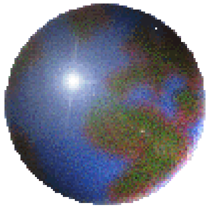

Ionospheric Effects on GNSS

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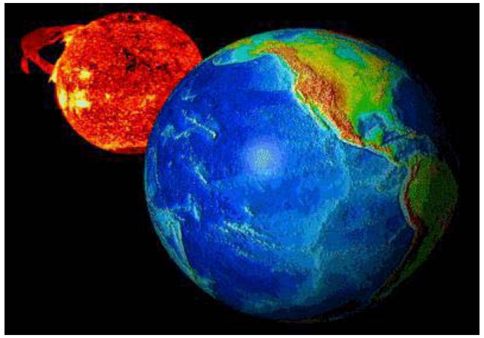
Second Workshop on Satellite Navigation Science and Technology for Africa

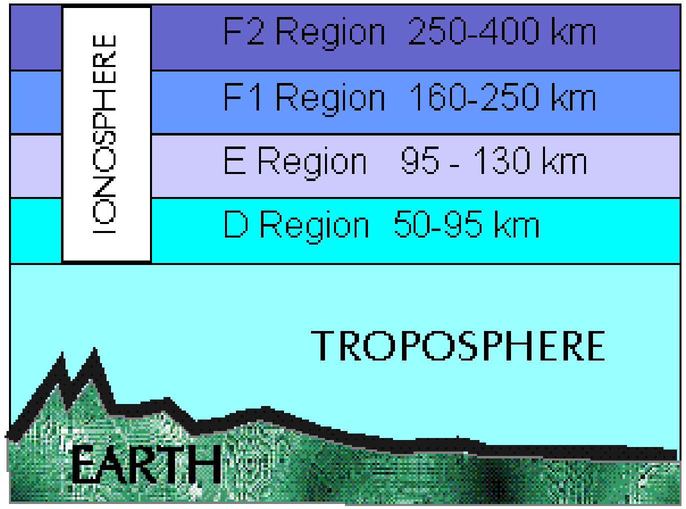
ICTP Trieste, Italy 6-24 April 2010

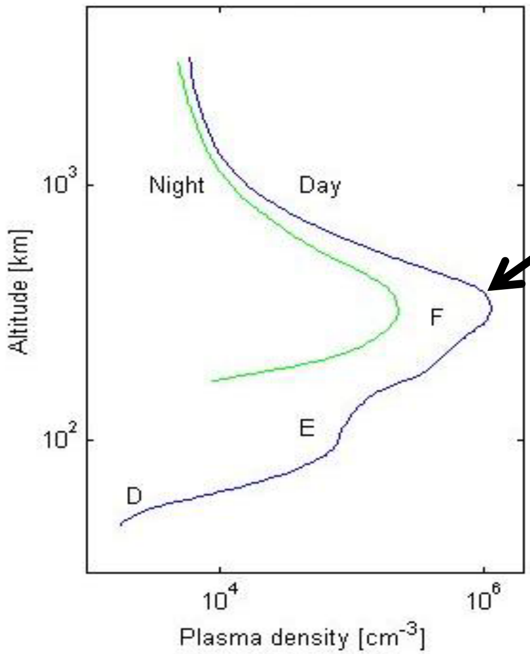
Outline

- What is the Ionosphere?
- Worldwide Ionosphere Characteristics
- Ionospheric Effects on Radio Waves
  - Range Delay
  - Amplitude and Phase Scintillation
- Mitigation of Ionospheric Effects
- Summary



What is the Ionosphere?





F Layer is most dense and highly variable.

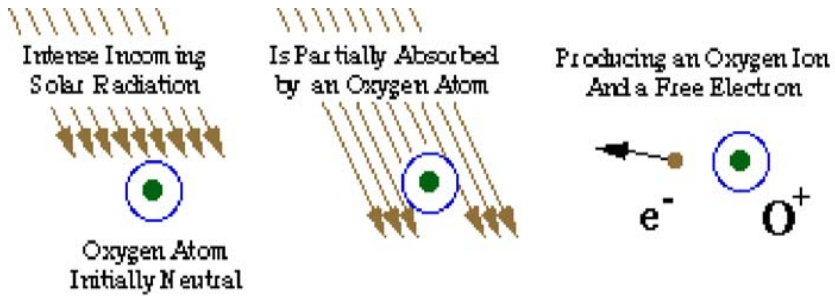
TEC is the integrated profile along a line of sight from a Rx to a Tx

The region of the atmosphere in which free electrons exist in sufficient quantities to affect the propagation of radio waves.

•Begins at about 50km and extends into space

•Produced by UV radiation from the Sun

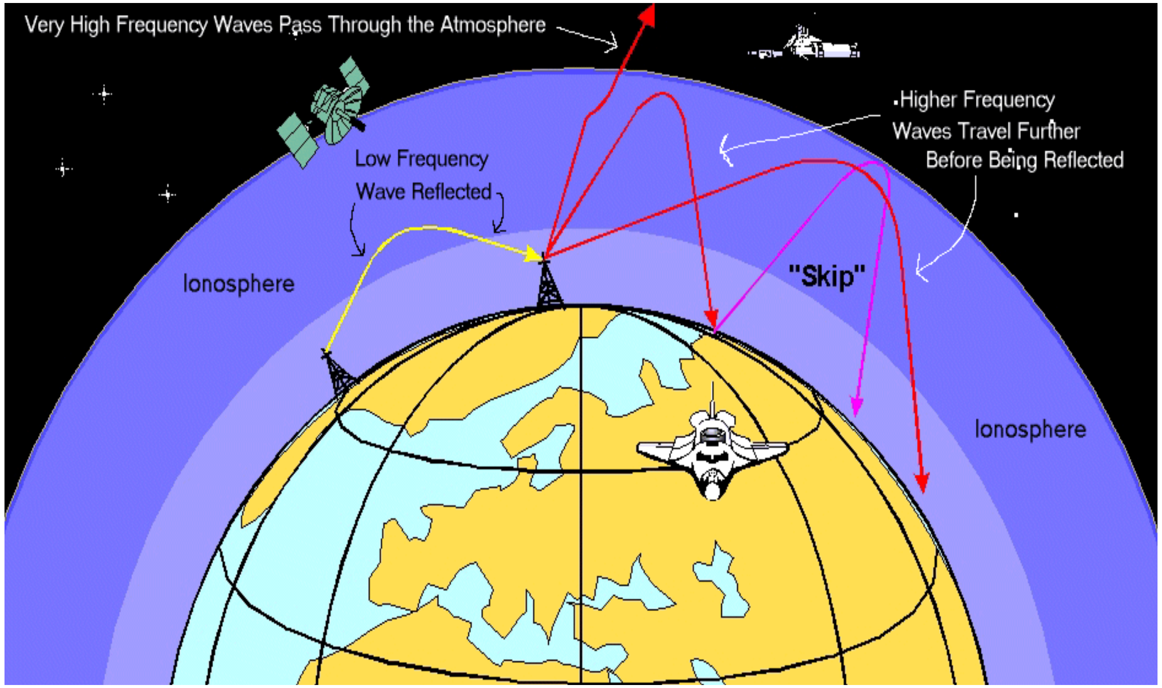
Photoionization



•Reverse process is ***Recombination***

•Controlled by chemical composition and transport by neutral winds

Ionospheric Effects on Radio Waves

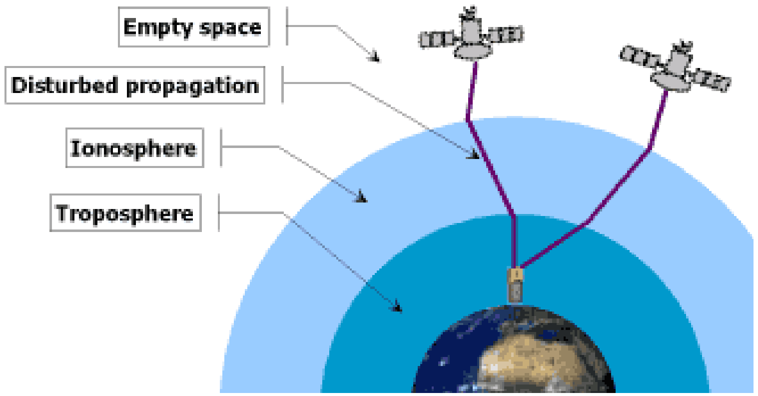


- **On frequencies below~30MHz, the ionosphere bends path traveled by the radio wave back toward earth, allowing long distance communication.**
- **At much higher frequencies, radio waves passes right through the ionosphere.**
- **The speed of the signal is dependent on the density of electrons in the ionosphere.**

STRONG FREQUENCY DEPENDENCE

Ionospheric Effects on Radio Waves > 100 MHz

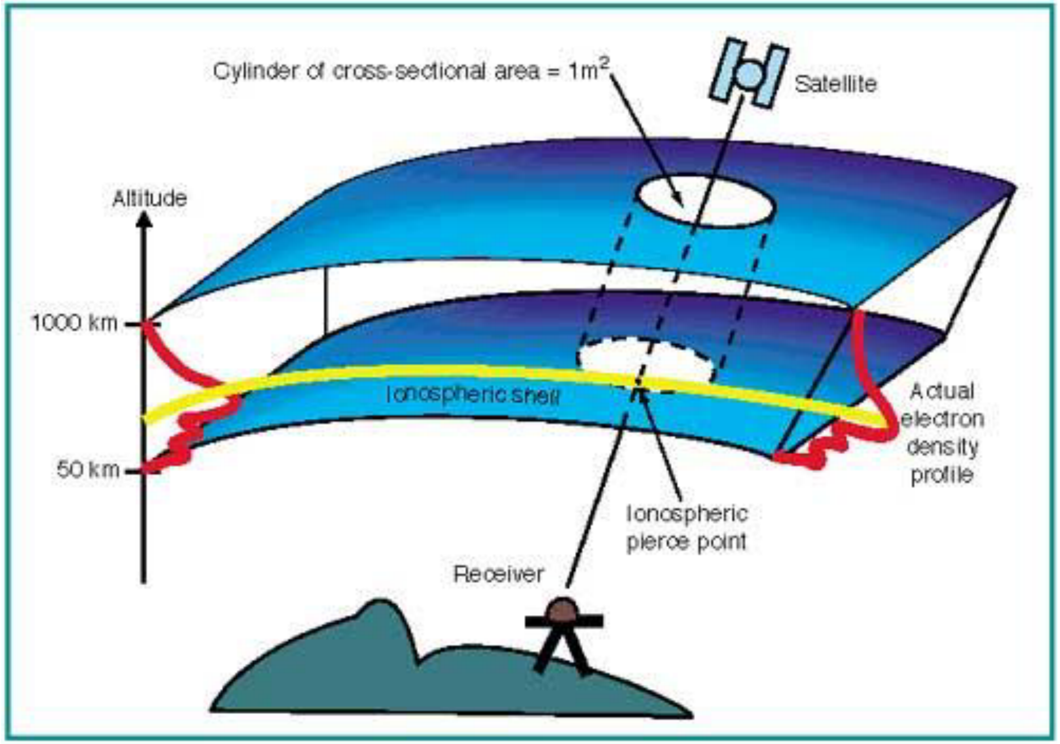
- Group Delay of Signal Modulation
- Carrier Phase Advance
- Scintillation (Amplitude and Phase)
- Faraday Rotation
- Absorption
- Ionospheric Doppler Shift
- Refraction
- Waveform Distortion
- Angular Refraction



Major Ionospheric Effects on GPS

- **Range Error**
  - **Due to a change in the speed of the signal**
    - **Group Delay of the signal modulation (absolute range error)**
    - **Carrier Phase Advance (relative range error)**
    - **Can vary from 1m to ~ 100m**
    - **Mainly due to Total Electron Content (TEC)**
  - **Directly proportional to TEC**
    - **Range Error = ±40.3 TEC/f^2 (in meters)**
  - **Potential large position errors can result if ionospheric delays not corrected … to the extent possible**
- **Scintillation**
  - **Changes in the amplitude and rapid fluctuations in signal phase**
  - **May induce temporary loss of lock**
  - **Can be severe after local sunset in the equatorial regions, especially near the peak of solar cycle**

Total Electron Content (TEC)



(Figure Courtesy of R. Langley)

