Space Weather Effects on Global Navigation Satellite Systems

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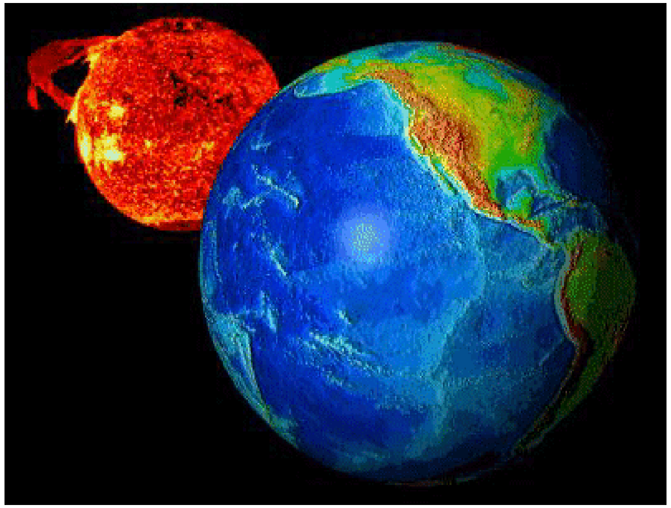
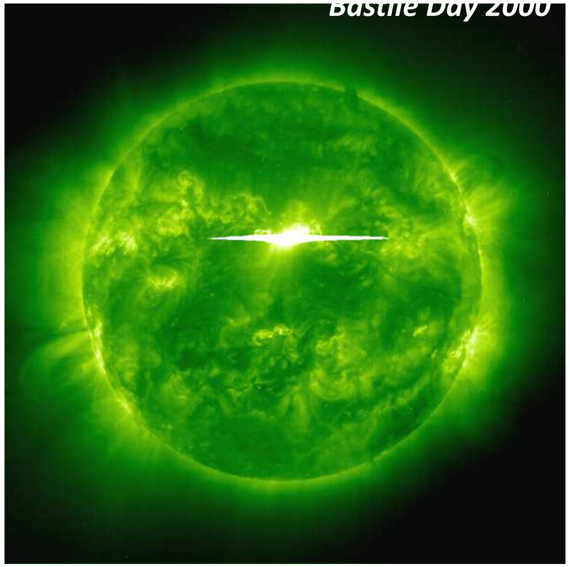
Outline

- Classic Space Weather: Impulsive Solar Events
  - Solar Flares & Coronal Mass Ejections
- Primary Effects on GNSS
  - Satellite Charging & Anomalies
  - Solar Radio Burst Interference
  - **Irregularities & Scintillation: Propagation Effects**
- “Quiet Time” Space Weather
- Summary

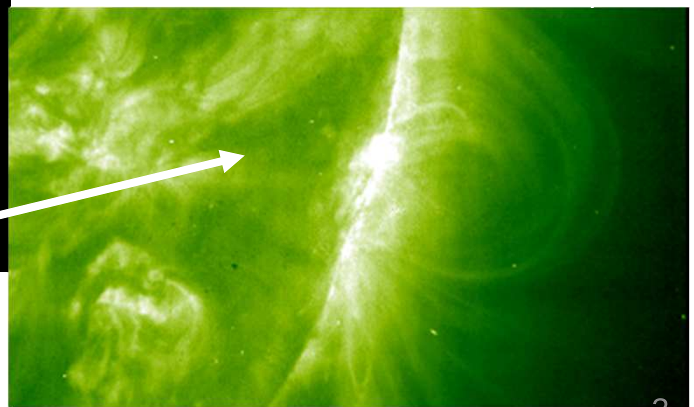


Solar Flares

The Largest Explosive Events of Our Solar System



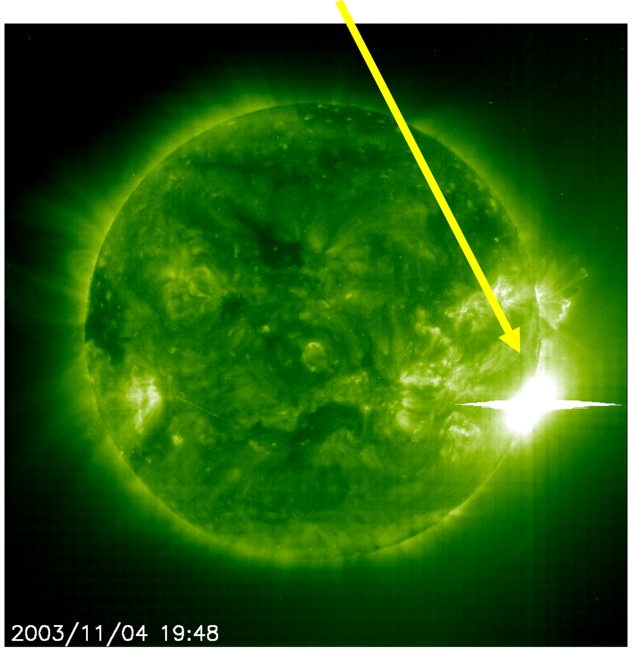
- Intense (short) releases of energy
  - Radiation (radio waves, X-rays, gamma rays)
  - Electrically charged particles
- Radiation travels at the speed of light
- Charged particles travel more slowly
- Three classes based on X-Ray energy
  - **C-Class M-Class X-Class**
  - Largest recorded flare (X28) on 11/4/03



Oct – Nov 2003 Storms

Actual System Impacts

Extreme X-ray / Optical Flare
4 November 2003
X-28 Flare



NASA/ESA

Largest Flare Ever Recorded

Numerous satellite, aircraft & ground anomalies, including:

- Loss of Japan's Midori satellite
- Anomalies on ~30 satellites
- Effects felt on 2/3 of NASA satellites
- FAA issued first-ever passenger alert
- FAA WAAS system: >100m errors
- Satellite communications interrupted
- Electric power service failure in Sweden

Coronal Mass Ejections (CMEs)

The Equivalent of a Hurricane

- Massive bubbles of plasma
- Disrupt the flow of solar wind
- Few per week at peak solar activity
- Occasionally causes geomagnetic storm on Earth
- Arrives in 1-5 days
- The most threatening of solar events

