Ionospheric Effects on GNSS

The Atmosphere and its Effect on GNSS Systems
14 to 16 April 2008
Santiago, Chile

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Overview

- Sun-earth environment
- Introduction to the ionosphere
- Ionospheric effects on GNSS
- Example data and illustrations
- The South American ionosphere

The Sun-Earth Environment

The Sun

- **The sun emits radiations which control earth's temperature, atmospheric composition and suitability for life**

- **The more energetic solar radiations are absorbed by the upper atmosphere, which is heated by them**

- **The sun also emits a stream of matter ("solar wind") with an embedded weak magnetic field ("interplanetary magnetic field")**
  - **The solar wind does not penetrate the atmosphere as it is deflected by the magnetic field of the Earth, but affects its behavior**

The Earth's Atmosphere

- The earth's atmosphere and magnetic field protect us from extremely lethal sun burns
- The atmosphere is relatively dense near the ground
  - Its composition is mostly oxygen and nitrogen
- Atmospheric density and pressure decrease with altitude
  - Only 0.1% of mass above 50 km
  - Only 0.000001% of mass above 100 km
  - Composition changes with altitude where lighter gases become dominant (hydrogen, then helium)

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The Sun-Earth Environment

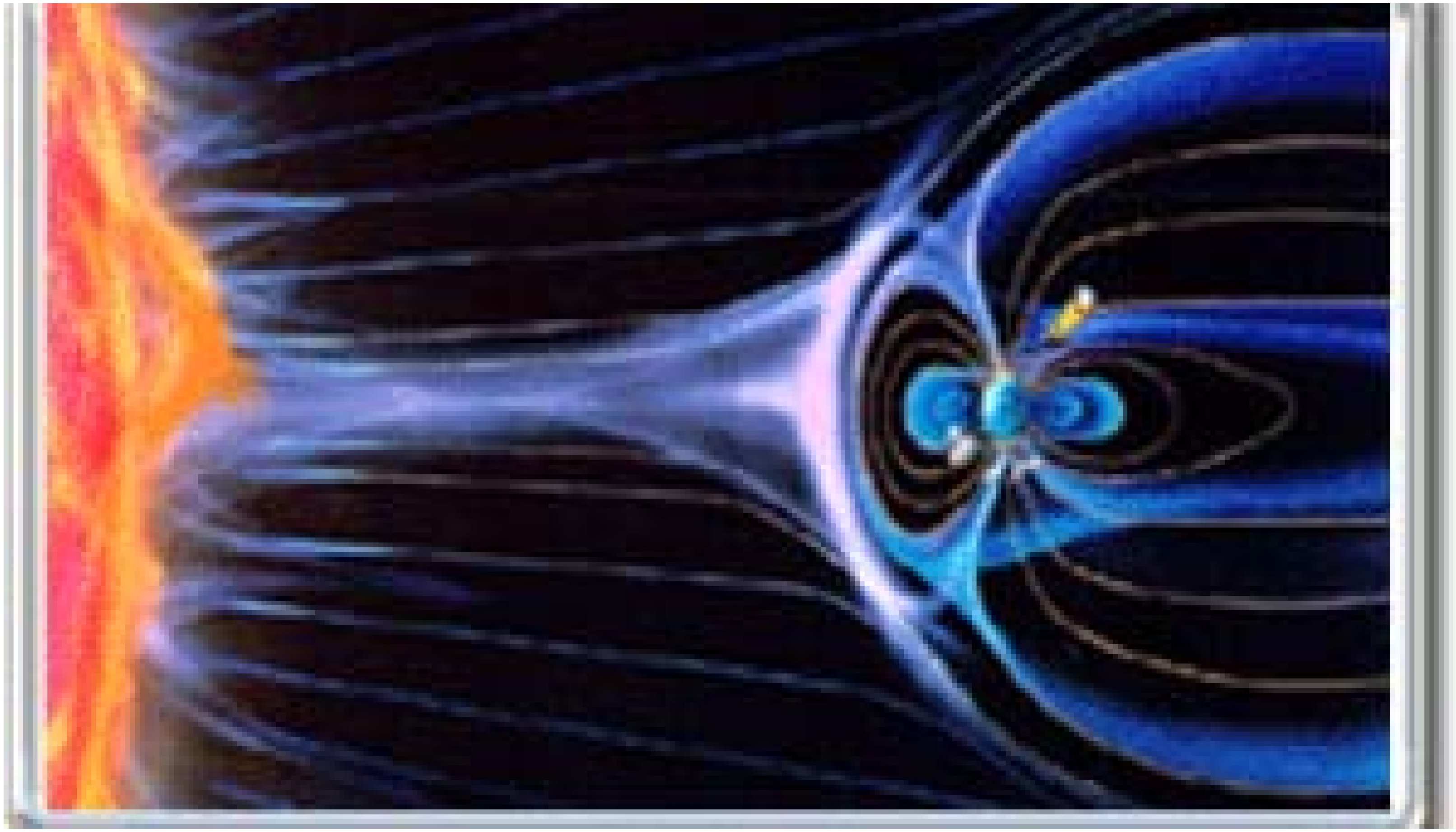

Figure reproduced from a briefing by Patricia Doherty, Boston College

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Introduction to the Ionosphere