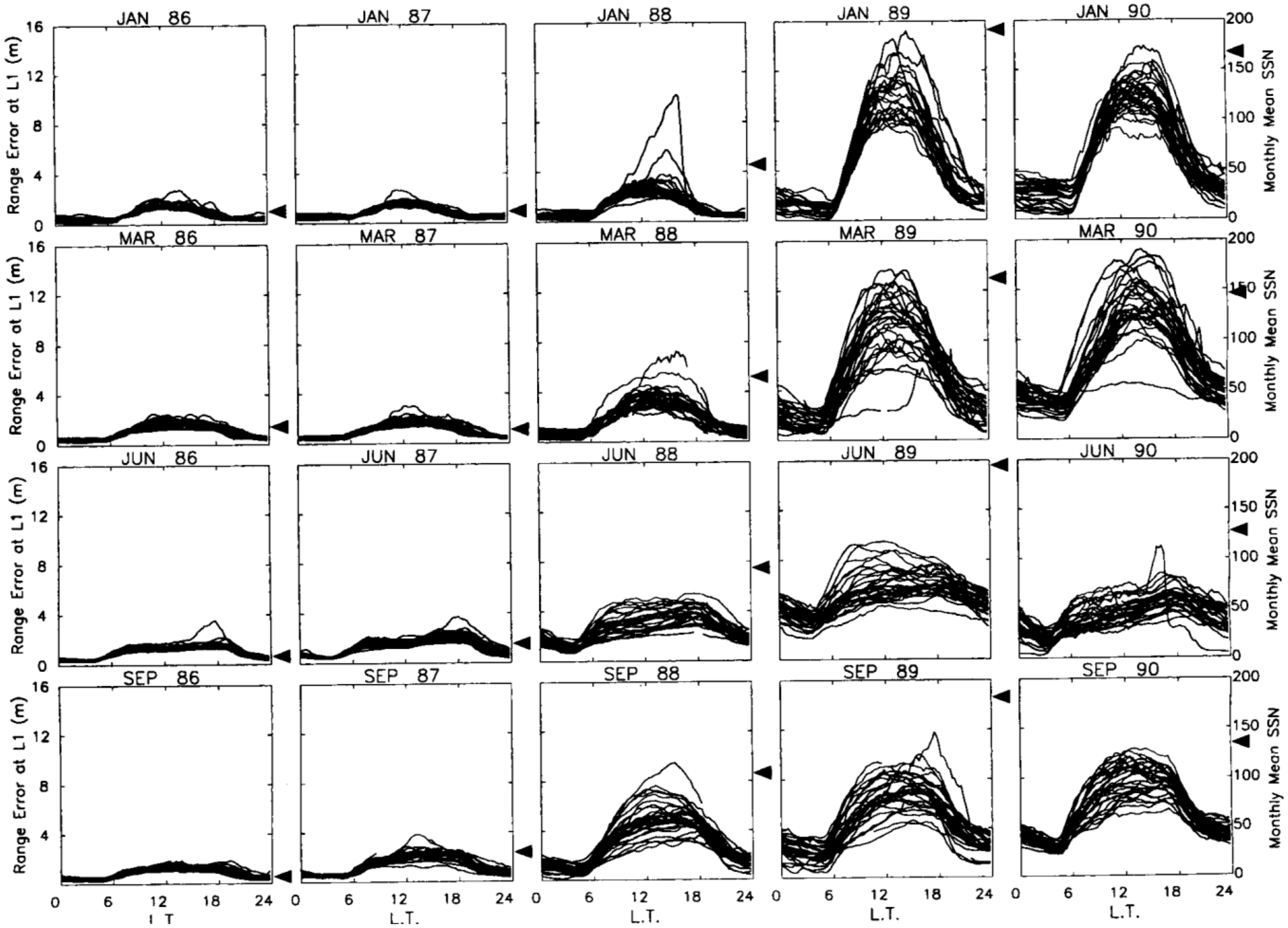
- Ionosphere is a thin shell surrounding the earth
- TEC = number of electrons in a tube of $1m^2$
- Mean height=~300-400km
- Ionospheric pierce point is the point of intersection between line-of-sight and peak height
- Slant to vertical corrections can be done with a simple mapping function

Mapping Function = [$\sin^{-1}$(.94792*cos*elev)]

$R_E/(R_E$+IonoHT)

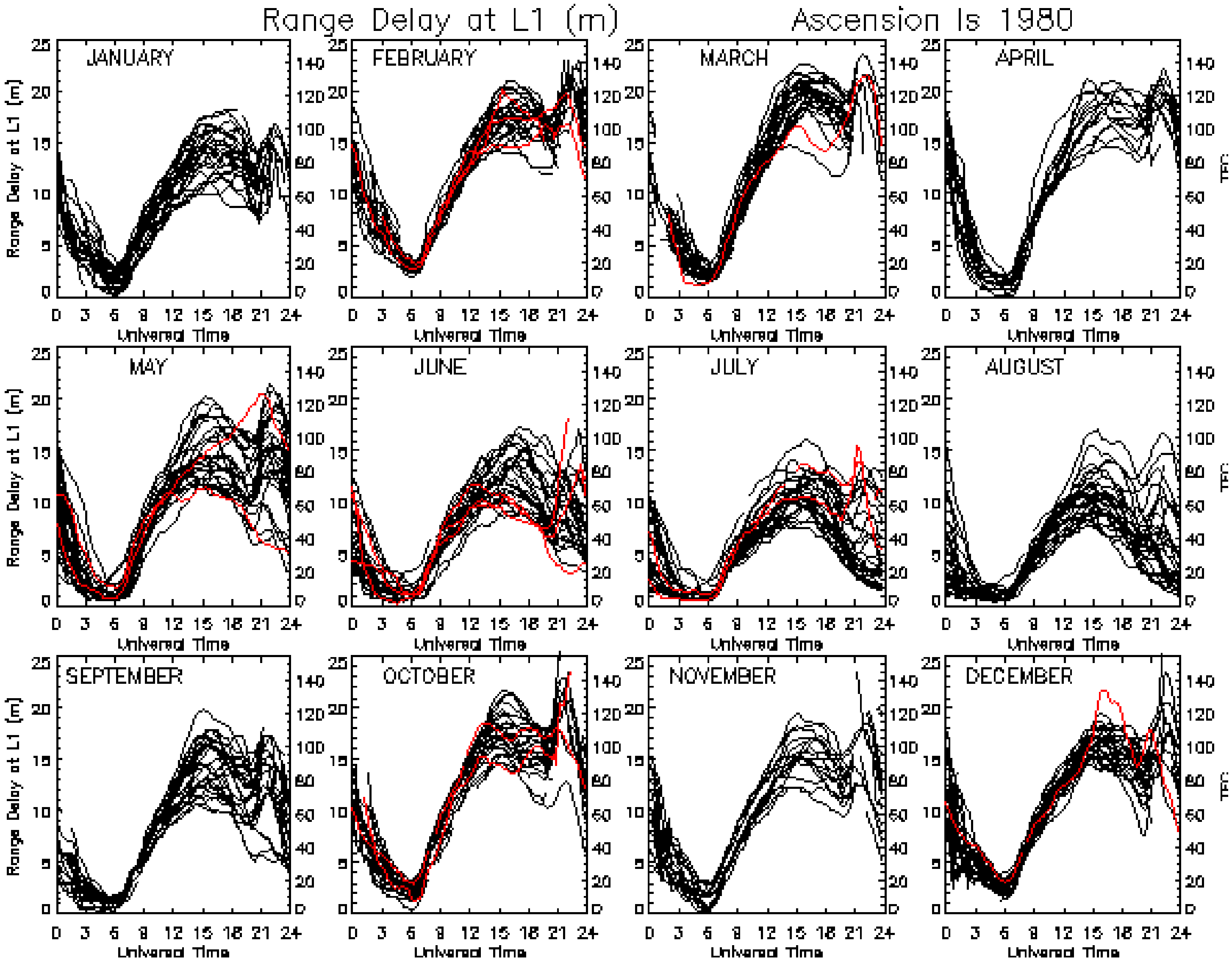
Highly variable!!!

Ionospheric Variability – Mid-Latitude



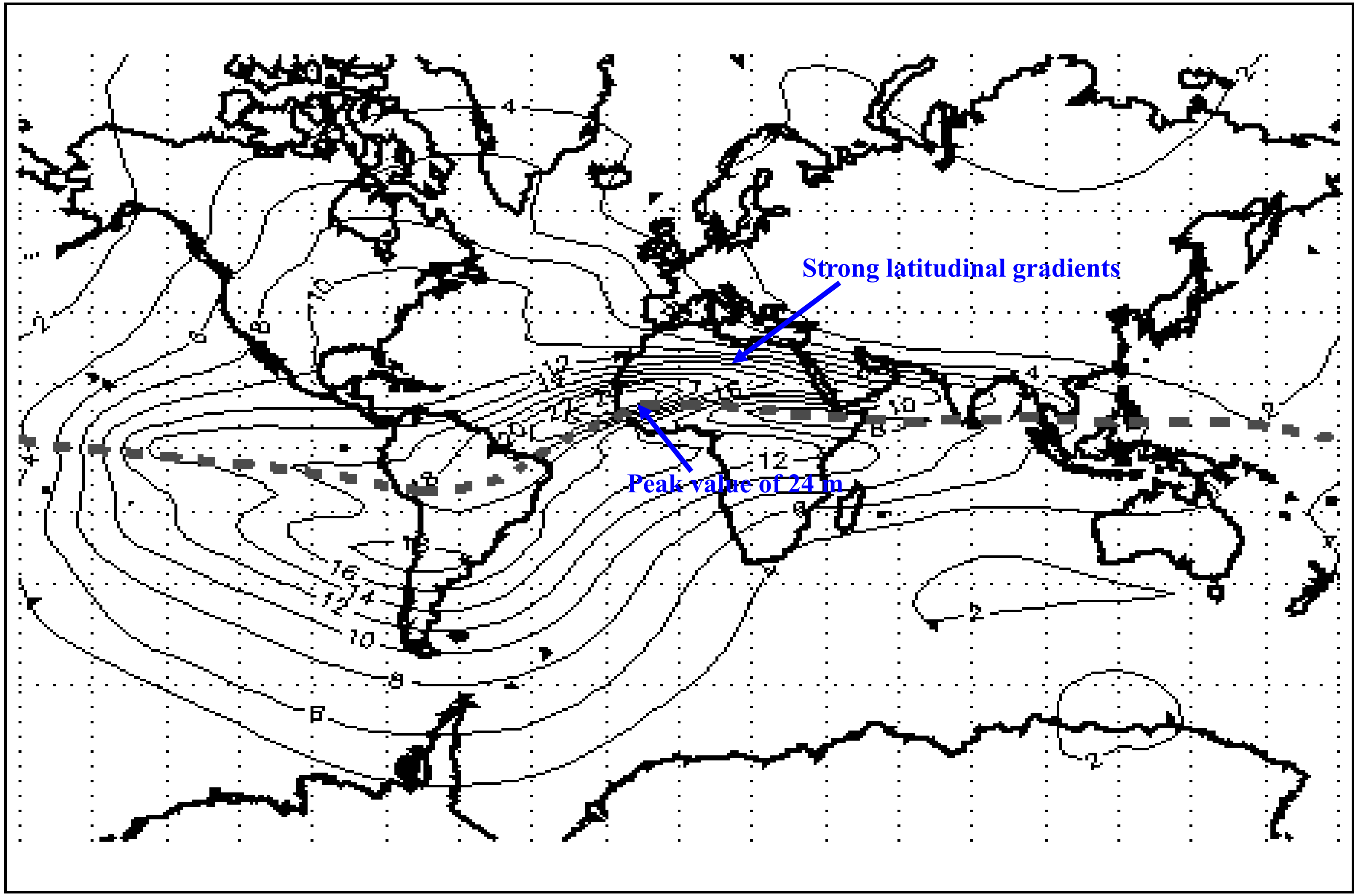
Ionospheric TEC varies with local time, solar activity, season, geomagnetic activity levels and geographic location.

