Space Weather Impacts on GPS/GNSS Systems

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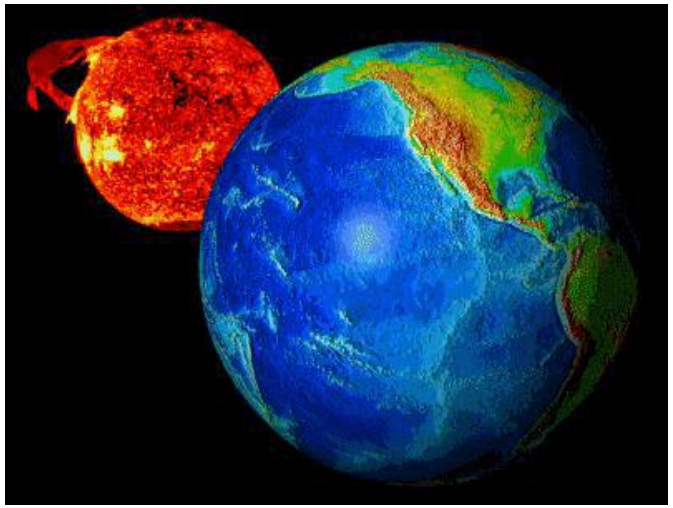
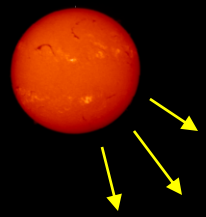
2017 Space Weather Workshop
Broomfield, CO
1-5 May 2017

Outline

- Impact Environment
- Irregularities & Scintillation
  - Position, Navigation & Timing Impacts
  - The Environment
  - Empirical Error Model
- “Quiet Time” Space Weather
- Summary



Space Weather Effects on Systems

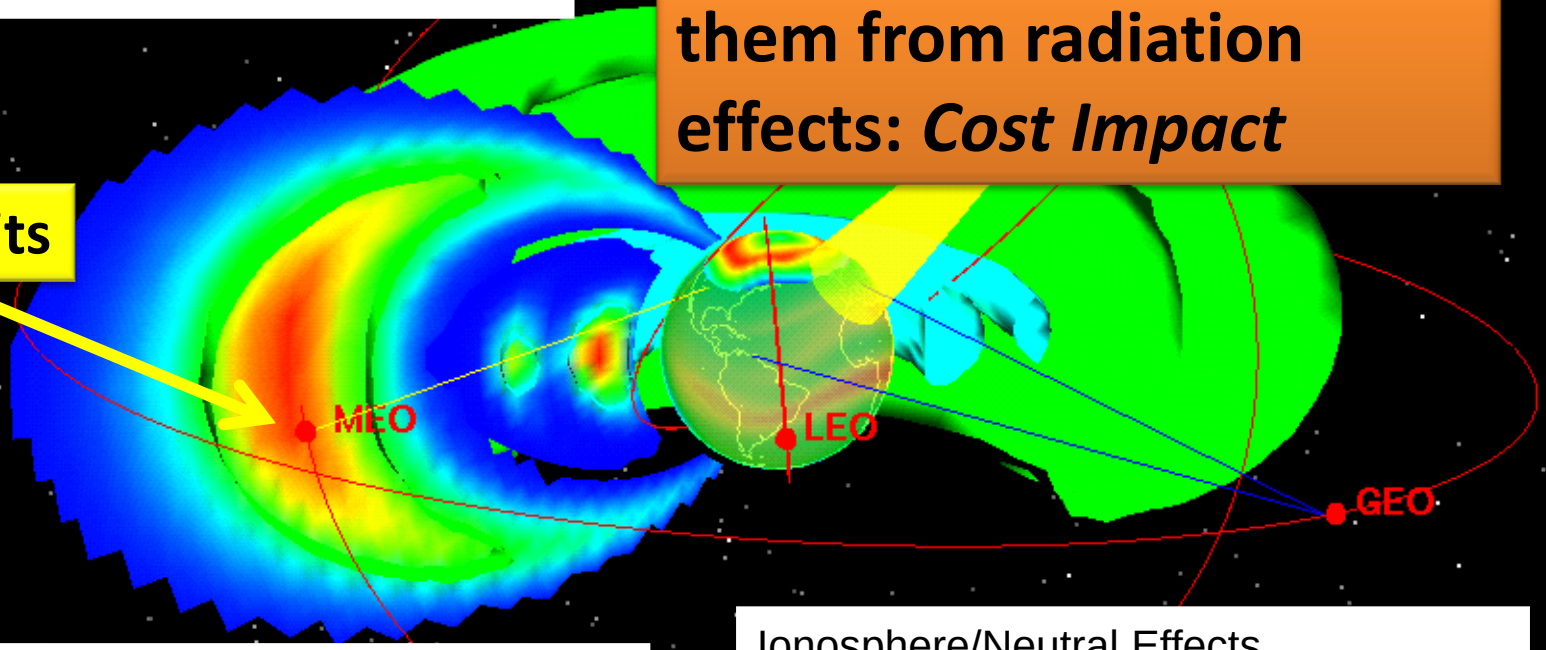


Direct Solar Processes

- 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



Space Particle Hazards

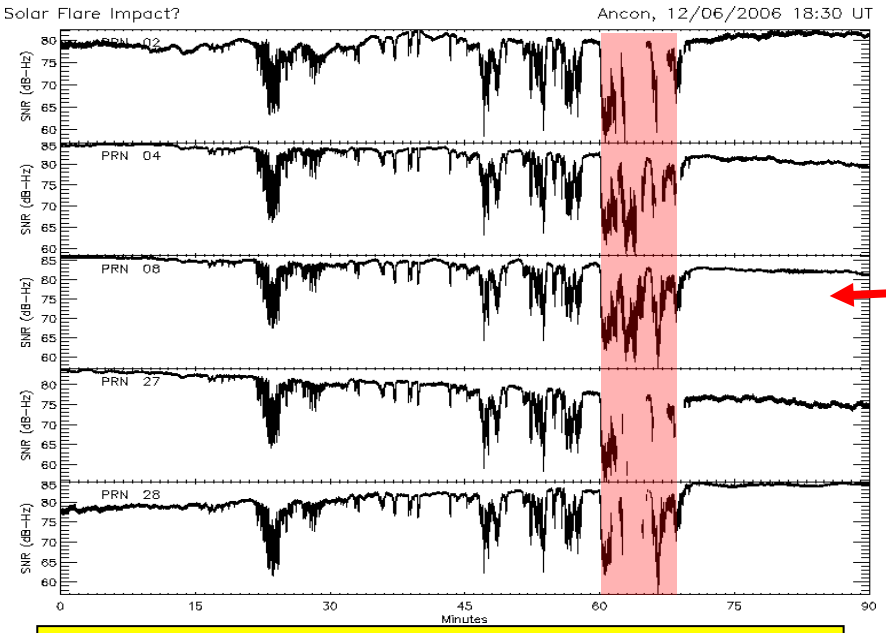
- Radiation degradation & electronics upsets
- Surface and internal charging / discharging
- Increased hazard for humans at high altitudes