The Ionosphere

- The ionosphere is a layer of the upper atmosphere ionized by radiations from the sun
  - From 50 km to about 1,200 to 1,600 km
  - Ionization mostly due to extreme ultra violet, but also hard and soft x-rays, and other radiations
  - Several layers (D, E, F1, F2) depending on depth of penetration of radiations
- The low atomic density causes the rate of re-combination to be low
  - So, the medium contains free ions and electrons
  - Free electrons determine behavior of medium
- The ionosphere is electrically conducting and can support strong electric currents

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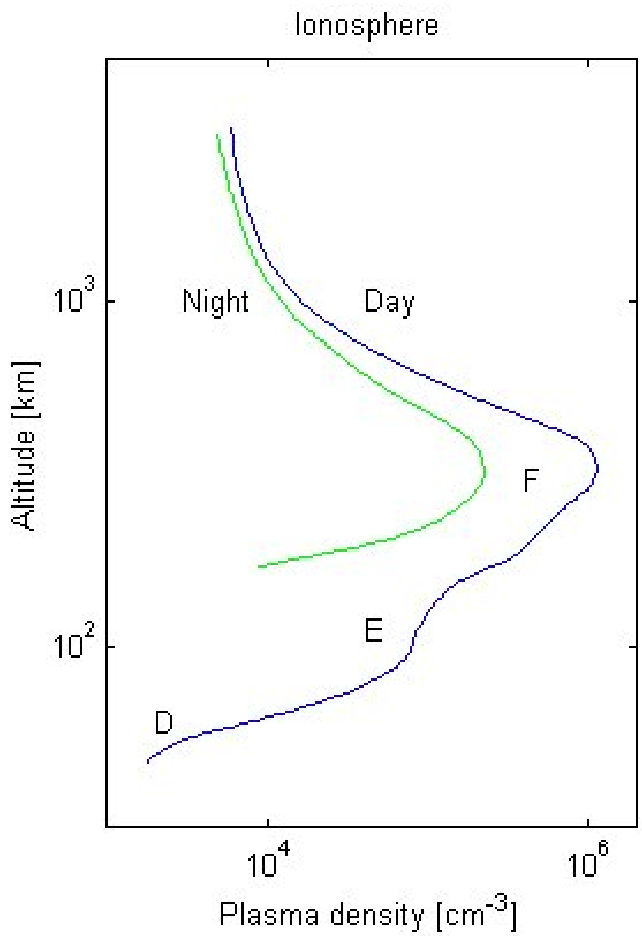
Electron Density Profile



Density profile of free electrons in the ionosphere (plasma density)

Ionospheric delay is a function of the Total Electron Content (TEC) along the propagation path and an inverse function of the square of the carrier frequency of L-band signals

F2 layer dominate effects on L-band (GNSS frequencies)

Figure reproduced from http://www.oulu.fi/~spaceweb/textbook/

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TEC Variability

- **The state of the ionosphere (TEC) varies with degree of exposure to the sun**
  - Day versus night
  - Season of year

- **It also depends on solar activity**
  - Peak versus valley of solar cycle (≈11 year cycle)
  - Geomagnetic conditions: quiet versus storm
    - Sudden bursts of solar energy (e.g. solar flares) can cause magnetic and ionospheric storms

- **It also depends on the observer's location**
  - Magnetic latitude

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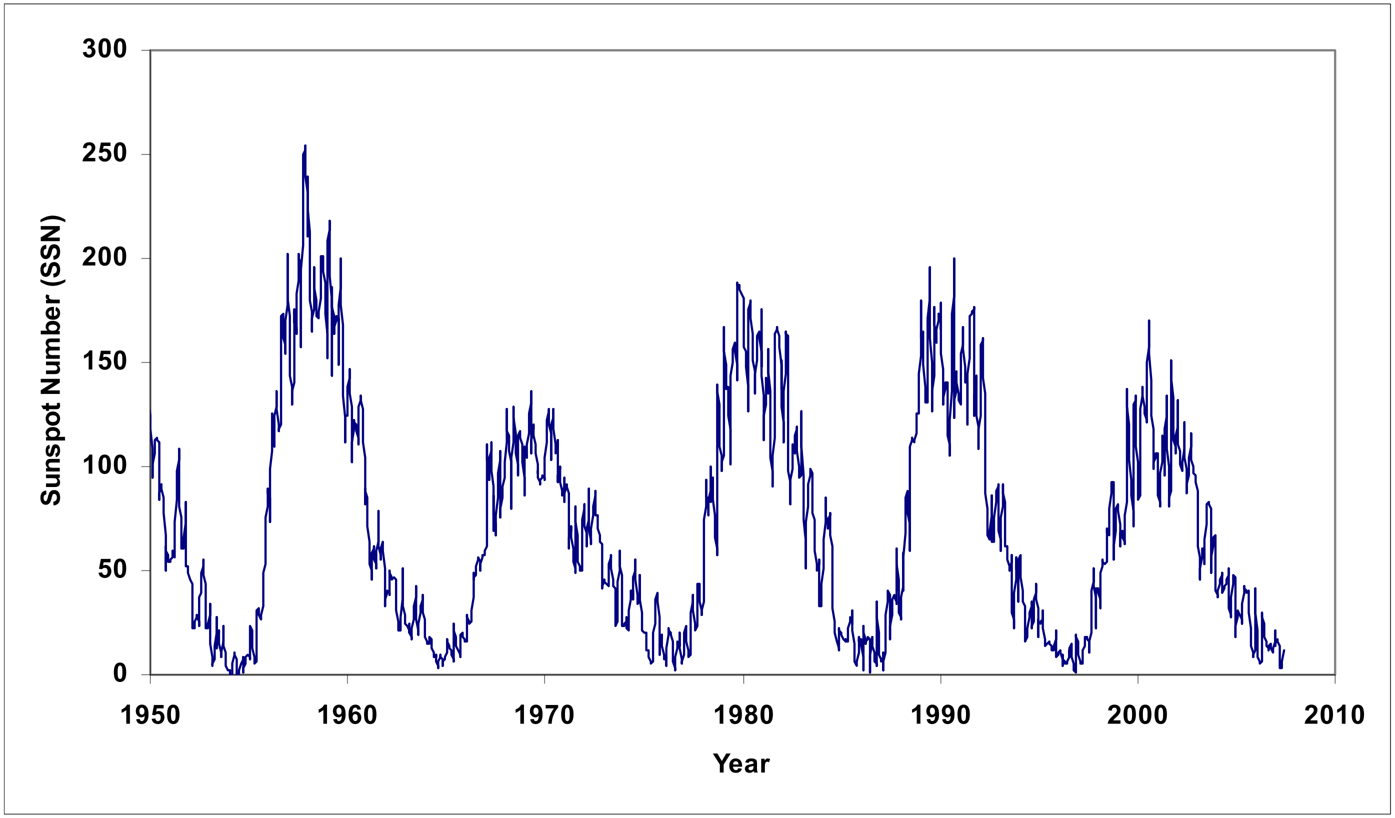
Solar Cycle