Low-latitude ionosphere range errors for a solar maximum year



TEC Varies Widely with Geographic Location - January 18UT

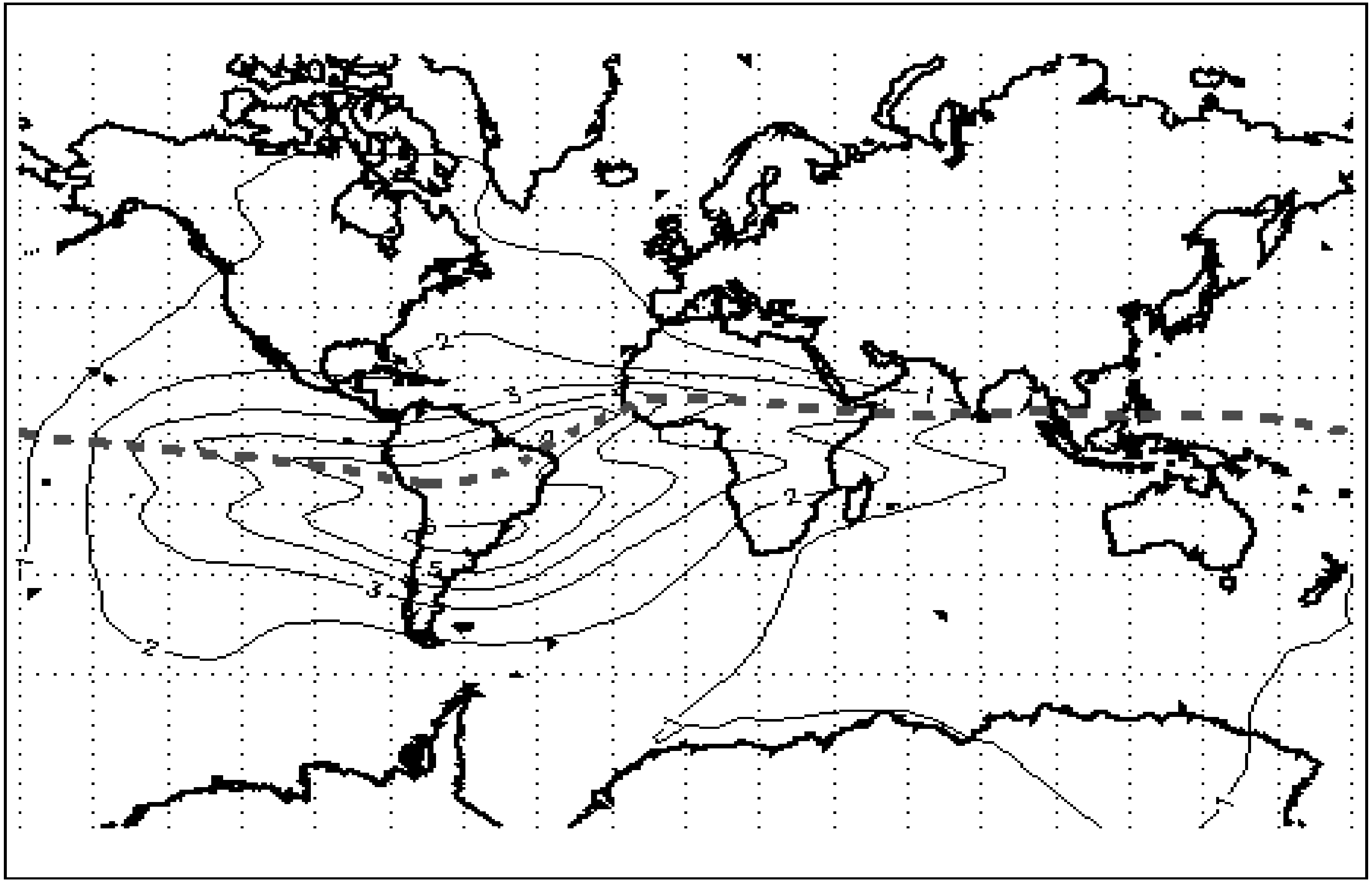
Solar Maximum – PIM Model



TEC Varies Widely with Geographic Location

PIM Model - January 18UT

Solar Minimum – PIM Model



The Formation of the Equatorial Anomaly (An Electrodynamic Force ExB)

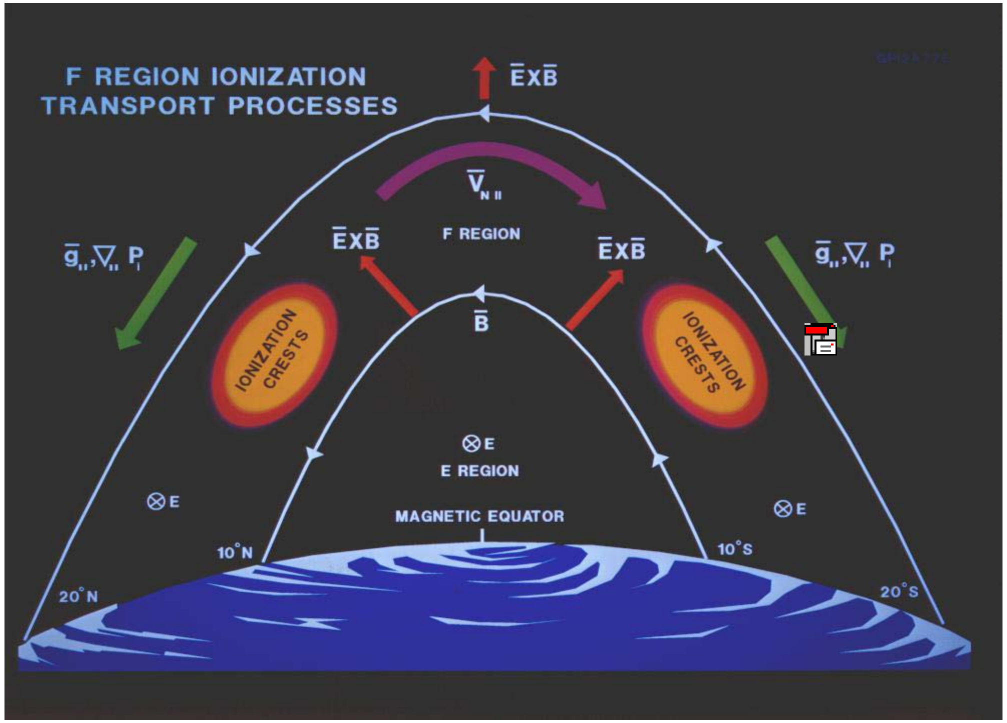


Figure Courtesy of Dave Anderson, NOAA

•Vertical drift velocities lift the F-region plasma to higher altitudes over the magnetic equator

•Pressure gradients and gravity force the heightened plasma downwards along magnetic field lines

•Strength of the drift velocities is highly variable

•Strong post-sunset ExB can cause an instability process that propagates a hole in the plasma to anomaly regions

Plasma Depletions (Bubbles)

Slant Delay from Rio and Rio-West (~90km apart)/PRN 11

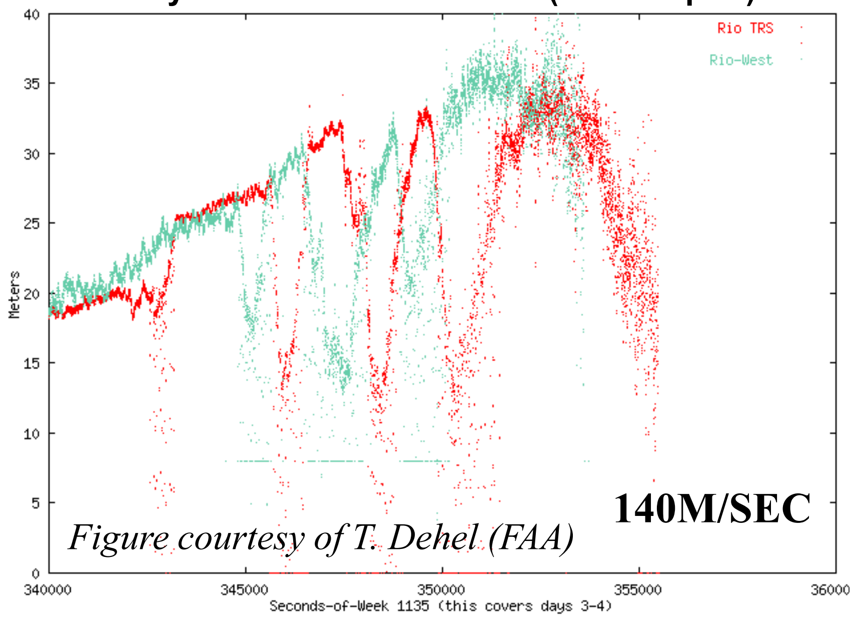
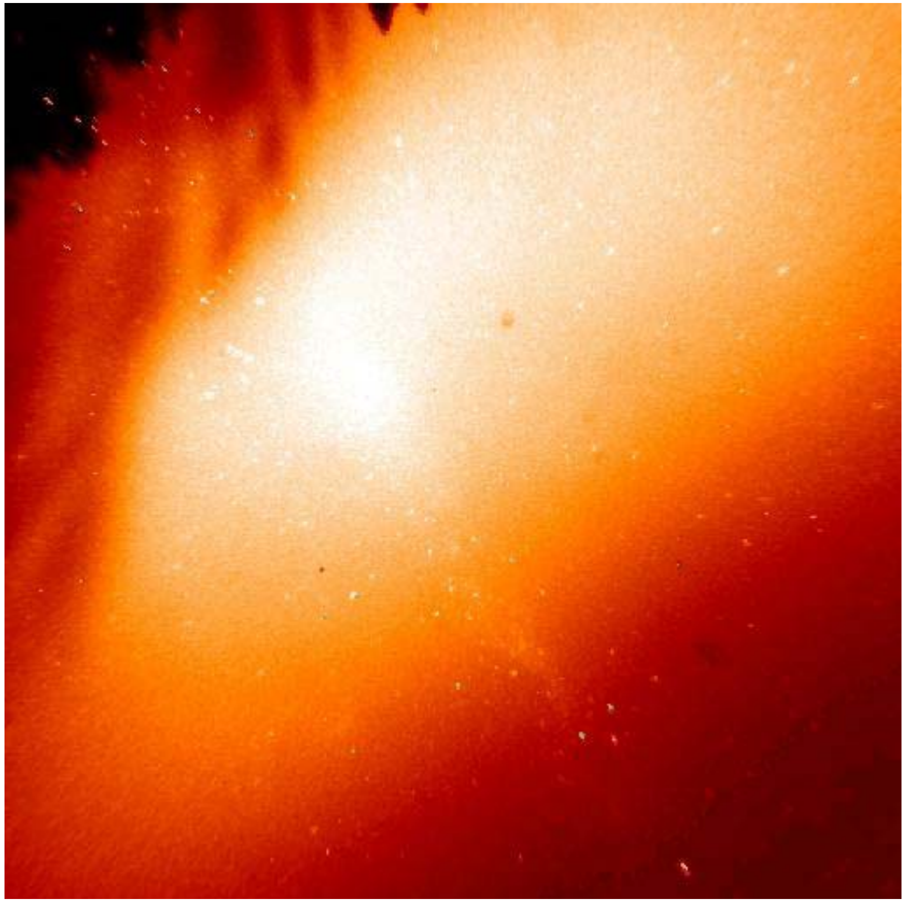


Figure courtesy of T. Dehel (FAA)

- Post-sunset feature
- Drifts east to west
- Size and frequency vary by season, location and solar activity levels
- Irregularities within a bubble induce scintillation

All-Sky Imager at Cachoeira Paulista

~ 21:00 TO 01:00 LT MARCH 18, 1999

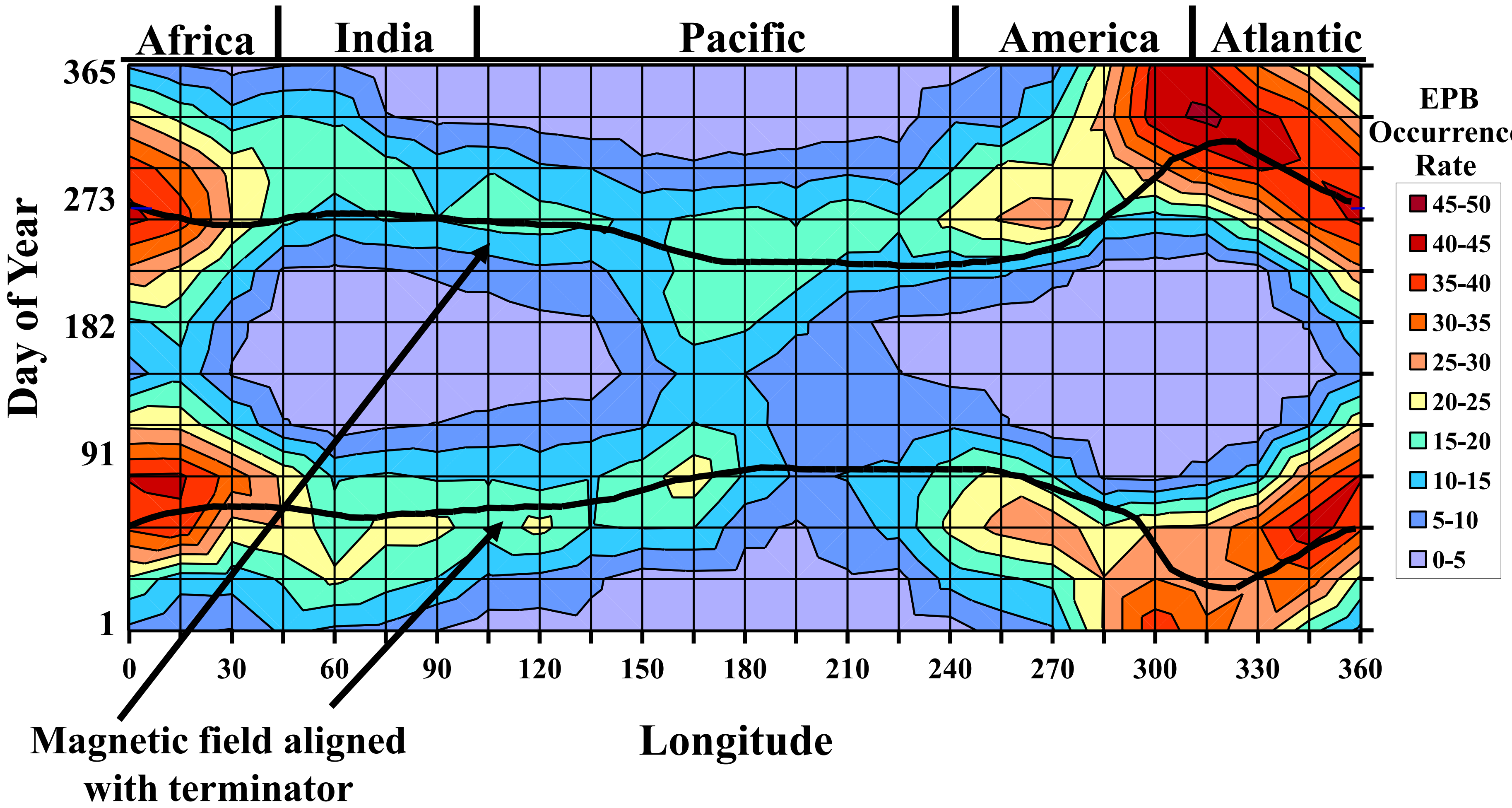


1200km x 1200km, at 250 km altitude

over Cachoeira Paulista (-17.32 dip latitude)