Ionosphere/Neutral Effects

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

Effects on GNSS: Solar Radio Burst

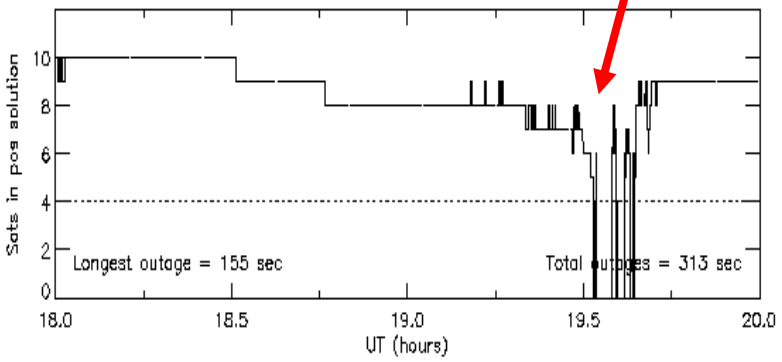
- Strong solar radio bursts impact GPS receivers (A. Cerruti, et al., 2006)
- Extended fades leading to complete outage of GPS positioning on Ashtech Z-12 receiver at Ancon Peru
- Unusual level of L-band power in RHCP mode matched to GPS signals



Similar effects observed across Pacific

Outages occurred here as receiver was unable to track any signals

- Total outage exceeded five minutes



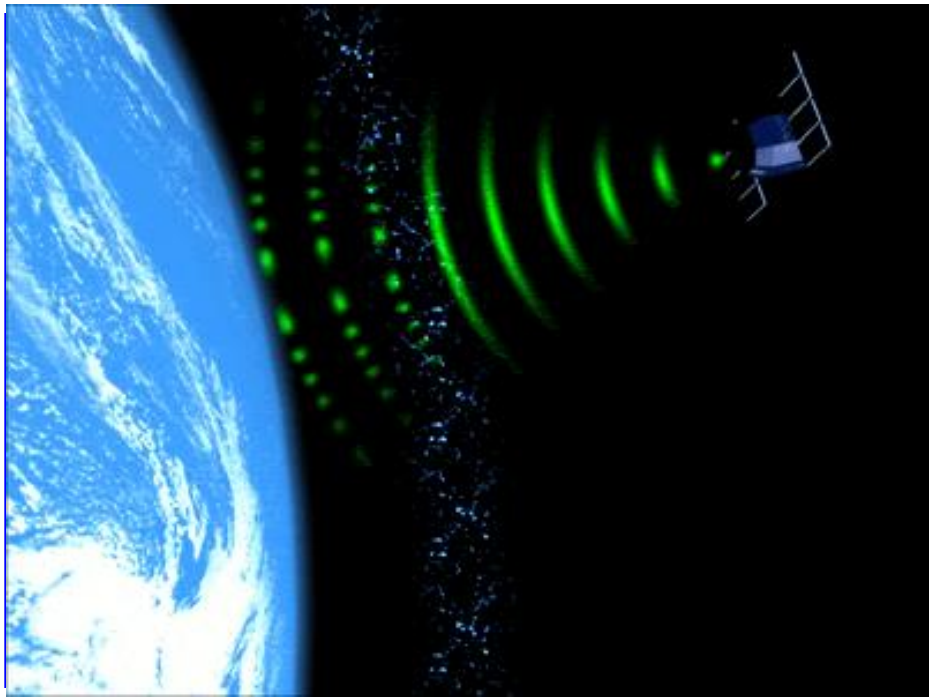
Carrano et al., 2009

Scintillation Physics: A Simple Picture

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

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

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



Courtesy C. Miller, Bath Univ.

- Phase variations on wave front from satellite cause diffraction pattern on ground
- Interference pattern changes in time and space
- User observes rapid fluctuations of signal amplitude and phase

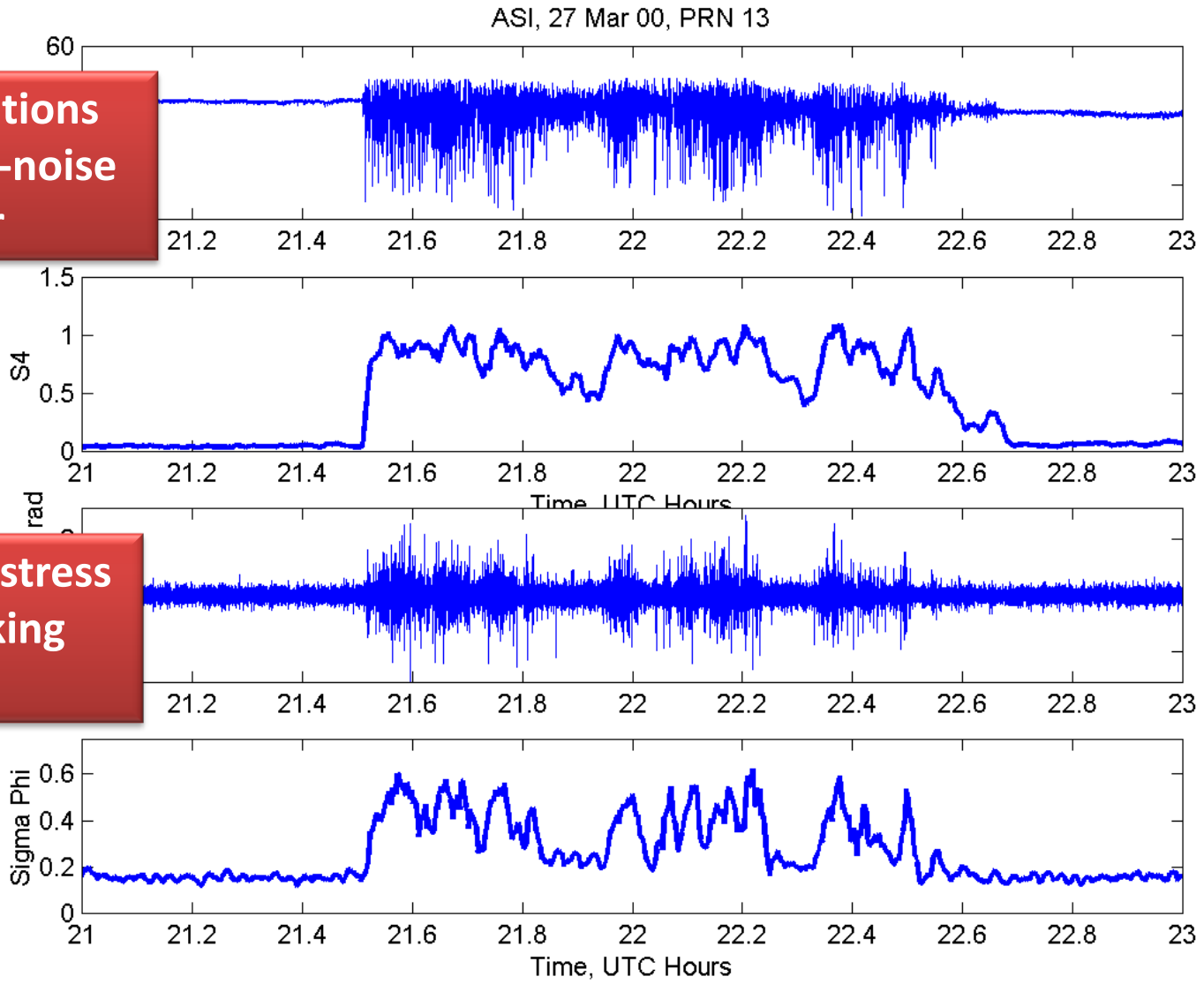
GPS Signal Fluctuations Caused by Ionospheric Scintillation