Solar Cycle as measured by the Sun Spot Number (SSN)

Note: we are currently at the very beginning of Solar Cycle 24; its peak is expected in 2011-2012

Ionospheric Storms

- Infrequent bursts of energy at the surface of the sun (e.g., solar flares) can cause magnetic storms
  - Material and radiations ejected by the sun at very high speeds cause changes in the magnetic field of the Earth
  - Changes in the magnetic field are characterized by various "indices" measured and published daily
    - Kp, Ap, Dst
- Magnetic (ionospheric) storms can cause large variations in TEC that can affect GNSS users
  - However, the intensity of these effects will vary depending on the location and time of the observations

Geomagnetic Perturbation Metrics

1 of 2

- **K index**
  - **Local measure of fluctuations in the horizontal component of earth's magnetic field at mid-latitude**
  - **Measured every 3 hours from data collected over 3-hour intervals**
  - **Range: 0-9 with 1/3 quantization**
- **Kp index**
  - **Small letter "p" stands for planetary**
  - **Computed from K indices reported by a number of observatories worldwide**
- **A index**
  - **K converted to a linear scale with range: 0 to 400**
- **Ap index**
  - **Daily, planetary average of A indices**

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Geomagnetic Perturbation Metrics

2 of 2

- **Dst**
  - **Measure of fluctuations in the horizontal component of earth's magnetic field in the equatorial region**
  - **A negative value indicates a storm is in progress**
    - **Storm induced ring currents around the earth cause Dst to become negative**

- **Magnetic storm severity**
  - **Minor: 30 ≤ Ap < 50**
  - **Major: 50 ≤ Ap < 100**
  - **Severe: Ap ≥ 100 (or Dst ≤ –100)**

