The Abdus Salam
International Centre for Theoretical Physics

2333-28

Workshop on Science Applications of GNSS in Developing Countries (11-27 April), followed by the: Seminar on Development and Use of the Ionospheric NeQuick Model (30 April-1 May)

11 April - 1 May, 2012

Ionospheric Irregularities and their Impacts on GPS

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Ionospheric Irregularities and their Impacts on GPS

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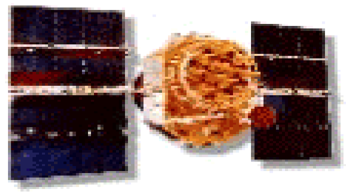
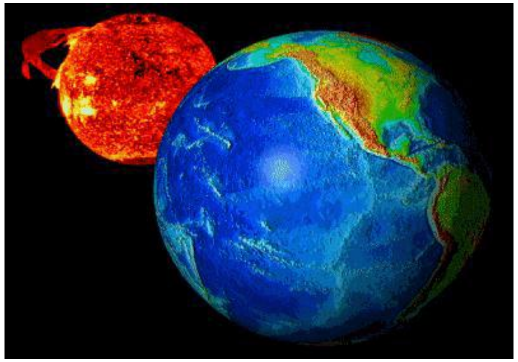
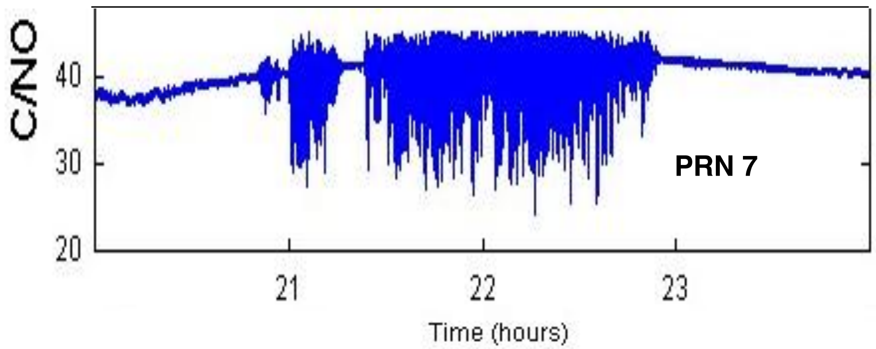
Workshop on Science Applications of GNSS in Developing Countries
11-27 April 2012

OUTLINE





- Ionospheric effects on propagation
- Scintillation environment
- Modeling impacts on GPS
- Conclusions



A short review of plasma physics

Nominal dielectric permittivity in "smooth" ionosphere

$$\langle \varepsilon \rangle = \left(1 - \frac{f_p^2}{f^2} \right) \varepsilon_o \qquad f_p^2 = \frac{e^2 N}{m_e \varepsilon_o}$$

Linearized description when weak density fluctuations are present

$$\varepsilon = \langle \varepsilon \rangle \left(1 + \varepsilon_1 (r, t)\right) = \varepsilon_o \left[\left(1 - \frac{f_p^2}{f^2} \right) + \left(\frac{f_p^2}{f^2} \right) \frac{\Delta N}{N} \right]$$

Putting in some numbers:

$$f_p \approx 10 \times 10^6 \; Hz$$

$$f = 1.575 \times 10^9 \; Hz$$

$$\Delta N / N \approx 0.10$$

$$\varepsilon = \varepsilon_o \underbrace{\left[1 - 4 \times 10^{-5} + 4 \times 10^{-6} \right]}_{\approx 1!}$$

Let's look at the integrated effect…

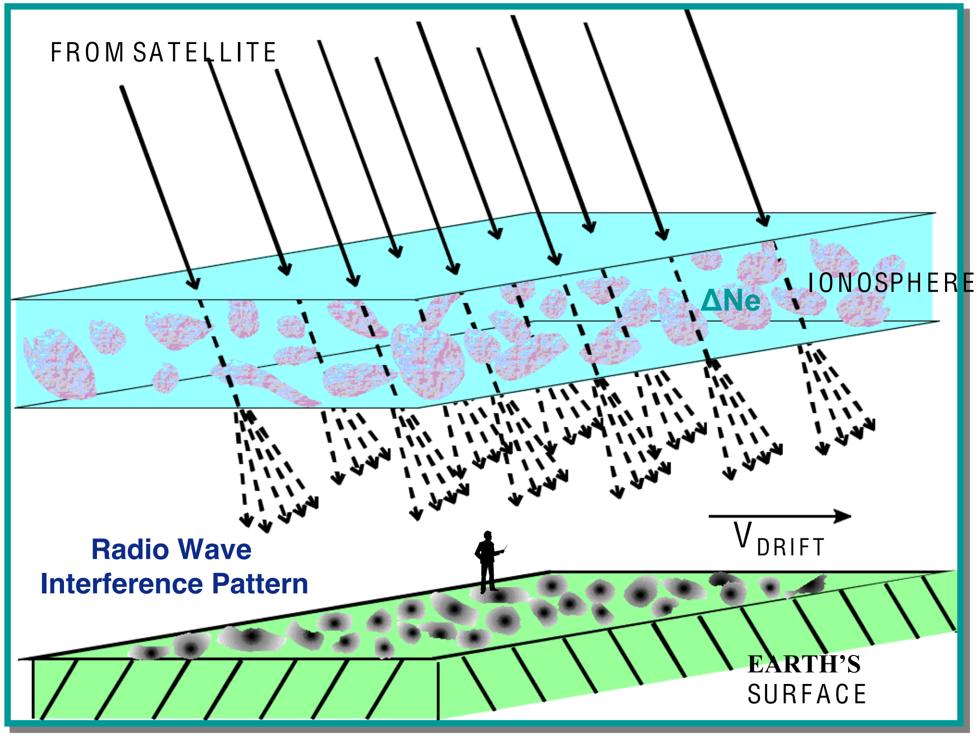
$$\tau_d = R/c + \frac{r_e c}{2\pi}\frac{N_{tot}}{f^2}$$

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

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

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)

Amplitude Scintillation & the Fresnel Scale

S4 and σ_φ can be related to physical parameters through phase screen theory (Rufenach, 1972; Rino, 1979), shown in simplified form below:

$$\sigma_\phi = \frac{K}{f^2}\int \left\langle \Delta N^2 \right\rangle GF\left(k_N,\, p_N\right) dk$$

$$S4^2 = \frac{K'}{f^2}\int \left\langle \Delta N^2 \right\rangle GF\left(k_N,\, p_N\right)\sin^2(k_r / k_f)^2\, dk$$

where $k_r^2 = k_x^2 + k_y^2$ $\quad$ $k_f^2 = 4\pi / \lambda z$

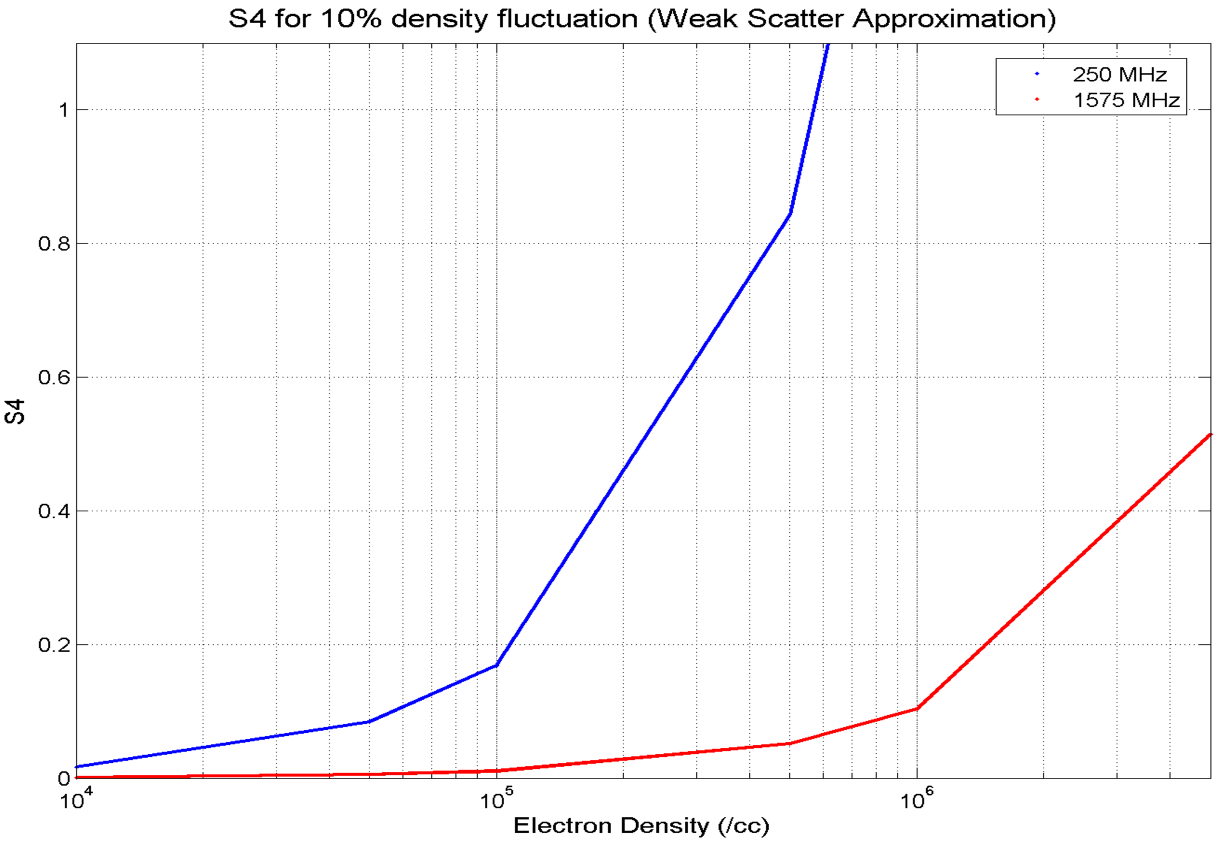
Intensity scintillation (*S*4) has vanishing contribution for irregularity scale sizes greater than the so-called Fresnel scale, $F_r = \sqrt{2\lambda z}$

where λ is the radio signal wavelength and *z* is the distance from the observer to the ionospheric phase screen (~350 km or more).

For GPS L1 frequency, F_r is typically 400-500 meters; density fluctuations larger than this scale size will not cause GPS amplitude scintillations.

Effect of Electron Density on S4

- 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)
- Density during post-midnight hours frequently too low