Intensity fluctuations reduce signal-to-noise in GNSS receiver

S4: Normalized Stand. Dev. Of Intensity

Phase variations stress GNSS signal tracking loops

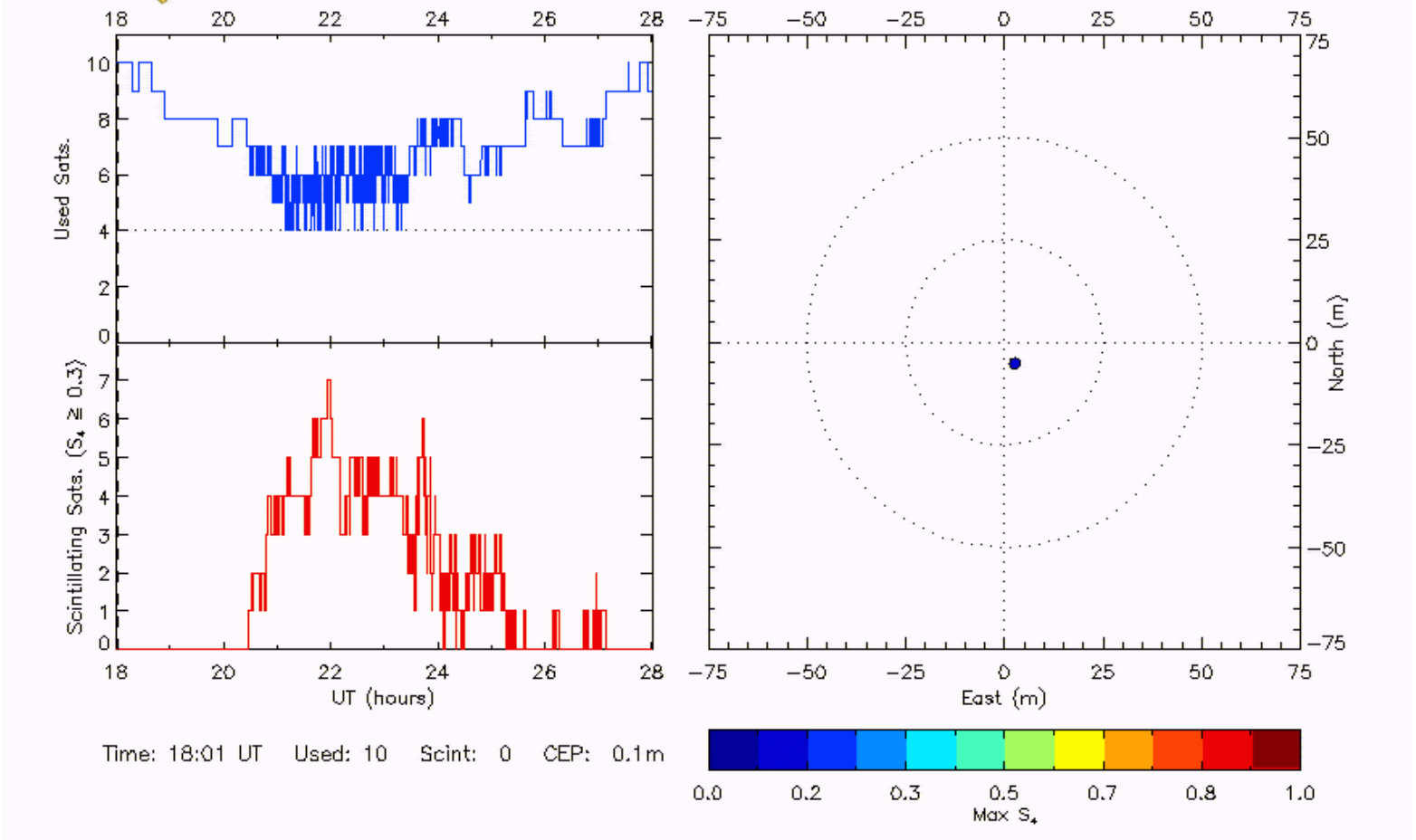
σ_ϕ : Stand. Dev. of Phase



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

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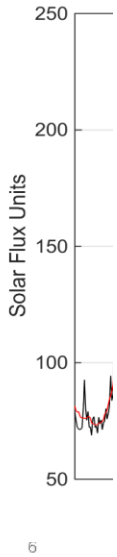
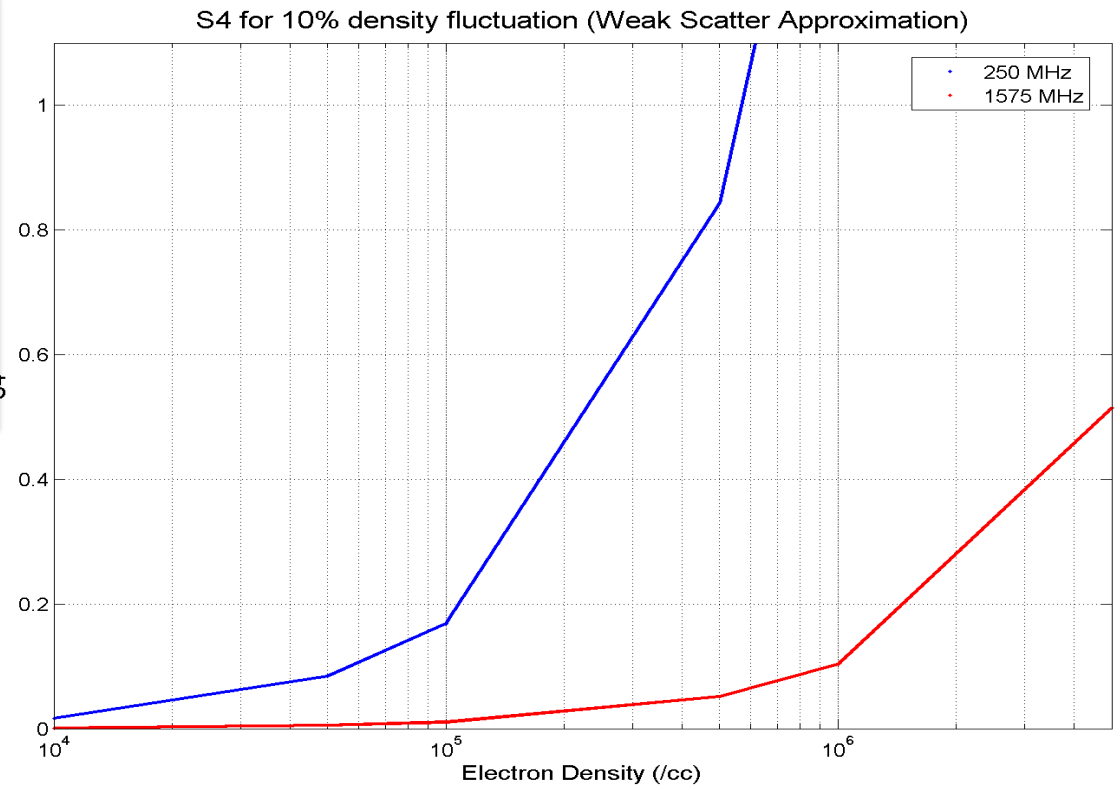