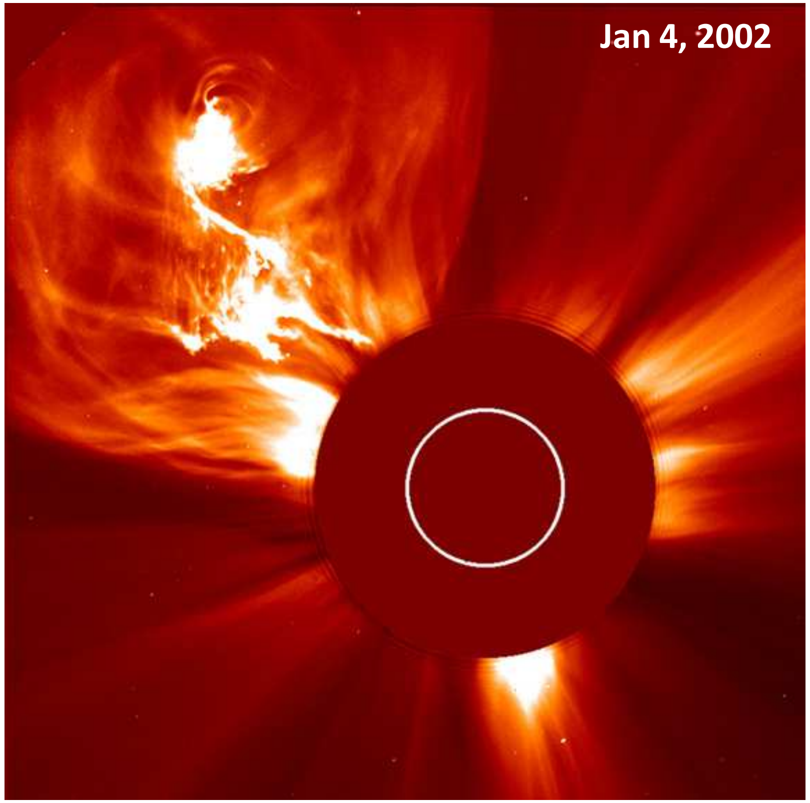
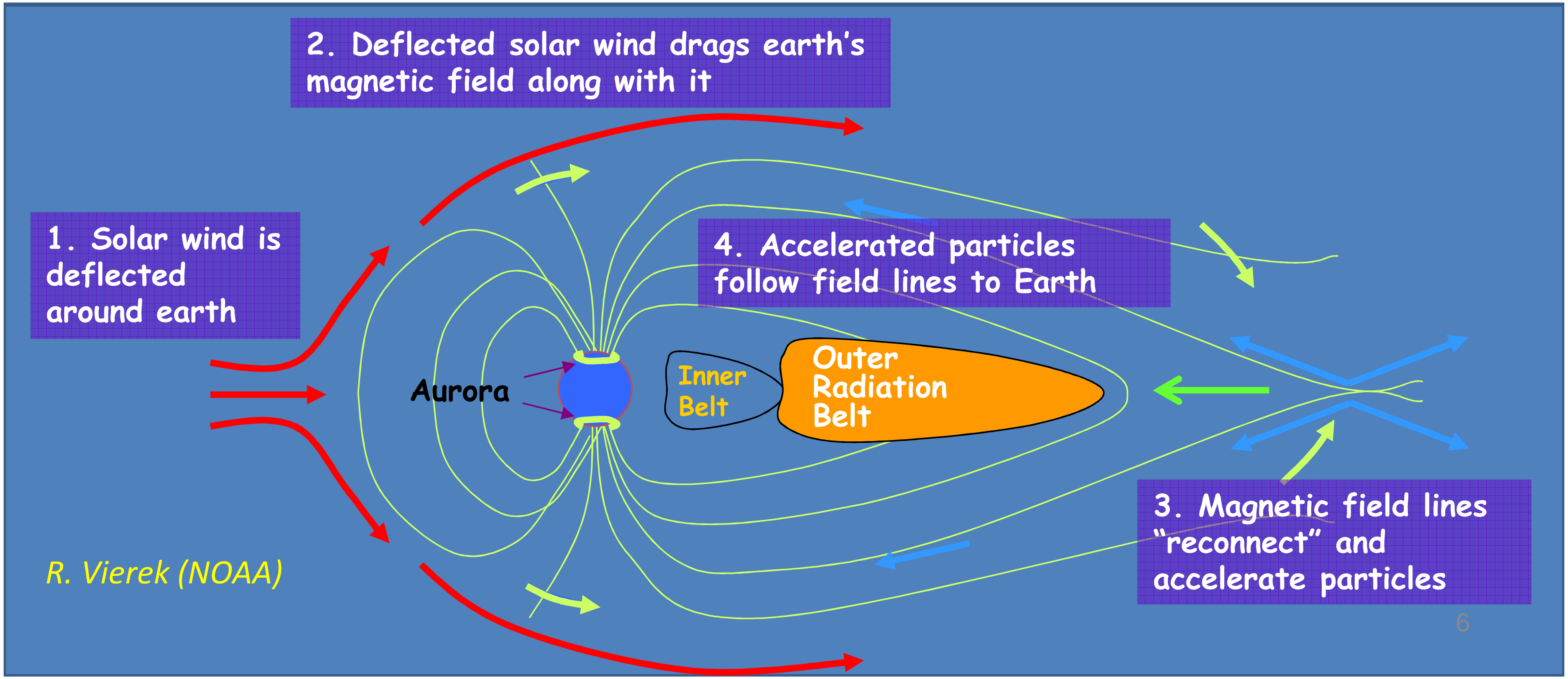


Image from SOHO

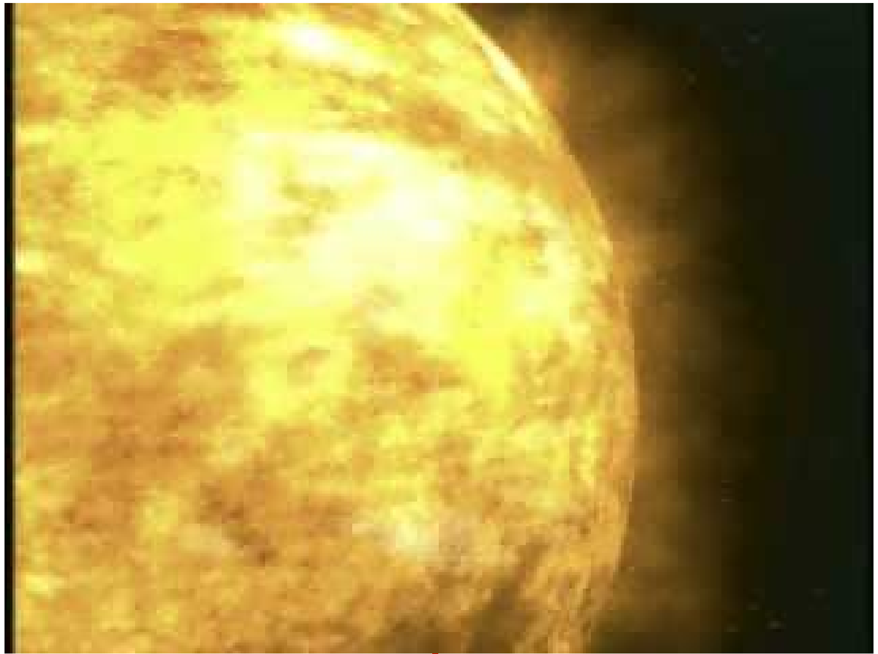
Thumbnail Sketch of a Magnetic Storm

- CMEs travel at speeds up to 2500km/sec (millions of miles/hr)
- Carrying billions of tons of plasma into the solar wind
- Earth' magnetic field deflects the solar wind, protecting the Earth from most of the harmful effects
- Particles enter the Earth's magnetic field where field lines reconnect
- The result – aurora and geomagnetic storms!