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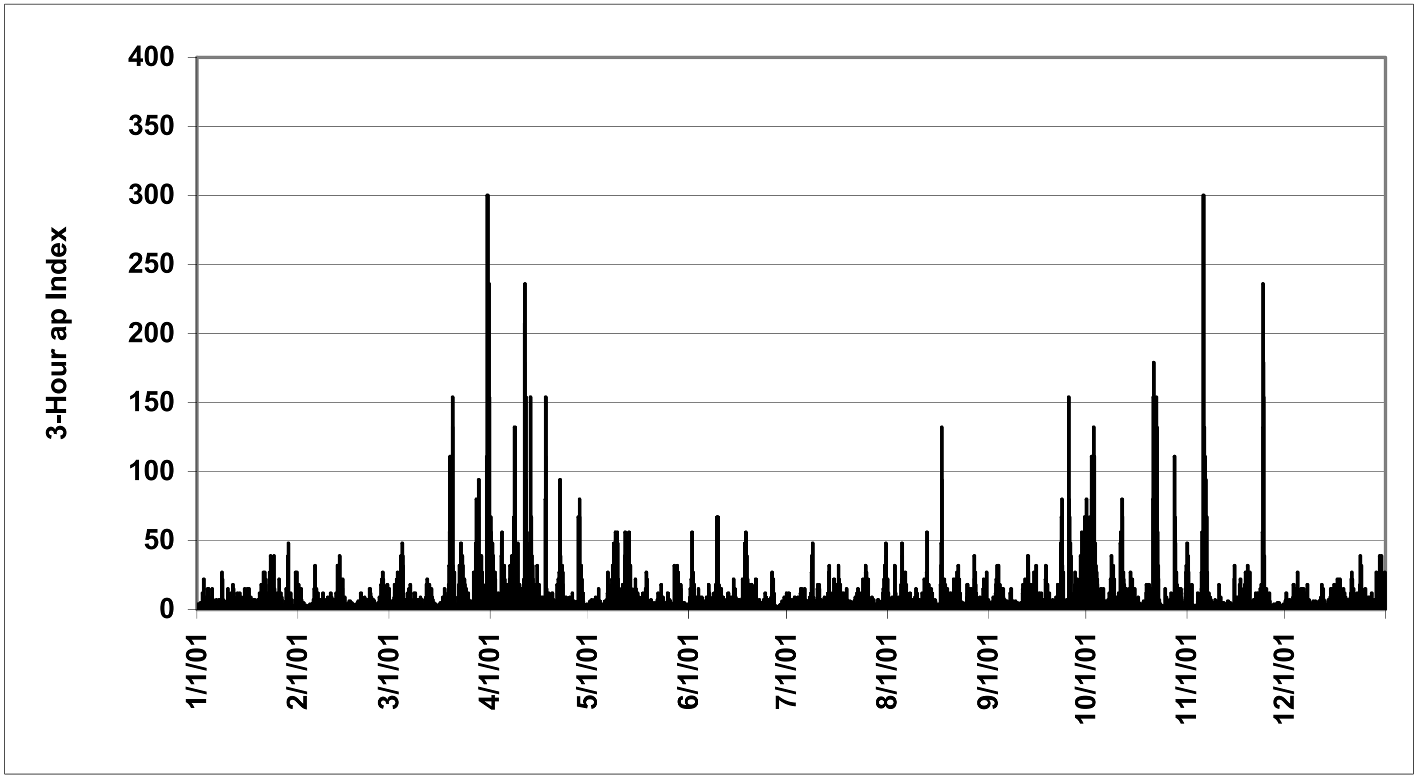
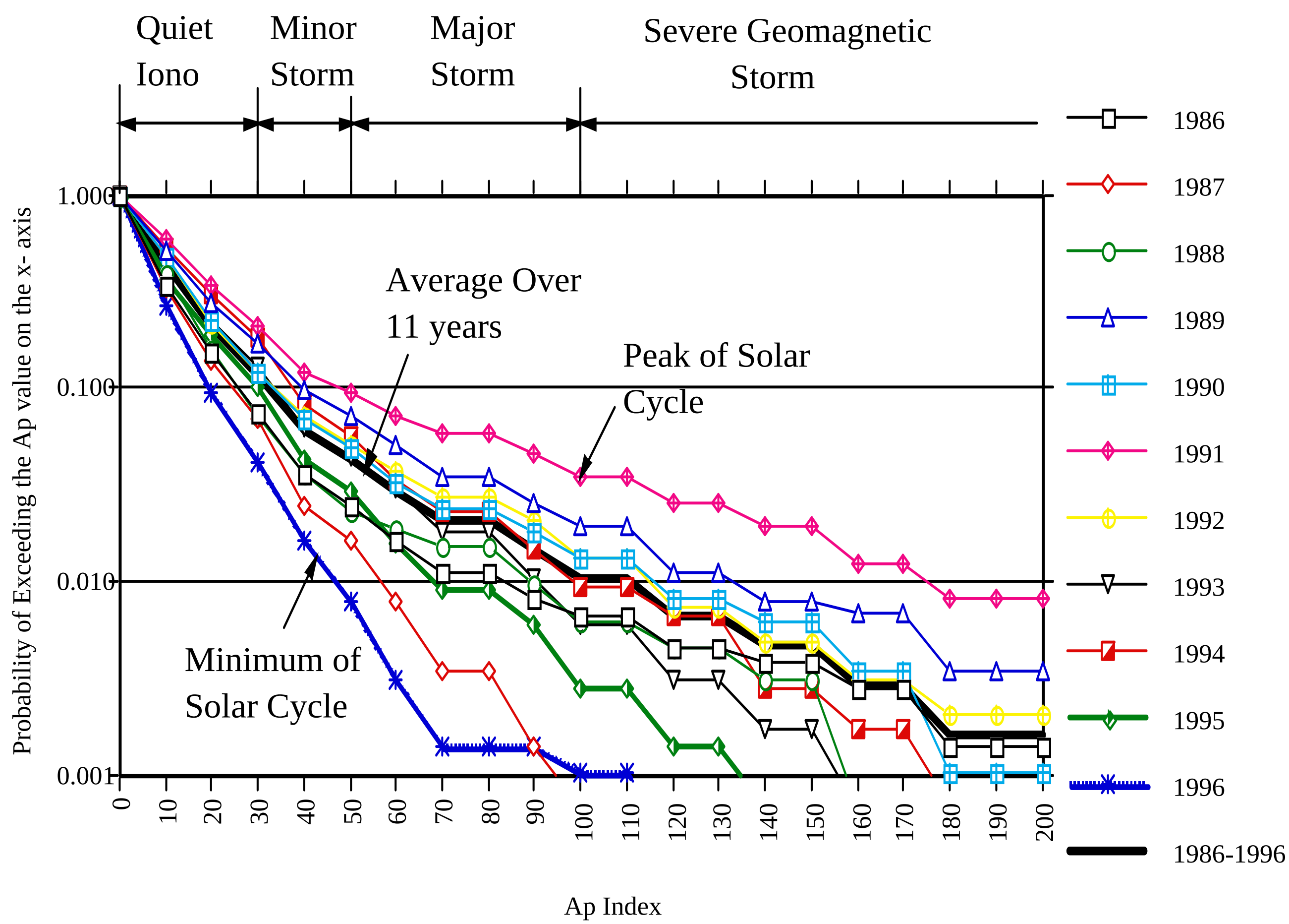
Ionospheric Storm Activity in 2001



