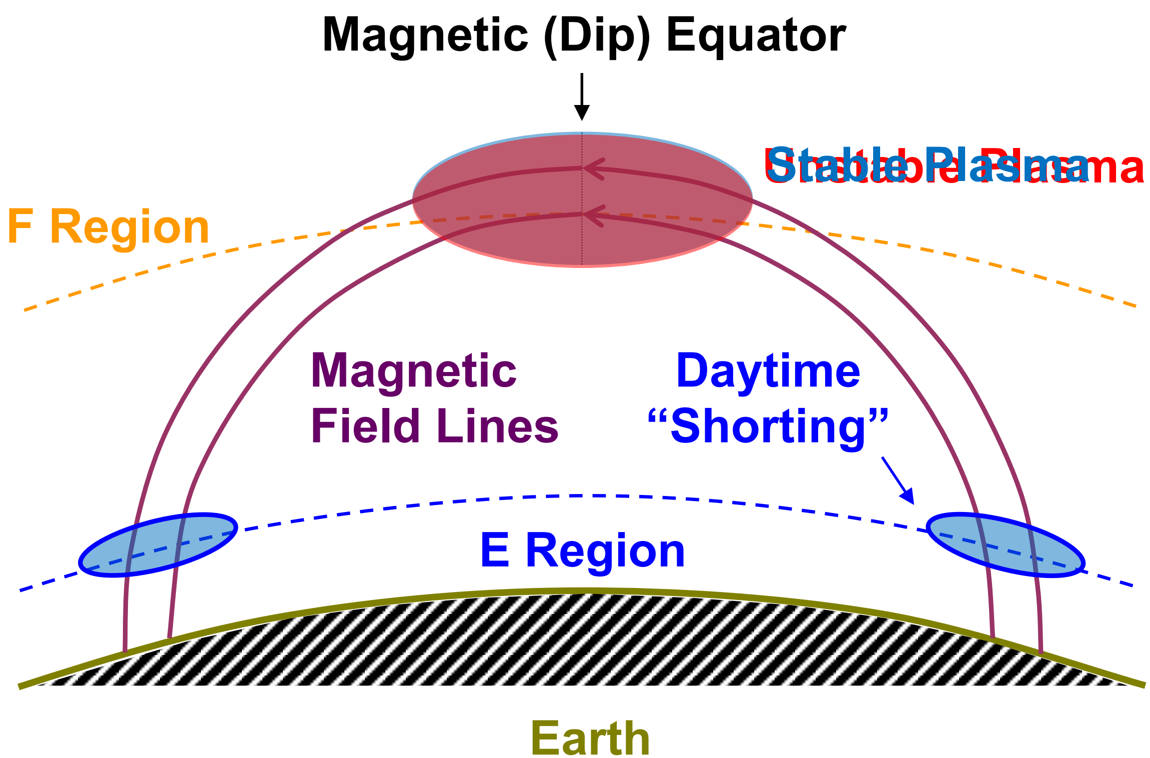
(View looking east)

Why Do Disturbances Form?

Unique Equatorial Magnetic Field Geometry

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

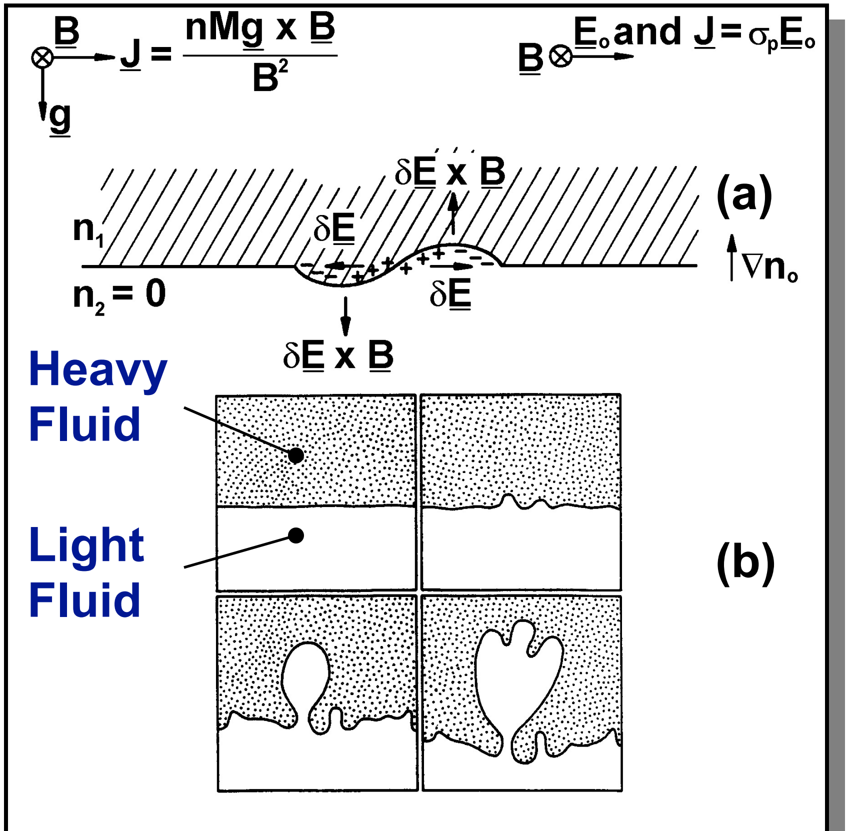
- Plasma moves easily along field lines, which act as conductors
- Horizontal field lines support plasma against gravity– unstable configuration
- E-region "shorts out" electrodynamic instability during the day



What Is Instability Process?

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)

What Controls the Instability Onset?