Classic Case: Magnetic Storms

Driven by Solar flares and coronal mass ejections (CMEs) on the sun



Animation courtesy of NASA

Iono Storm Physics

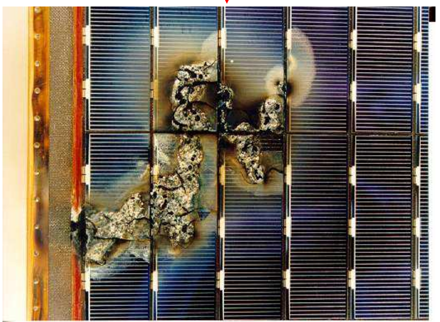
Buonsanto, M. Space Science Reviews (1999) 88: 563. doi:10.1023/A:1005107532631

Phenomena & Effects

http://www.swpc.noaa.gov/phenomena

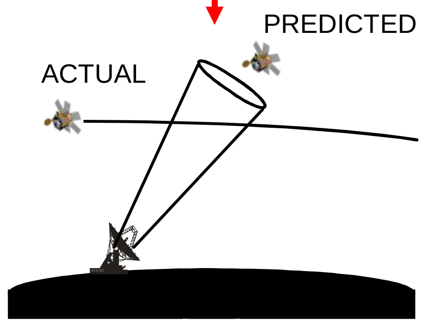
Effects

Degrades Satellite Instruments



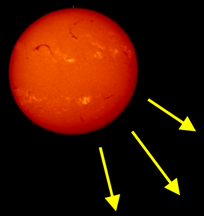
Dangerous Particles to Electronics and People

Disrupts GNSS and Satellite Comms



Possible Collisions in Space

Space Weather Effects on Systems

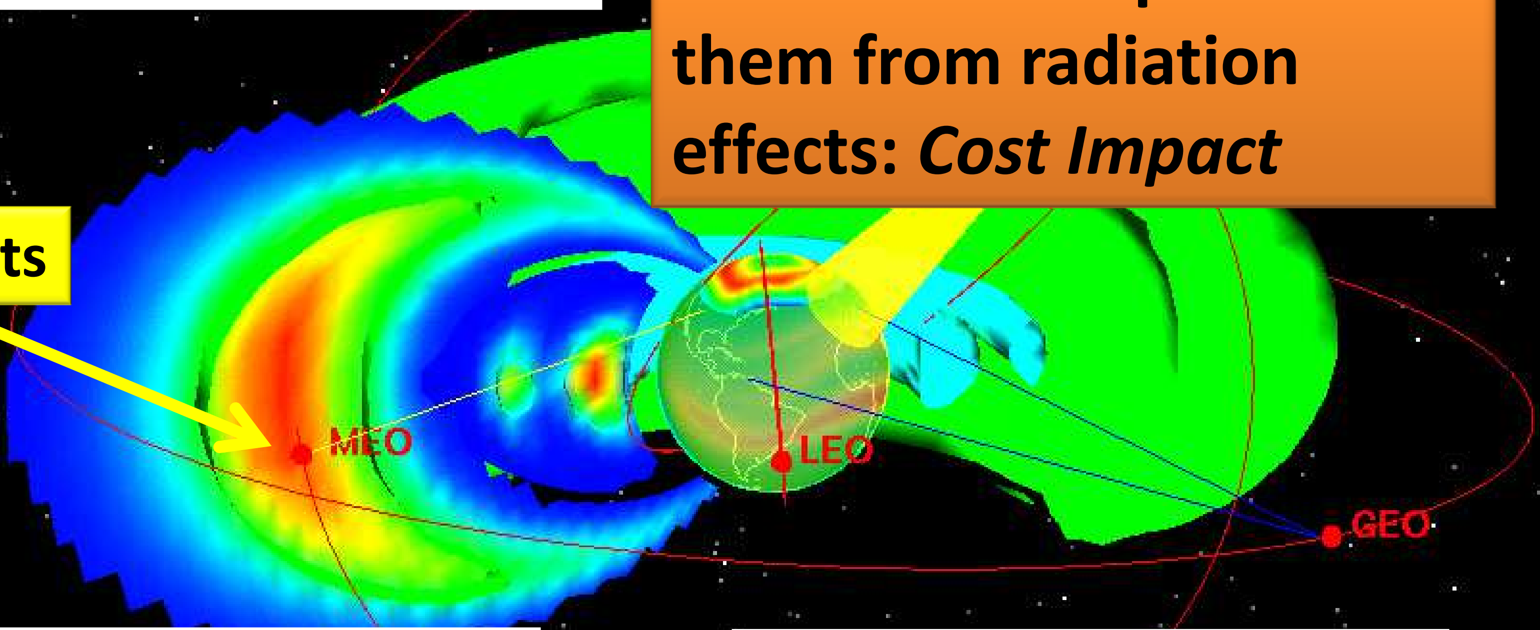


Direct Solar Processes

- Radio, optical and 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

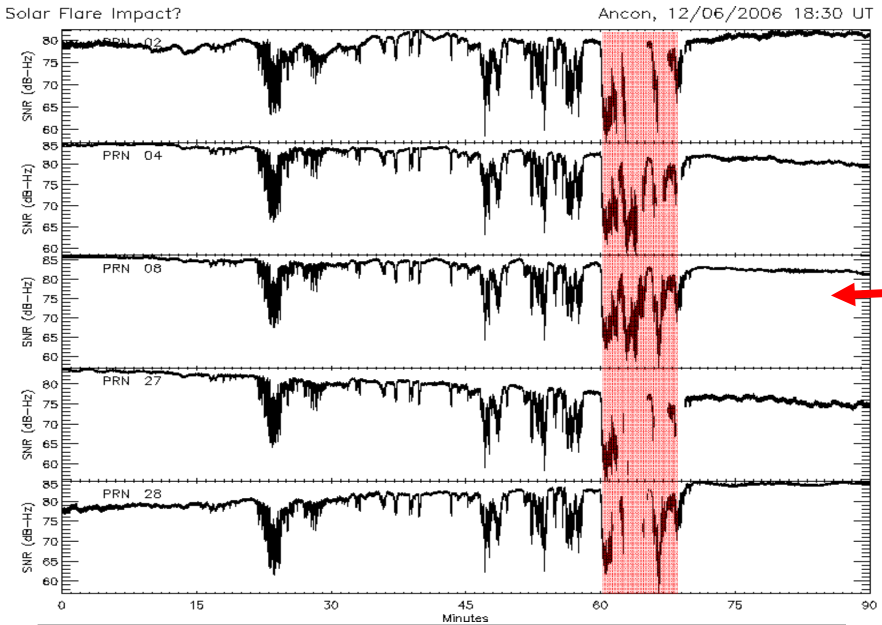
- Radiation degradation and electronics upsets
- Surface and internal charging / discharging
- Increased hazard for humans at high altitudes (space/aviation)

Ionosphere/Neutral Effects

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

Effects on GNSS: Solar Radio Burst

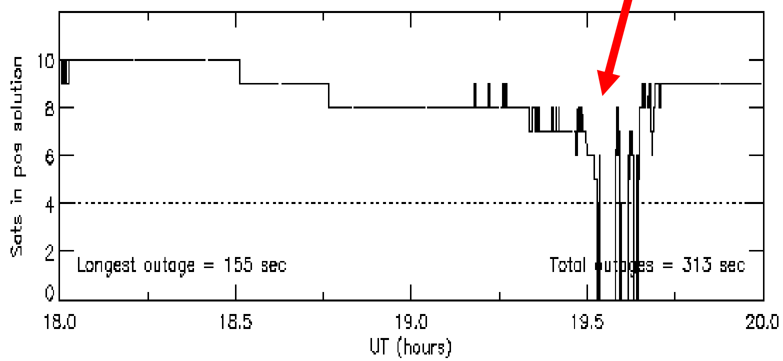
- Strong solar radio bursts impact GPS receivers (A. Cerruti, et al., 2006)
- Extended fades leading to complete outage of GPS positioning on Ashtech Z-12 receiver at Ancon Peru
- Unusual level of L-band power in RHCP mode matched to GPS signals