Ionospheric storm activity in 2001 (last solar cycle peak)

Note: Severe storm conditions correspond to Ap ≥ 100

Frequency of Ionospheric Storms



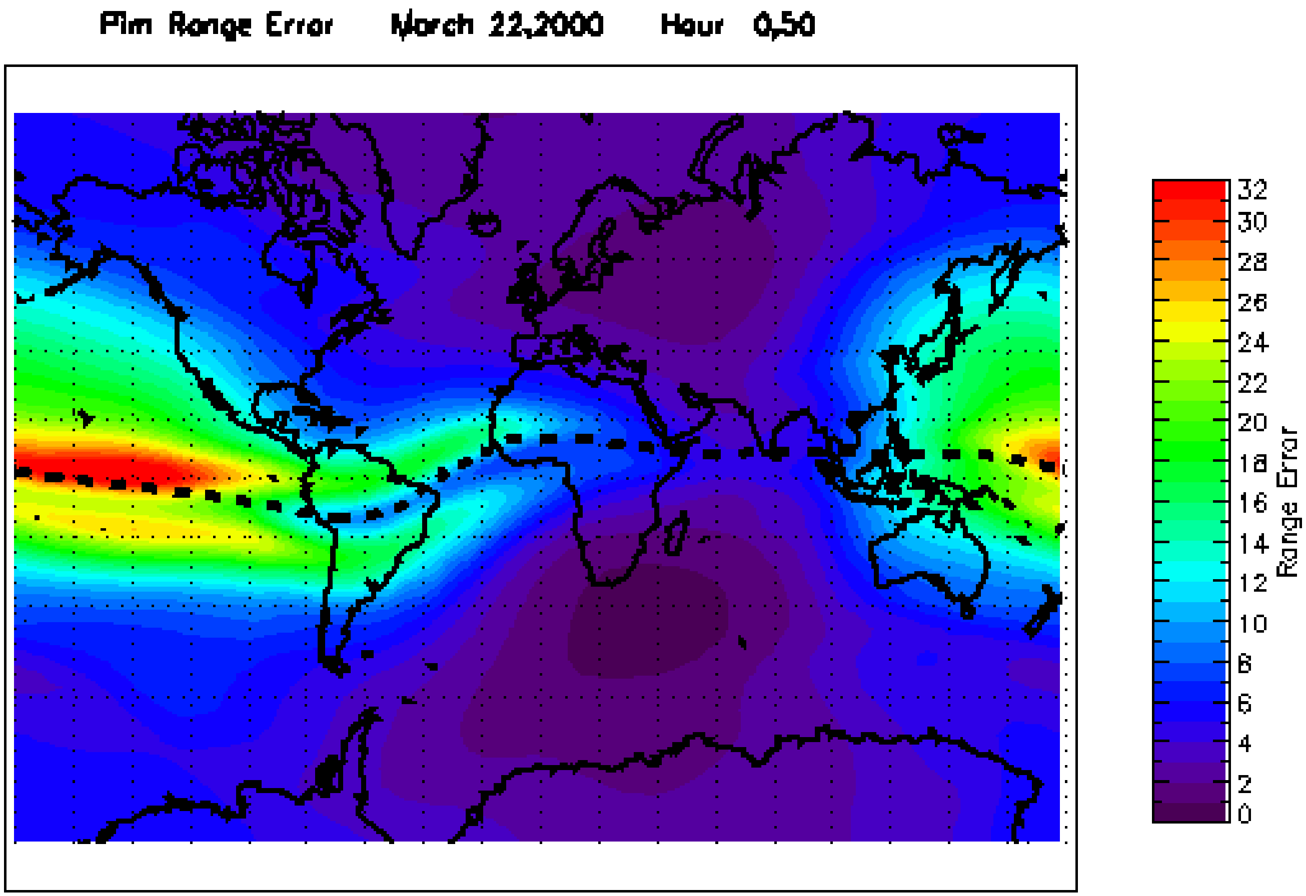
In 1991, the most active year over Solar Cycle 22, *Ap* ≥ 100 (severe storm) 3.4% of time.

Equatorial Anomalies

- **Crests of electron content on both sides of the geomagnetic equator**
  - **Form during the local late afternoon hours, then disappear during the night**
  - **Result in large TEC gradients at the edges of these crests**
  - **The equator side of the crests is often subject to depletions and high scintillation**
  - **Locations of crests vary from day to day, but typically between 15ºN and 20ºN and 15ºS and 20ºS magnetic**
    - **Northern and Southern crests are not necessarily equal or symmetric**
  - **Amplitudes of crests also varies from day to day**
    - **But typically larger near the peak of the solar cycle**

Example TEC Map

(from Parameterized Ionosphere Model, PIM)



Figures reproduced from a briefing by Patricia Doherty, Boston College

Ionospheric Effects on GNSS

Ionospheric Effects on L-Band Signals

- **Group delay**
  - Different frequencies travel at different speeds, which causes
    - A delay in the modulation (code measurements)
    - An advance in phase measurements
  - The combination is referred to as "code/carrier divergence"

- **Scintillation**
  - Rapid variations in signal amplitude and phase

- **Faraday rotation**
  - Does not affect circularly polarized signal (i.e., GPS)