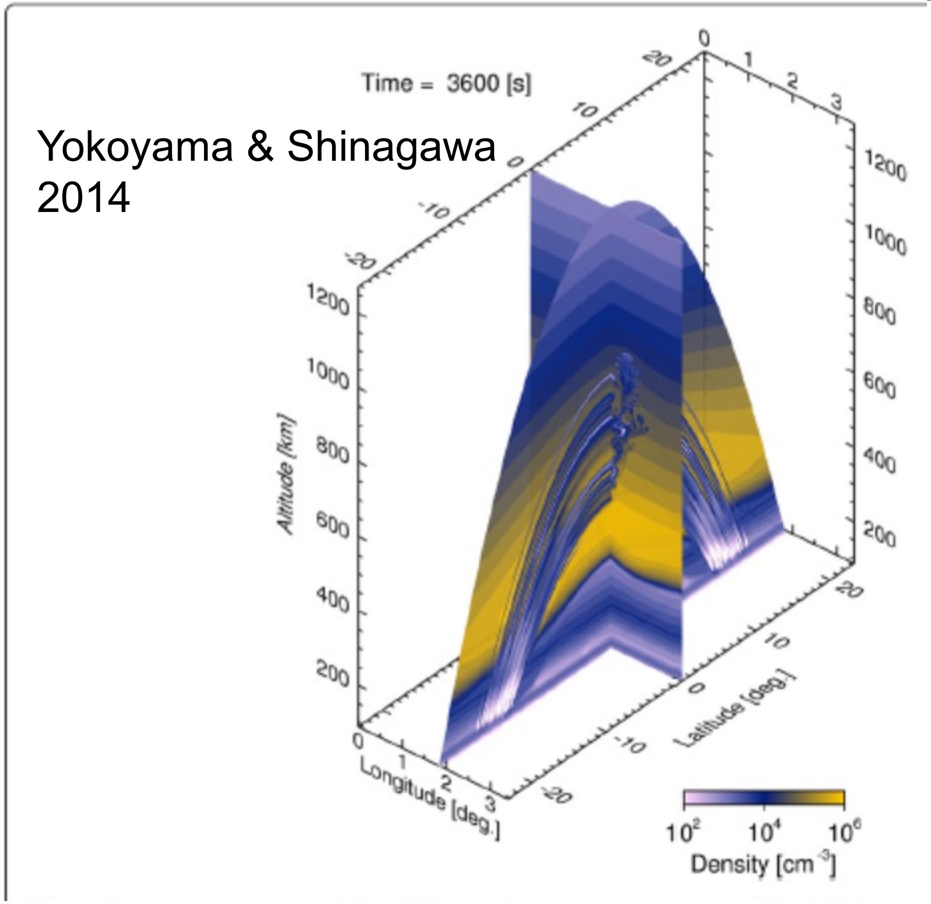
- The linear growth rate of the Rayleigh Taylor Instability (RTI) does not depend on a strong solar driver:

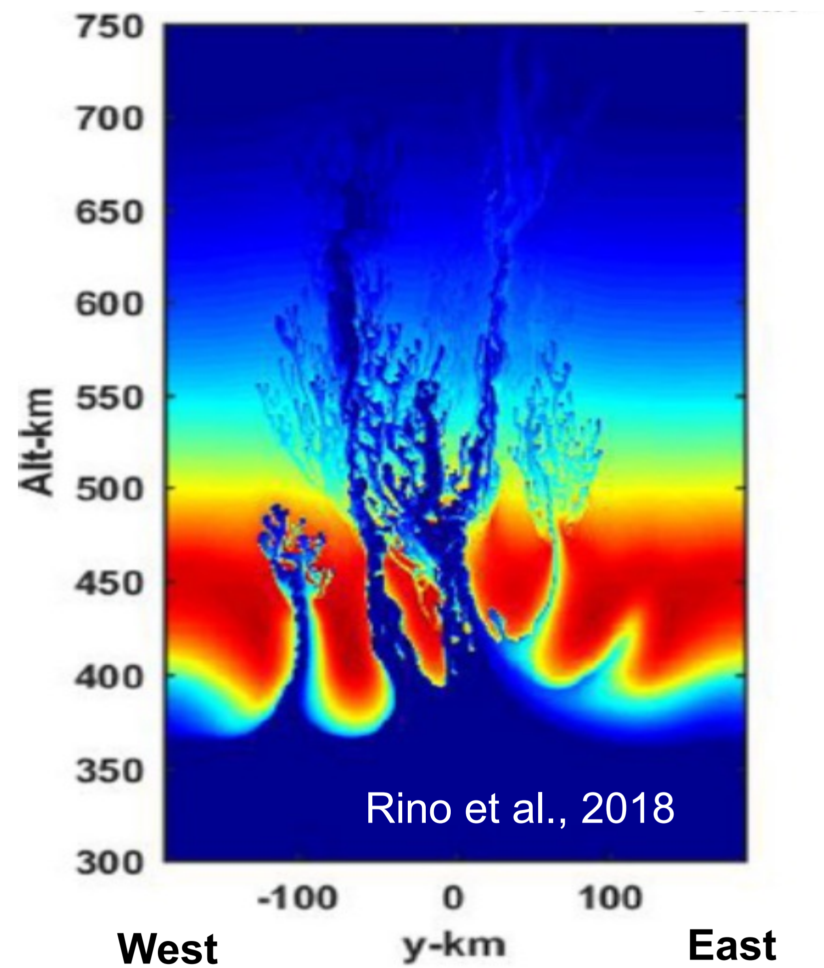
$$\gamma \approx \underbrace{\frac{\Sigma_F}{\Sigma_F + \Sigma_E}}_{\text{F-region \& E-region conductivity}} \left[\underbrace{\frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}}_{\text{vertical plasma drift}} + \underbrace{U_n}_{\text{horizontal neutral wind}} + \underbrace{\frac{g}{\nu^{eff}}}_{\text{ion-neutral collision frequency}} \right] \underbrace{\frac{1}{N}\frac{\partial N}{\partial h}}_{\text{vertical density gradient}}$$

- After sunset the first term rapidly approaches unity when the terminator is aligned with the magnetic flux tube (E-region dark on both ends of field line)
- The 2nd term becomes the primary driver in most cases; it gets a boost near sunset due to the zonal density gradient imposed by the solar terminator
- All terms can play a role depending on conditions; longitudinal differences in activity may provide important insights into the relative importance