Similar effects observed across Pacific

Outages occurred here as receiver was unable to track any signals

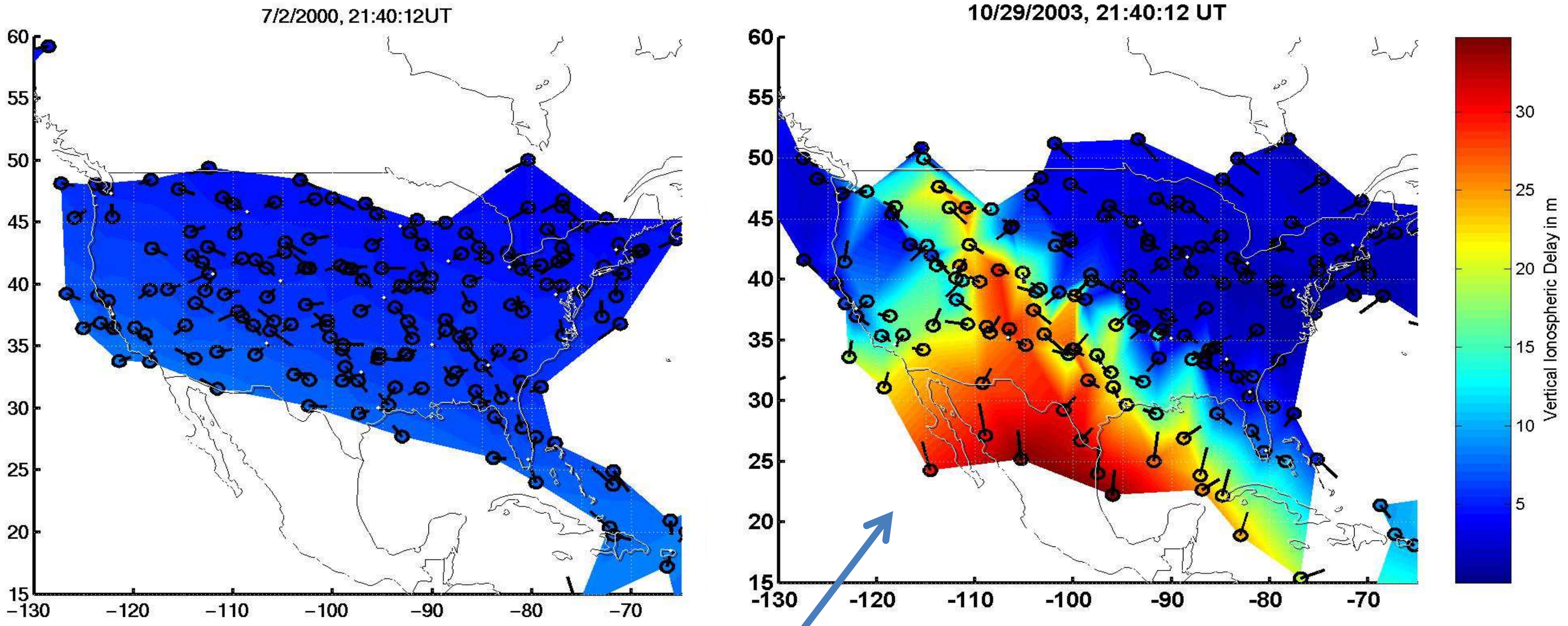
- Total outage exceeded five minutes



Carrano et al., 2009

Quiet versus Disturbed Ionosphere: Enhanced Mid-Latitude Density Gradients

WAAS Reference Station Measurements



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

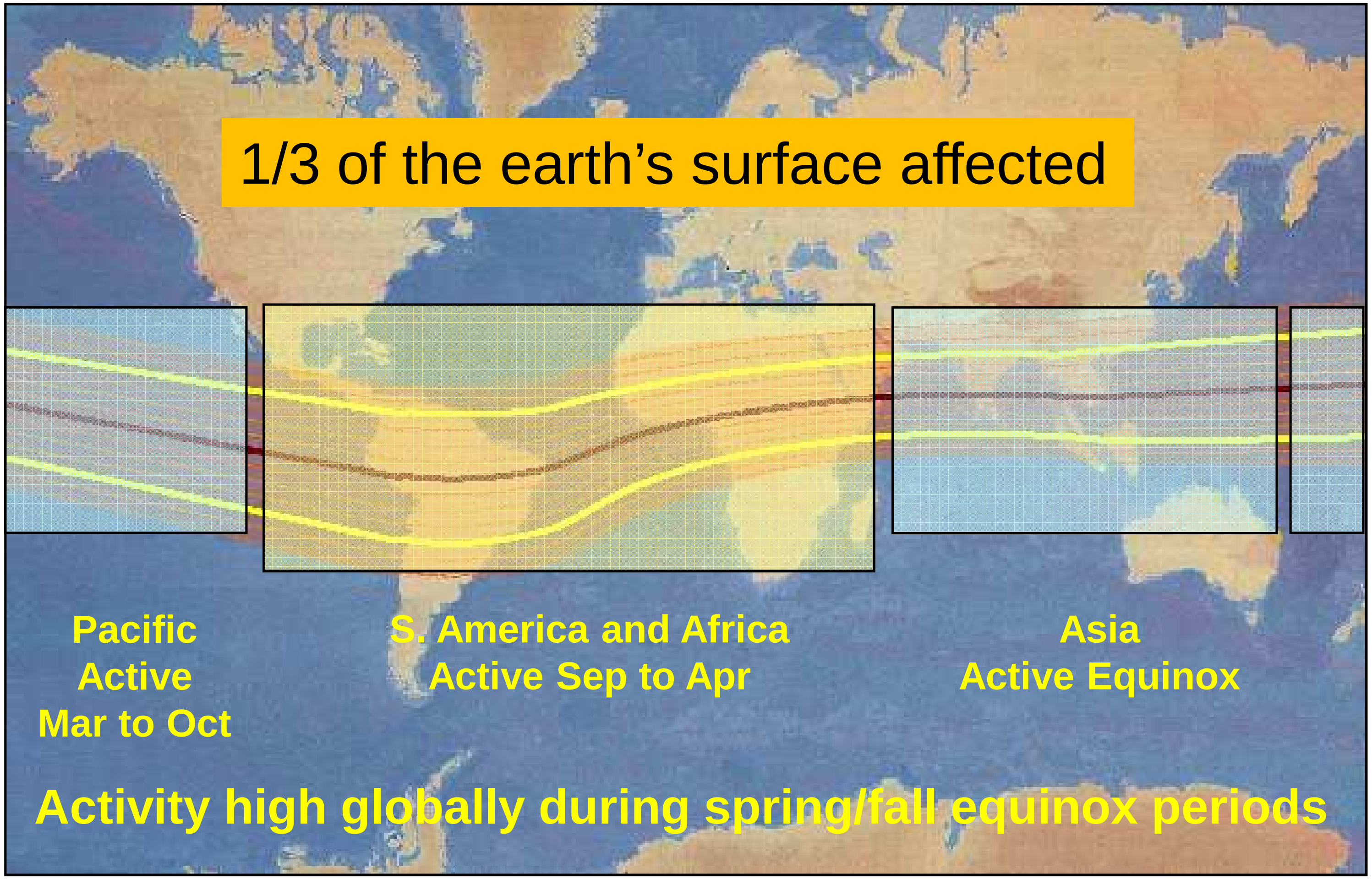
Results in loss of vertical guidance availability