Figure courtesy of E. De Paula (INPE)

DMSP Bubbles 1989 - 2002



From Burke & Huang, 2004

Magnetic Storm Effects

Geomagnetic storms affect

- Ionospheric range delays: largest departures from mean values
- Auroral region:
  - Expands to equatorward and poleward latitudes
  - Has large spatial and temporal variability
  - Significant scintillation fading and phase scintillation effects are possible
- Equatorial anomaly region
  - Scintillation effects can be either quenched or enhanced

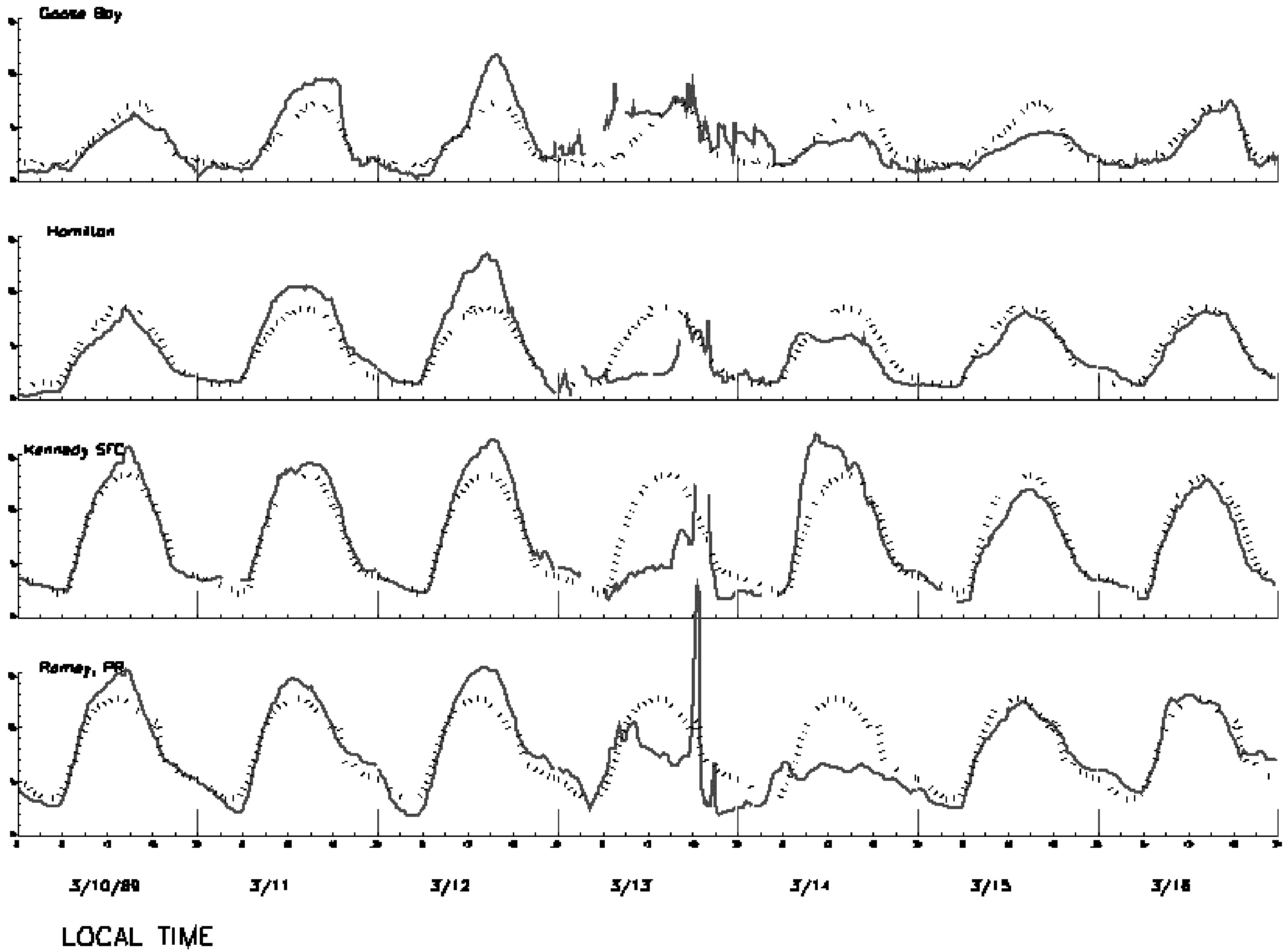
Large TEC enhancements

- Occur in late afternoon hours
- Particularly a problem in Eastern CONUS region

Equatorial electrojet

- Usually independent of geomagnetic storm activity

Historical Measurements of the Geomagnetic Storm of March 1989



Spatial Decorrelation – Undisturbed Conditions

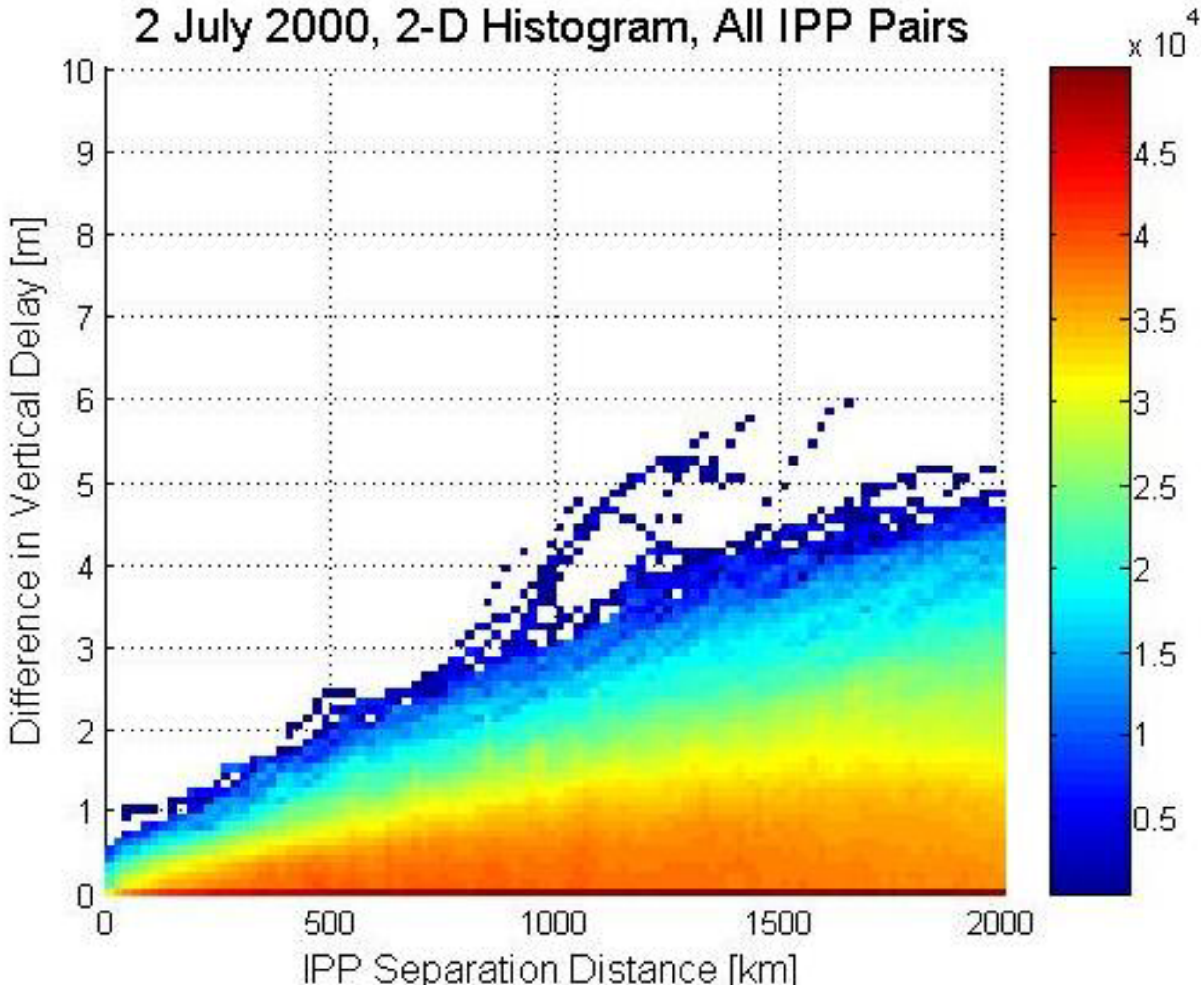


Figure Courtesy of S. Datta-Barua, BC/Stanford

Spatial Decorrelation – Disturbed Conditions