3D Model Realizations of Bubbles

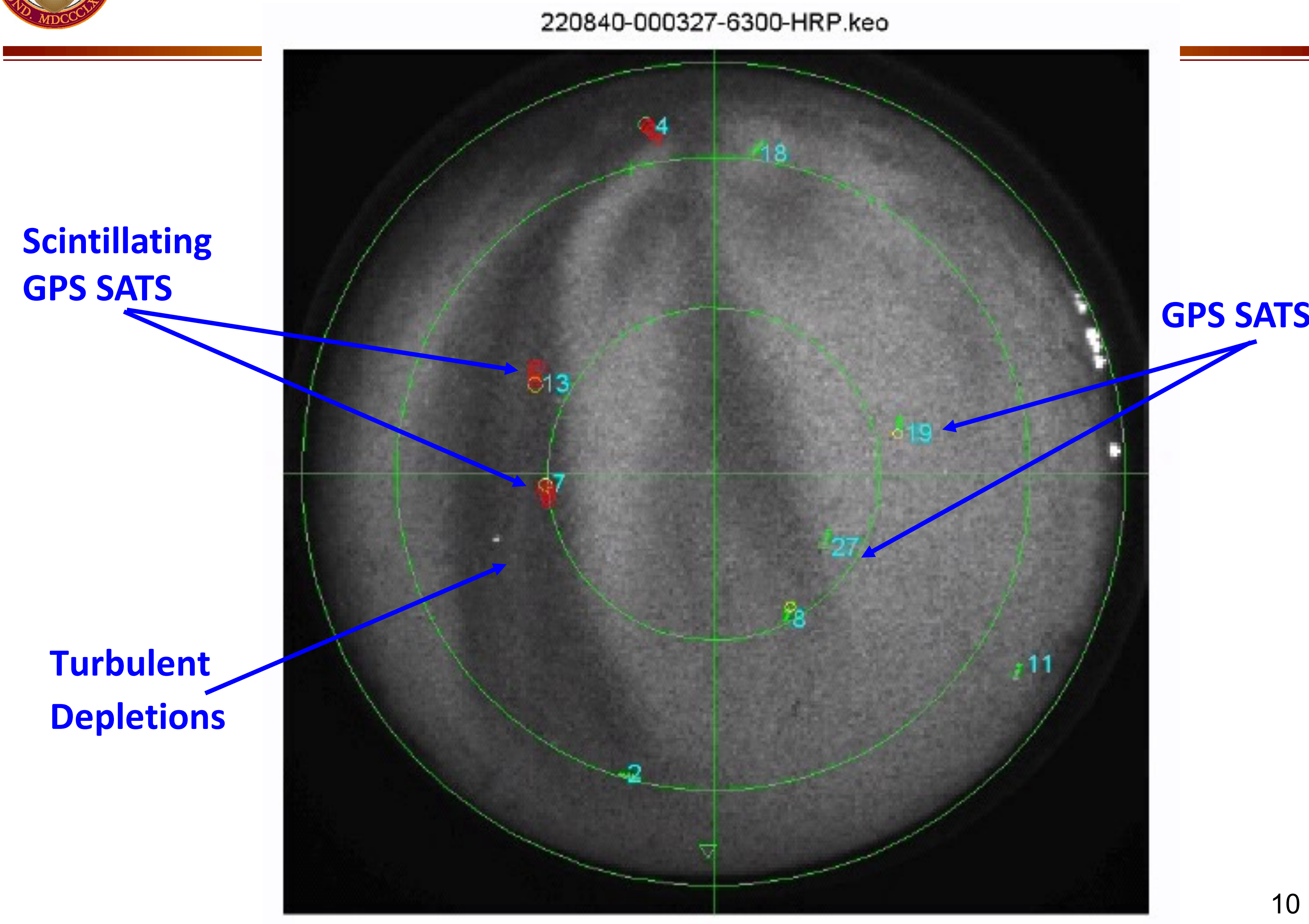
Nonlinear fluid calculations of fully developed instability





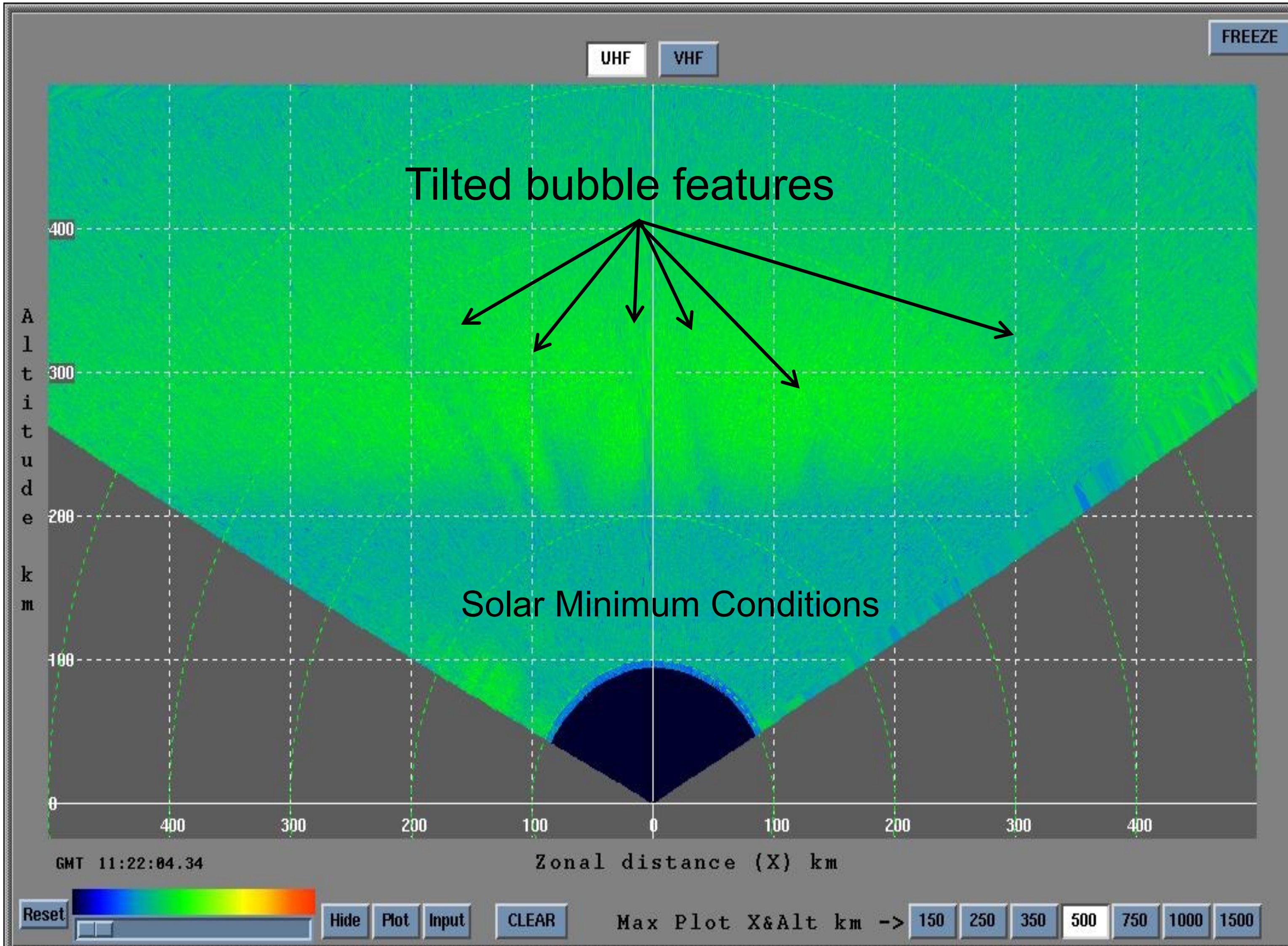
- Full fluid treatment simulations at scintillation-scale spatial resolution (~500 m)