Effect of Electron Density on S4

Scintillation requires two ingredients:

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

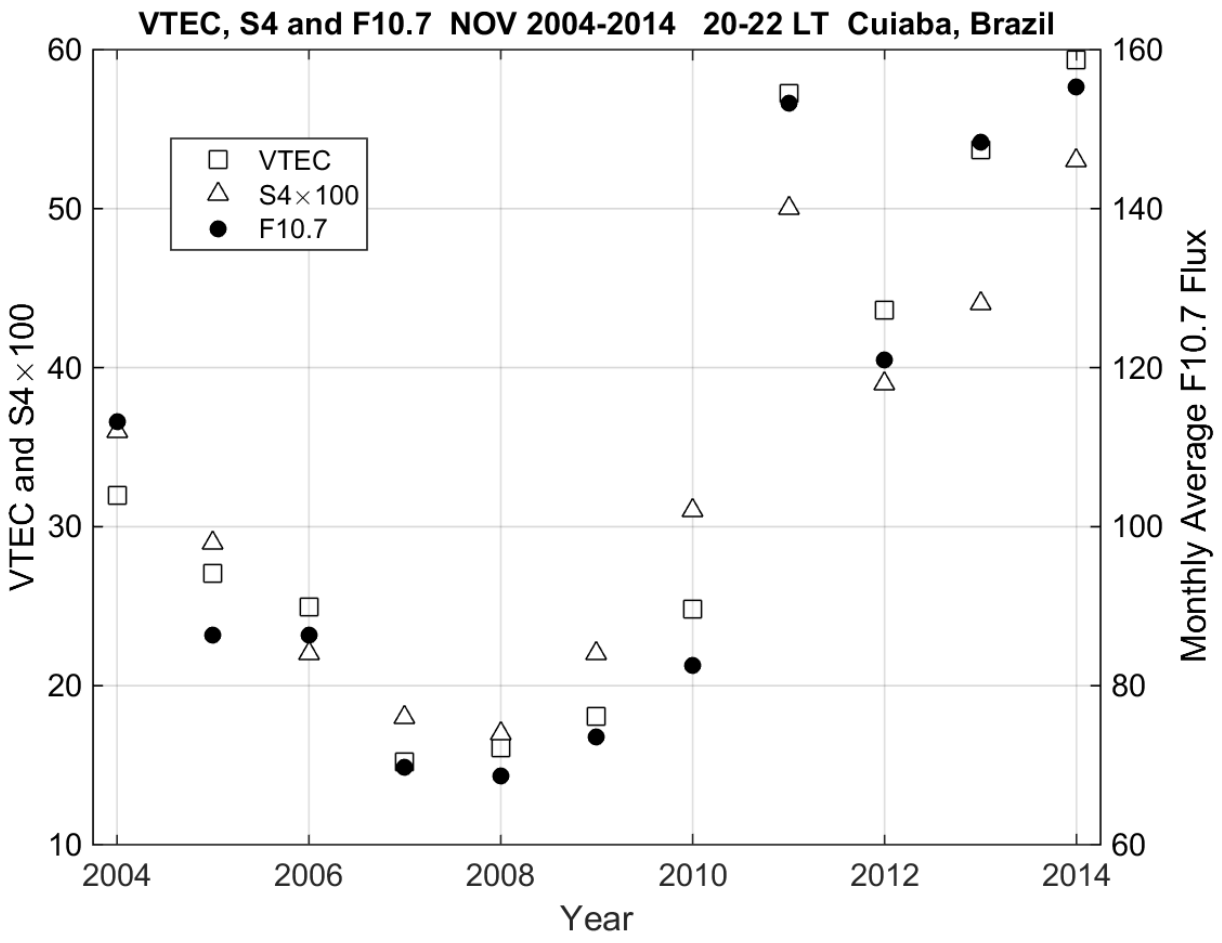


- Significant relative density fluctuations will not cause scintillation if the background electron density is too low
- Must exceed ~1e5/cc for VHF, ~1e6 for GPS (~50 TEC units)