Figures courtesy of Seebany Datta-Barua

"Quiet Time" Space Weather

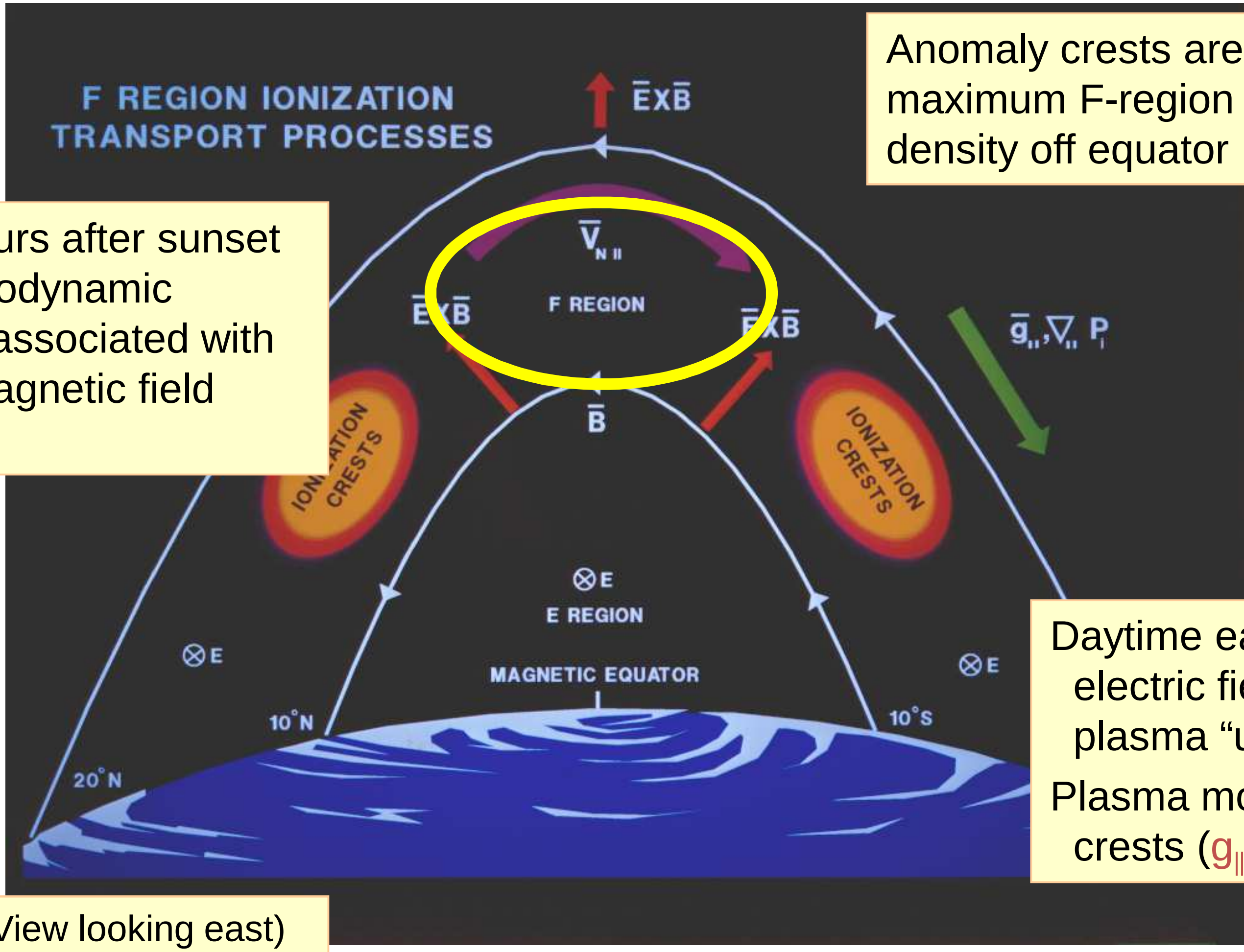
Seasonal and Local Time Dependence

- Equatorial scintillation generally occurs 2000 to 0100 LT in listed seasons
- Most severe impacts on GNSS observed in solar maximum years



Equatorial Irregularity Occurrence

Primarily Caused by Interactions in a “Closed” Ionosphere-Thermosphere System



Anomaly crests are areas of maximum F-region ionization density off equator

Instability occurs after sunset due to electrodynamic interactions associated with horizontal magnetic field geometry

Daytime eastward electric field (E) drives plasma “up” ($E \times B$)

Plasma moves toward crests ($g_{||}$, $\nabla_{||}P_{||}$)

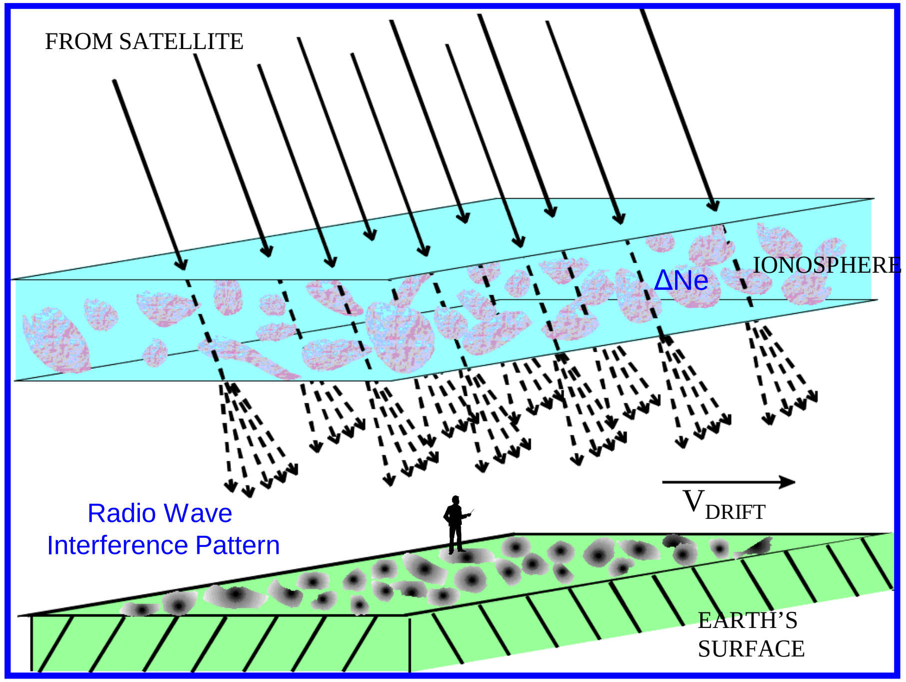
(View looking east)