Ionospheric Effects on GNSS

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- **Signal propagation delay**
  - Can vary from equivalent of about 1 meter to more than 100 meters at GPS L1 frequency
  - Delay directly proportional to TEC and inversely proportional to square of carrier frequency
  - Potentially large position errors could result if ionospheric delays were not corrected to the extent possible
- **Scintillation**
  - Amplitude and phase scintillation
  - Can cause temporary loss of lock on the signal
  - Can be severe after local sunset in equatorial region, especially near peak of solar cycle

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Ionospheric Effects on GNSS

2 of 2

- Ionospheric (magnetic) storms
  - Can cause large spatial and temporal delay gradients
  - Can have major effect in all regions
- Equatorial (Appleton) anomalies
  - Two crests of TEC roughly 15 to 20 degrees of latitude on each side of the magnetic equator during the local evening hours
  - Cause large spatial and temporal gradients
- Equatorial depletions (plasma bubbles)
  - Long and narrow structures depleted of TEC can form at the edges of the equatorial anomalies
  - Often accompanied by increased scintillation activity

Ionospheric Effects by Region

- **From the perspective of ionospheric effects on GNSS, the globe can be divided in 3 main regions**
  - **High latitudes (φ > |65º| geomagnetic)**
    - **Relatively low TEC, but high TEC gradients**
    - **Phase scintillation, especially during magnetic storms**
  - **Mid latitudes (|30º| < φ < |65º| geomagnetic)**
    - **Relatively moderate TEC**
    - **For all practical purposes, no scintillation**
  - **Low latitudes (φ < |30º| geomagnetic)**
    - **Relatively high TEC and high TEC gradients**
    - **Amplitude and Phase scintillation**

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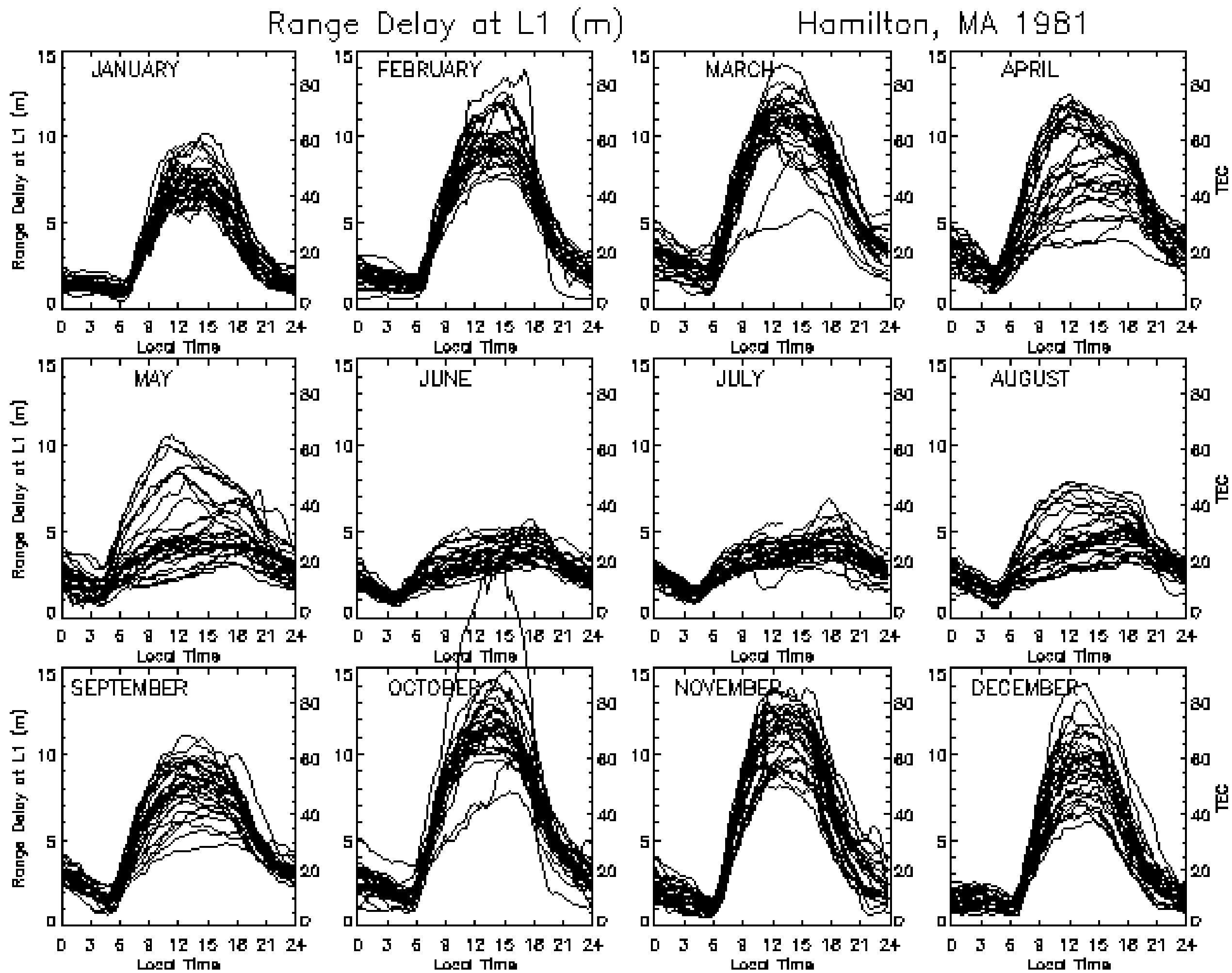
Examples of Data and Illustrations