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

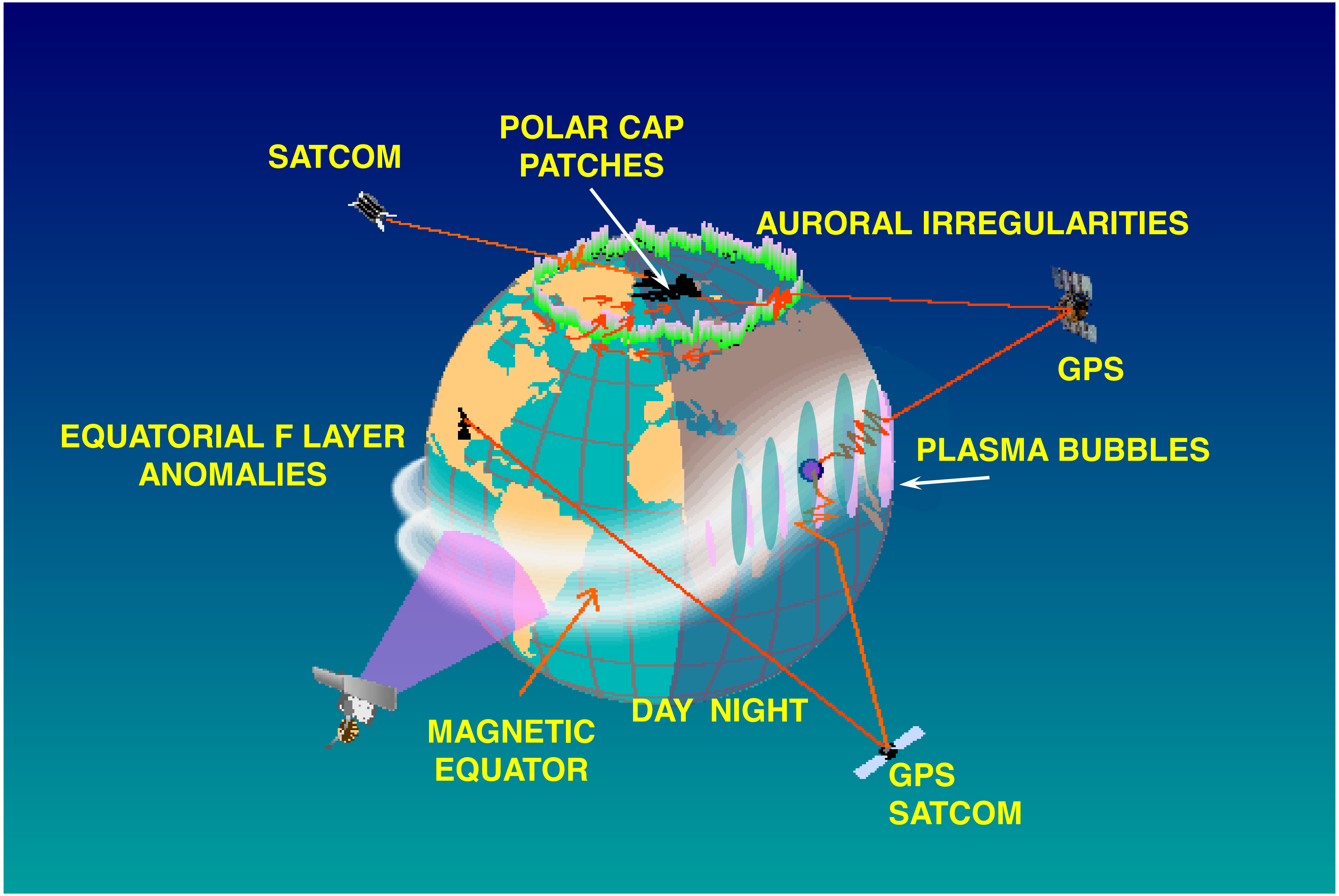
Weak Scatter Approximation

Implications for the Ionosphere

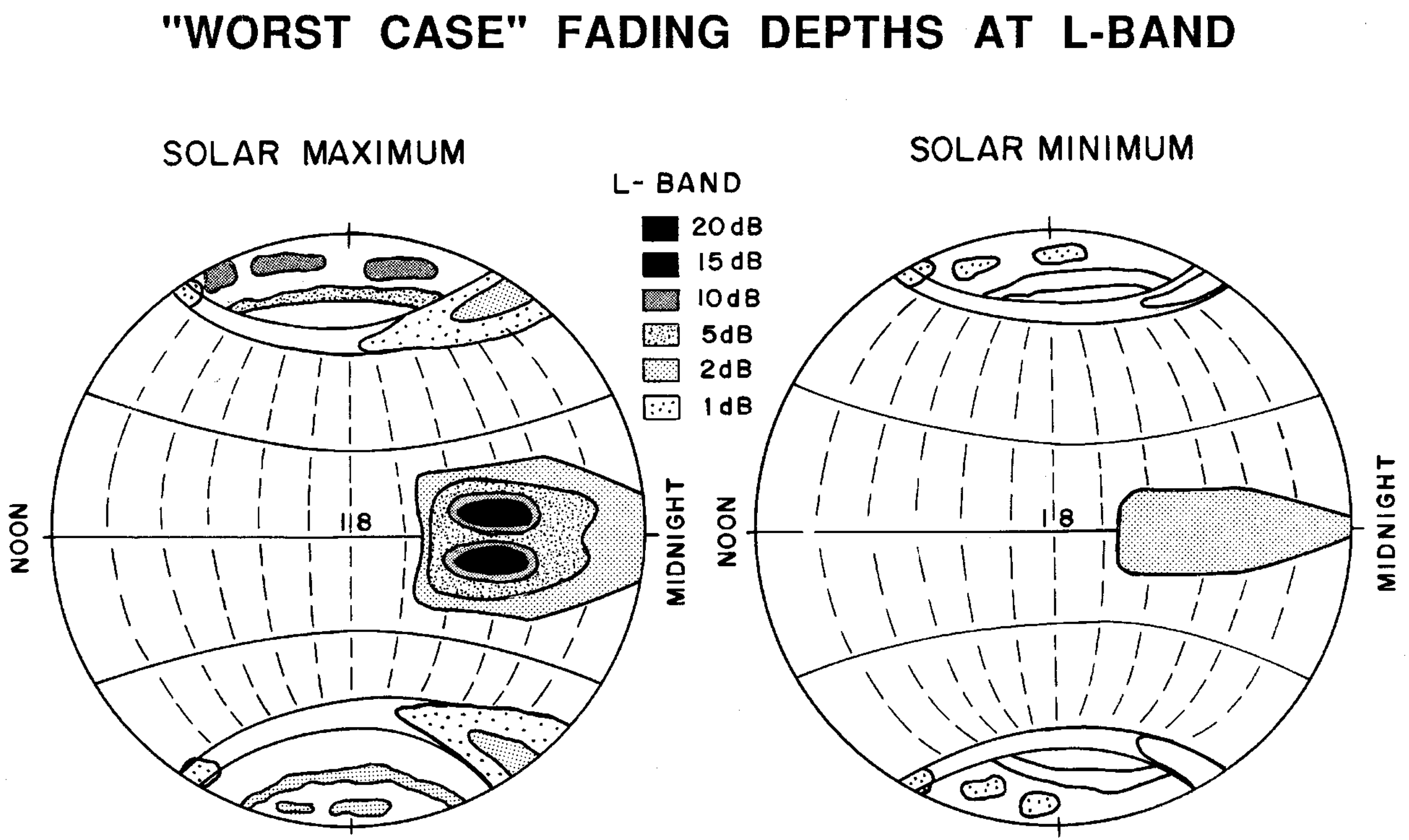
So that means at L1 we need ~0.6 TEC unit variations over spatial scales of a few 100 meters to achieve strong scintillation; lesser variations will cause correspondingly weaker intensity fluctuations

- Solar max TEC ~ 50-100
  - Small relative density fluctuations required
- Solar min TEC ~ 1-5 (nighttime)
  - Large relative density fluctuations required
- 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)

Disturbed Ionospheric Regions and Systems Affected by Scintillation

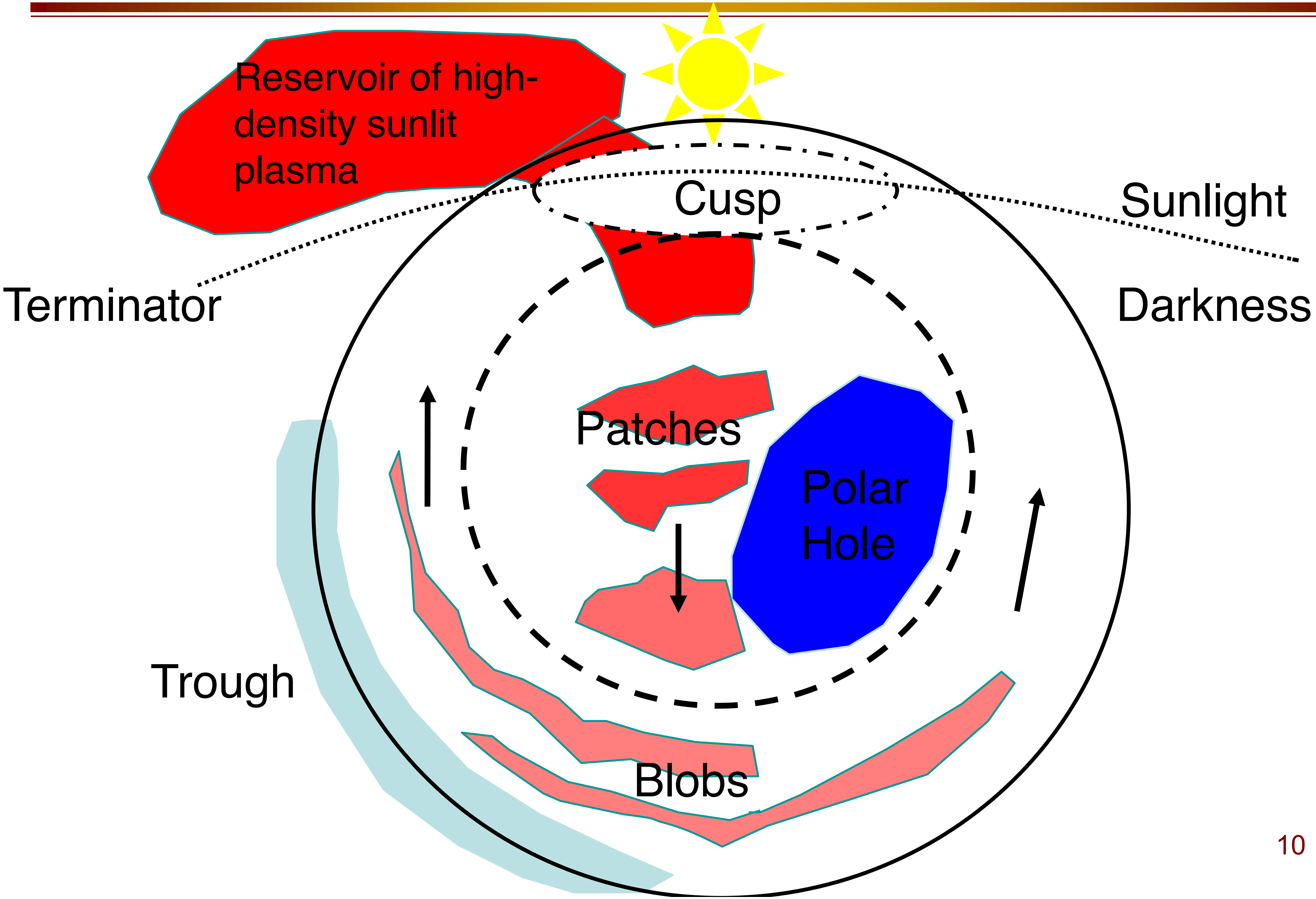


Global Morphology

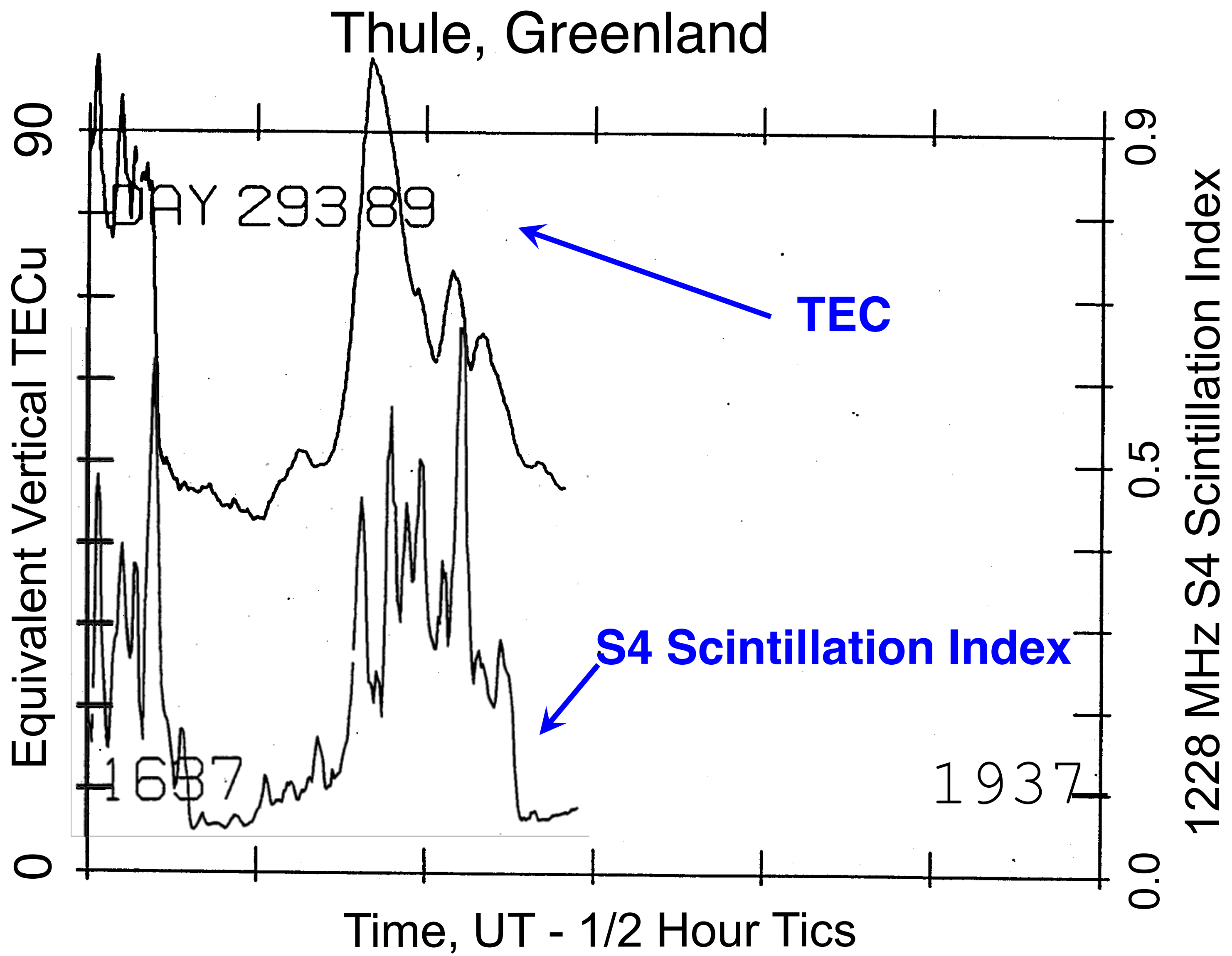


[After Basu, et al.]

Polar Ionosphere Density Regimes
(Winter, Bz < 0)

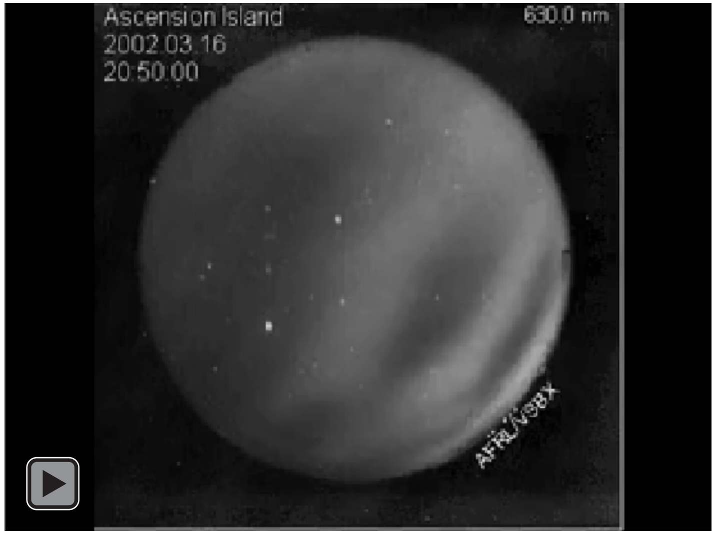


TEC Fluctuations and Scintillation during Patch Events



Bishop, et al.

Equatorial Scintillation vs Polar



movies

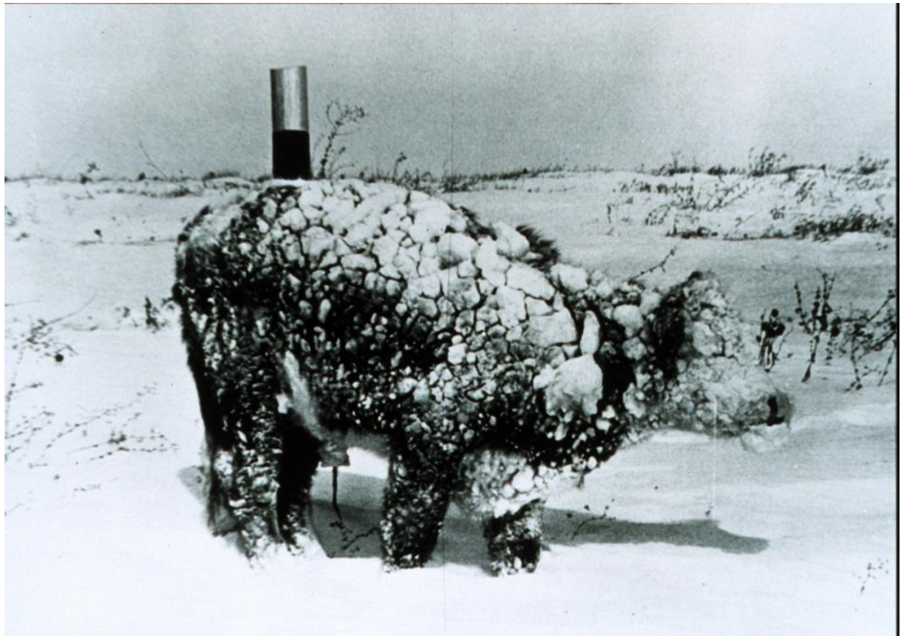
EQUATOR

- Well-ordered zonal progression after instability develops
- Modest drift velocities (~100 m/sec)
- Macro-scale changes relatively slowly

POLAR

- Chaotic development & evolution
- Large drift velocities (~>1 km/sec)
  - Much larger spatial scales affect signal raypaths
- Driven by external forcing (magnetosphere) difficult to predict