Scintillation Physics: A Simple Picture

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

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

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



- 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

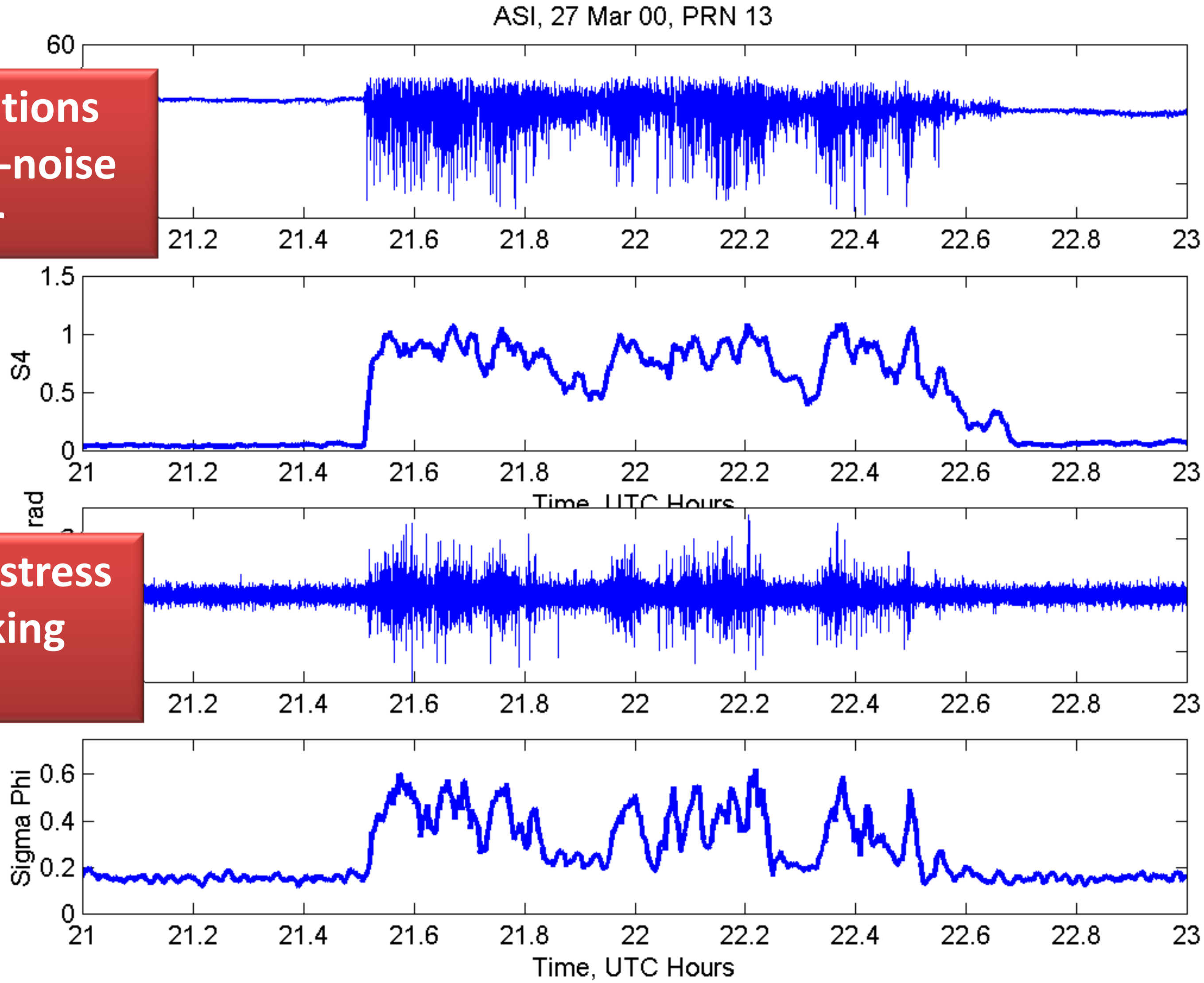
GPS Signal Fluctuations Caused by Ionospheric Scintillation