6300Å All-sky Imagery



ALTAIR Incoherent Scatter Radar Scan

27 Sep 2008 11:22 UT



ALTAIR Coherent Scatter Radar Scan

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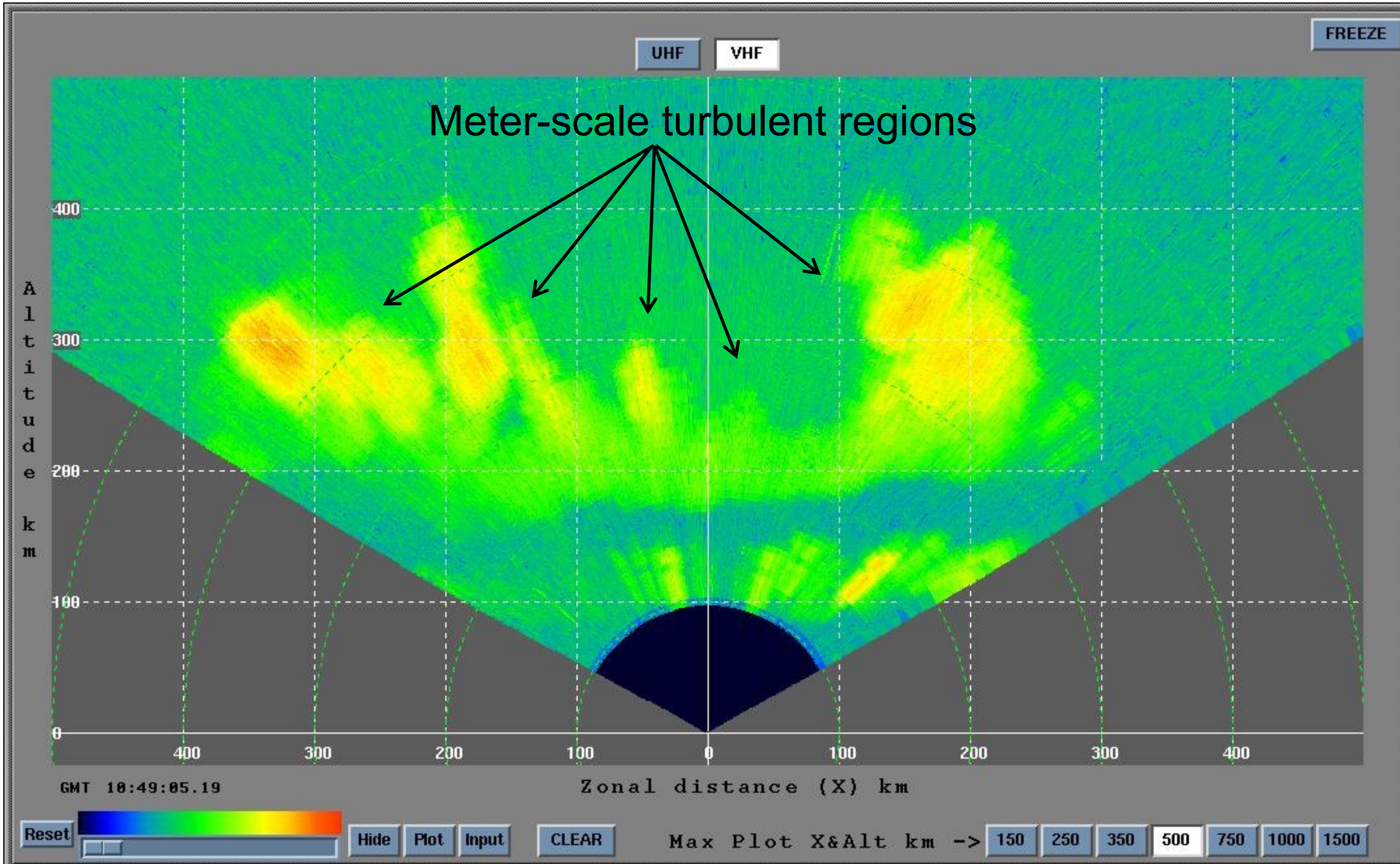
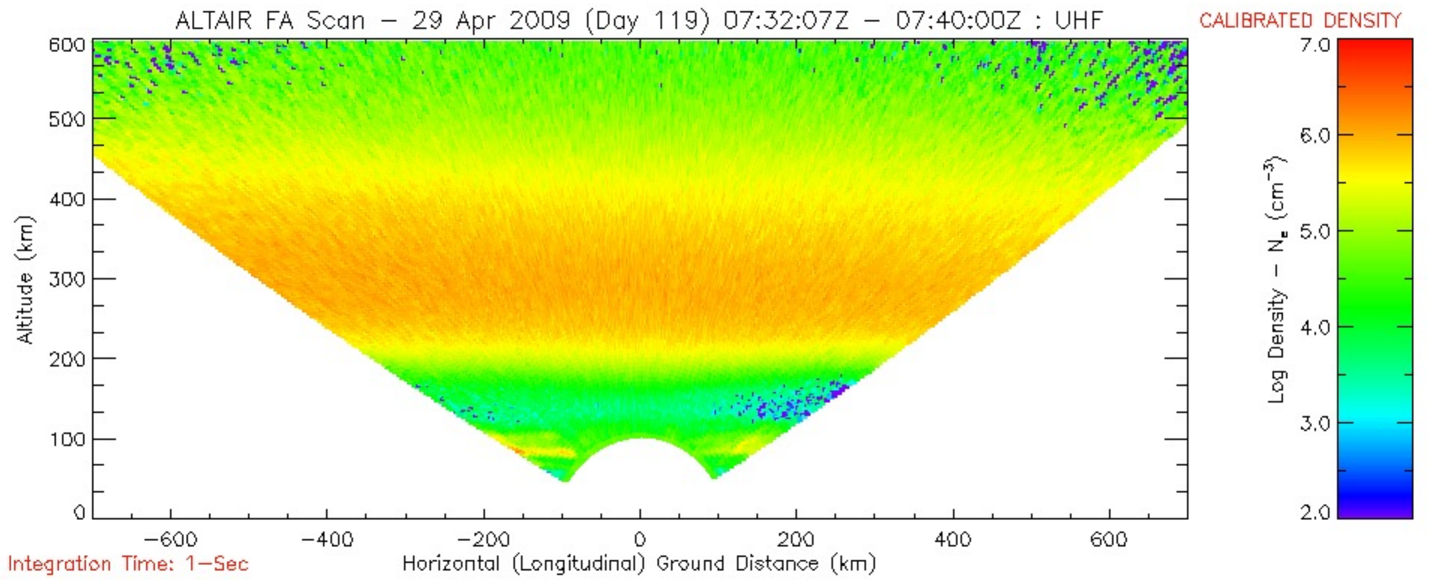
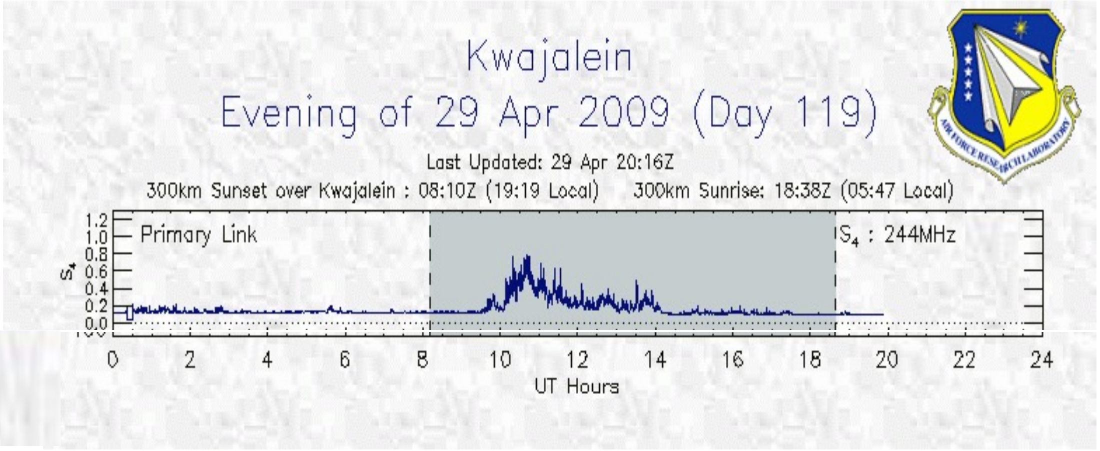