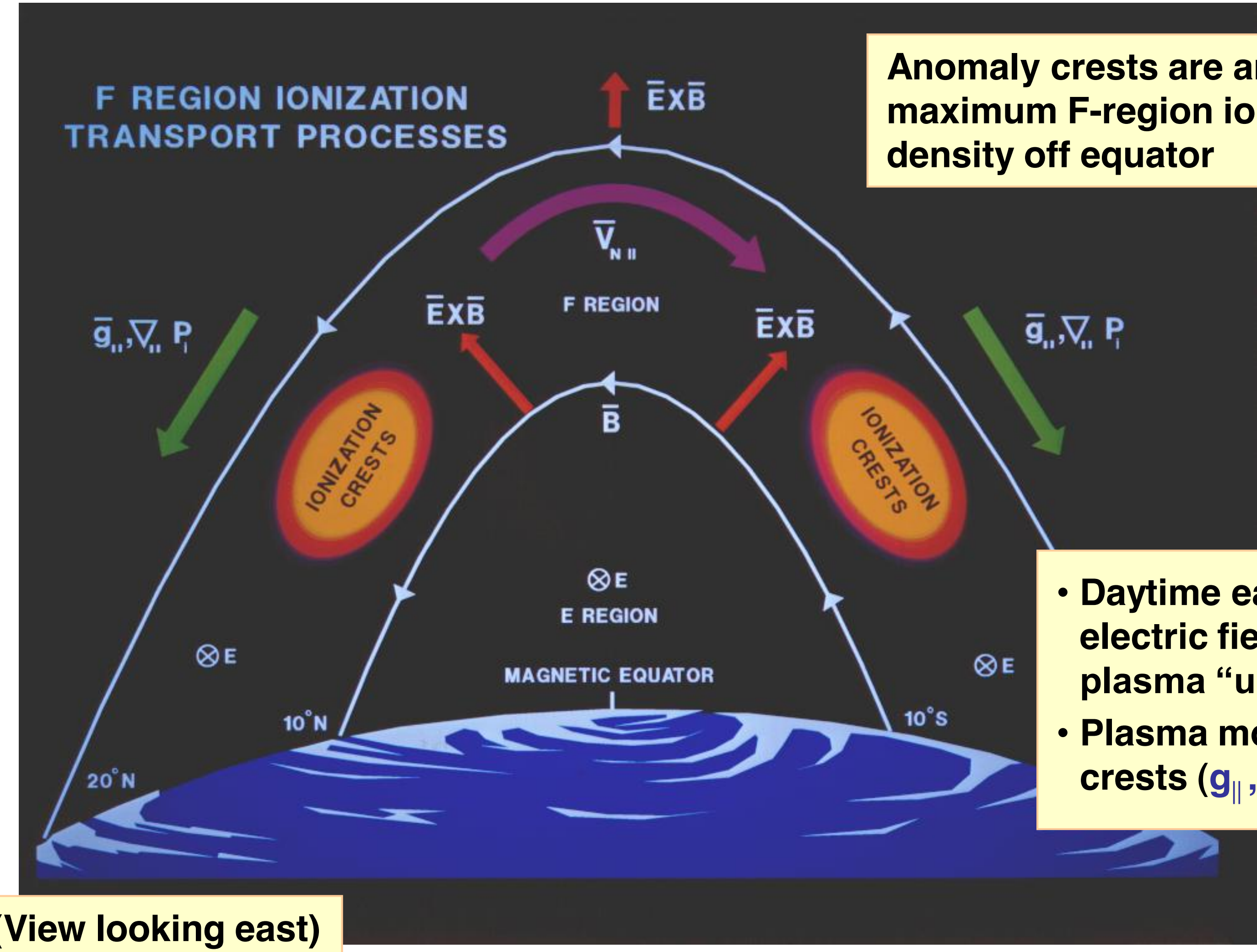
Equatorial Scintillation vs Polar



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

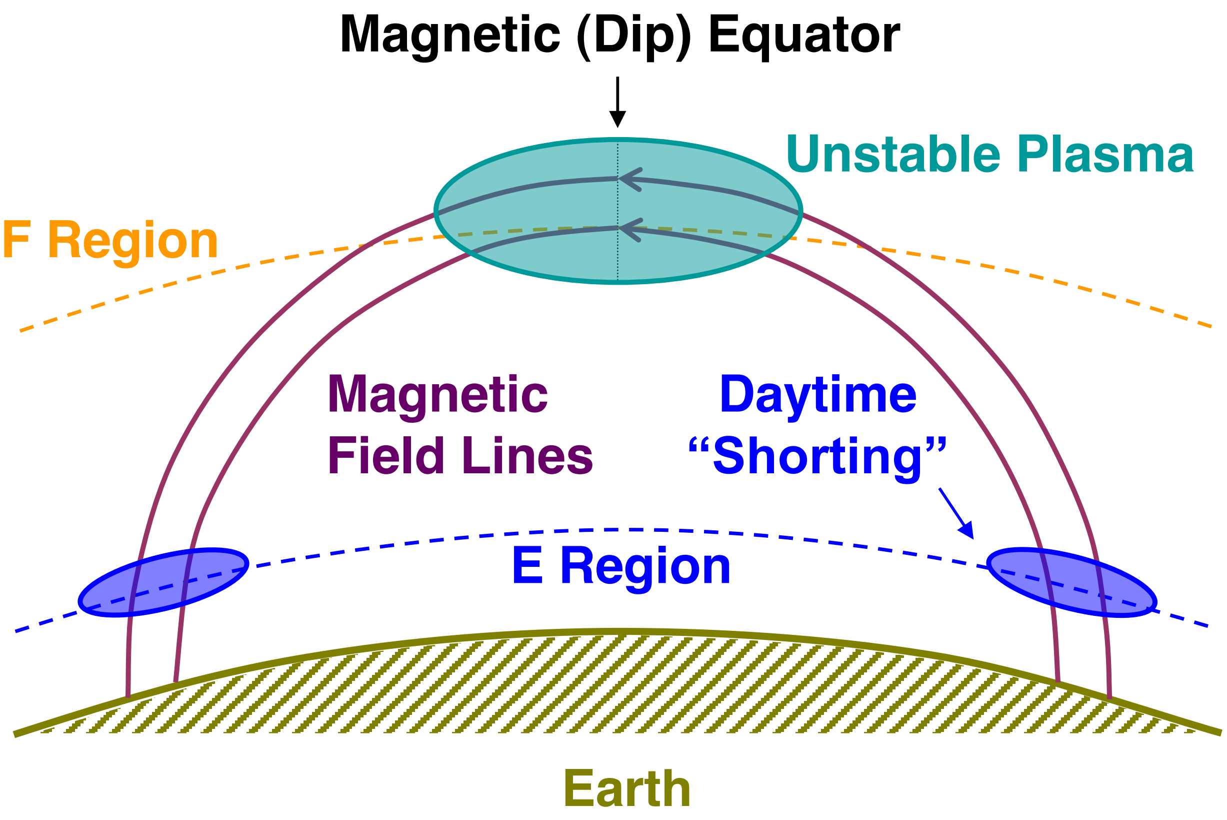
(View looking east)

Why Do Disturbances Form?

Unique Equatorial Magnetic Field Geometry

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

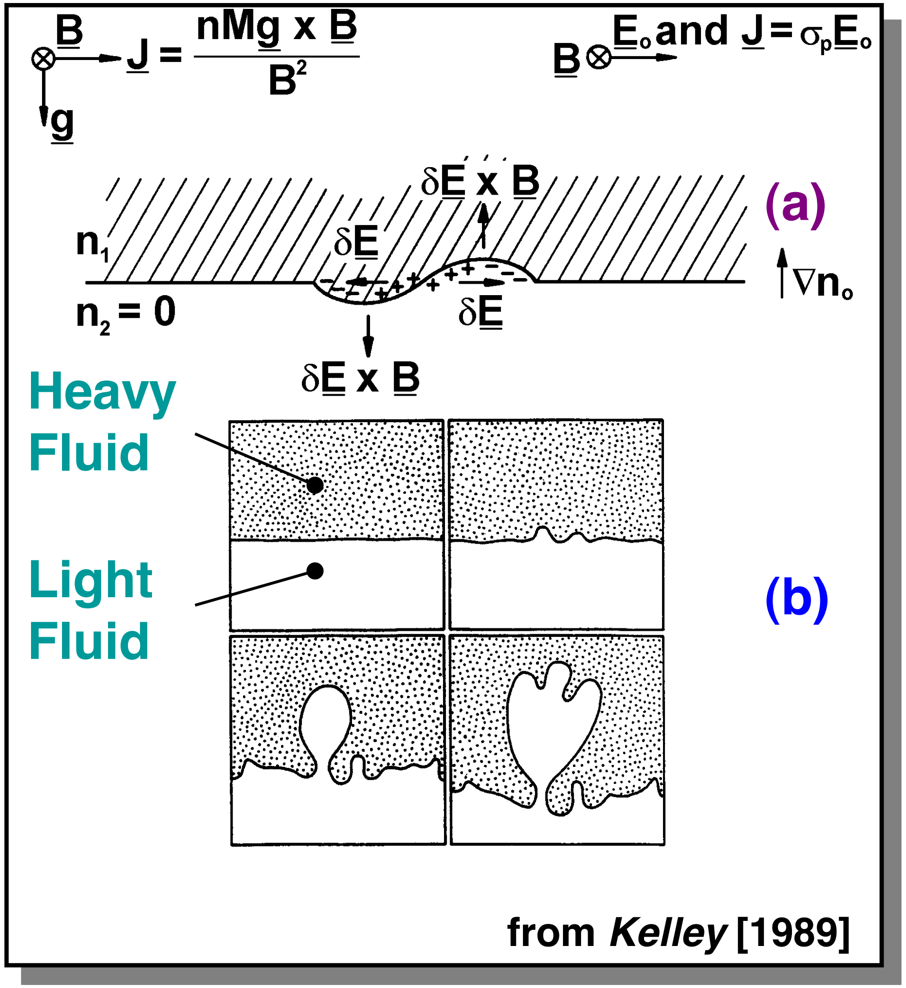
- Plasma moves easily along field lines, which act as conductors
- Horizontal field lines support plasma against gravity– unstable configuration
- E-region "shorts out" electrodynamic instability during the day



What Is Instability Process?

Basic Plasma Instability

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

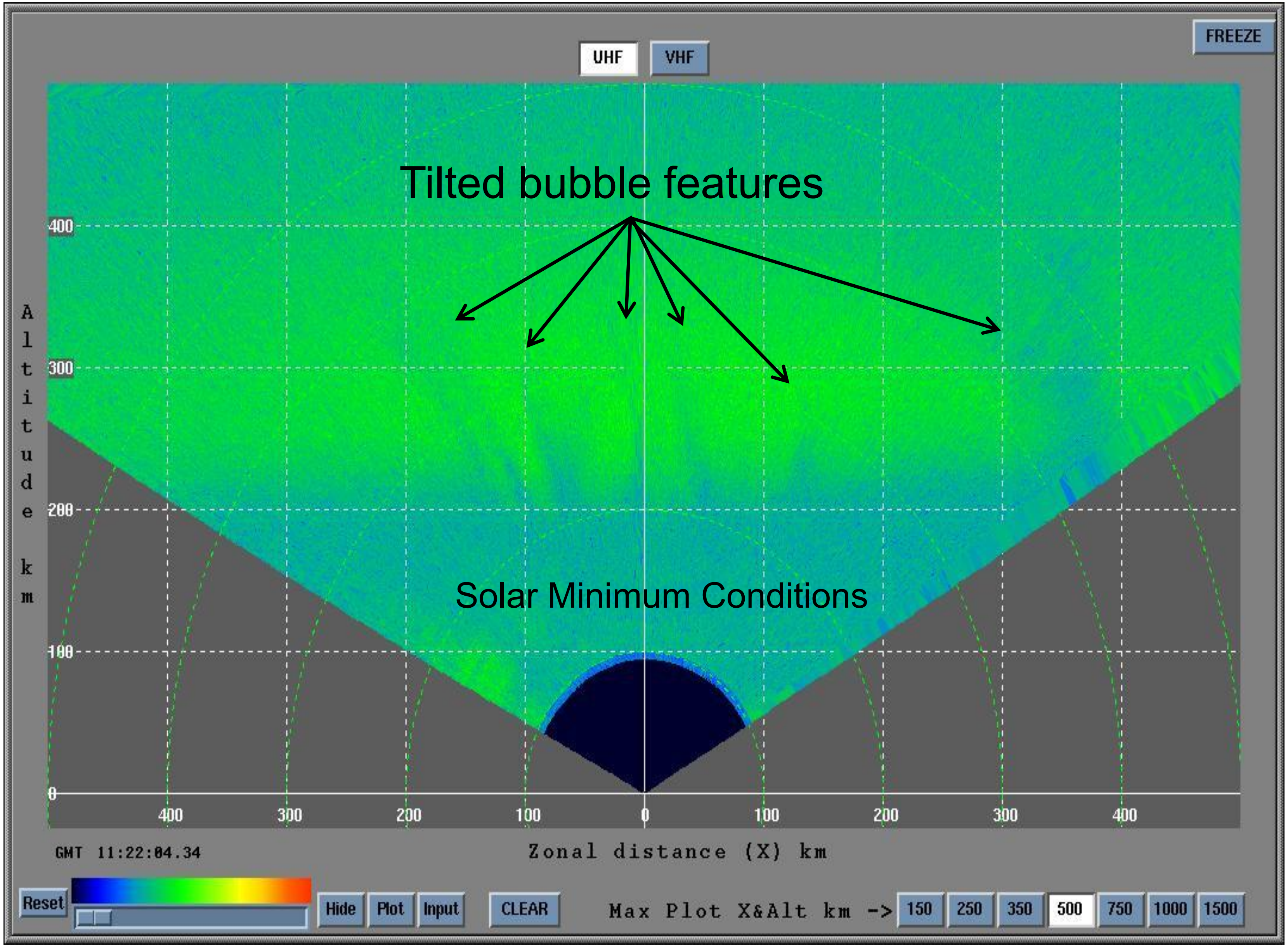


Plasma supported by horizontal field lines against gravity is unstable

- (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)