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

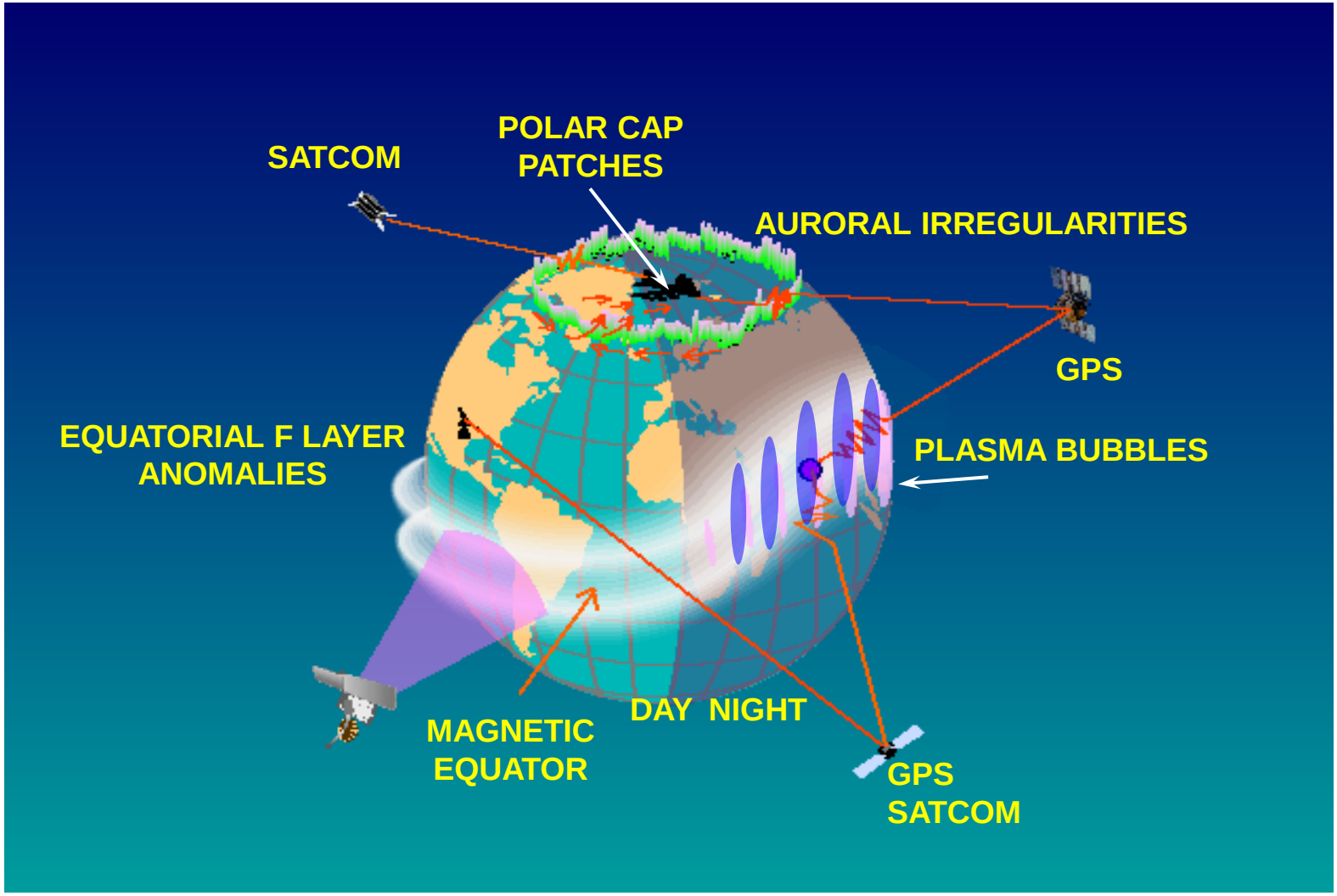
Weak Scatter Approximation

Solar Flux, Density & S4



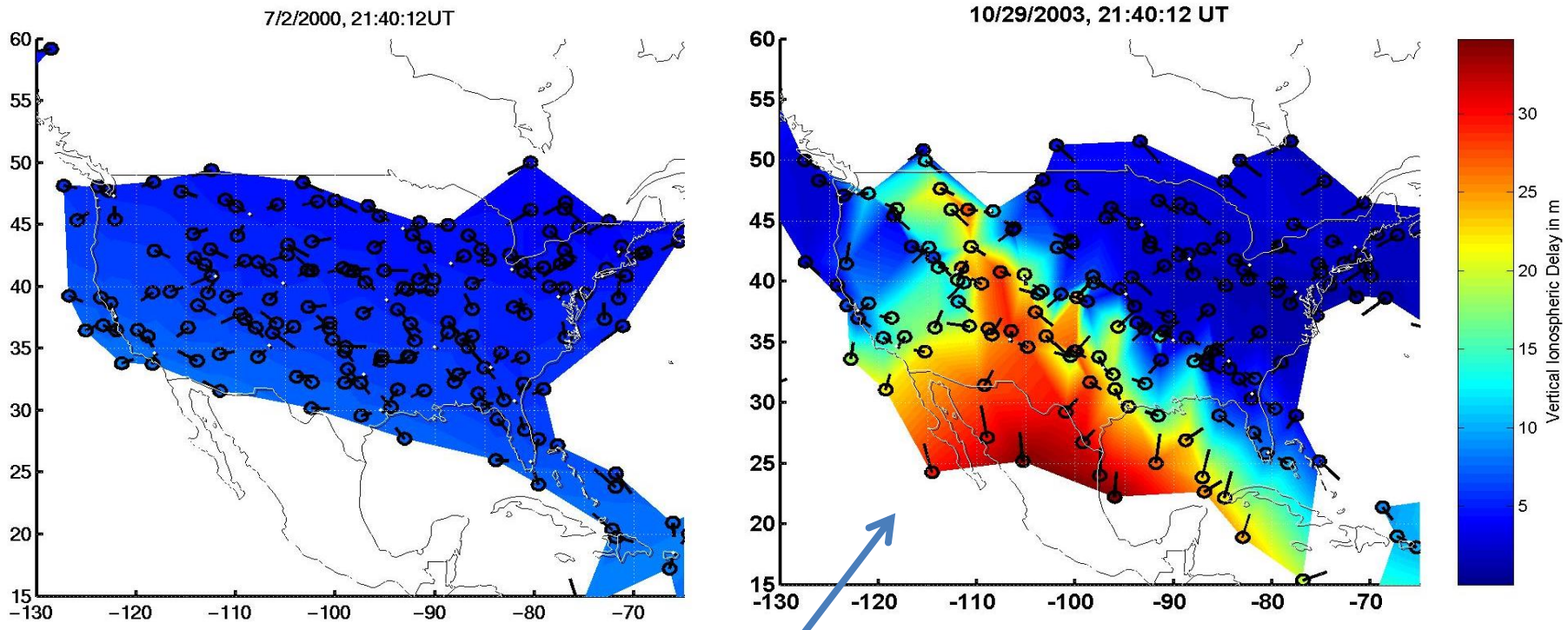
Solar flux determines electron density which determines S4

Disturbed Ionospheric Regions and Systems Affected by Scintillation



Quiet versus Disturbed Ionosphere: Enhanced Mid-Latitude Density Gradients

WAAS Reference Station Measurements



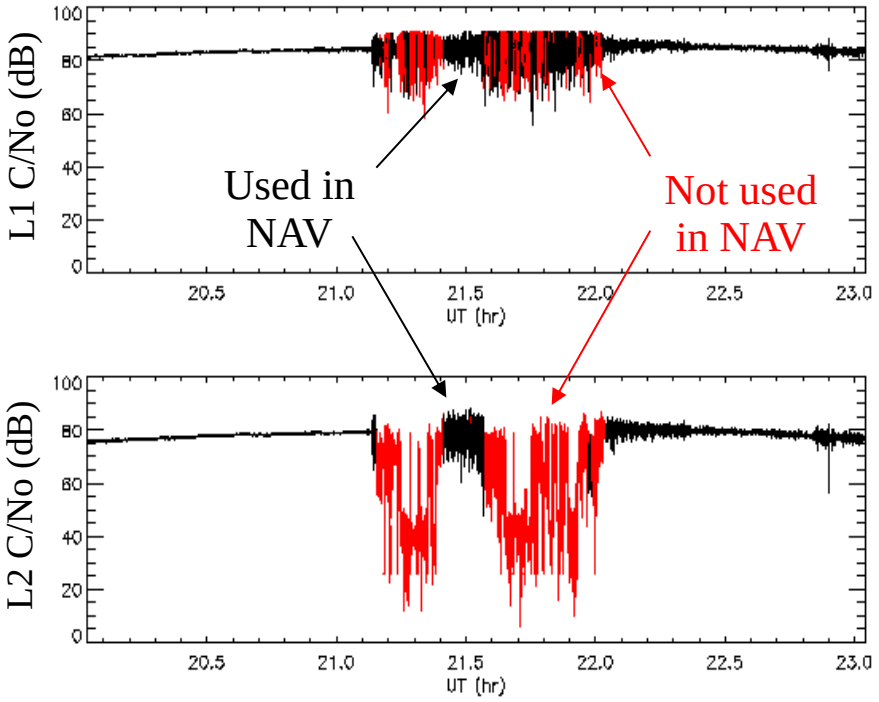
Storm-time Enhanced Density (SED) [Foster 1993, Foster et al., 2002]