From J. M. Retterer

Campaign Summary
29 APRIL 2009 – Day 119

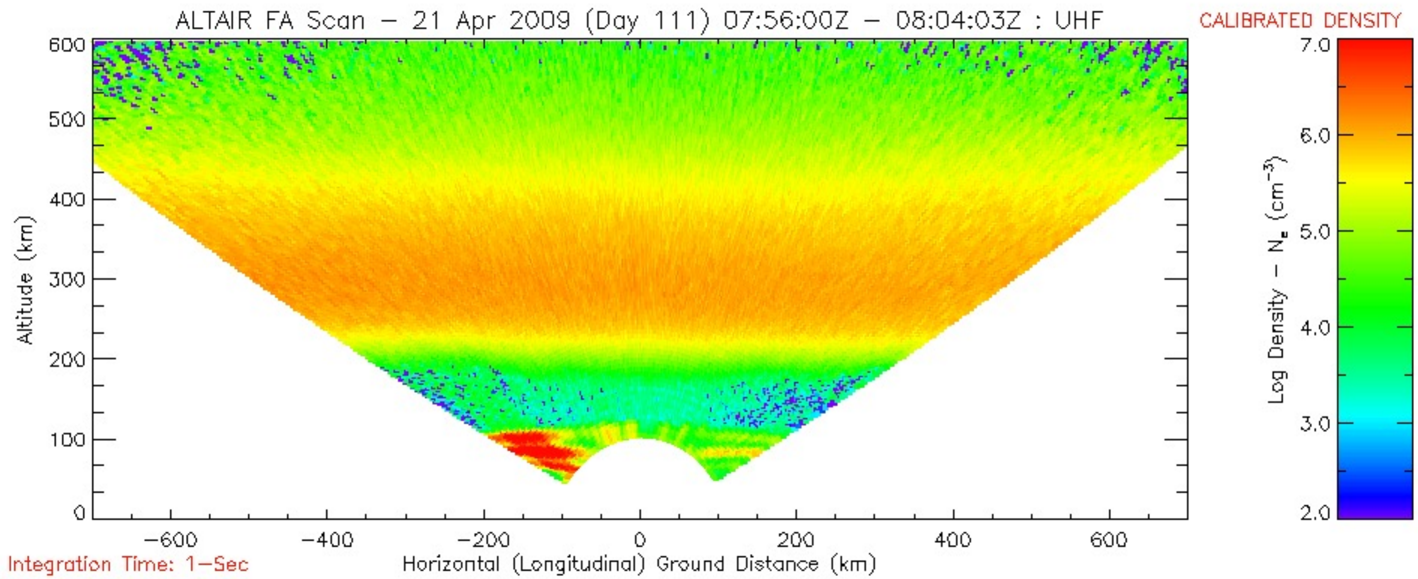
Perp-B Scan

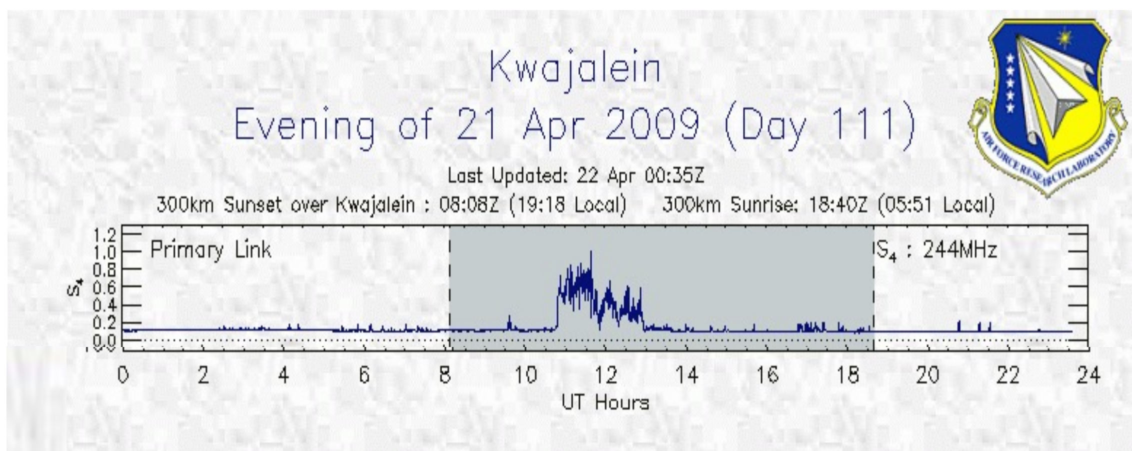




Campaign Summary
21 APRIL 2009 – Day 111

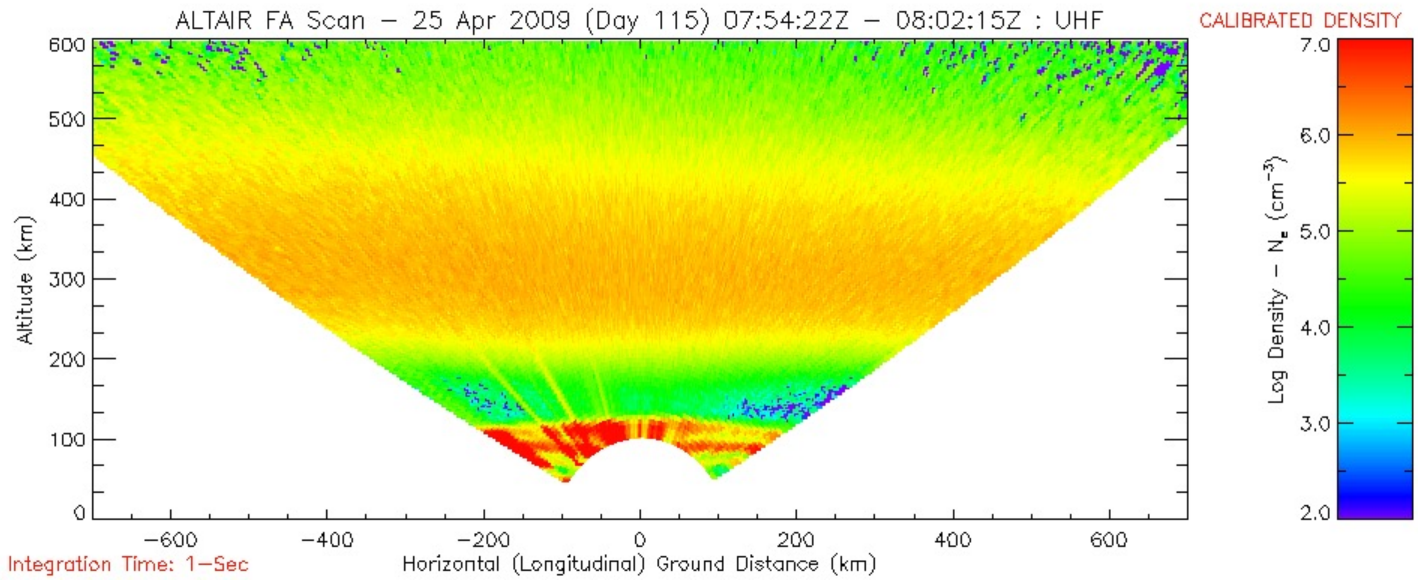
Perp-B Scan

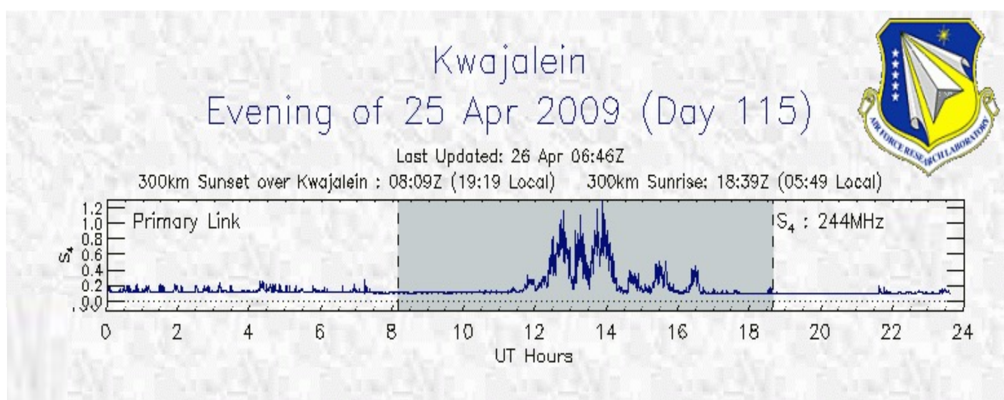




Campaign Summary
25 APRIL 2009 – Day 115

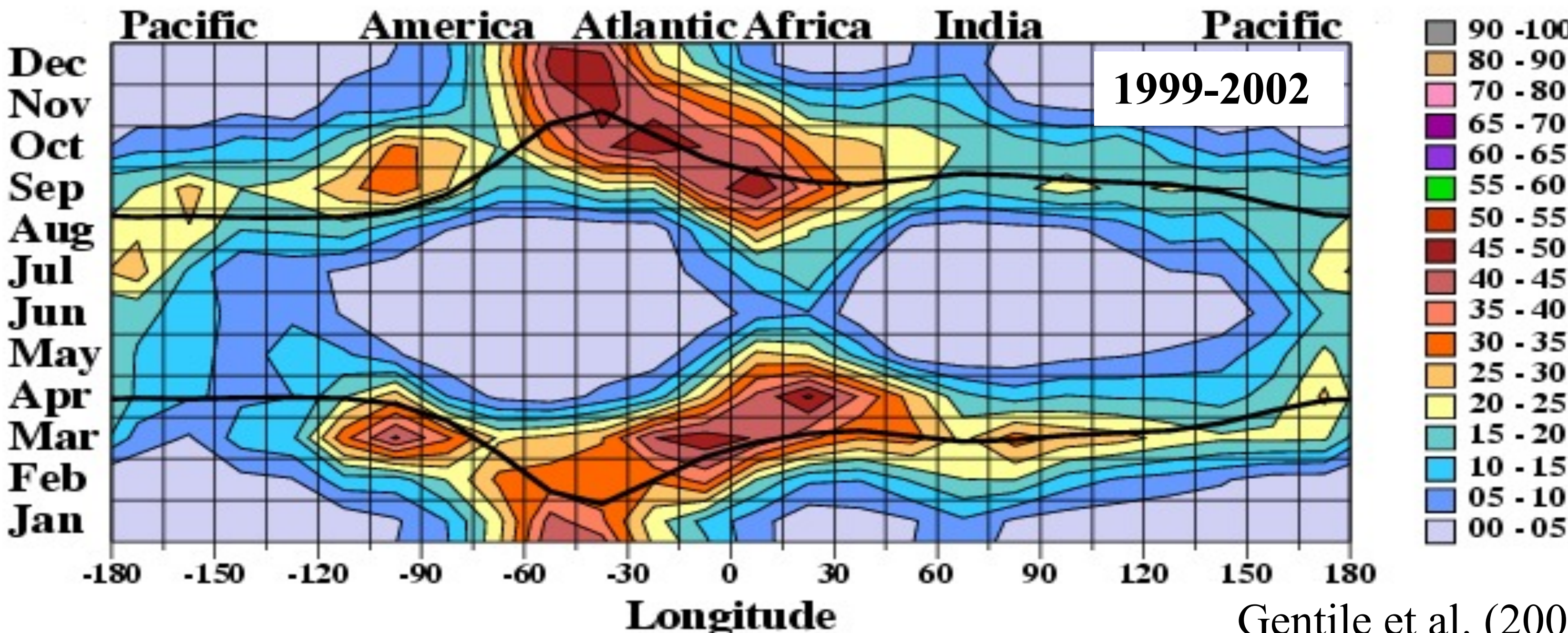
Perp-B Scan





How Routinely Occurring are the Instabilities?

DMSP Observations Solar Cycle 23



Gentile et al. (2006).