ALTAIR Incoherent Scatter Radar Scan

27 Sep 2008 11:22 UT

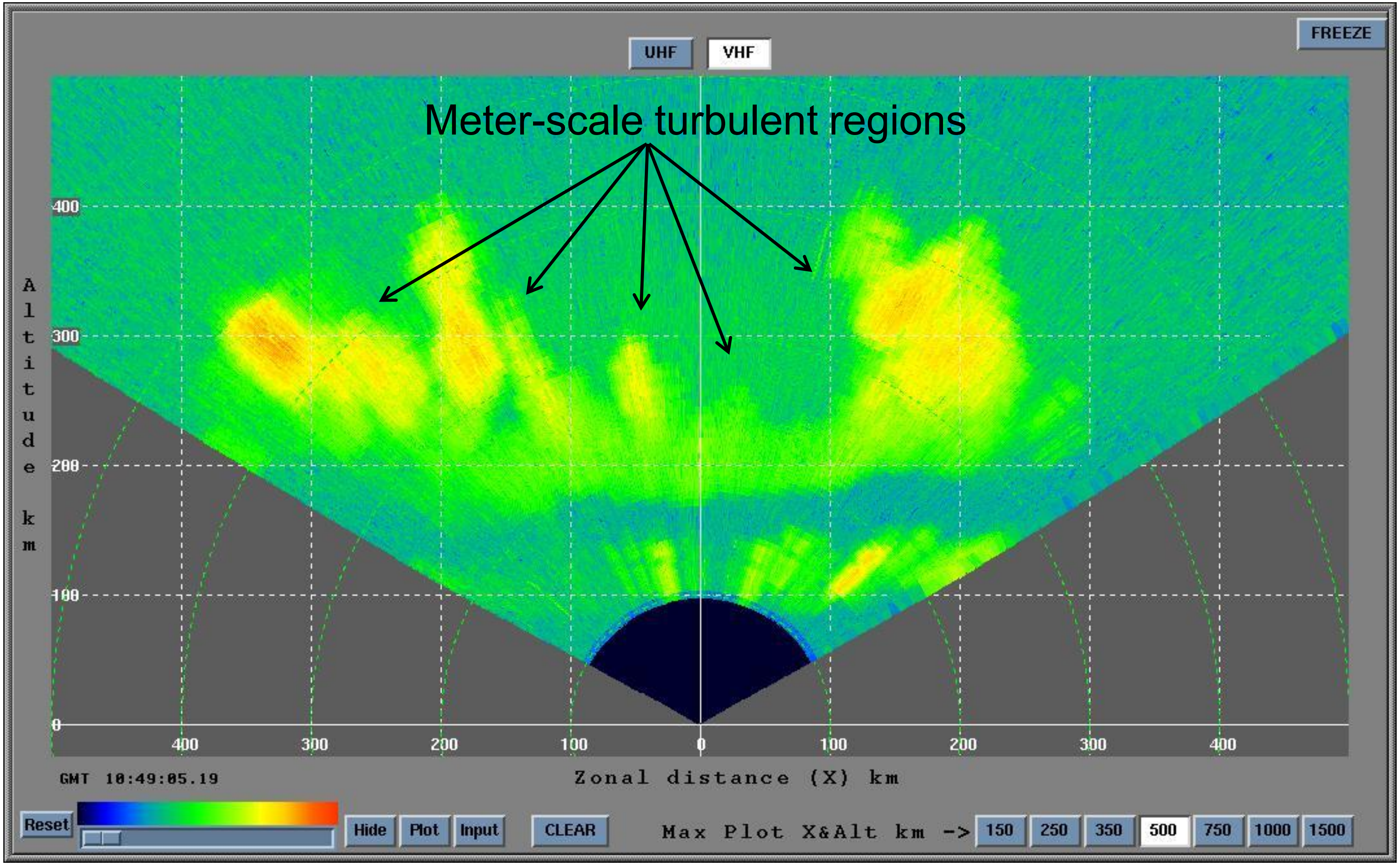


Preliminary result: Real-time display

From J. M. Retterer

ALTAIR Coherent Scatter Radar Scan

27 Sep 2008 10:49 UT

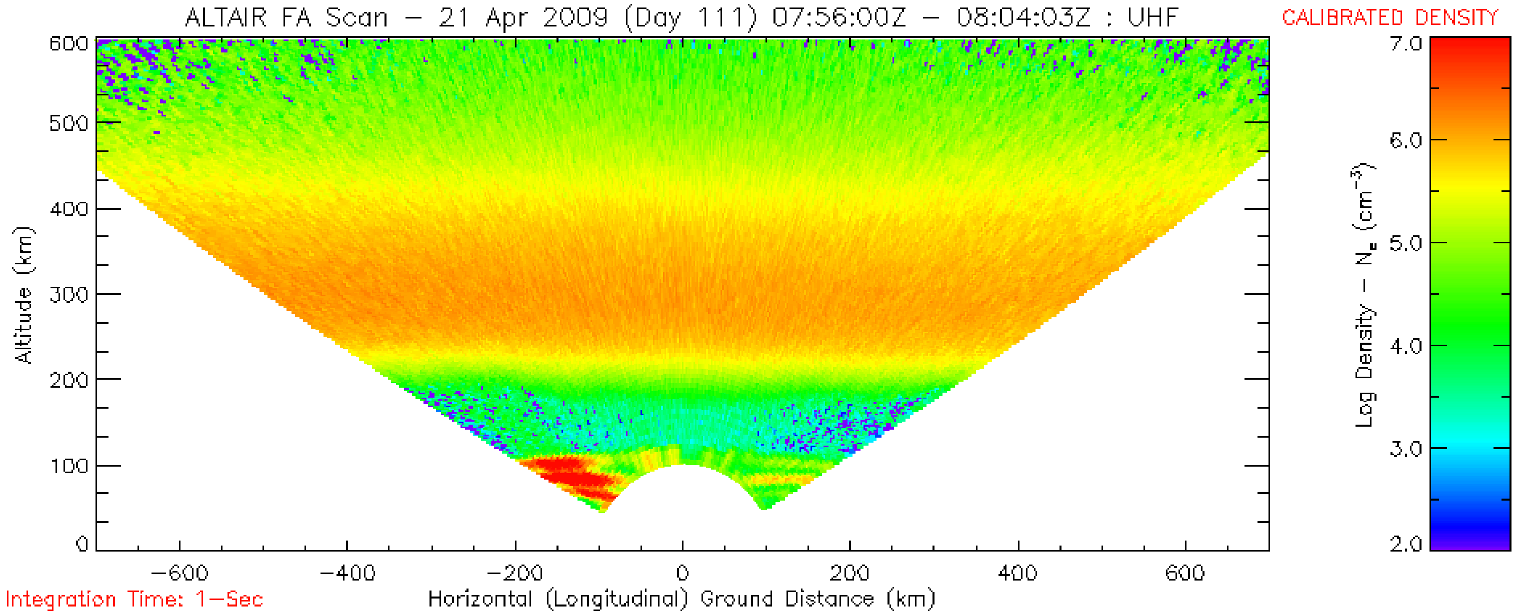


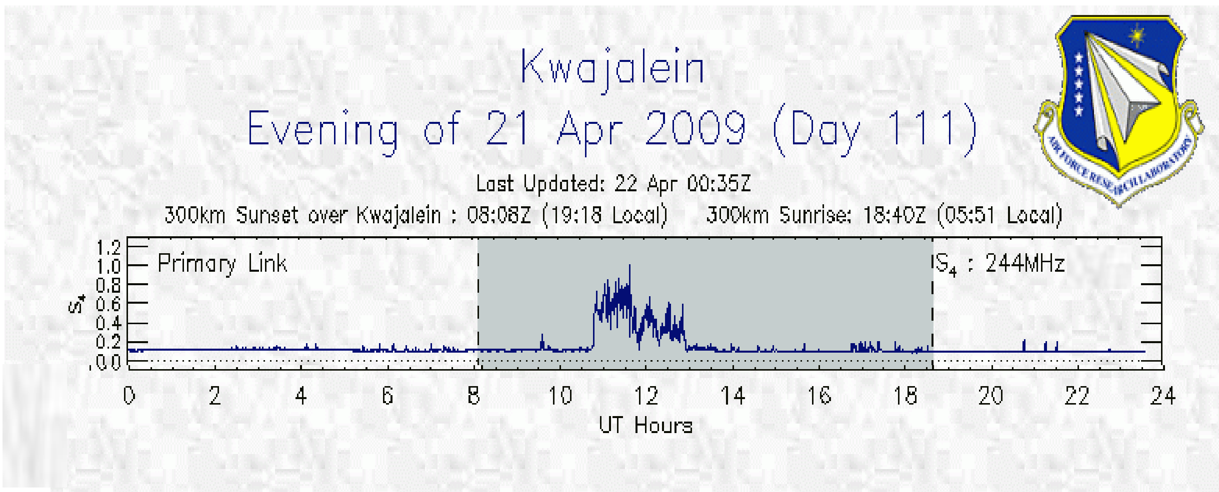
Preliminary result: Real-time display

From J. M. Retterer

Campaign Summary
21 APRIL 2009 – Day 111

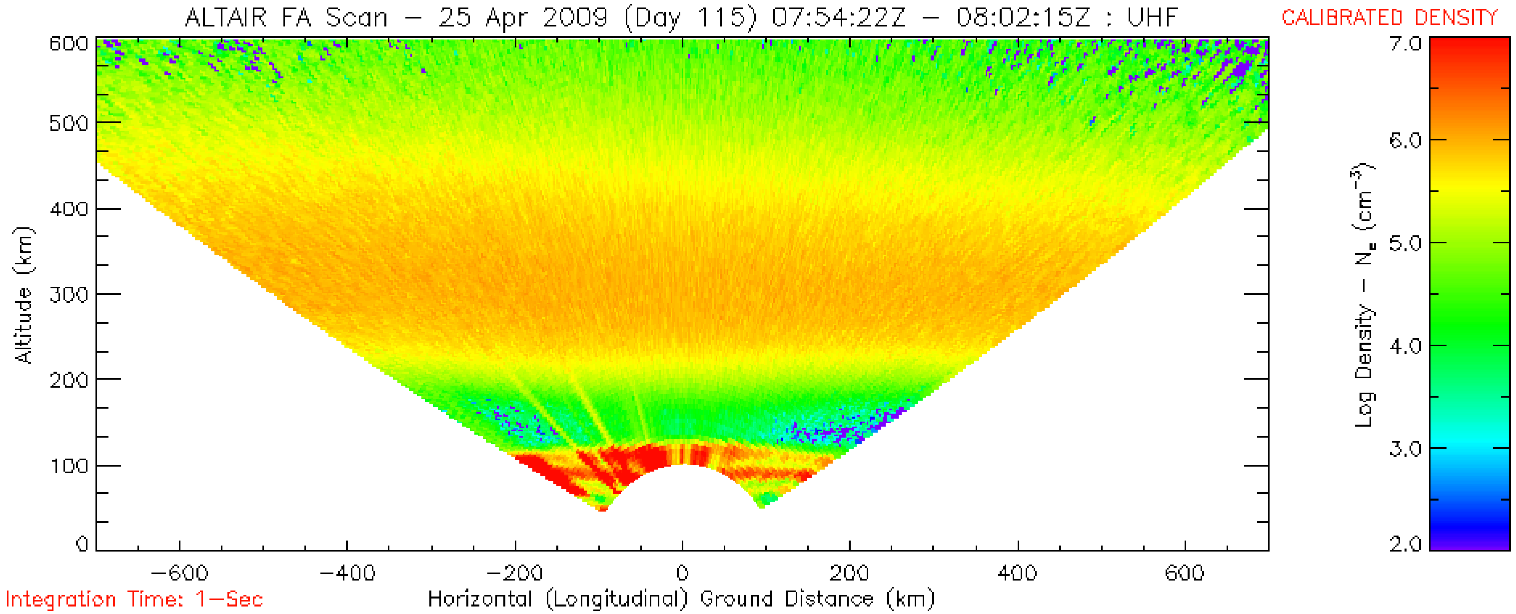
Perp-B Scan

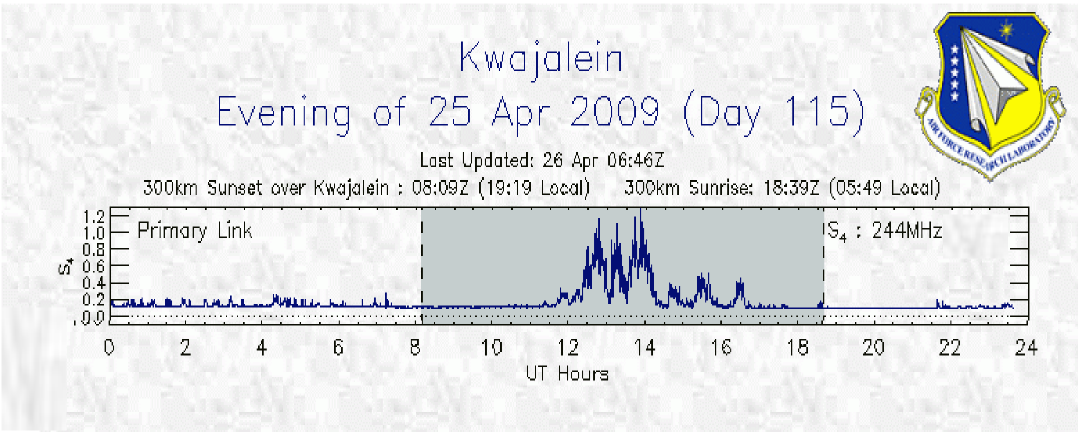




Campaign Summary
25 APRIL 2009 – Day 115

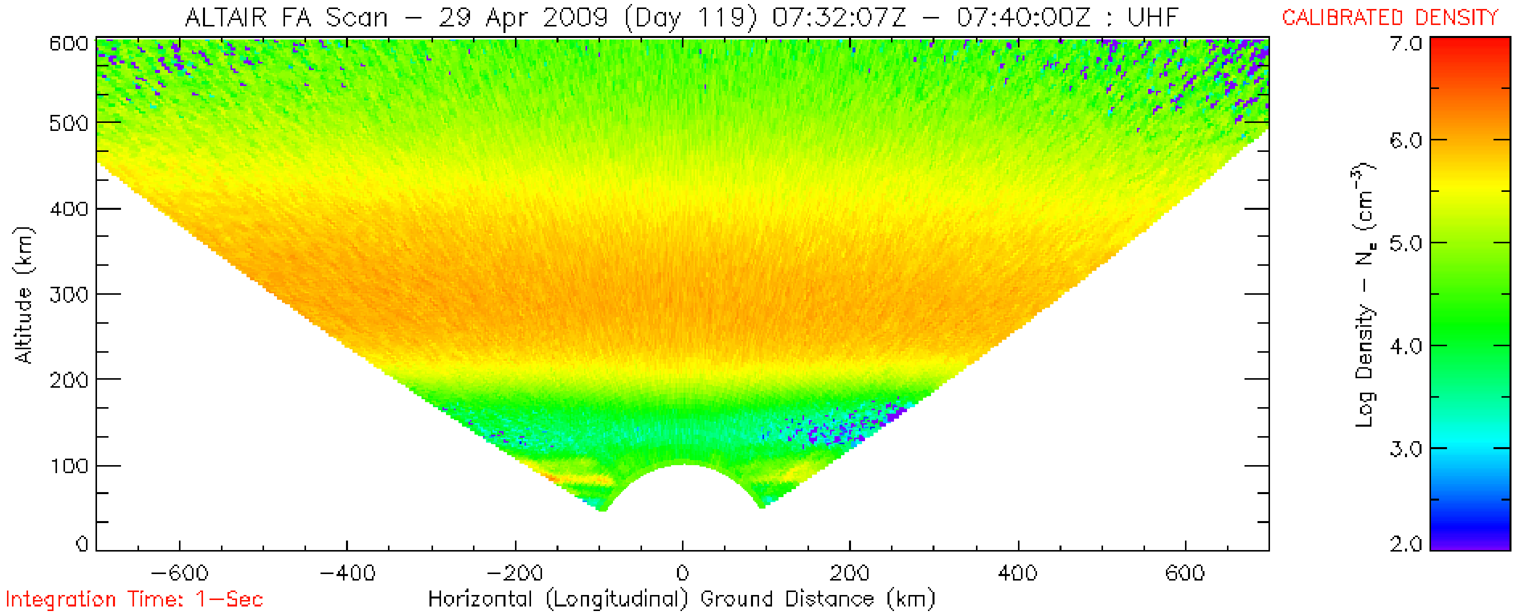
Perp-B Scan

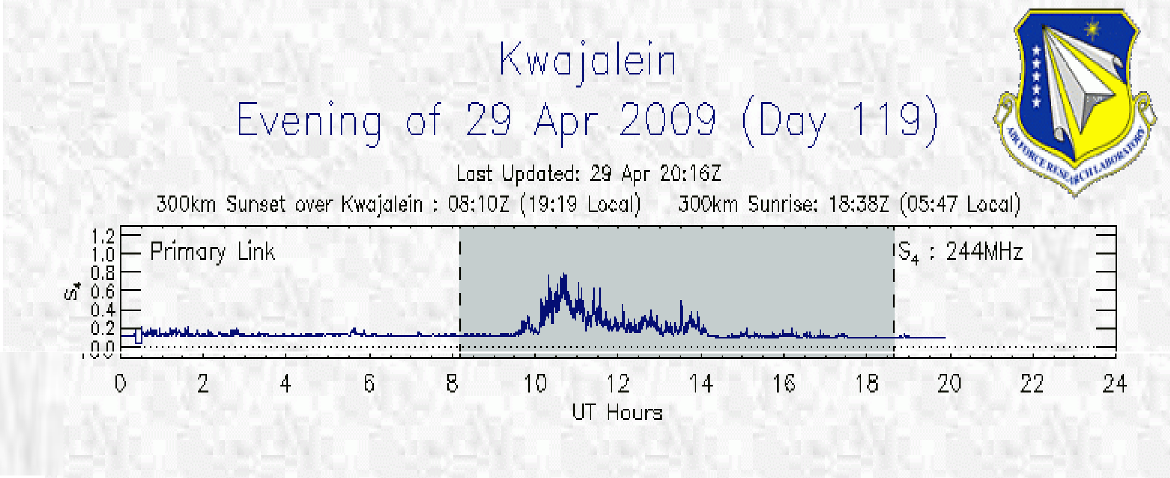




Campaign Summary
29 APRIL 2009 – Day 119

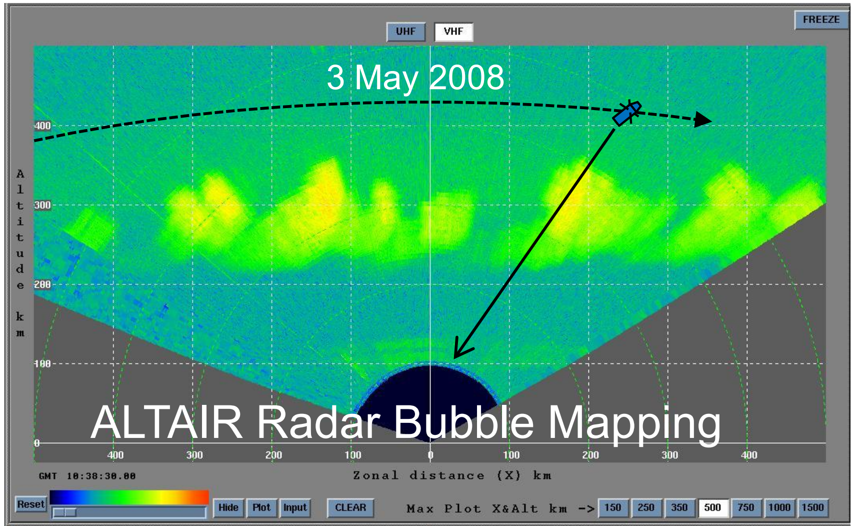
Perp-B Scan



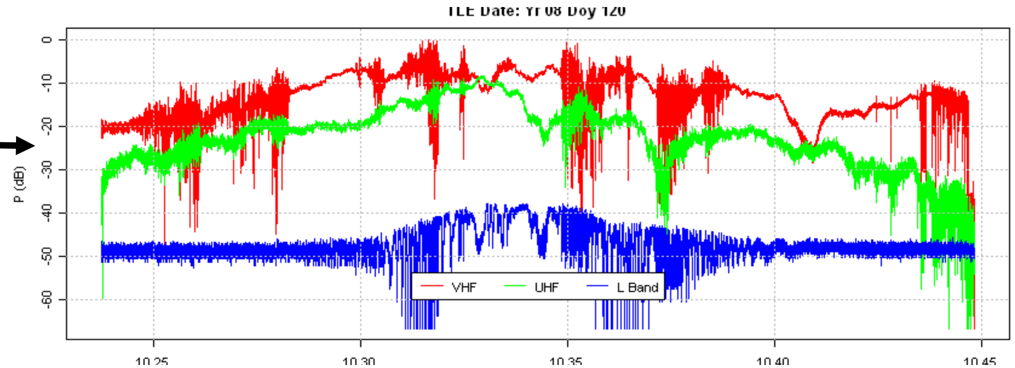


Ground-based Scintillation Nowcast Validation

Kwajalein Atoll, M.I. May 2008



C/NOFS Tri-band beacon signals



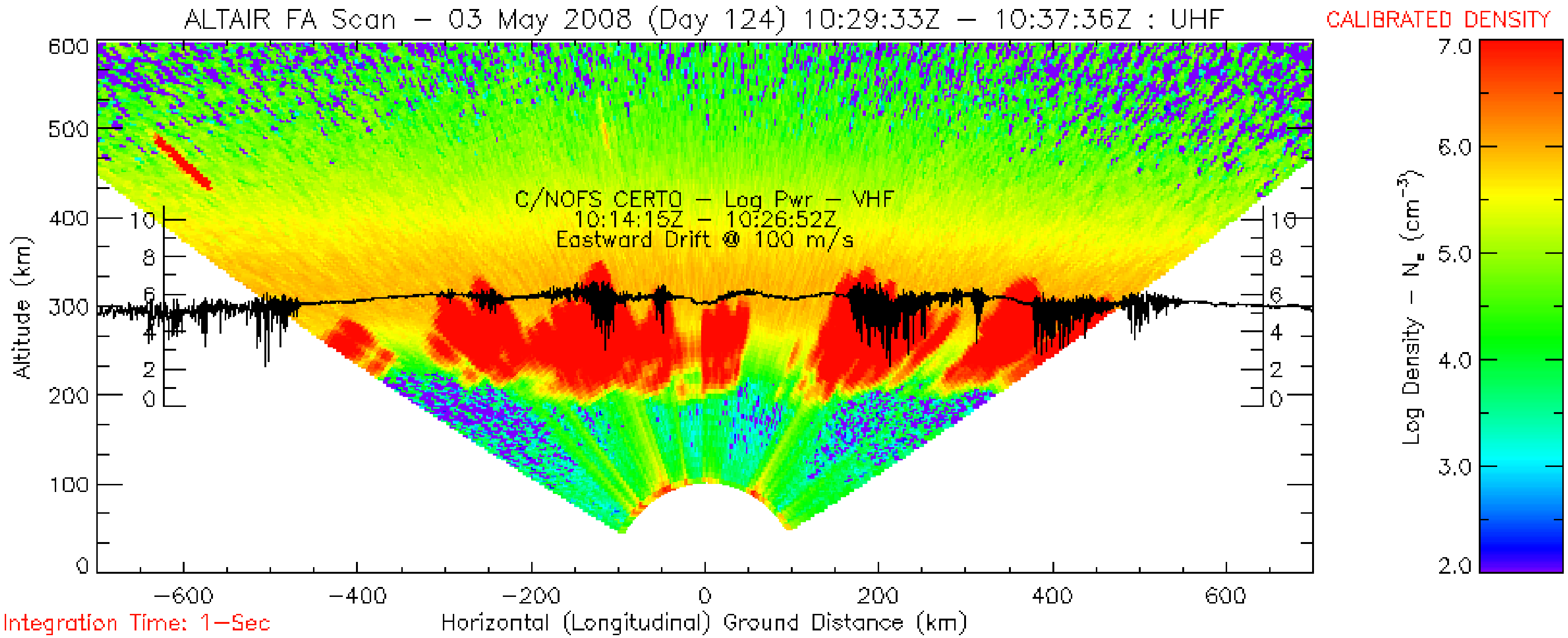