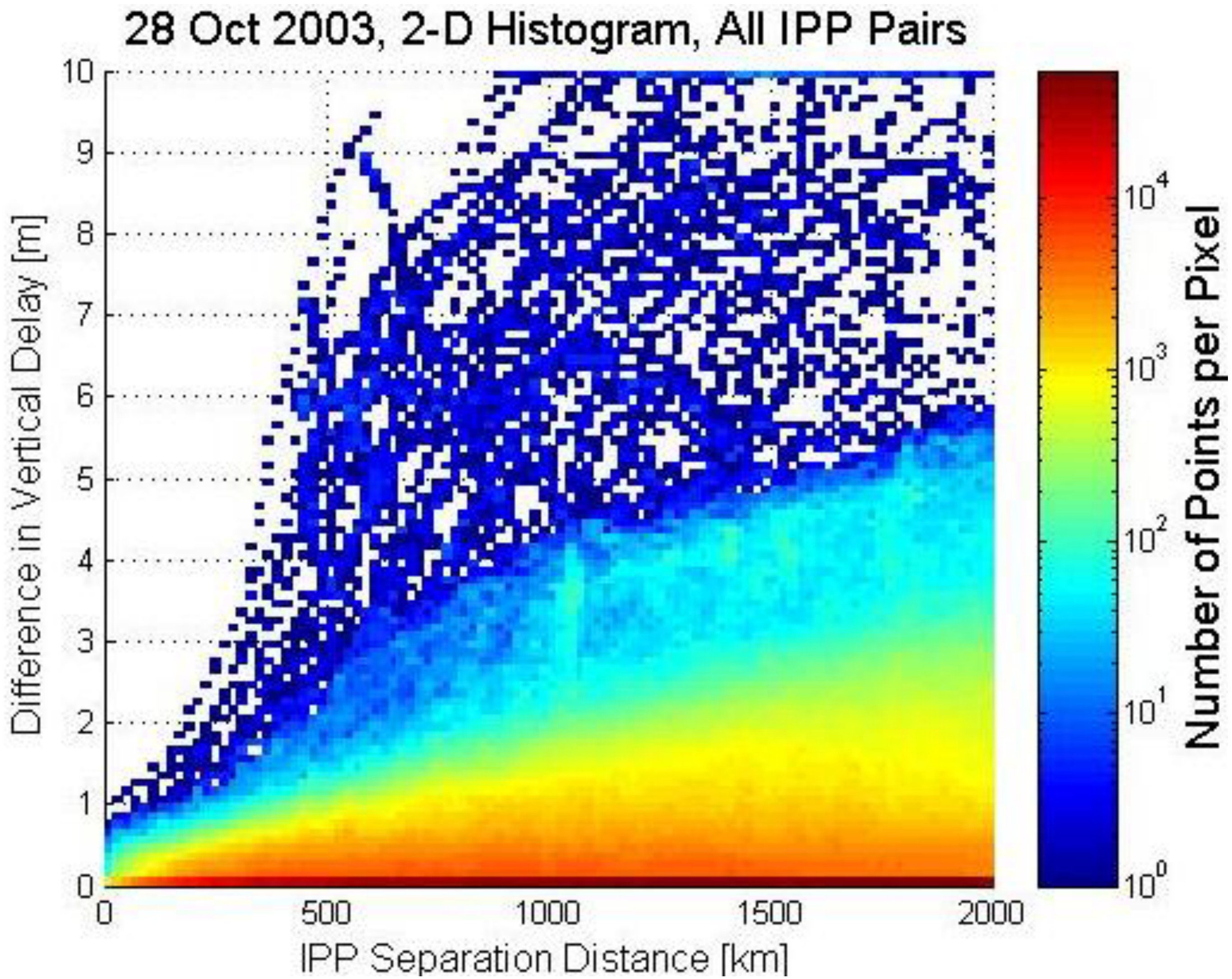
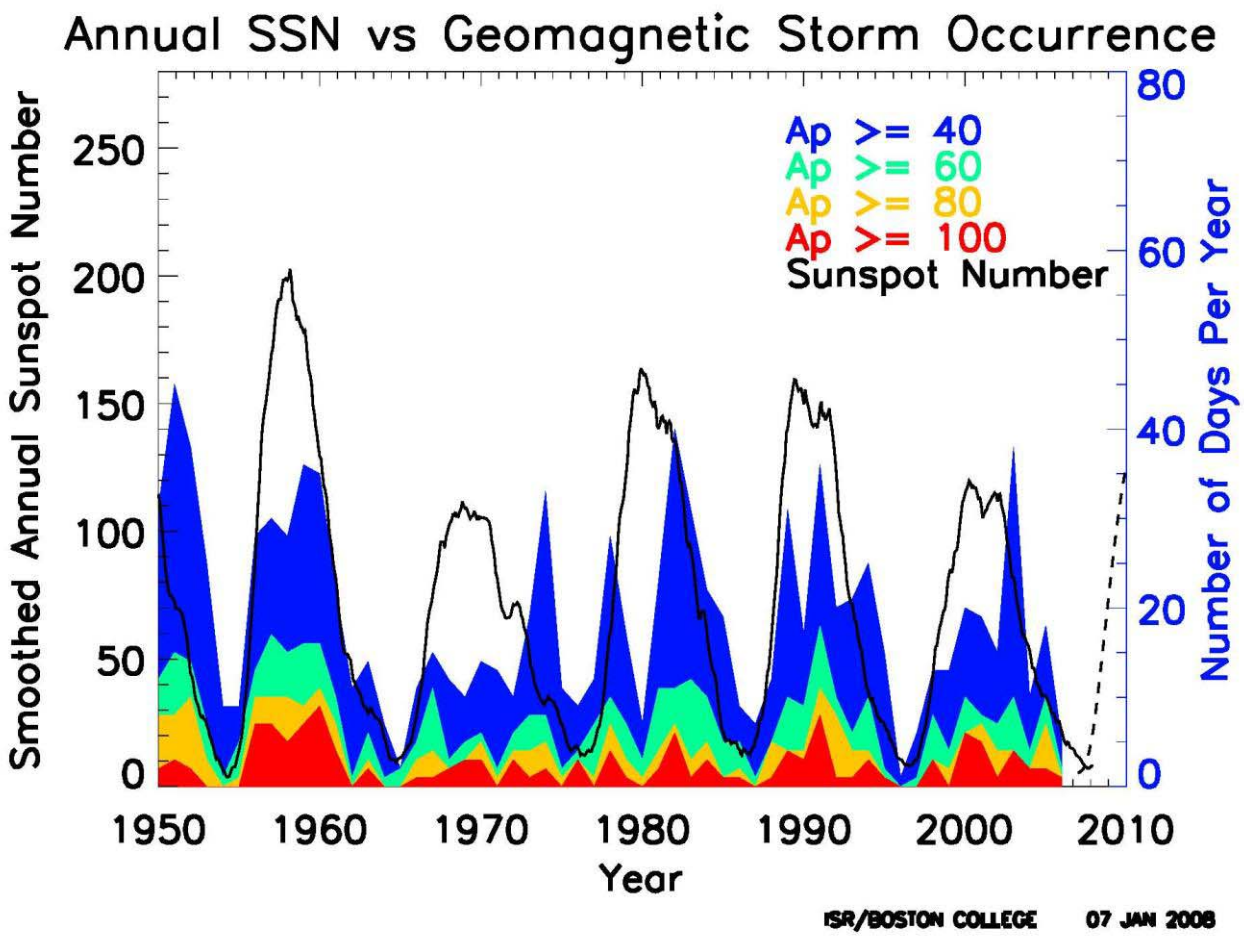


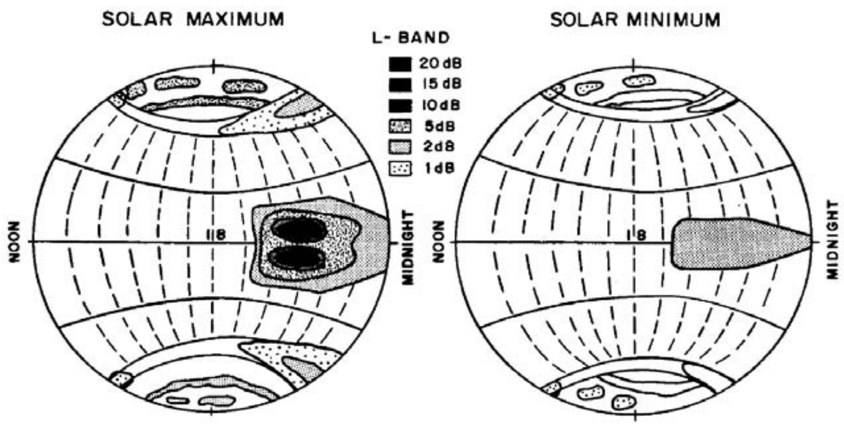
Figure Courtesy of S. Datta-Barua, BC/Stanford

Geomagnetic Storm Occurrence vs SSN



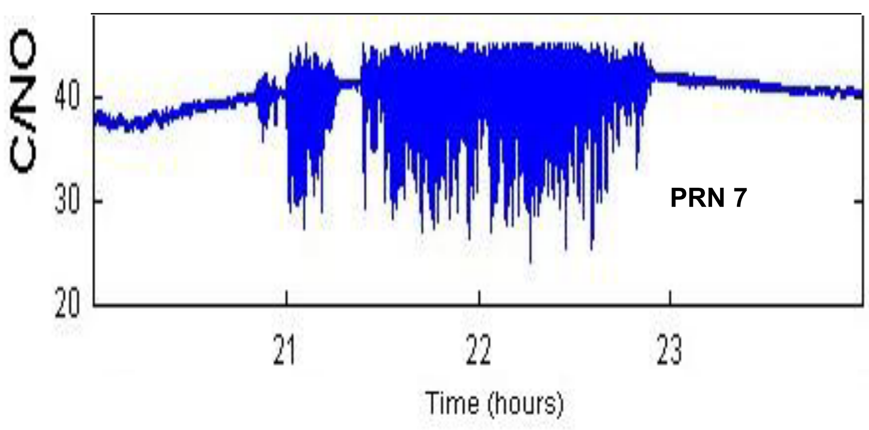
Ionospheric Scintillation

- Ionospheric scintillation - rapid fluctuations in the amplitude and phase of radio waves due to fluctuations in the index of refraction along the propagation path
- Commonly associated with electron density irregularities in the ionosphere due to equatorial spread F
- Can cause intermittent loss of lock on the GPS signals and ranging errors, both of which contribute to errors in estimating receiver position
- While dual frequency receivers can effectively mitigate the effects of group delay due to TEC, both single and dual frequency receivers are adversely impacted by scintillation

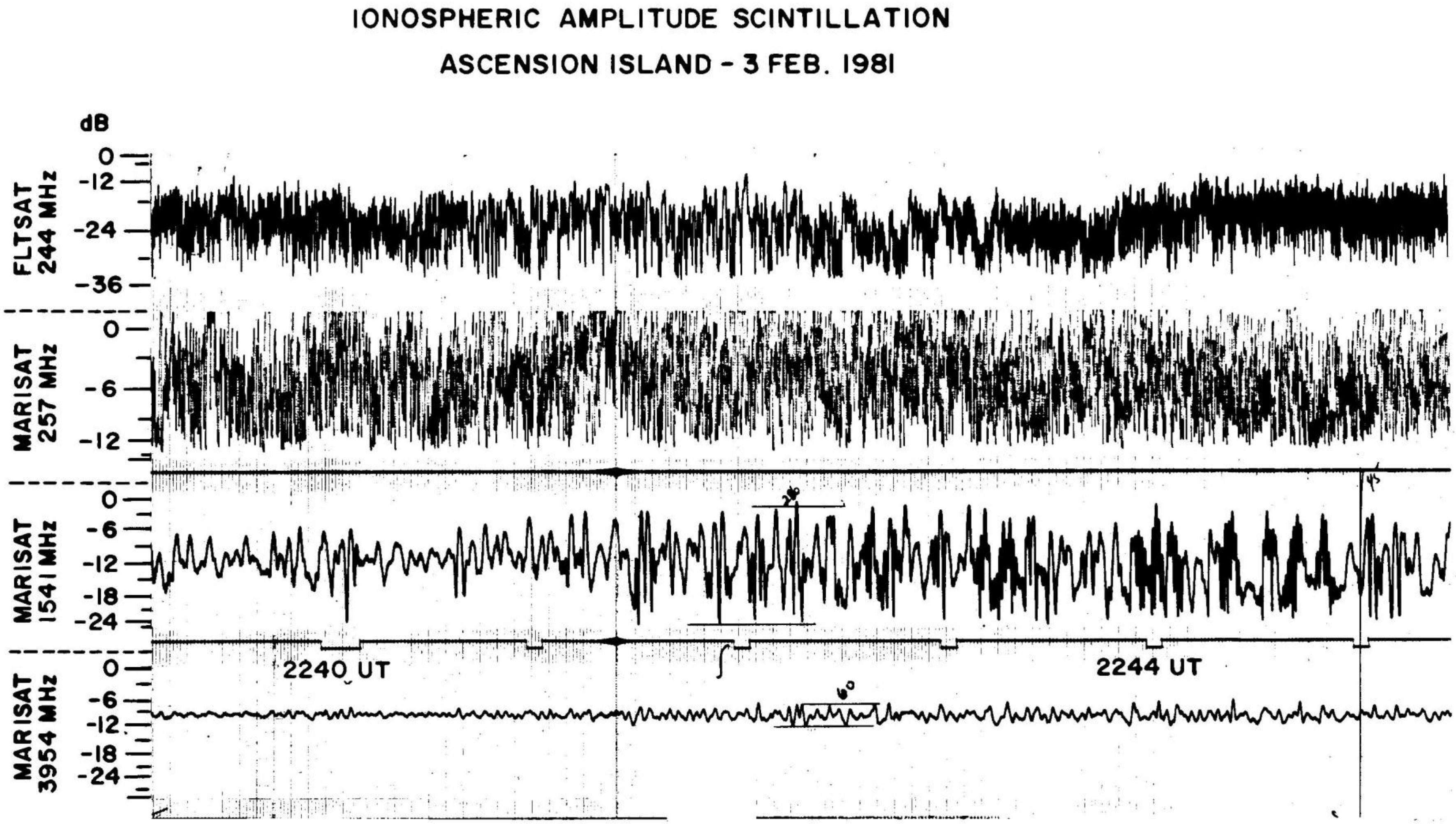


Latitude / local time morphology (after Basu)