- Peak occurrence rates ≥ 50% were observed during active periods in the American-African longitude sectors
- This sensor only samples bubbles higher than ~825 km (underestimates actual occurrence percentage by as much as 50%); bubble height is a function of longitude—detection rates outside the American sector will be less accurate
- During solar minimum very low detection rates were observed due to a combination of lower bubble occurrence and lower bubble altitudes.

Scintillation Physics Simple Picture

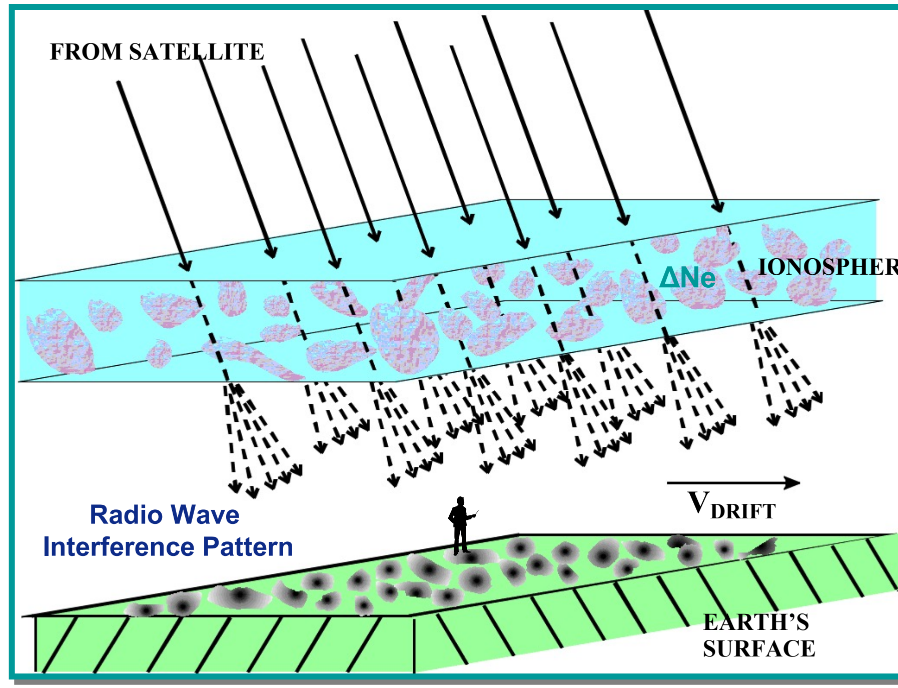
$$\tau_d = R/c + \frac{r_e c}{2\pi}\frac{N_{tot}}{f^2}$$