ALTAIR VHF/UHF Radar

- Direct comparison of ionospheric structure observed with radar and deduced from C/NOFS beacon signal
- C/NOFS radar tracks also performed to validate in situ space-based scintillation nowcasts; analysis in progress
- Physics-based model applied to test forecast capability

- **Fused space- and ground-based scintillation nowcasts provide unprecedented accuracy and resolution**

Scintillations and Radar Backscatter

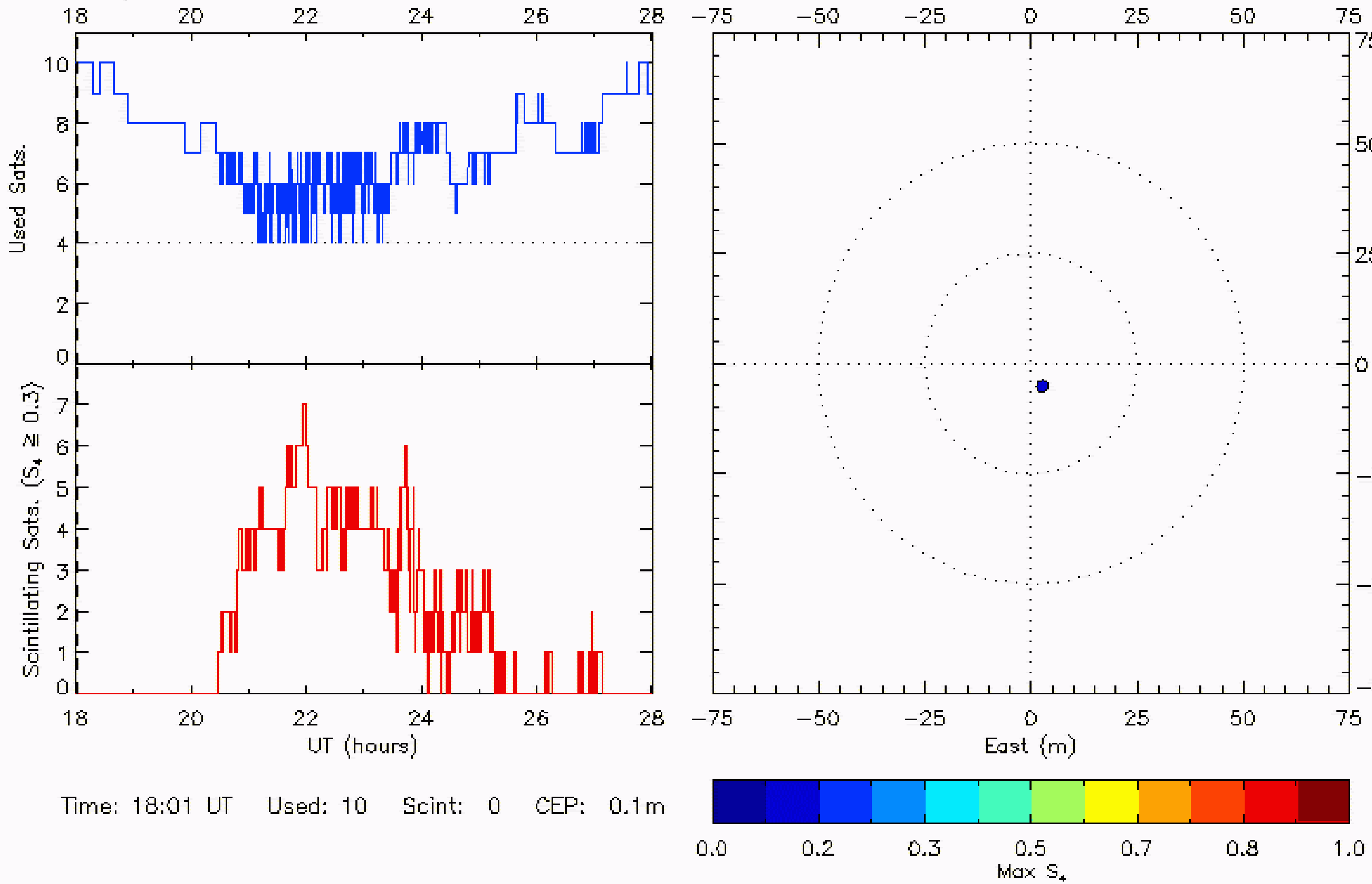
- CERTO beacon on C/NOFS superimposed on ALTAIR Radar Plots: CERTO-VHF, ALTAIR-UHF-10:29Z FA Scan



- Scintillations do not occur until instability interacts with high electron density near F-region peak
- Both intensity and spatial extent of these regions increase during solar maximum

GPS Positioning Errors During Solar Max

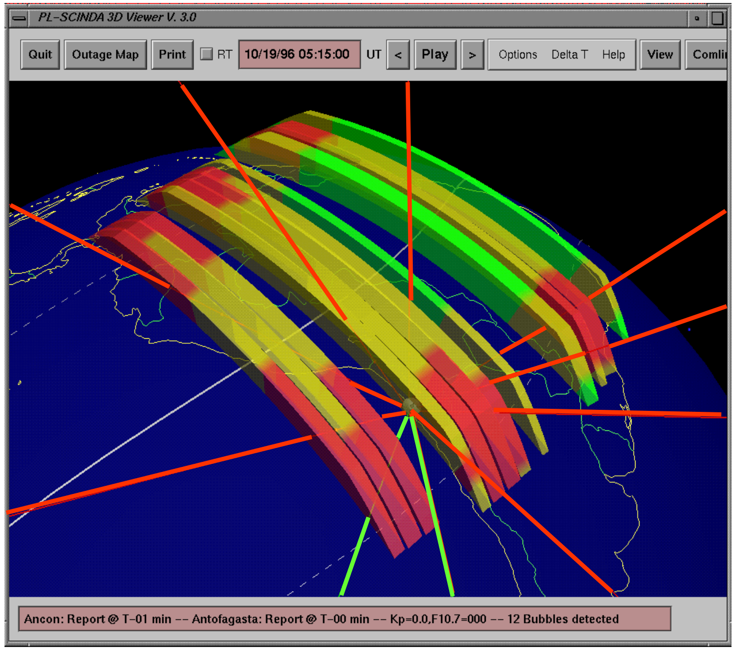
Scintillation can cause rapid fluctuations in GPS position fix;
Typical night from recent field experiments