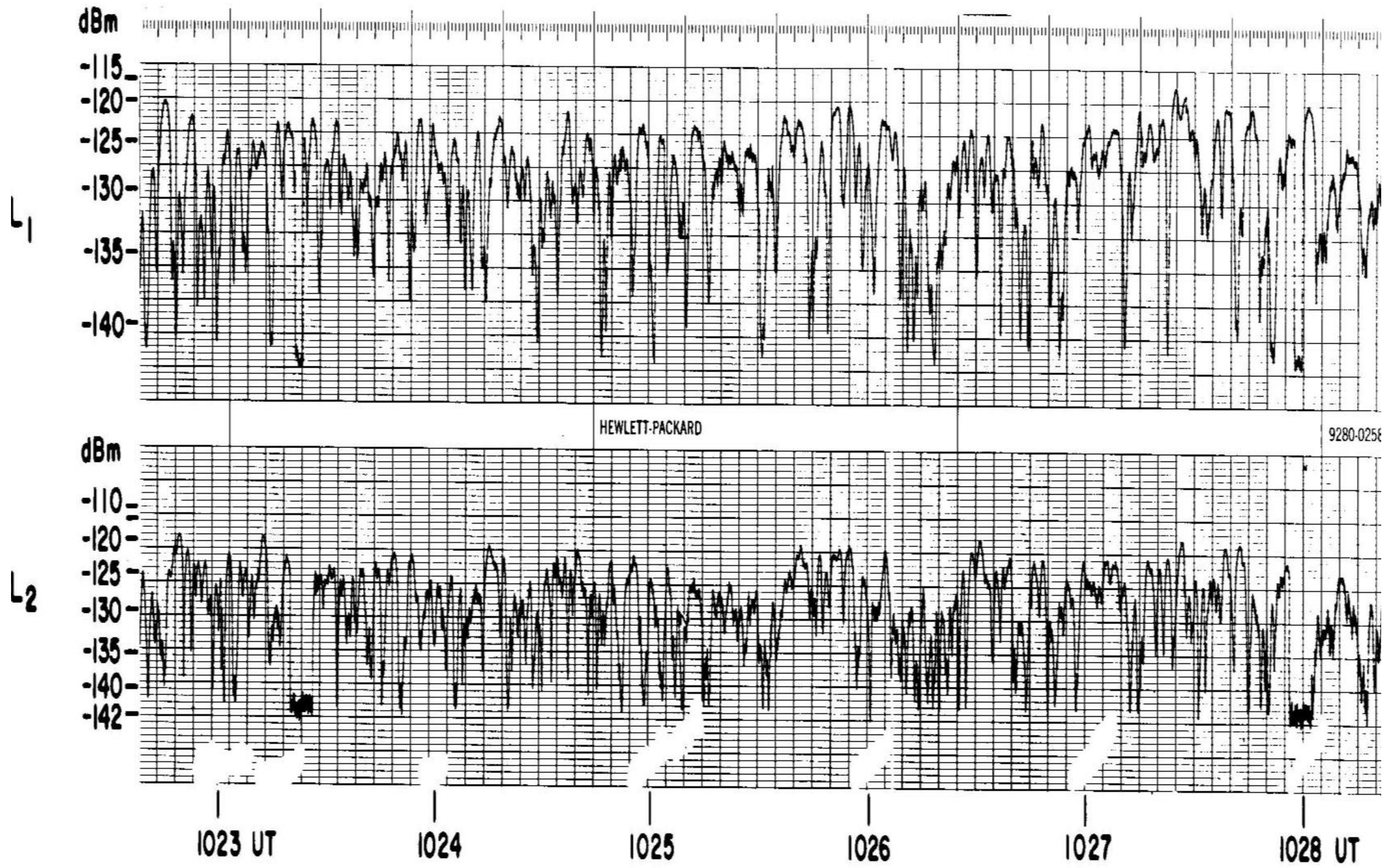
Scintillated GPS Signal



Amplitude Scintillation -Example of Scintillation Fading at Frequencies from 244 MHz to 3.954 GHz

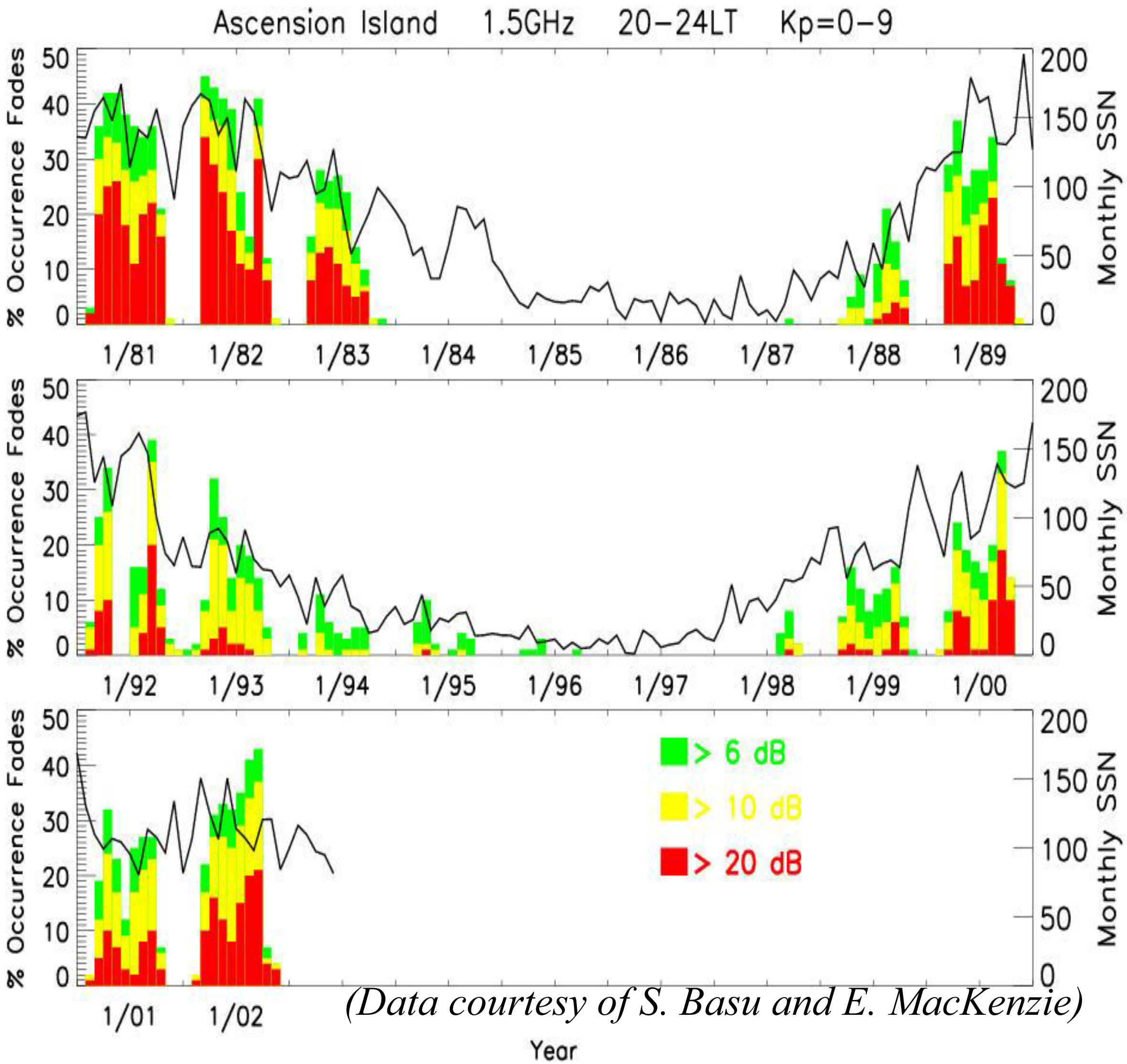


GPS Amplitude Scintillation on Both L1 and L2 from Kwajalein Island (August 24, 1980)



Scintillation versus Solar Cycle at Ascension Island

- L-band scintillation very dependent on solar cycle, but irregularities are still present
- This represents a limitation on monitoring irregularities with GPS during solar minimum
- CA code on L2 (1.2 GHz) will improve sensitivity



(Data courtesy of S. Basu and E. MacKenzie)

Impacts due to Ionospheric Scintillation

Principal impacts of ionospheric scintillation on GPS performance:

- Loss of lock / outages
- Induced ranging errors

Consequences of these effects on GPS positioning accuracy depends on constellation geometry

For example, losing multiple satellites in the same region of the sky can lead to large errors

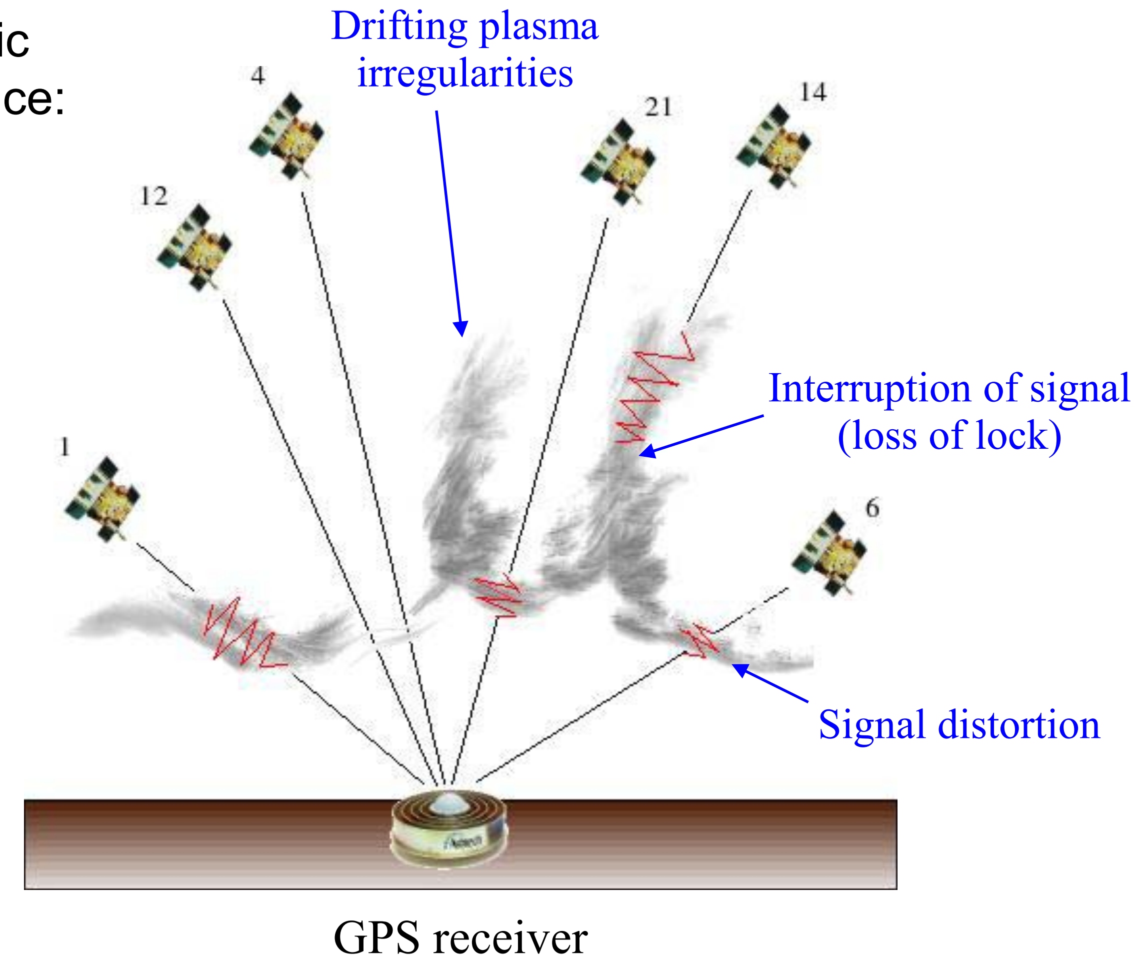
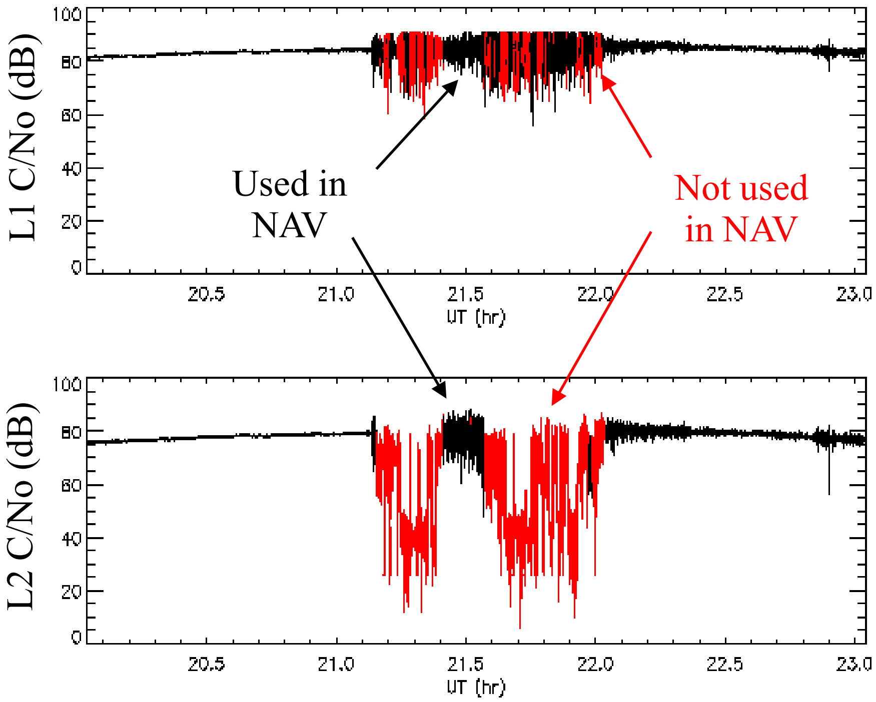