Results in loss of vertical guidance availability

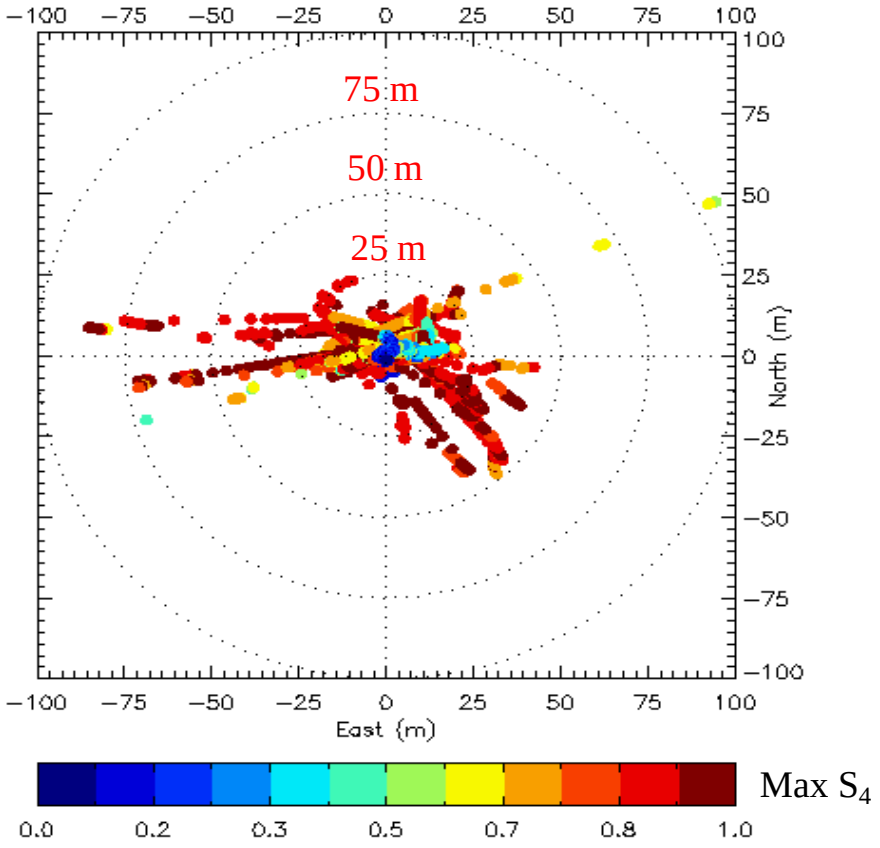
Figures courtesy of Seebany Datta-Barua

Modeling Effects on Positioning Accuracy

16 Mar 2002, ASI



Scintillation Causes Fading of L1 and L2 GPS Signals



Resulting Positioning Error

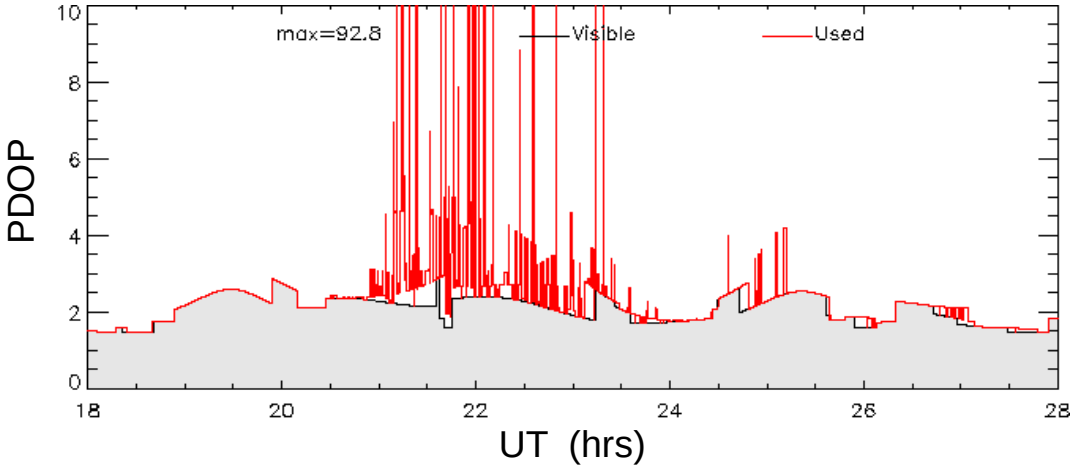
Geometrical Errors and Ranging Errors

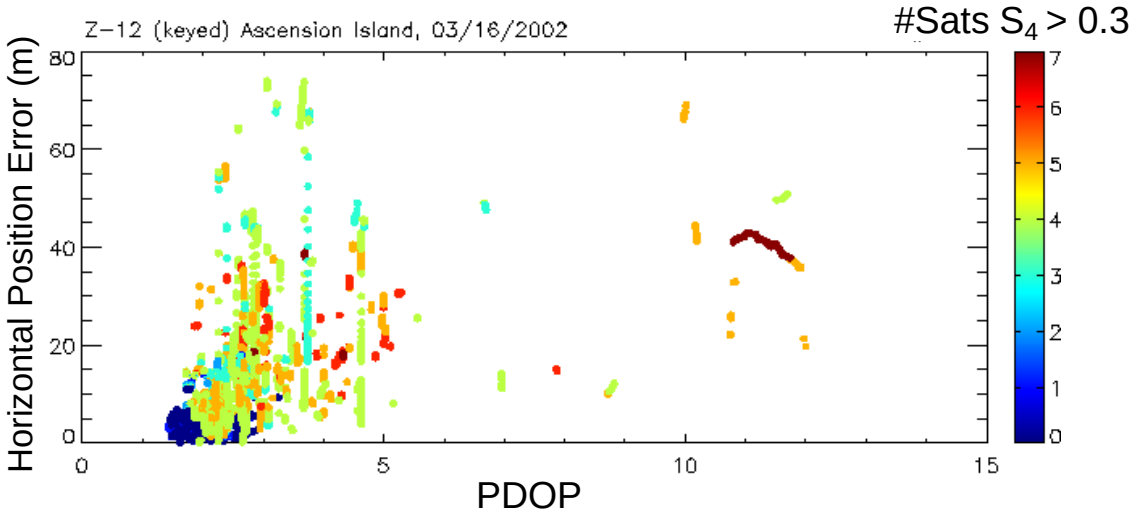
Theoretical and measured Dilution of Precision (DOP)

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*

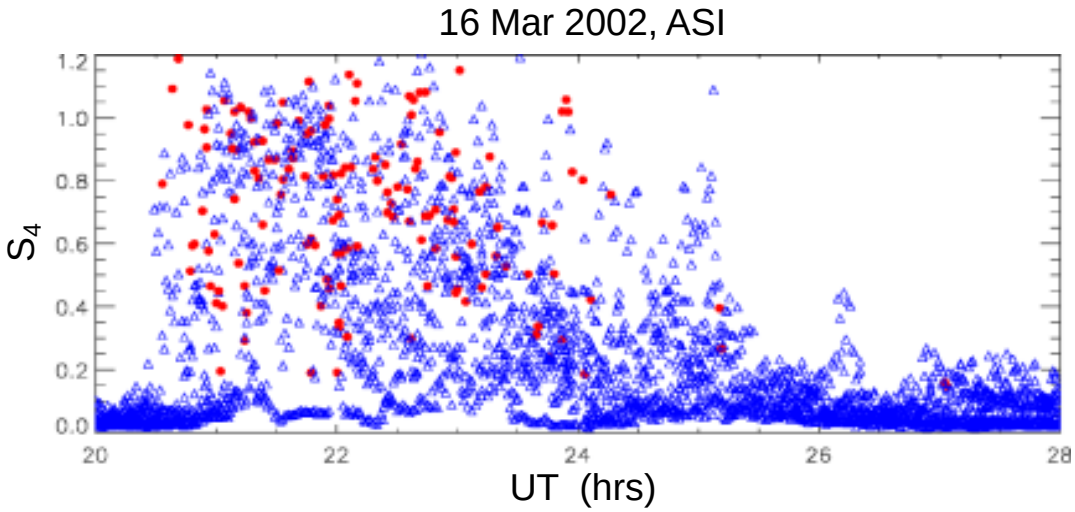
Modeling GPS Satellite Availability During Scintillation