Assessing Impacts on GPS Navigation

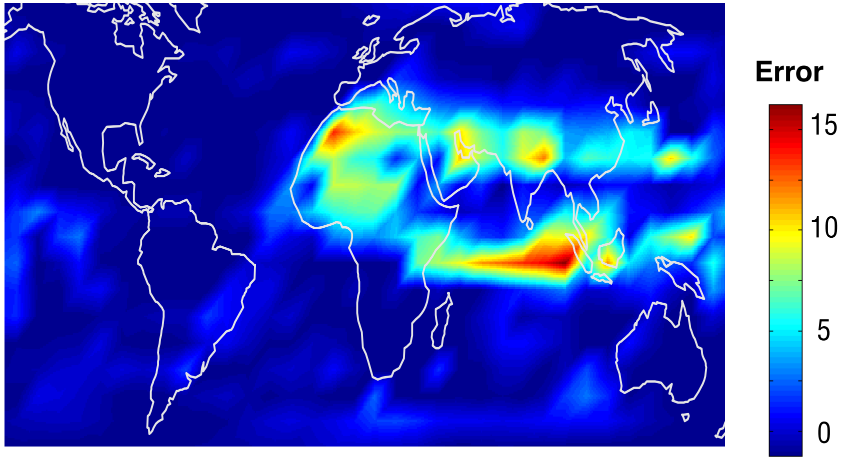
L-Band Impacts at Solar Maximum

Multiple GPS-ground links will be affected simultaneously



Actual Ionospheric Disturbance Structures

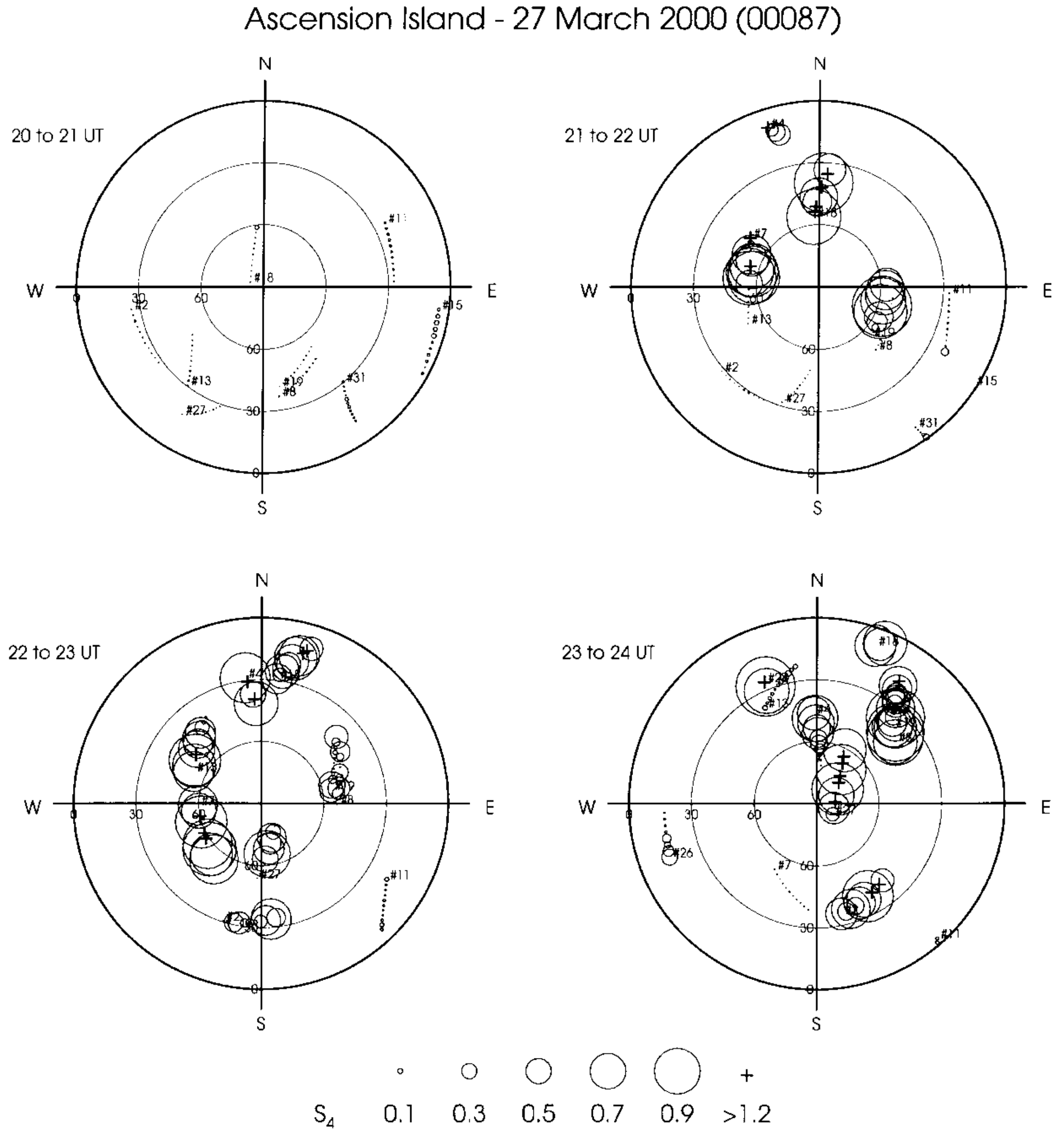
Objective to produce scintillation-induced GPS position error maps



Equatorial scintillation structures may routinely degrade optimal navigation solution geometry; full extent of impacts under investigation

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

Scintillation Sky Coverage at Ascension Island

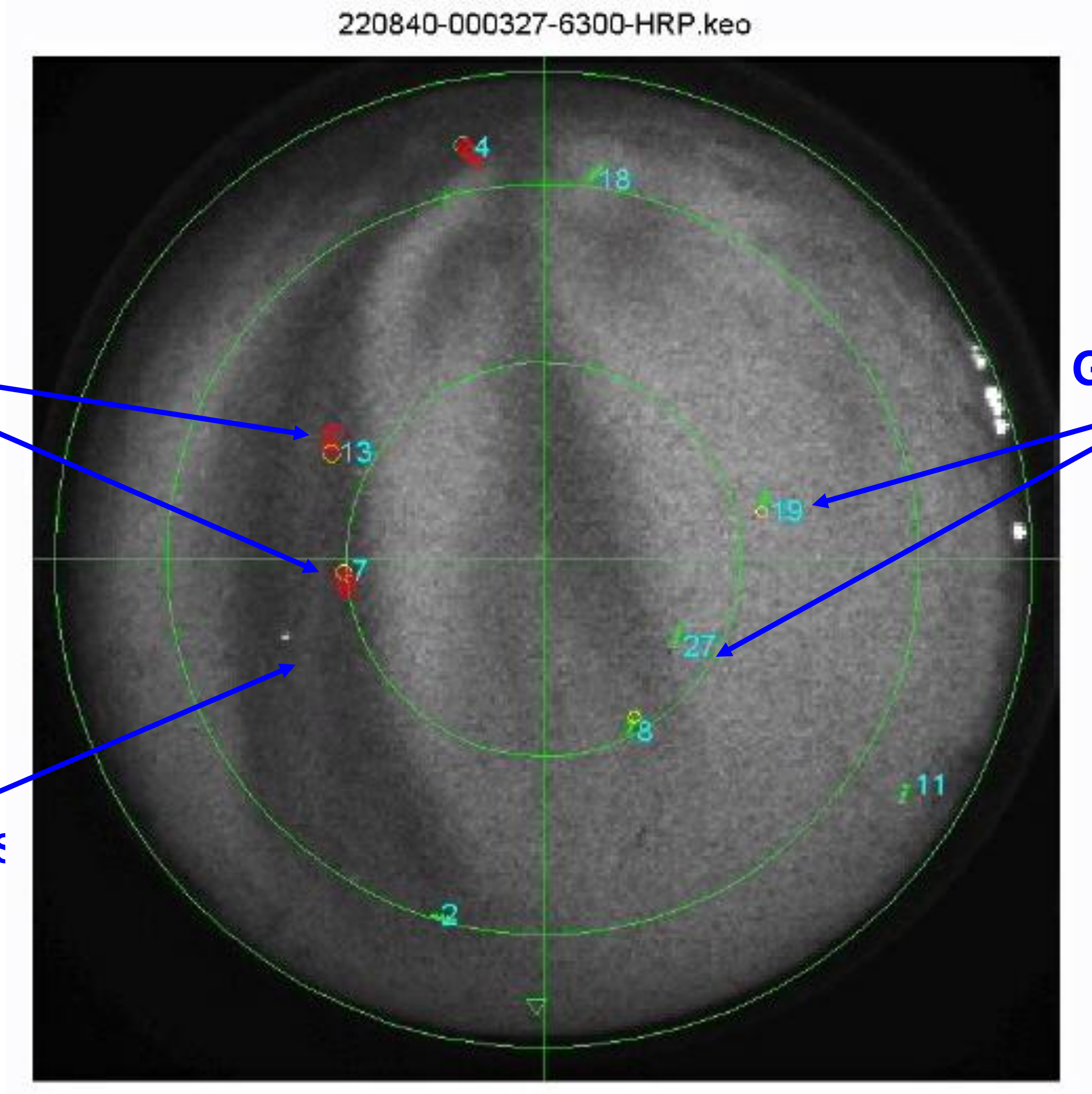


6300 Å All-sky Imagery

Scintillating GPS SATS

GPS SATS

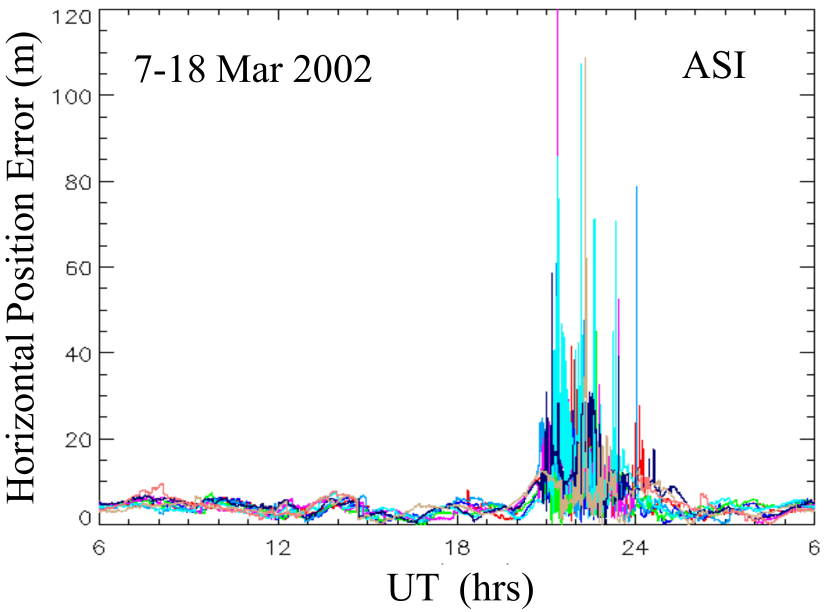
Turbulent Depletions



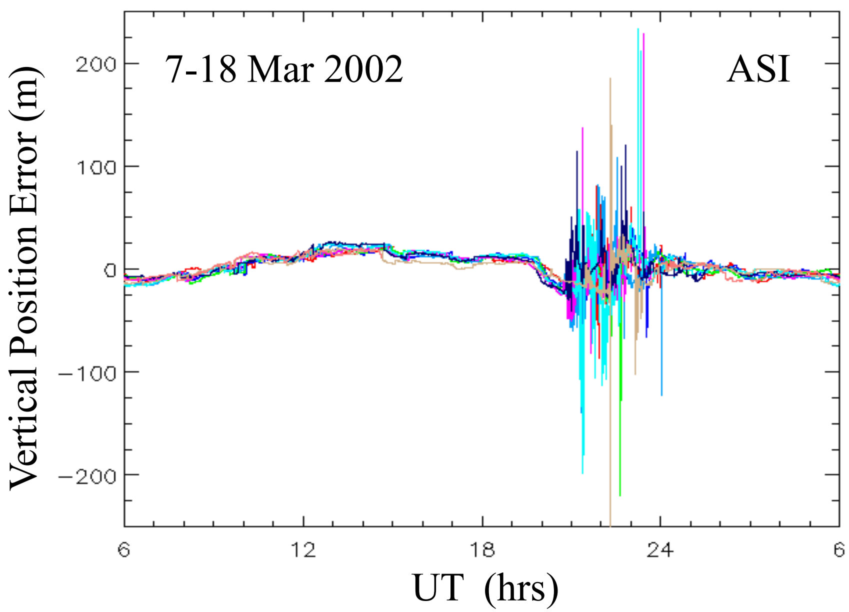
Representative Positioning Errors Near Solar Maximum

Active Ionosphere
21:00-23:30 UT

Position from dual frequency receiver



Horizontal Error >100 m

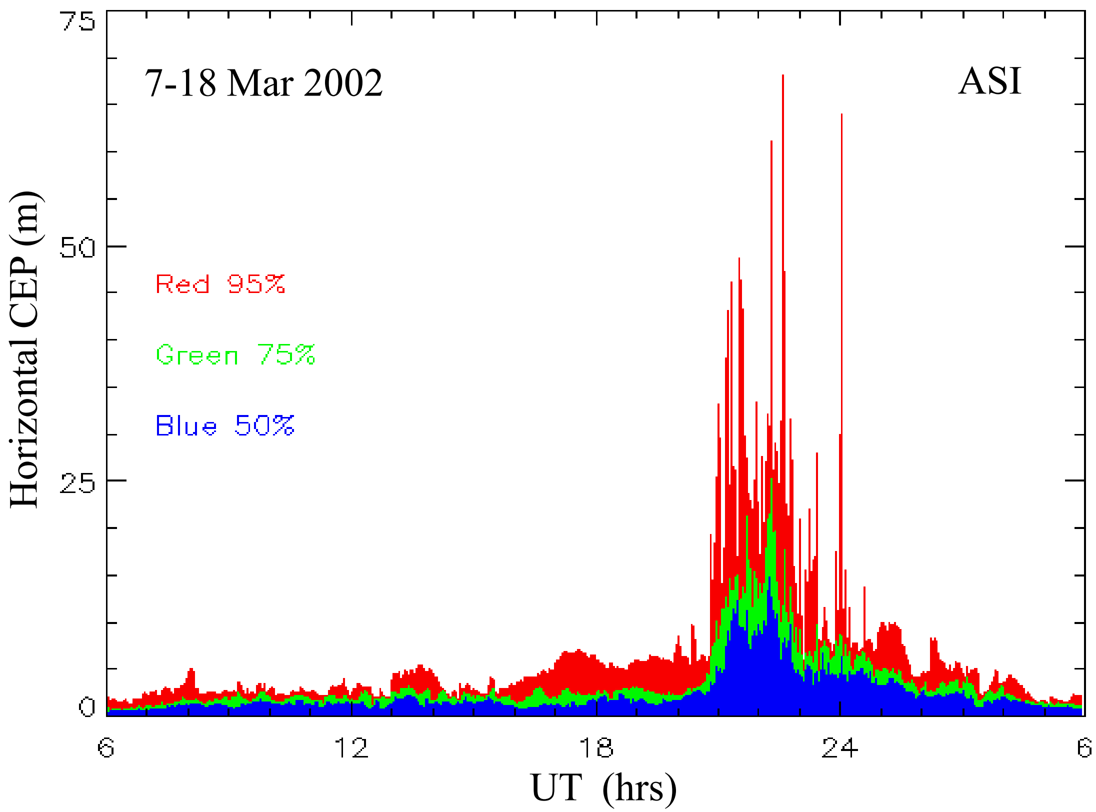


Vertical Error > +/- 200 m

Statistical Analysis of Positioning Errors

Circular Error Probability: probability that median error will exceed a given level