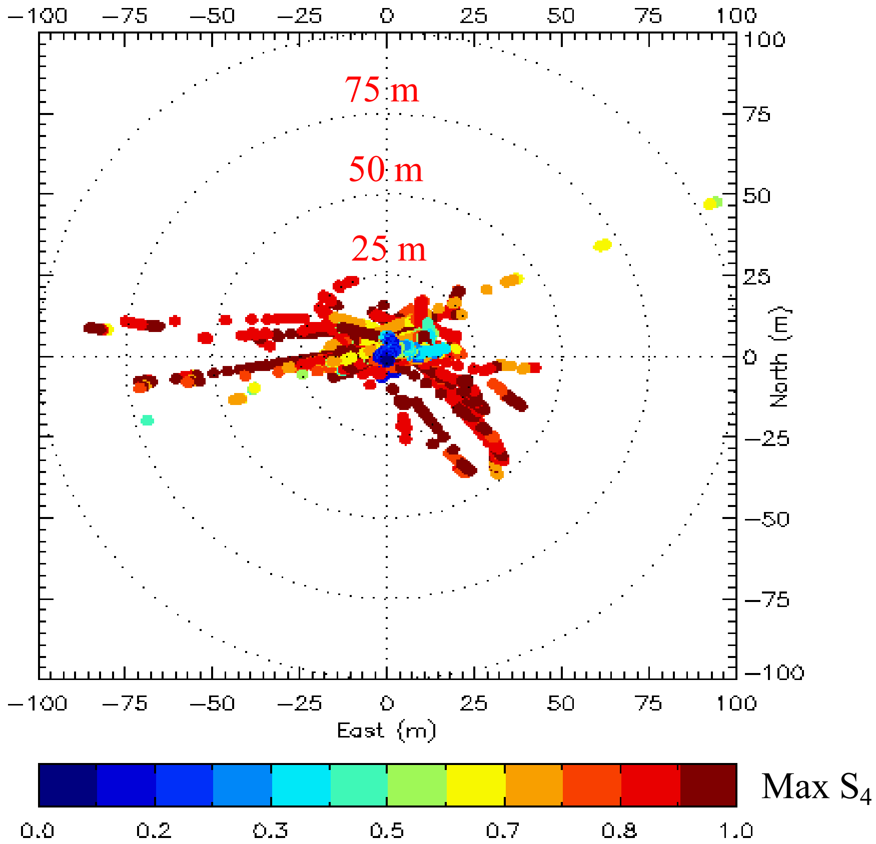
Figure Courtesy of C. Carrano, BC

Fading of GPS Satellite Signals and Positioning Accuracy

Ascension Island (7.98S, 345.59E) - 16 Mar 2002

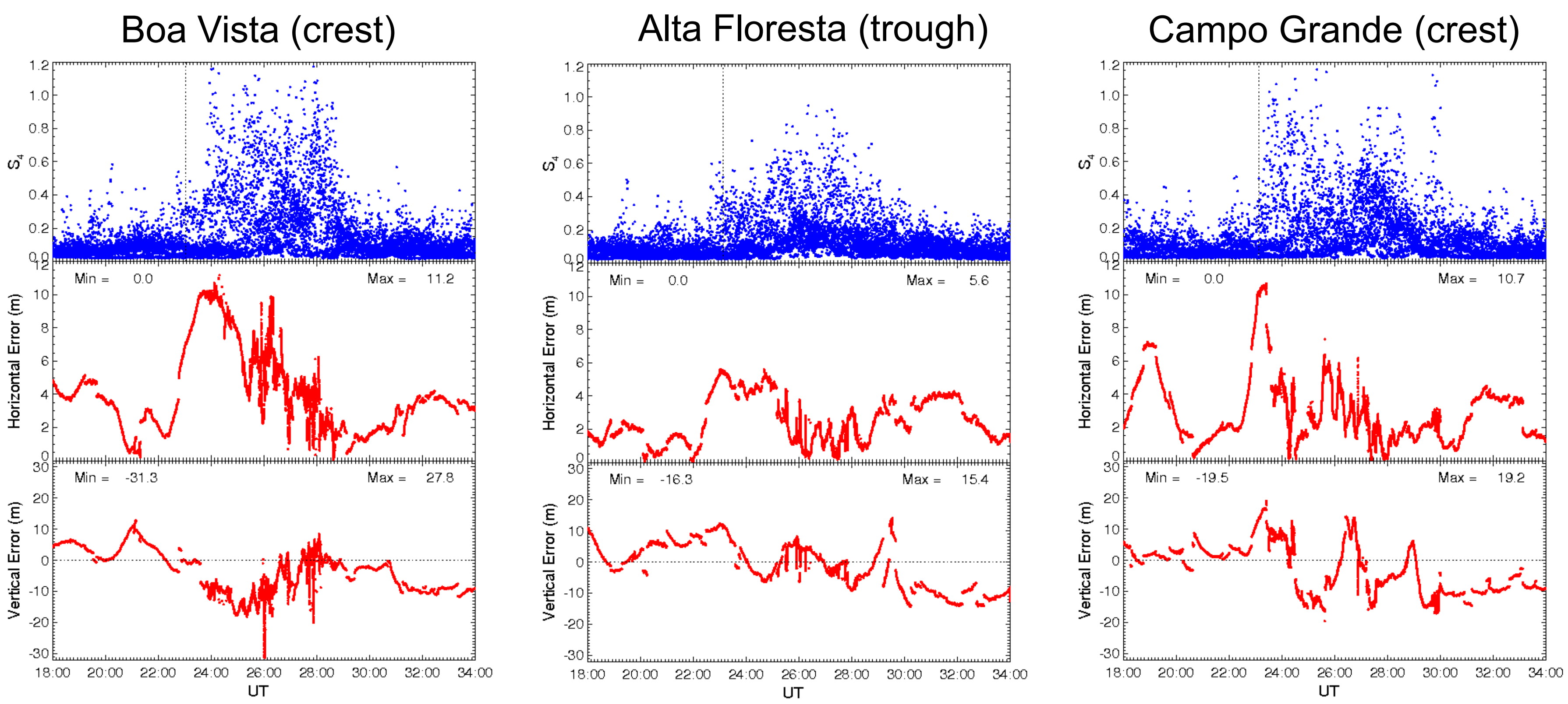


Fading of the L1 and L2 Signals (from one GPS satellite)



Resulting Positioning Error

GPS Positioning and the Appleton anomaly (latitude dependence)



<u>Max Position Error</u>
11 m horizontal, 31 m vertical

<u>Max Position Error</u>
6 m horizontal, 16 m vertical

<u>Max Position Error</u>
11 m horizontal, 20 m vertical

Geographic locations near the crests of the Appleton anomaly typically experience more intense scintillation and larger GPS positioning errors

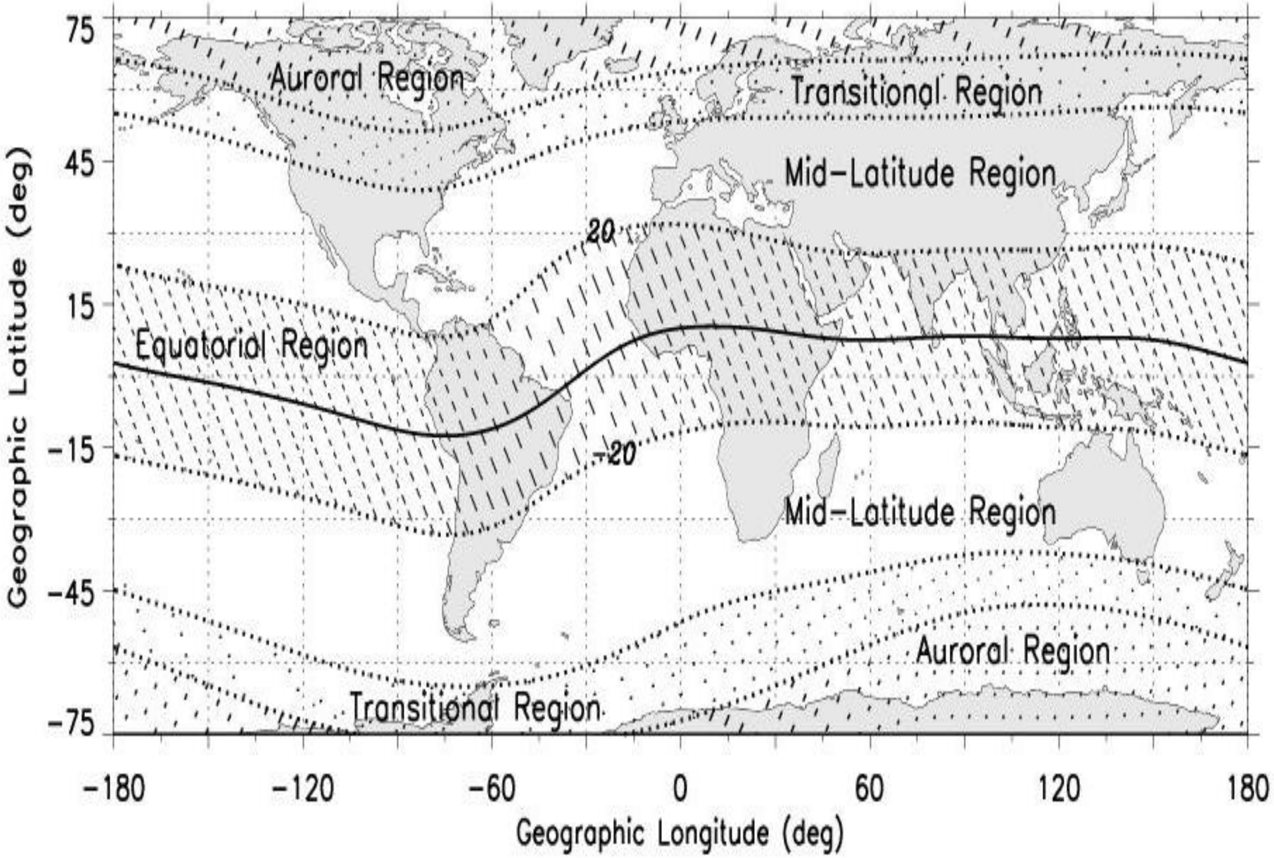
Ionospheric Regions of the World

Equatorial latitudes: strongest effects, scintillation limited to post-sunset and pre-midnight, seasonally dependent, not correlated with magnetic activity

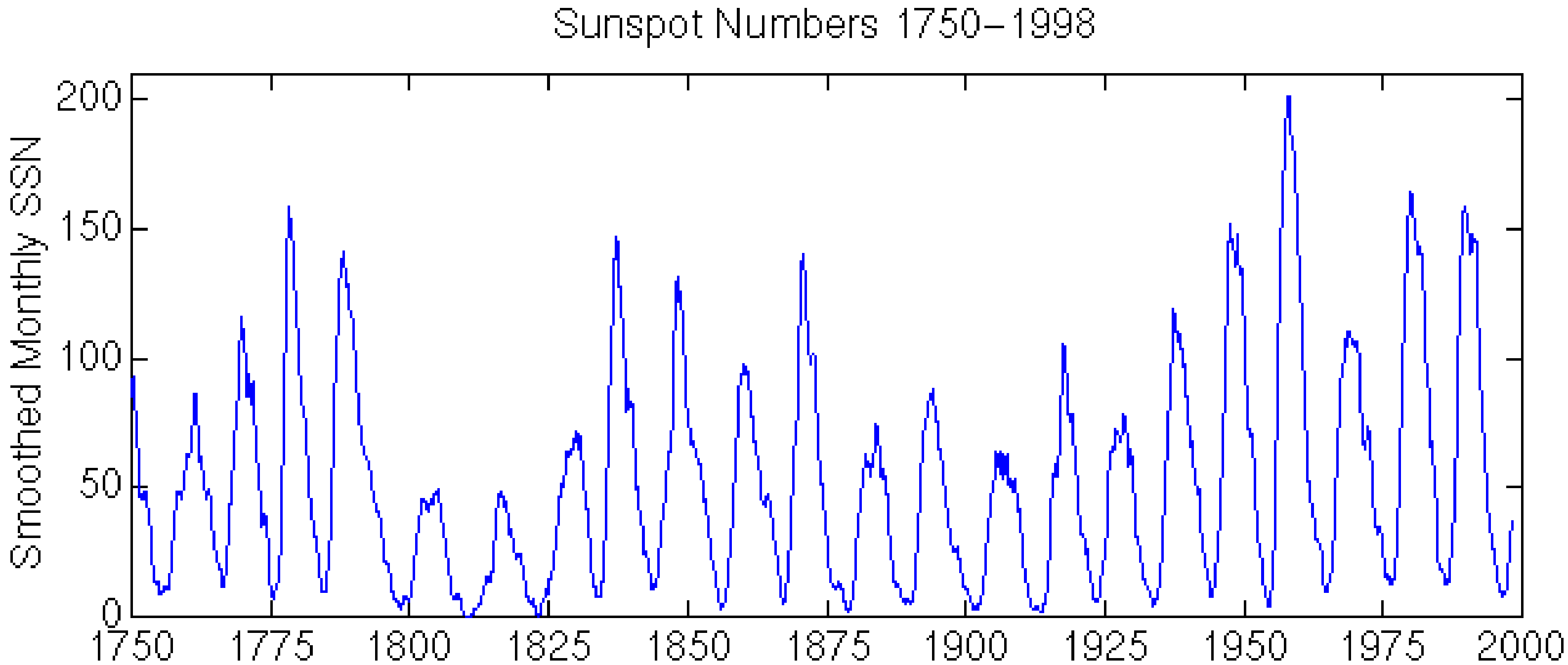
Mid-Latitudes: strong gradients and phase scintillation - only during extreme levels of geomagnetic activity

Auroral latitudes: related to geomagnetic activity, less intense than low latitude effects

More intense and frequent during high solar activity in all regions.