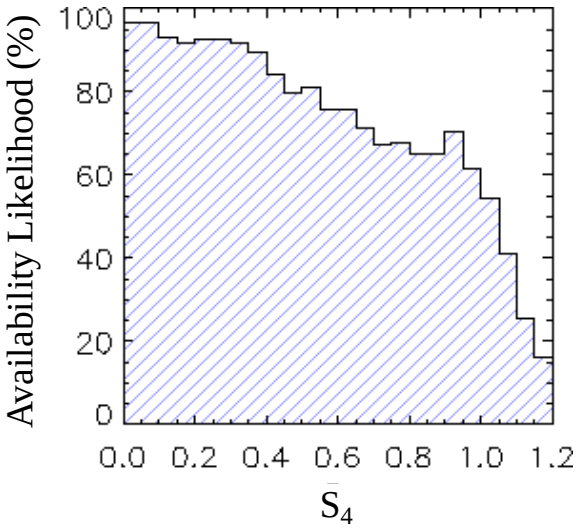
Quality receivers report which satellites used in NAV

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:

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

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 $\boldsymbol{D} = (\boldsymbol{A}^T \boldsymbol{A})^{-1} \boldsymbol{A}^T \boldsymbol{L}$

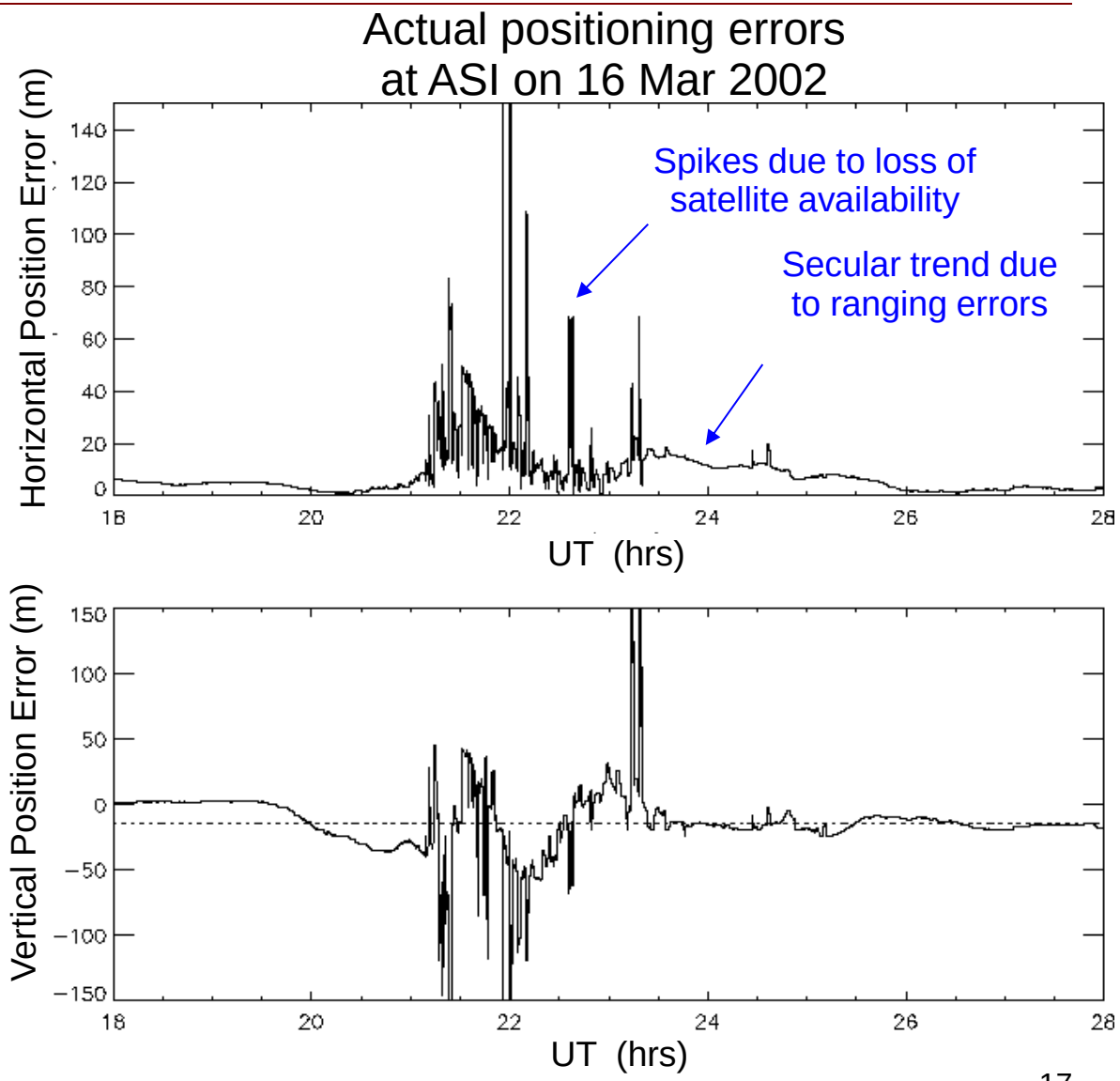
Update the receiver position $\boldsymbol{R}_r \rightarrow \boldsymbol{R}_r + [D[1], D[2], D[3]]^T$ and repeat until convergence.

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.