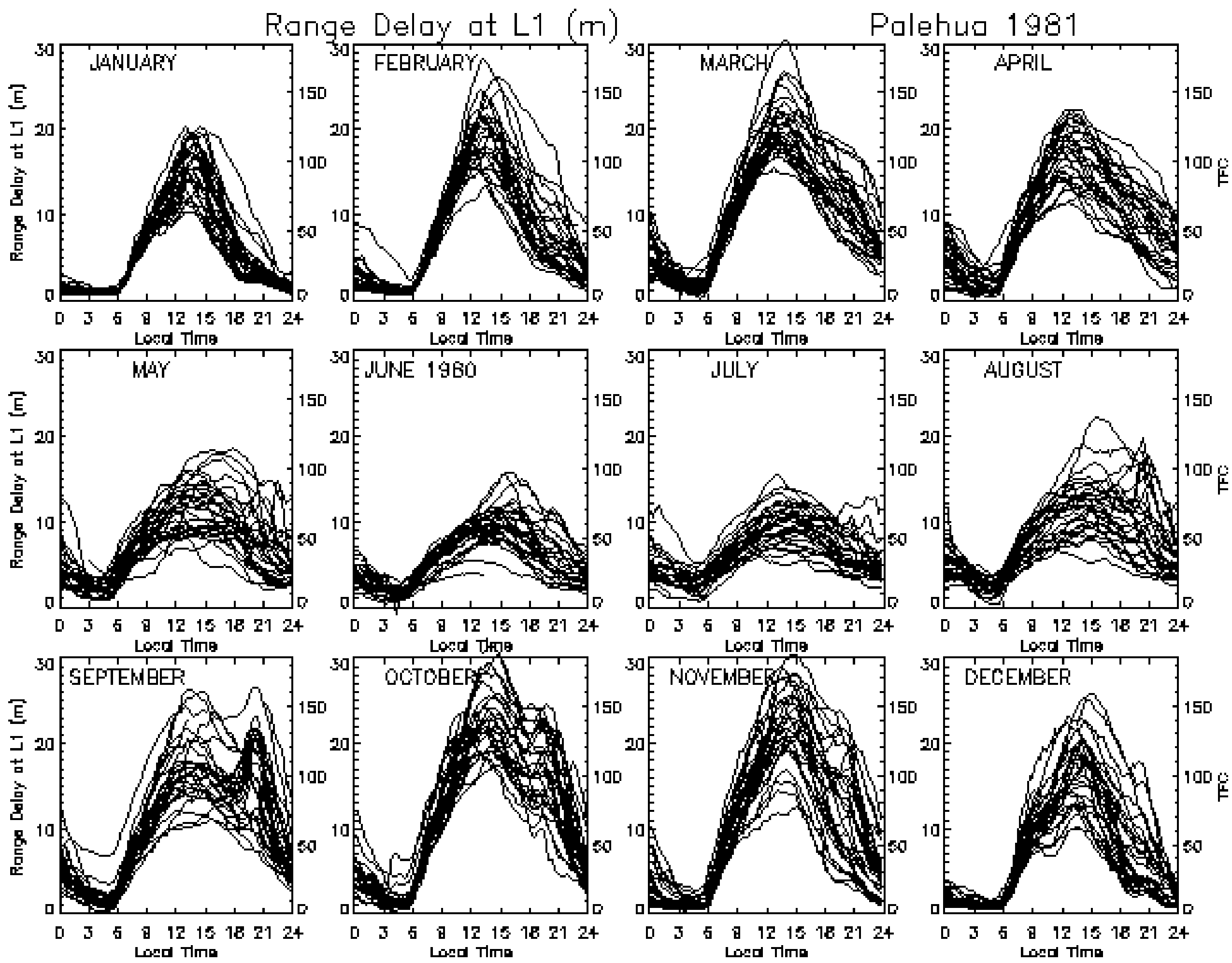
Range Delay (TEC) Observations
Hamilton, Massachusetts) – 1981 Data