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

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

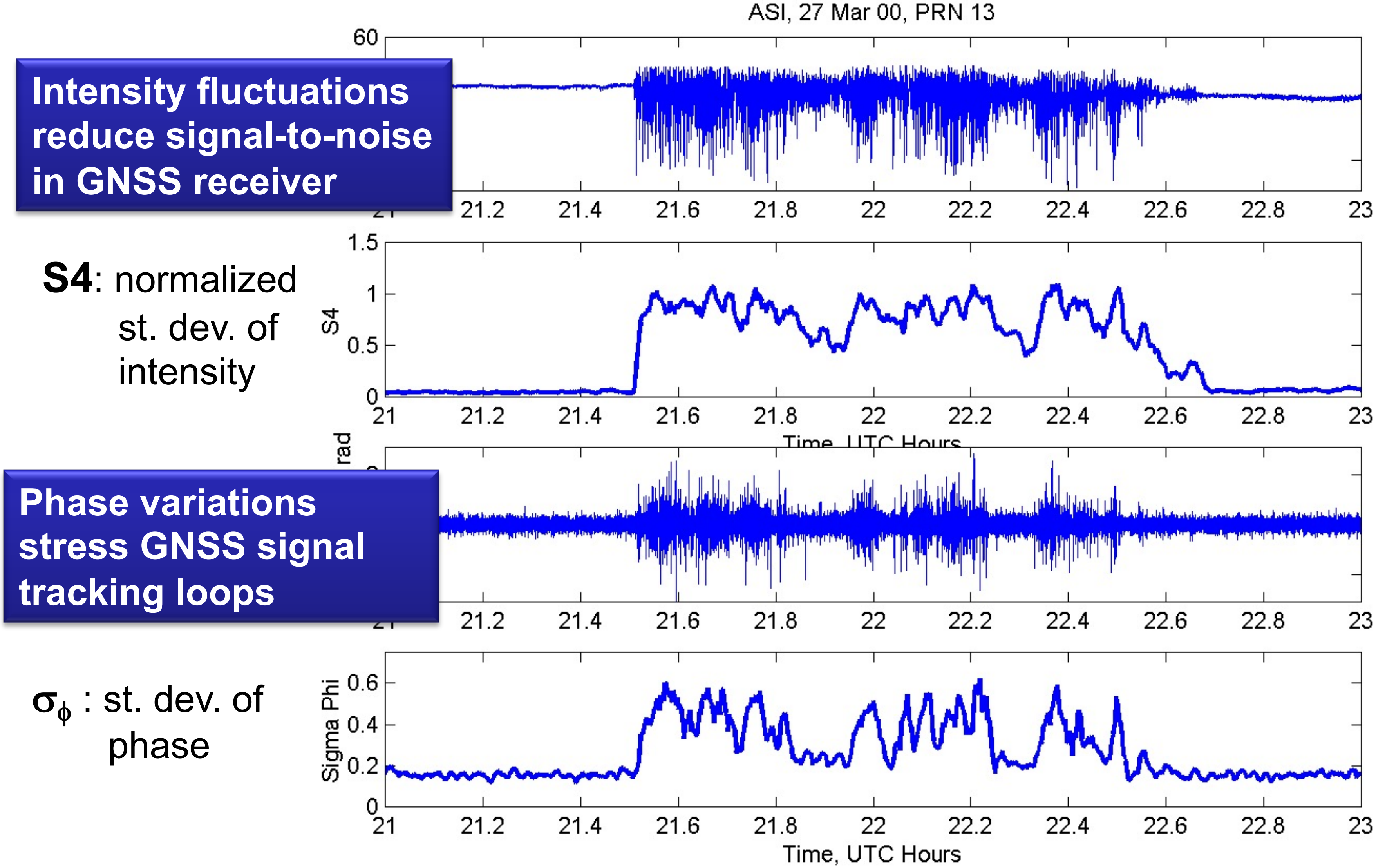
Phase change due to ionized layer

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



- 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)

GPS Signal Fluctuations Caused by Ionospheric Scintillation



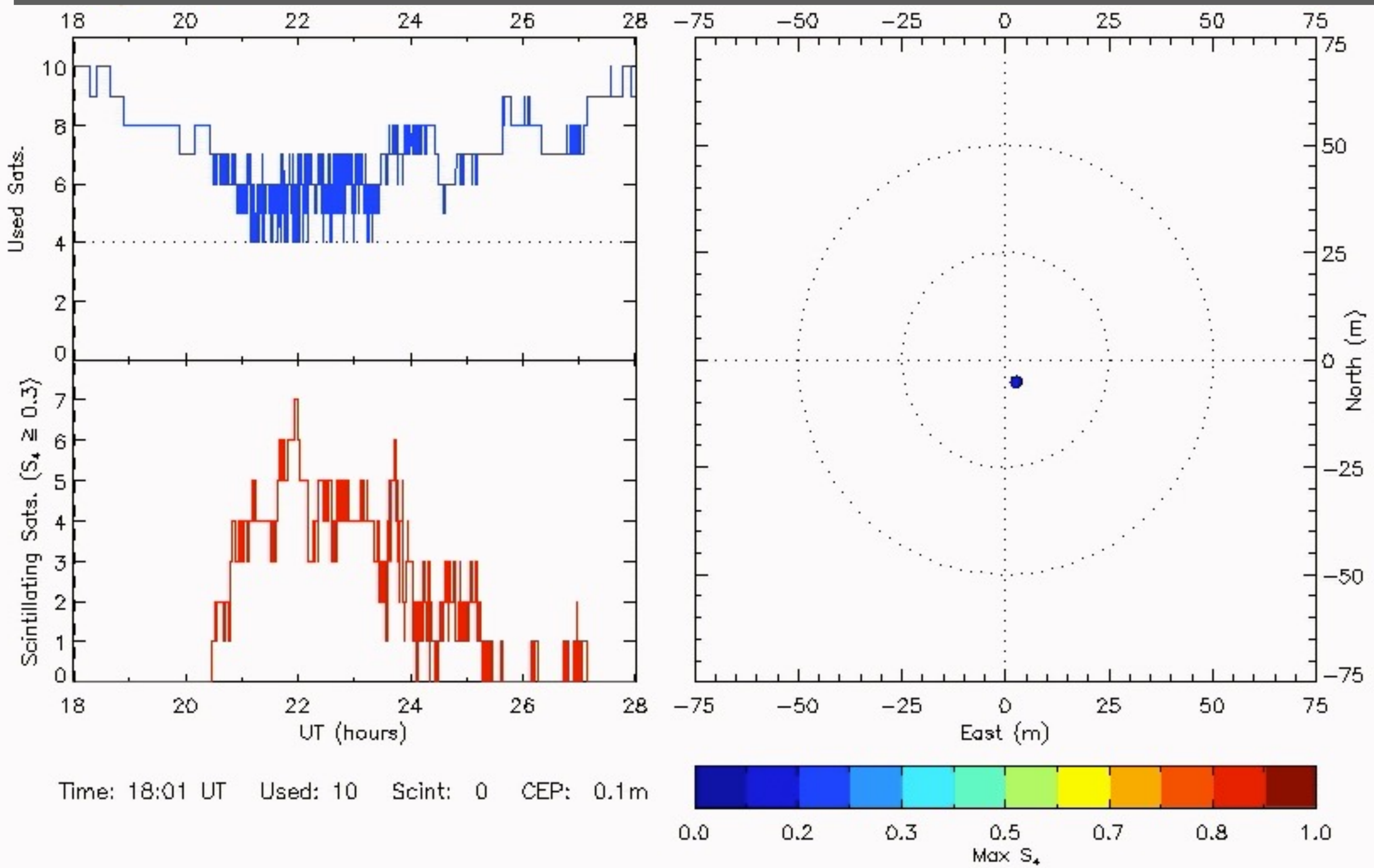
S4: normalized st. dev. of intensity

σ_ϕ : st. dev. of phase

GPS Positioning Errors During Solar Max

Scintillation can cause rapid fluctuations in GPS position fix

Typical night from field experiments during solar maximum



Summary

- Instabilities occur routinely at low magnetic latitudes affecting nearly ½ the earth's surface in the absence of eruptive solar events and magnetic storms
- The instabilities produce small-scale irregularities that can generate strong scintillation affecting frequencies from HF to L-band (solar maximum)
- Numerous scintillation-induced GNSS performance impacts have been observed and documented during solar maximum periods
- Although the instabilities occur routinely and the source mechanisms and evolution are largely understood, the ability to make nightly forecasts of such activity more than ~2 hrs in advance remains elusive
- While some relatively robust physical models exist, our ability to specify the initial state of the ionosphere/thermosphere is inadequate—we simply cannot determine the ionized and neutral atmospheres' densities and drifts with sufficient resolution and coverage to give the models a chance

Thank you for your attention!