The Solar Cycle

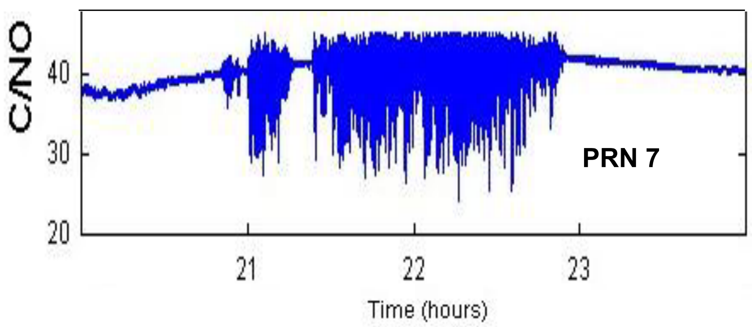


Magnitudes of the Ionosphere and its effects are strongly tied to the Year Solar Cycle

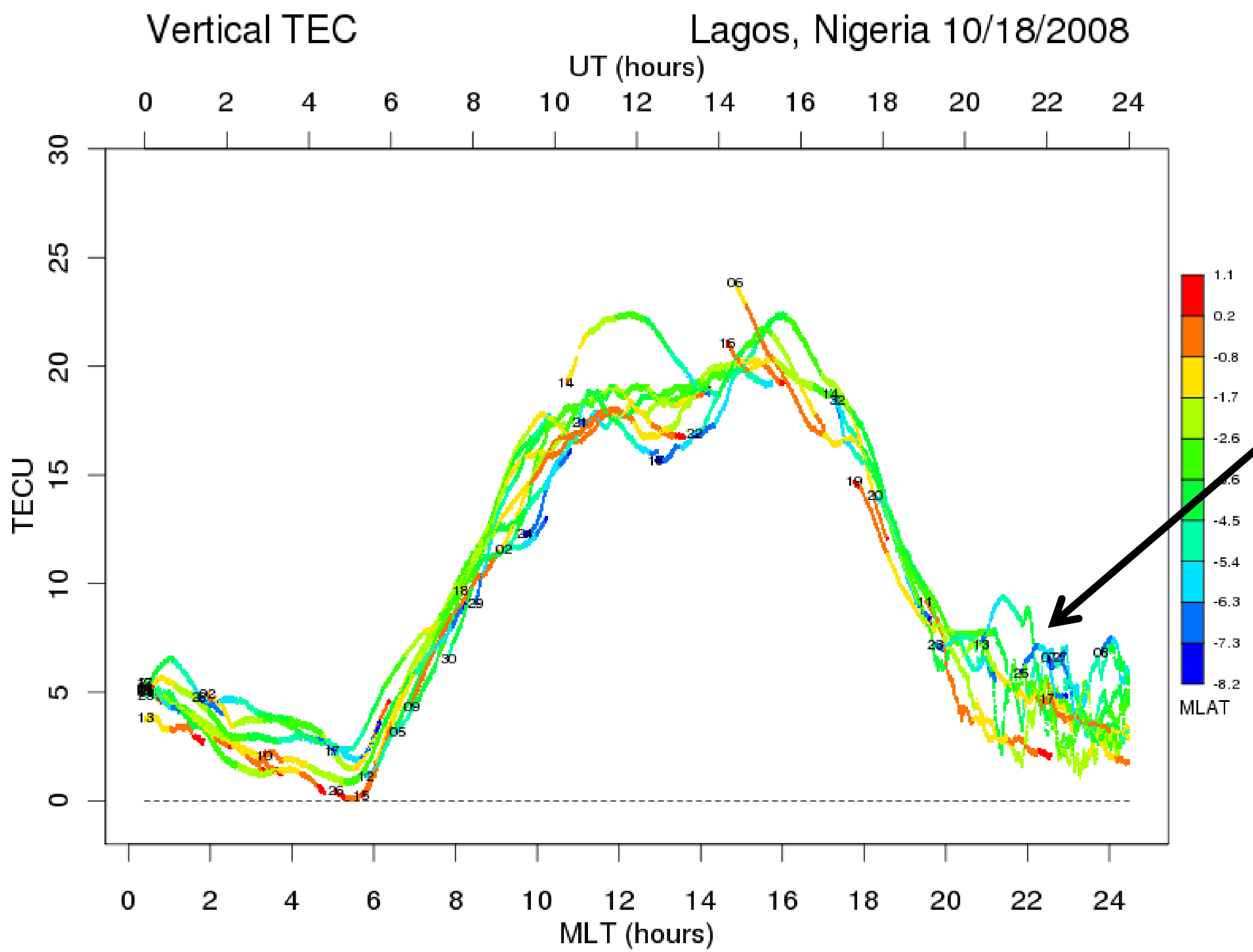
What about the African Ionosphere?

- Generating reliable ionospheric delay corrections in near-equatorial Africa will be challenging
  - Steep, time-varying gradients due to equatorial anomalies
  - Narrow depletions (traveling at speeds of 100m/s and more)
- Uncertain magnetic storm effects near mid-latitudes
- Scintillation will cause receivers to lose lock on multiple satellites signals at certain times (post-sunset, high-solar activity, seasonal dependence)

Education, infrastructure and measurements are needed to quantify these effects



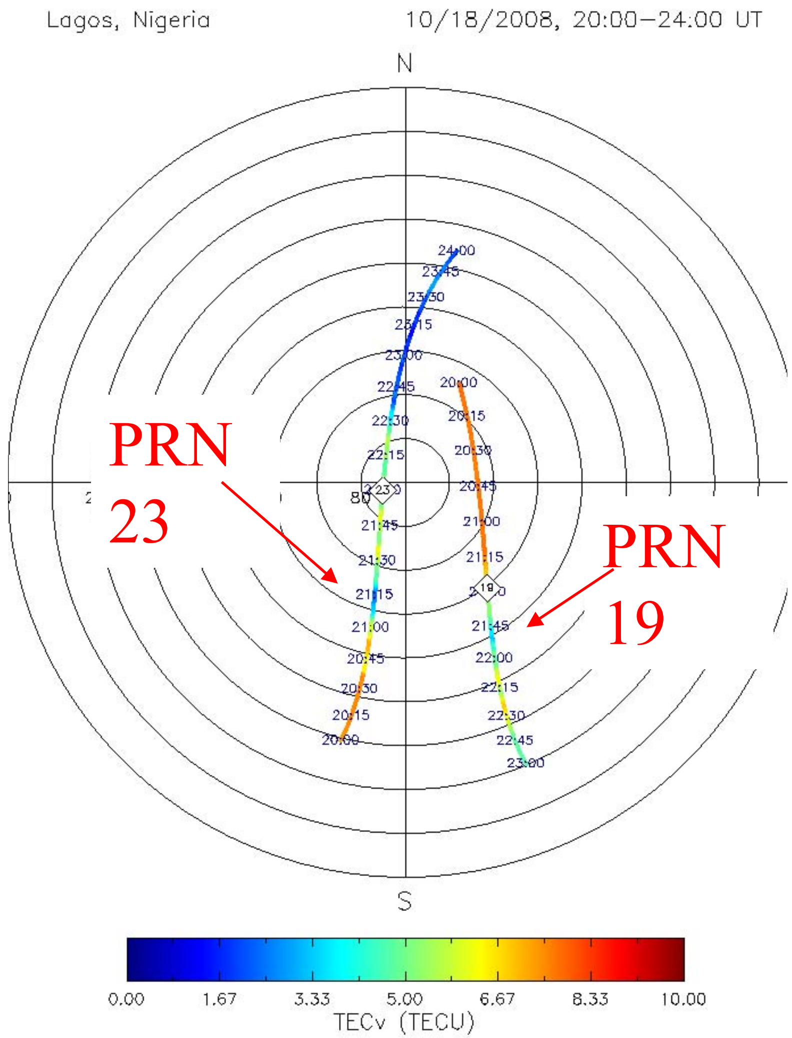
GPS TEC Measurements over Nigeria, 18 Oct 2008



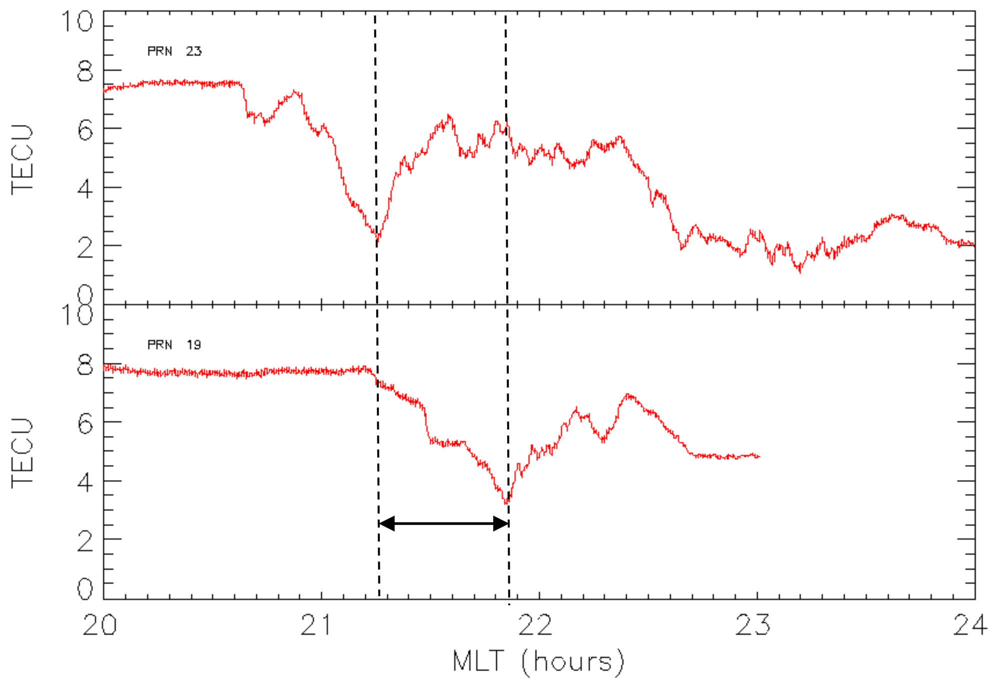
Irregularities due to Rayleigh-Taylor instability occur after shortly after local sunset

Propagation of radio waves through regions of depleted TEC (bubbles) can produce radio wave scintillation

Measuring the Zonal Drift of the Irregularities Using GPS



The zonal drift velocity can be measured by observing the rate a which depletions move from one GPS link to the next



$$V_{zonal} \approx (\text{IPP separation}/\Delta t)\ \text{Sin}(\text{azimuth-declination})$$

$$= 200000\text{m}/1800\text{s}\ \text{Sin}(117° - -5.0°) = 94\ \text{m/s}$$

Future of Ionospheric Effects on GNSS

- Ionospheric delay problems will essentially disappear (*we'll see*) once dual-frequency signals are available to civil users (GALILEO, Modernized GPS with L5, GPS III)

- Scintillation is not going away……
    - L5 (1176.45 MHz) will be somewhat more sensitive to scintillation than L1 (1575.MHz), but the signal will be better than L1 (C/A)
    - Building robustness in receiver design is most important
    - More satellites of opportunity (GALILEO, GLONASS, others) will help with positioning with scintillation present

Education, equipment and measurements are needed for research and applications

Summary – What did you learn?

What are the 2 major ionospheric effects on GNSS?	Range Errors and Scintillation
Where are these effects most serious?	Near-equatorial regions
Where due ionospheric depletions occur?	Near-equatorial regions
When do they occur?	Post-sunset (LT)
What happens to TEC in the US in response to an extreme magnetic storm?	Strong spatial gradients and phase scintillation
When do they happen in relationship to the solar cycle?	Near the peak of solar max (just past the peak)
How many kinds of scintillation are there?	2 – Amplitude and Phase
Is scintillation frequency dependent?	Yes – of course
What can scintillation do to a GPS signal?	Cause loss of lock
What are two most important future benefits of GALILEO and GPS Modernization?	Range errors could disappear More satellites for positioning during scintillation

Thank you for your attention!

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