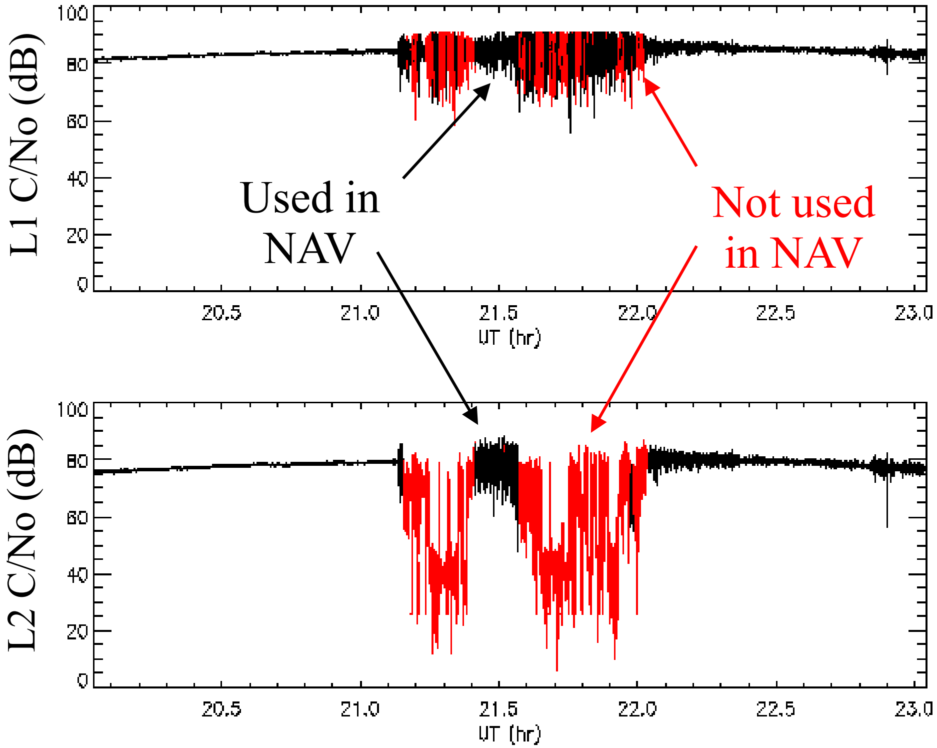
A possible metric for a position error product



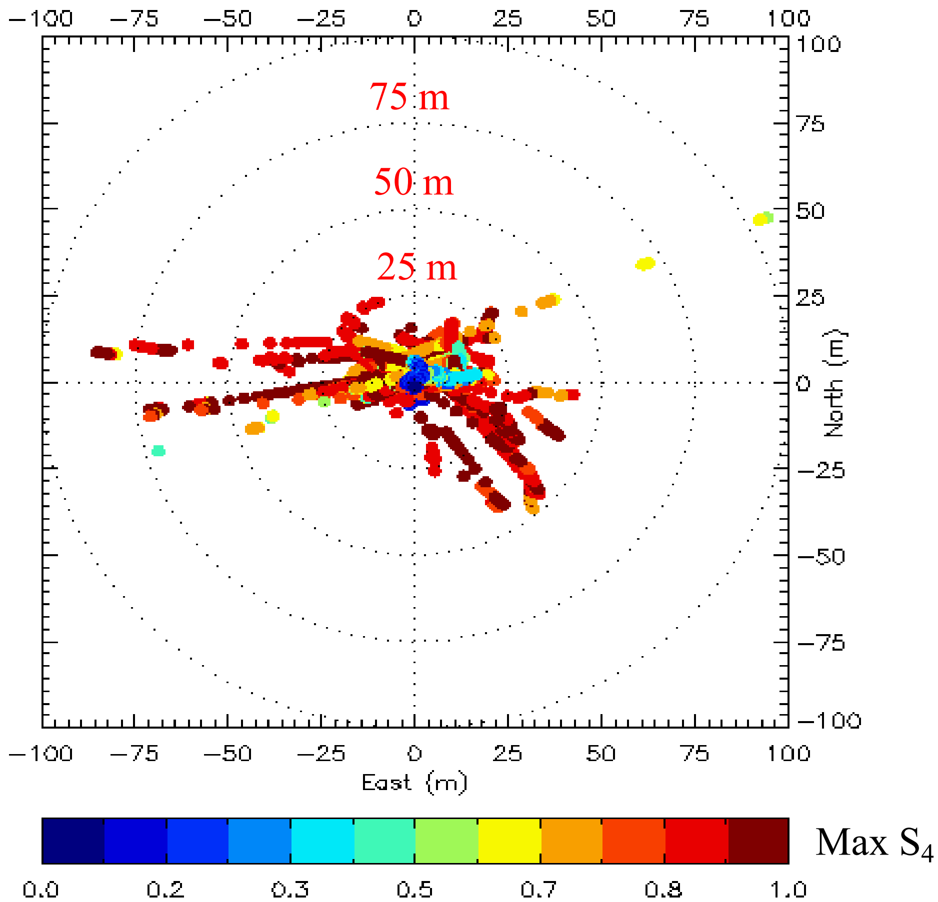
Single point positioning error (2D) better than 10 meters 95% of the time ... except during scintillation

Modeling Effects on Positioning Accuracy

16 Mar 2002, ASI



Scintillation Causes Fading of L1 and L2 GPS Signals

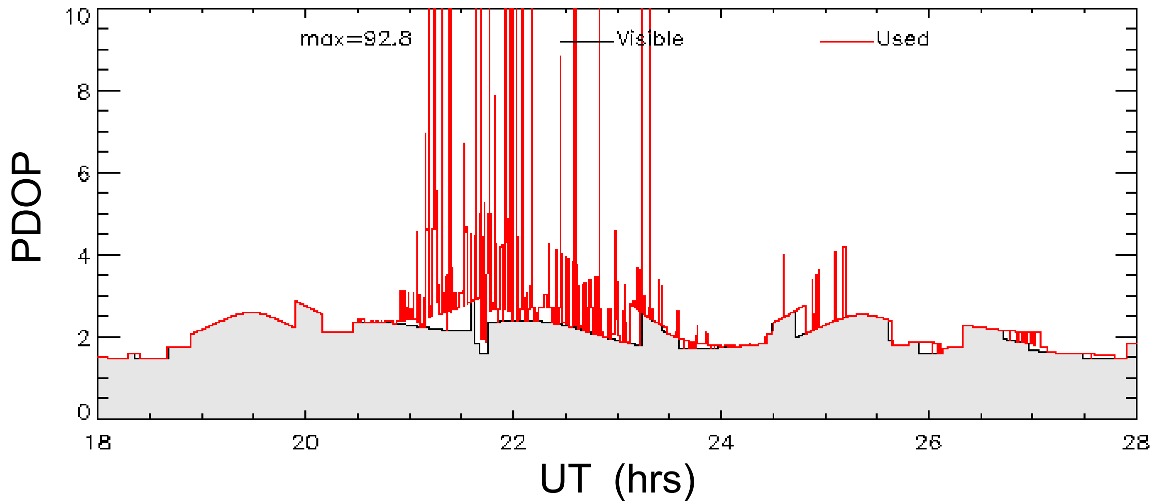


Resulting Positioning Error

Geometrical Errors and Ranging Errors

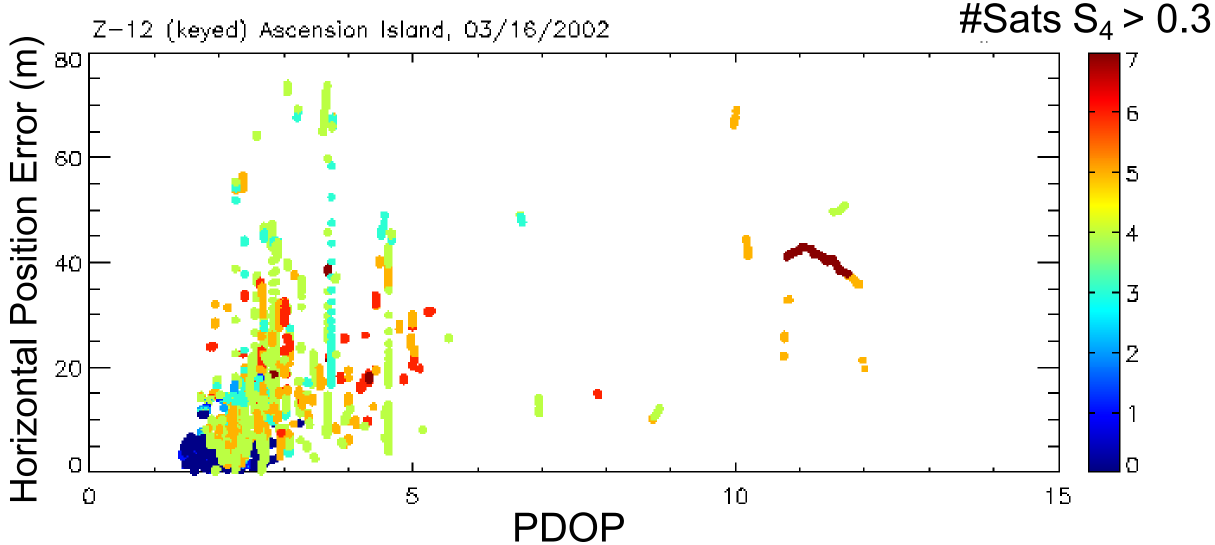
Theoretical and measured Dilution of Precision (DOP)

Spikes occur when a satellite becomes temporarily unavailable (timescale ~ seconds)



Large DOP generally leads to large errors, but ...

Position error can be large even when DOP is good (>70 m with PDOP of 3)!



Conclusion: scintillation causes *ranging errors*

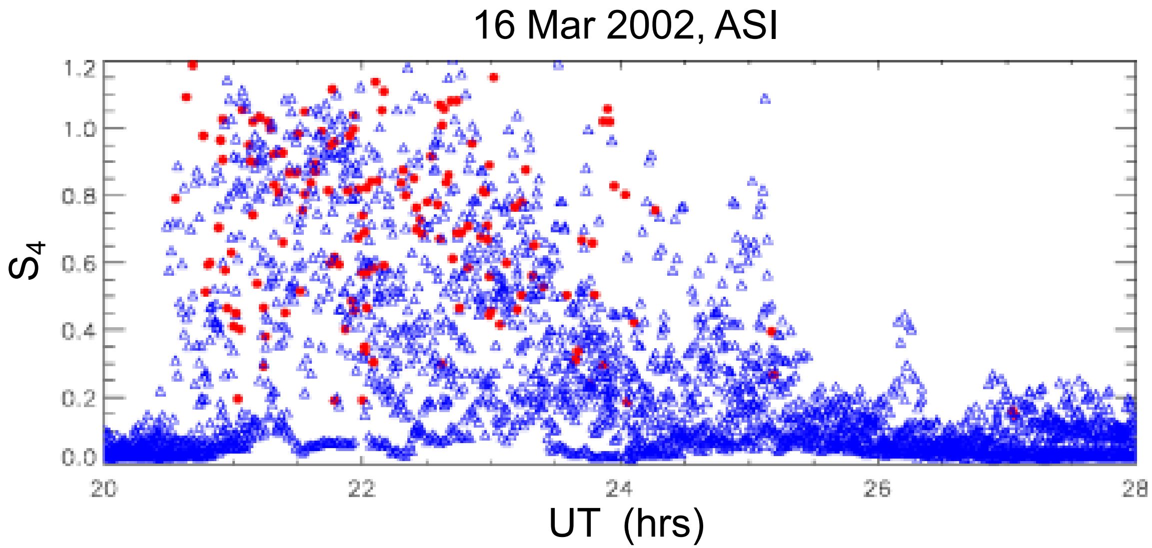
Modeling GPS Satellite Availability During Scintillation

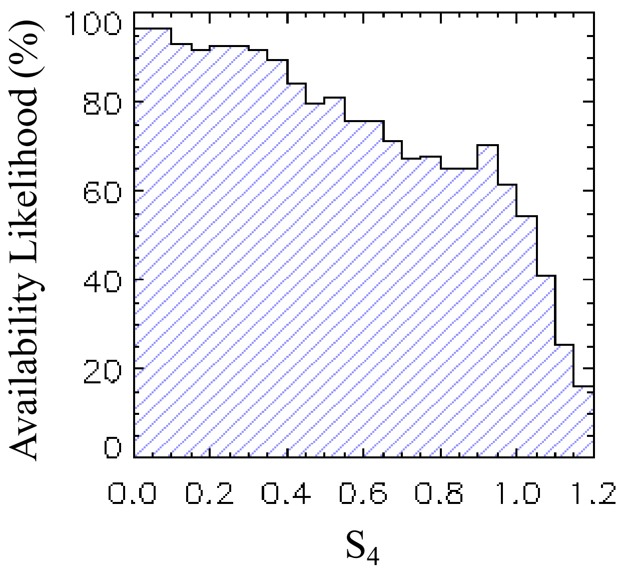
Quality receivers report which satellites used in NAV

Example:

blue = used in NAV

red = not available (corresponds to spike in DOP)





Likelihood satellite will be available decreases as scintillation intensity increases. Each receiver type will have its own distribution.

Best metric might depend on receiver's "failure mode"

- If fades tend to break delay lock loop (DLL), use S_4.
- If phase fluctuations tend to break the phase lock loop (PLL), use σ_φ
- Other parameters (e.g., decorrelation time) should also be considered

Simulating GPS Position Errors

Once we have modeled which satellites the receiver will track, we model the ranging errors and perform a standard navigation solution for the perturbed receiver position.