Intensity fluctuations reduce signal-to-noise in GNSS receiver

S4: Normalized Stand. Dev. Of Intensity

Phase variations stress GNSS signal tracking loops

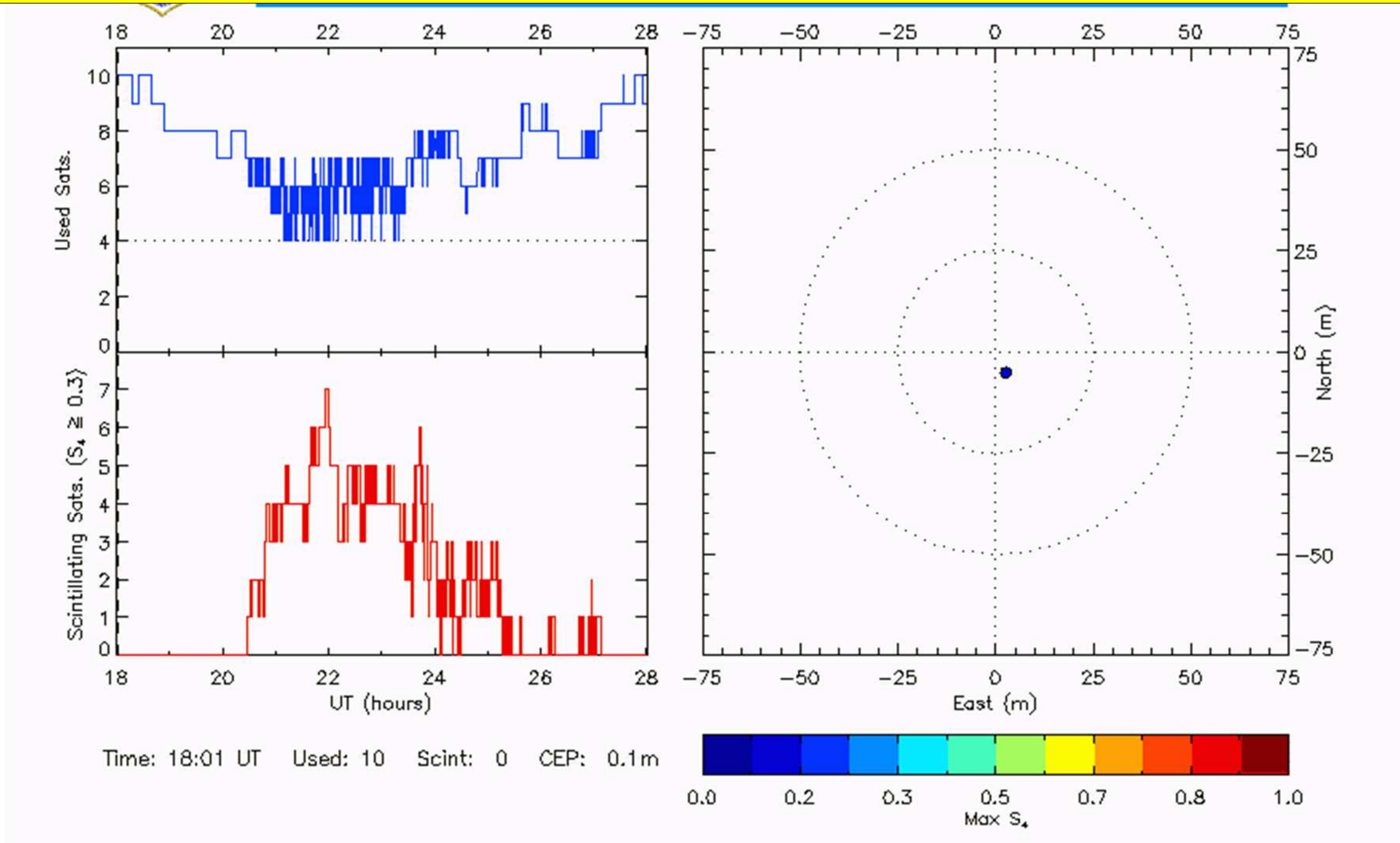
σ_ϕ : Stand. Dev. of Phase



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

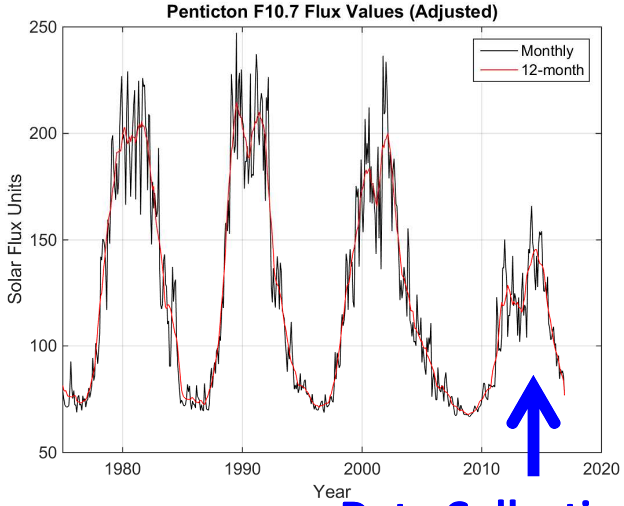


GPS Positioning Errors from Space Weather

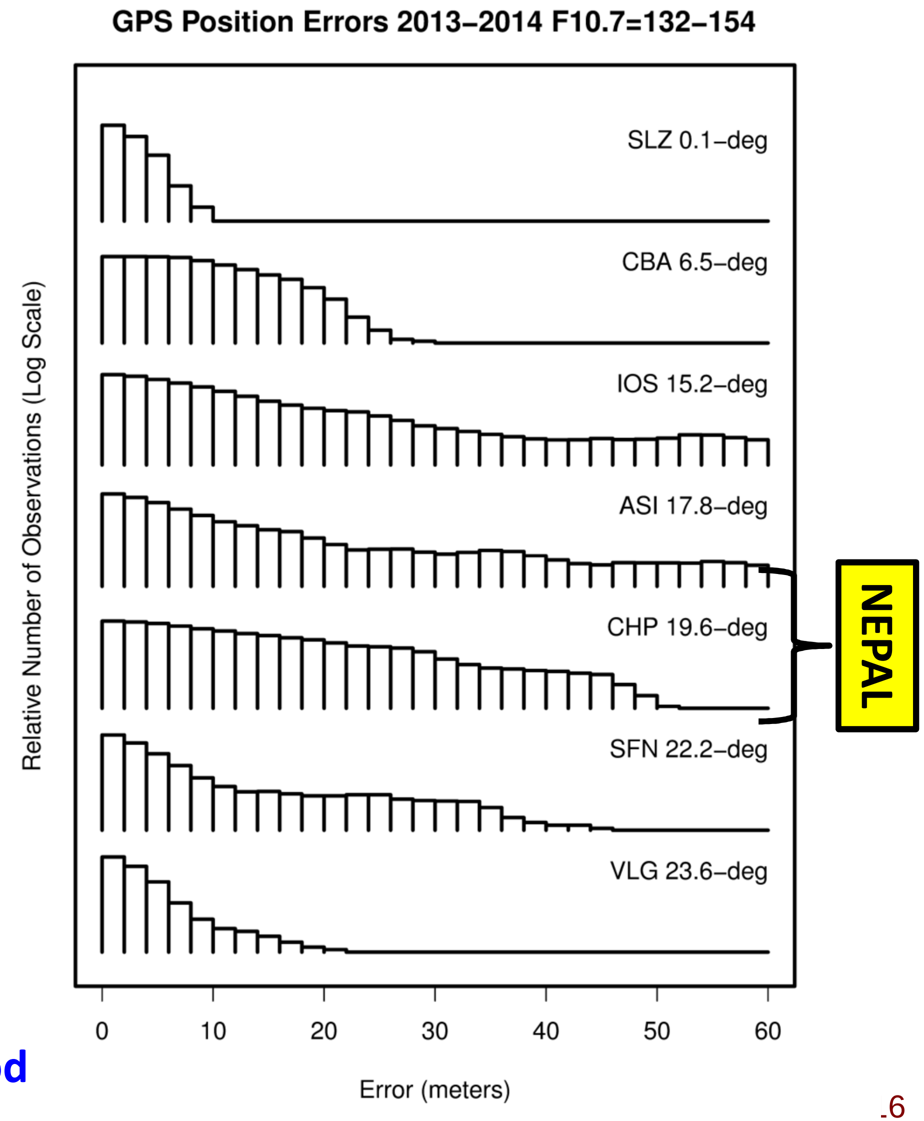
Magnetic Latitude Dependence

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

Solar Cycle Intensity



Data Collection Period



Summary

- Space weather impacts GNSS satellite design & cost
- Propagation effects include interference & scintillation
- Most significant impacts result from scintillation in the post-sunset low latitude ionosphere: 10s of meter of positioning error have been documented on GPS
- Modern receivers perform better but are still impacted; multi-constellation reception will definitely help
- Difficult to compare performance from previous solar cycles—the most maximum was not large by historical standards

Final Comment

- **Data presented here are GPS ONLY.**
- **Results apply in general to all GNSS systems*, but specific performance impacts will vary by system**
- **Research on other constellations is needed!**

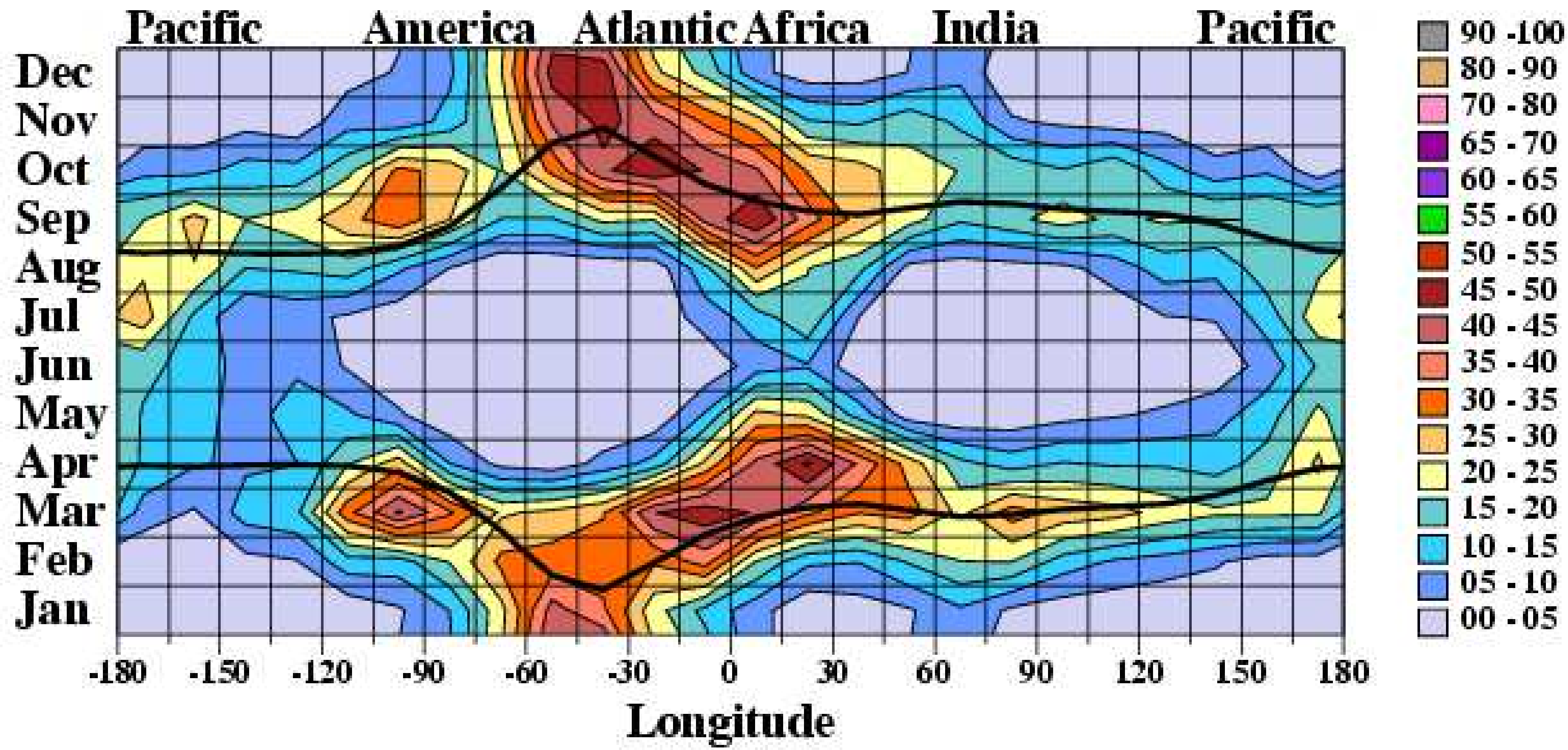
*IRNSS S-band signal will be less impacted than other GNSS signals