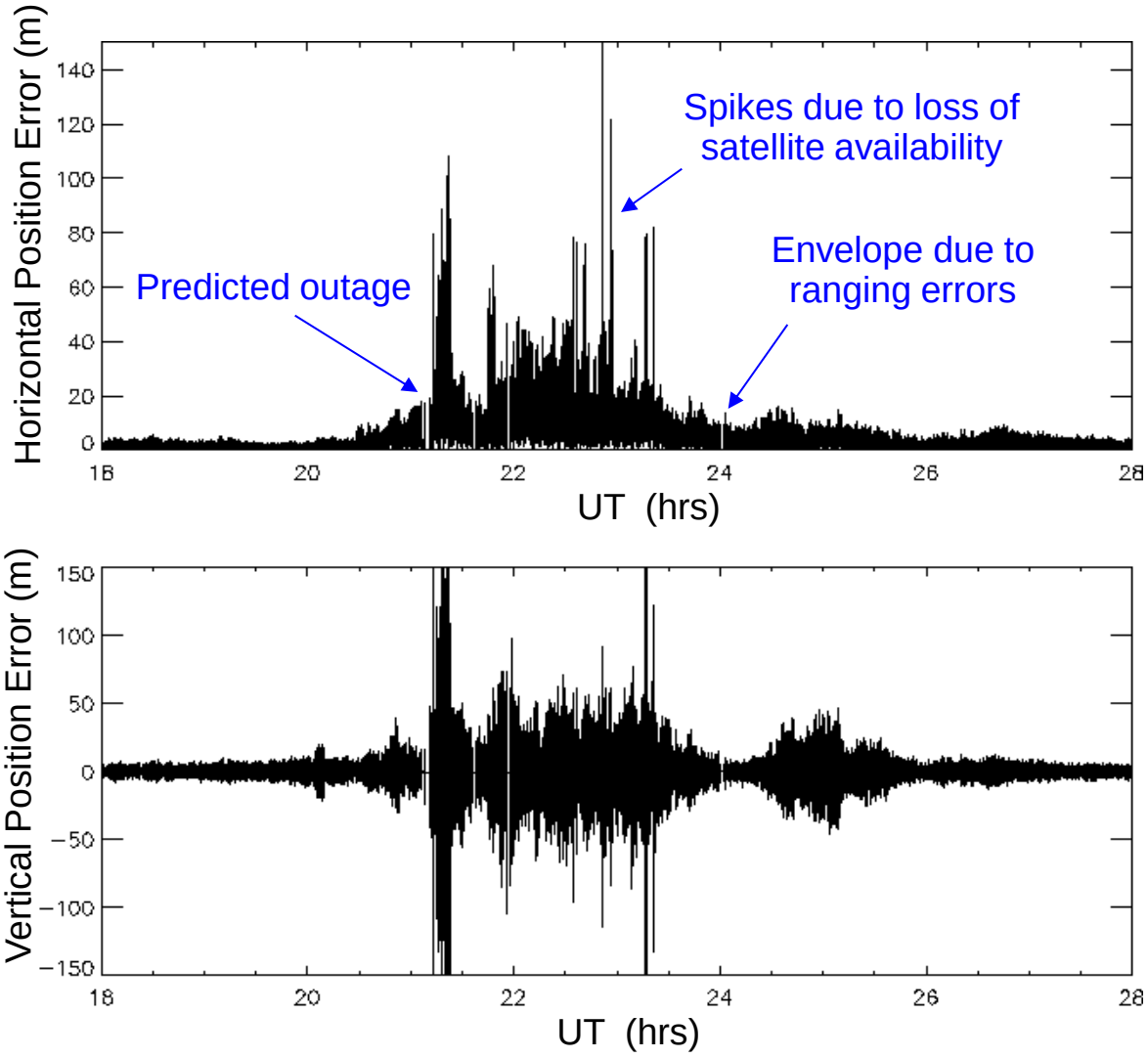
Preliminary Simulation Results

Simulation results using the scaling factor, γ_s = 70 m

Explanation for rapid fluctuations:

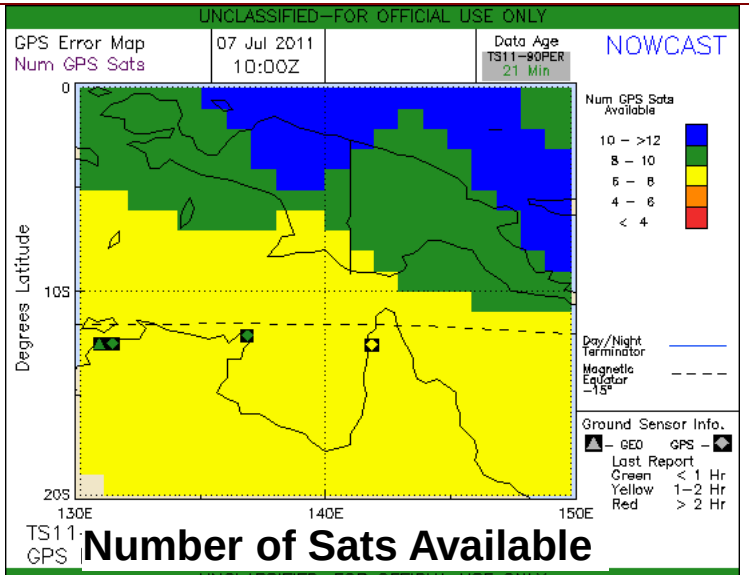
Random range perturbations are not correlated in time, unlike in the real world

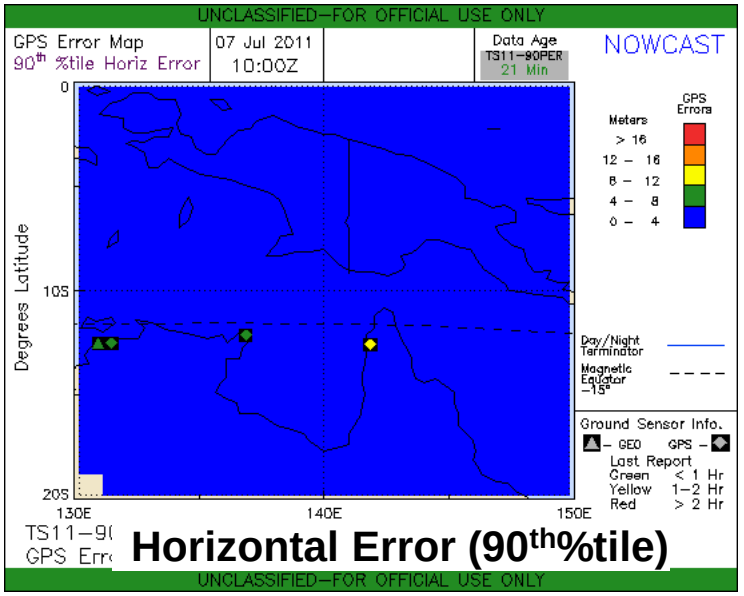
Even though we have an S_4 measurement only once per minute, we evaluate the model every second so we can do statistics.

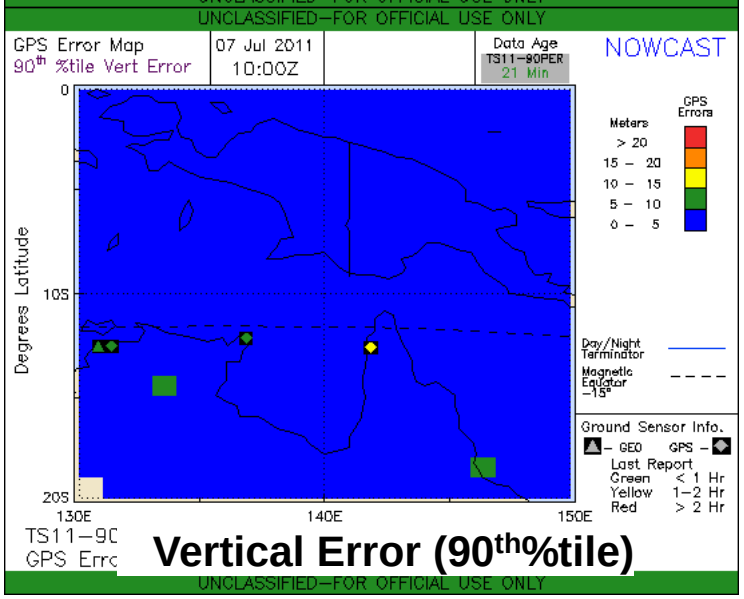


Dual-Frequency Nav Error Product

- Proto-type dual-frequency GPS error maps based on geometry, empirical model and local GPS receiver data
- Actually employed in joint exercise in 2011







Summary

- Scintillation impacts the performance of both single and dual-frequency receivers
- Prevalent in the post-sunset equatorial region and at high latitudes, but may have greatest impact at mid-latitudes during storm periods
- Simple empirical approaches to model errors may provide meaningful information to users; detailed modeling of receiver processing algorithms more difficult
- A useful error product will include all sources of GNSS error, not just ionospheric contributions (geometry, clock bias, satellite health, terrain, multi-path etc.)
- Results presented here were all GPS, but in principle similar propagation effects will impact all L-band GNSS systems
- Research on other constellations is needed