GPS range equation for each satellite, *k*:

$$P_{rs}^k + C_r + E_{rs}^k = \|\boldsymbol{R}_r - \boldsymbol{R}_s^k\|, \quad k = 1, \ldots, n$$

We model the k^{th} pseudorange:

$$\underbrace{P_{rs}^k}_{modeled\ pseudorange} = \underbrace{\|\boldsymbol{R}_r^0 - \boldsymbol{R}_s^k\|}_{true\ range\ (via\ ephemeris)} + \underbrace{[\gamma_s \hat{\phi}] S_4^k}_{scintillation\ induced\ ranging\ error}$$

Linearize the range equations about an initial estimate and solve by iteration:

$$\underbrace{\begin{bmatrix} (X_r - X_s^1)/R_{rs}^1 & (Y_r - Y_s^1)/R_{rs}^1 & (Z_r - Z_s^1)/R_{rs}^1 & (-1) \\ (X_r - X_s^2)/R_{rs}^2 & (Y_r - Y_s^2)/R_{rs}^2 & (Z_r - Z_s^2)/R_{rs}^2 & (-1) \\ \vdots & \vdots & \vdots & (-1) \\ (X_r - X_s^n)/R_{rs}^n & (Y_r - Y_s^n)/R_{rs}^n & (Z_r - Z_s^n)/R_{rs}^n & (-1) \end{bmatrix}}_{\boldsymbol{A}} \underbrace{\begin{bmatrix} dx \\ dy \\ dz \\ dc \end{bmatrix}}_{\boldsymbol{D}} = \underbrace{\begin{bmatrix} P_{rs}^1 - R_{rs}^1 \\ P_{rs}^2 - R_{rs}^2 \\ \vdots \\ P_{rs}^n - R_{rs}^n \end{bmatrix}}_{\boldsymbol{L}}$$

where

$$R_{rs}^k = \|\boldsymbol{R}_r - \boldsymbol{R}_s^k\|$$

Least squares solution to the over-determined system $\boldsymbol{A}\boldsymbol{D} = \boldsymbol{L}$ is $\boldsymbol{D} = (\boldsymbol{A}^T \boldsymbol{A})^{-1} \boldsymbol{A}^T \boldsymbol{L}$

Update the receiver position $\boldsymbol{R}_r \rightarrow \boldsymbol{R}_r + [D[1], D[2], D[3]]^T$ and repeat until convergence.

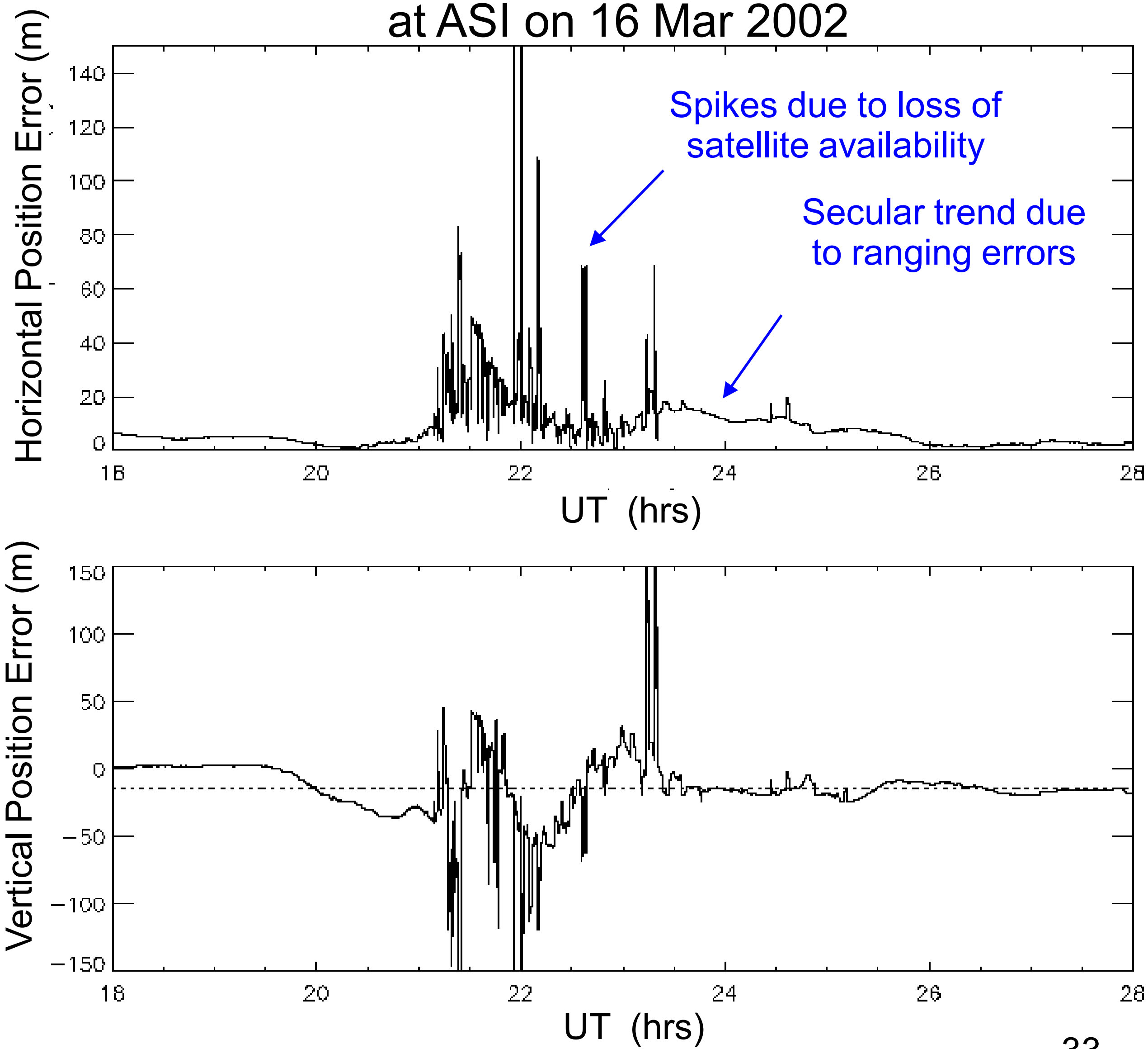
Application of the Model: Positioning Errors at Ascension Island

Goal:

- Using only S4 measurements and precise ephemeris, reproduce these position error results.

Only scintillation errors are included, assumes other effects negligible by comparison, including satellite and receiver clock errors, tropospheric errors, etc.

Actual positioning errors at ASI on 16 Mar 2002



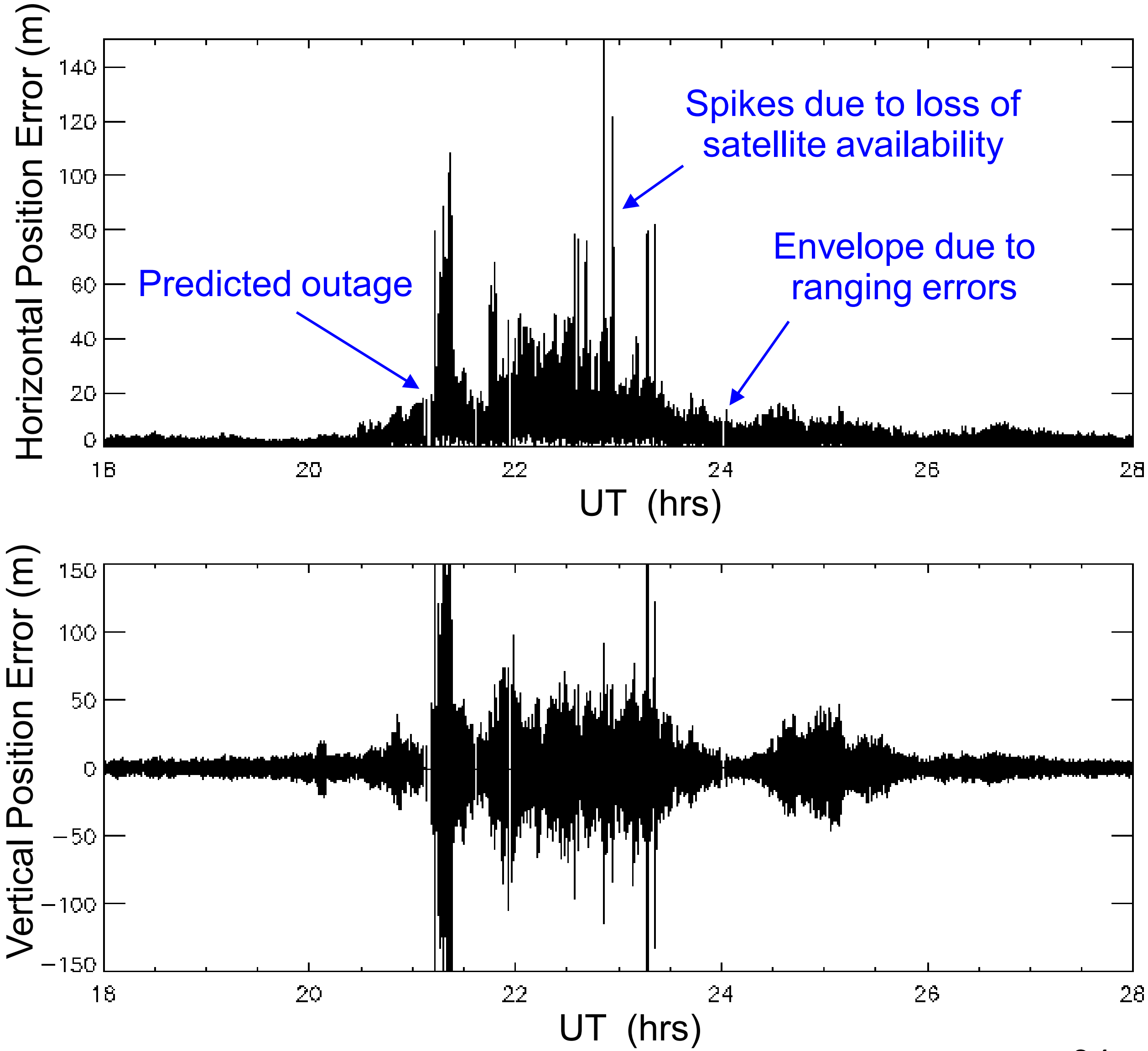
Preliminary Simulation Results

Simulation results using the scaling factor, γ_s = 70 m

Explanation for rapid fluctuations:

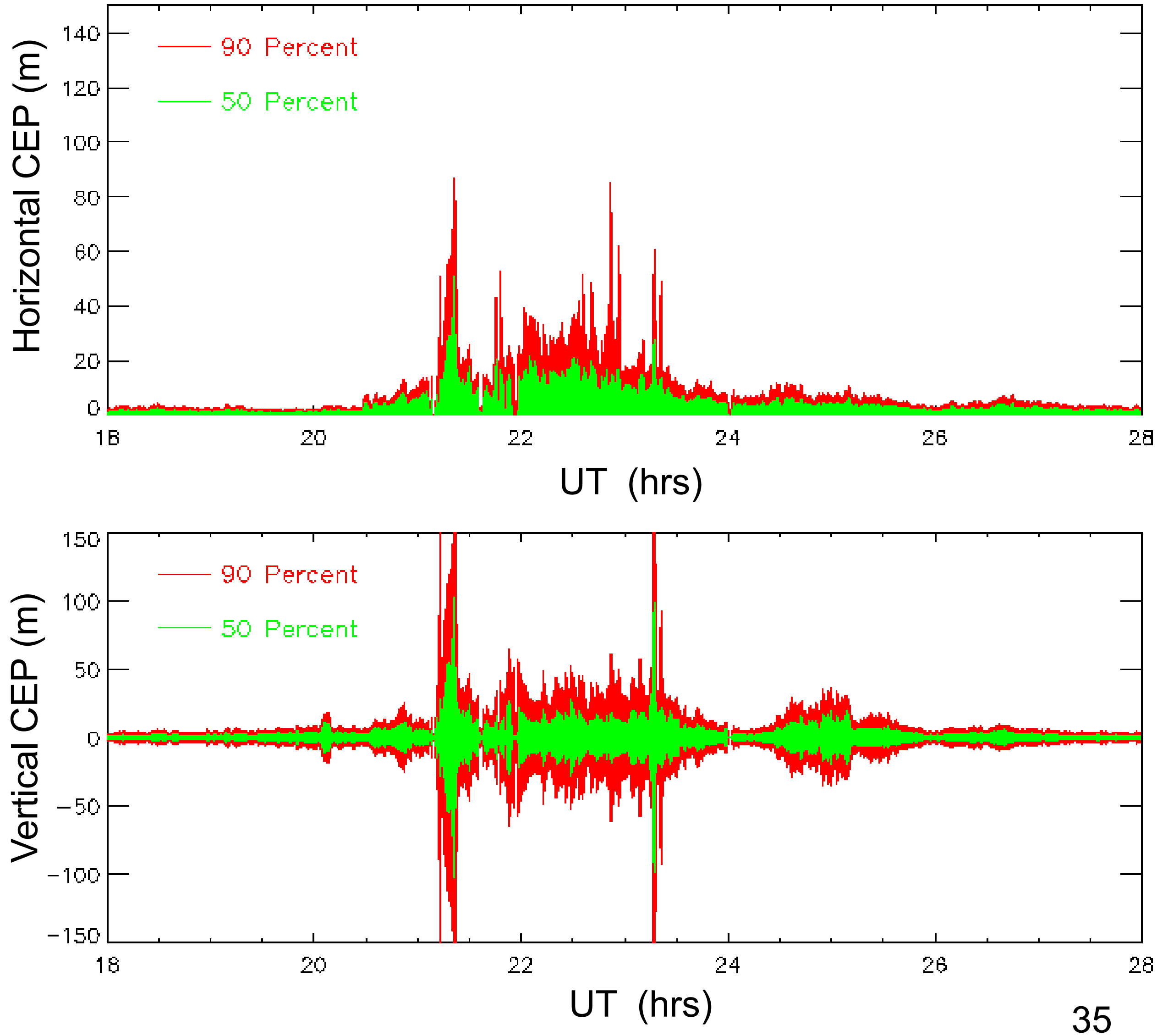
Random range perturbations are not correlated in time, unlike in the real world

Even though we have an S_4 measurement only once per minute, we evaluate the model every second so we can do statistics.



Statistical Analysis of Simulation Results

- Sixty realizations per minute allow us to estimate CEP
- We can also invert these statistics, e.g., for a given accuracy requirement, report the probability that this requirement is met



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
  - Such impacts are generally limited to high periods of solar flux
- The details of how system performance is degraded remains poorly understood, but it has not been extensively studied
  - Opportunity for research in this area
- Additional modeling is needed to fully assess the vulnerability of modern GPS systems to scintillation activity
- Observations in Africa over the next few years can contribute significantly to this topic