Thank you for your attention

DMSP Bubbles 1999 - 2002

In situ irregularities detection statistics
800 km circular polar orbit

Relative Occurrence Climatology

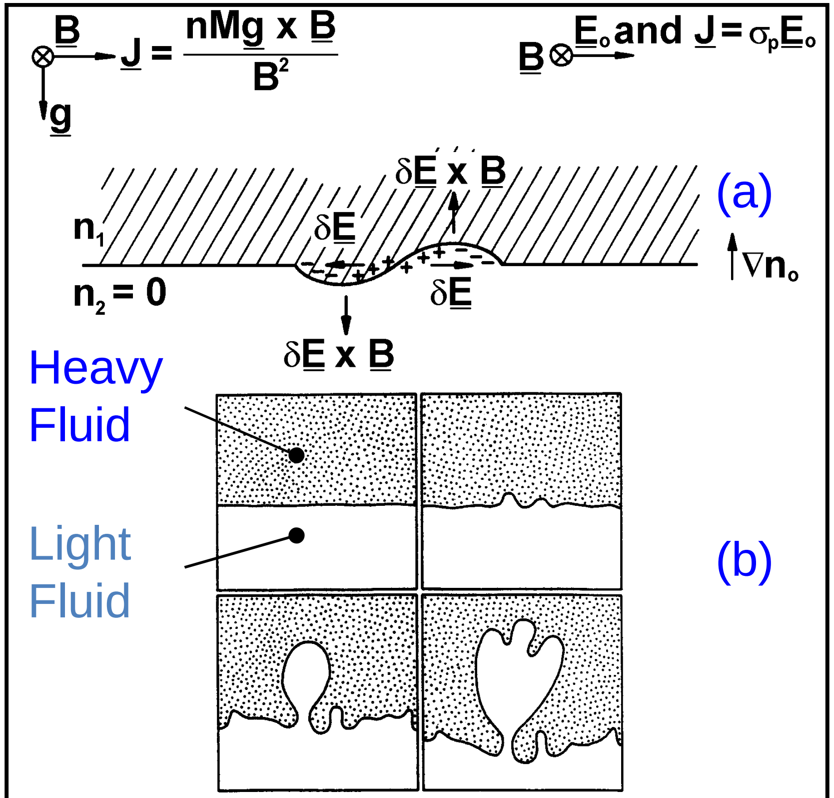


From Burke & Huang [2004]

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)

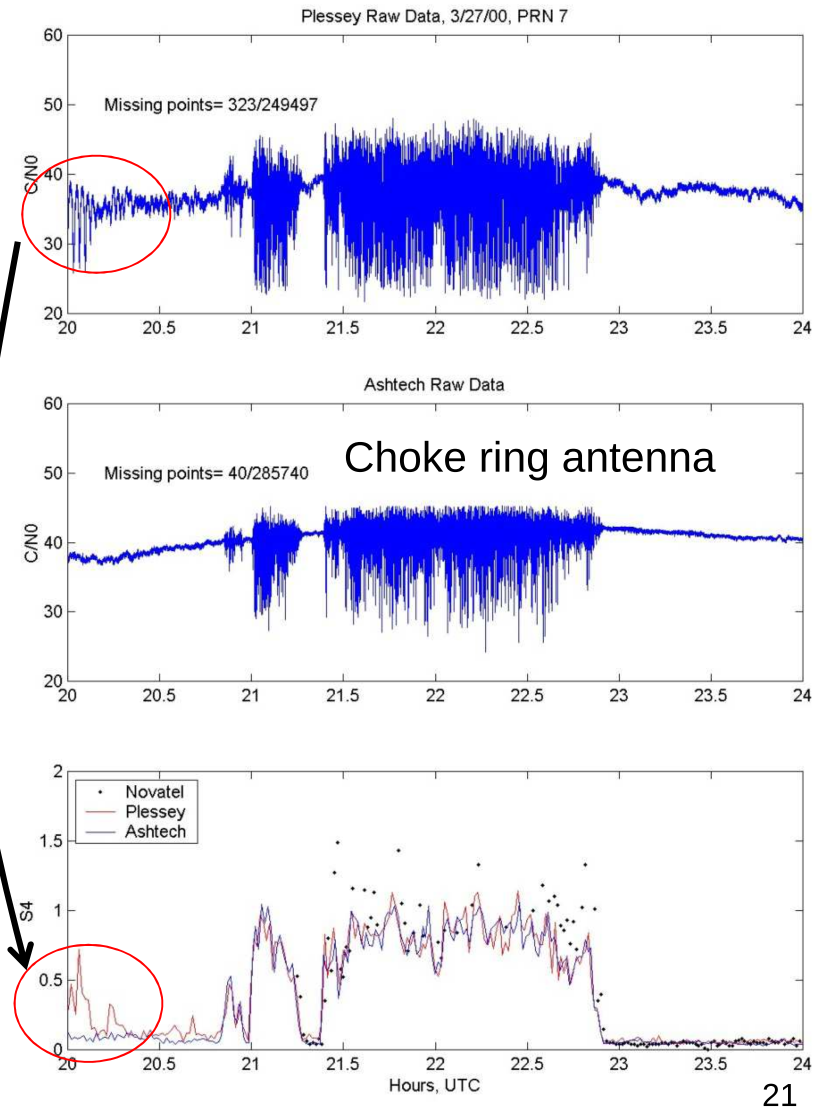
(b) Analogy with fluid Rayleigh-Taylor instability

Perturbations start at large scales (100s km)

Cascade to smaller scales (200 km to 30 cm)

GPS Receiver Comparison
Scintillation & Multi-Path

- Multi-path occurs because of beating between direct and reflected signals as GPS satellites move across the sky
- Power fluctuations result in elevated scintillation parameters
- Fluctuations
on type of ar
environment



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