Data collected by Patricia Doherty, Boston College, and Jack Klobuchar, ISI

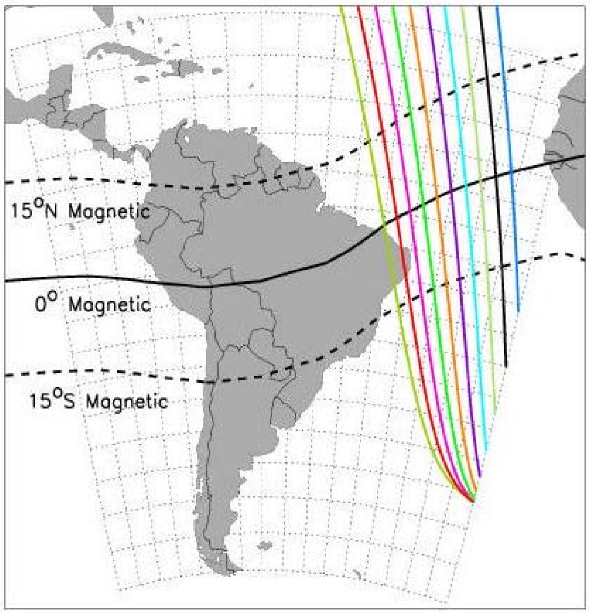
Range Delay (TEC) Observations

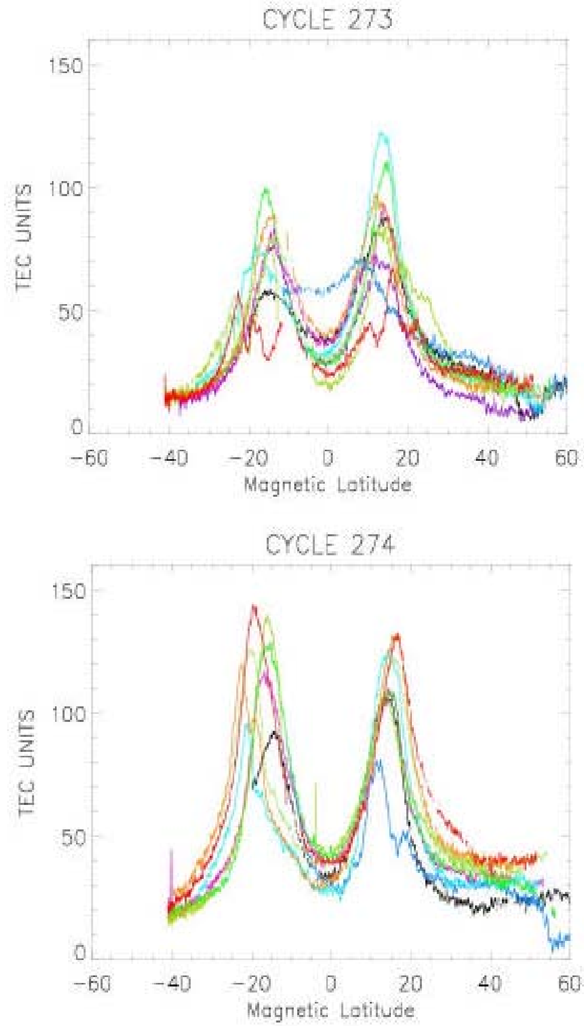
Palehua, Hawaii (21ºN Geomagnetic) – 1981 Data



Data collected by Patricia Doherty, Boston College, and Jack Klobuchar, ISI

Variability of the Post-Sunset Anomaly in Brazilian Sector (TOPEX 2/10/00 – 2/29/00)





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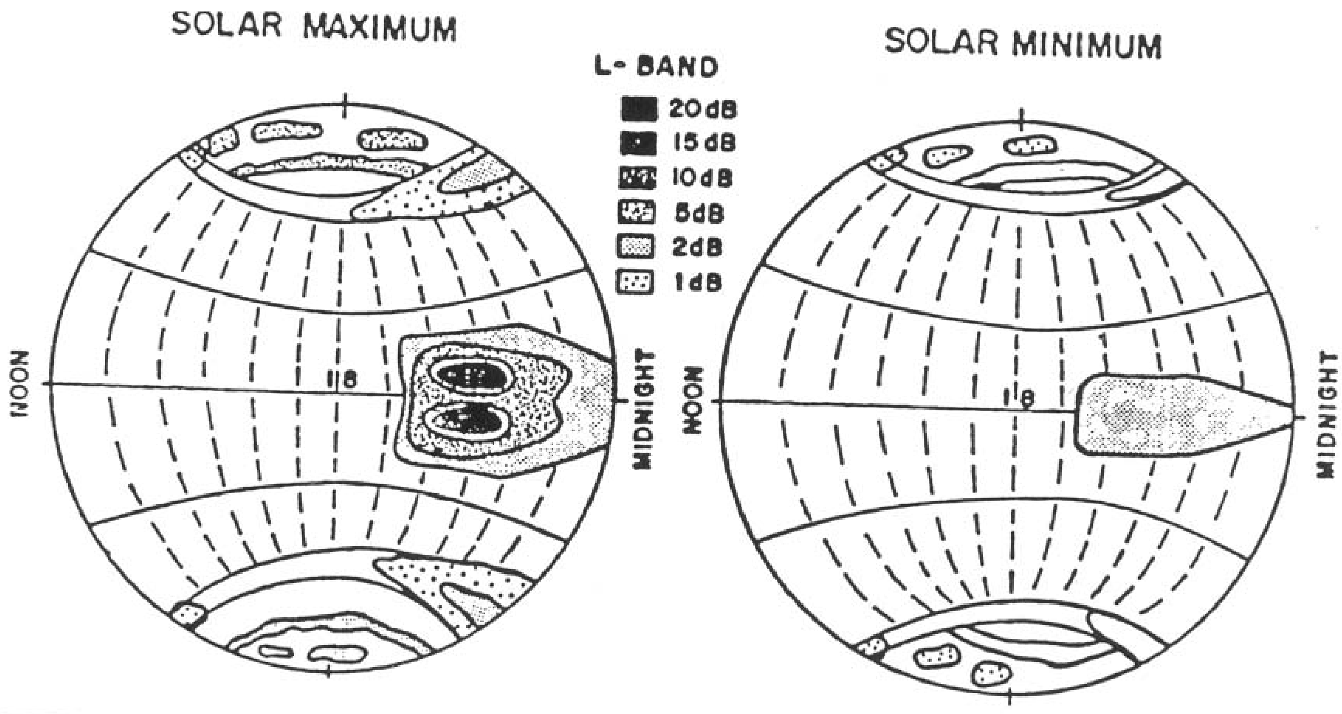
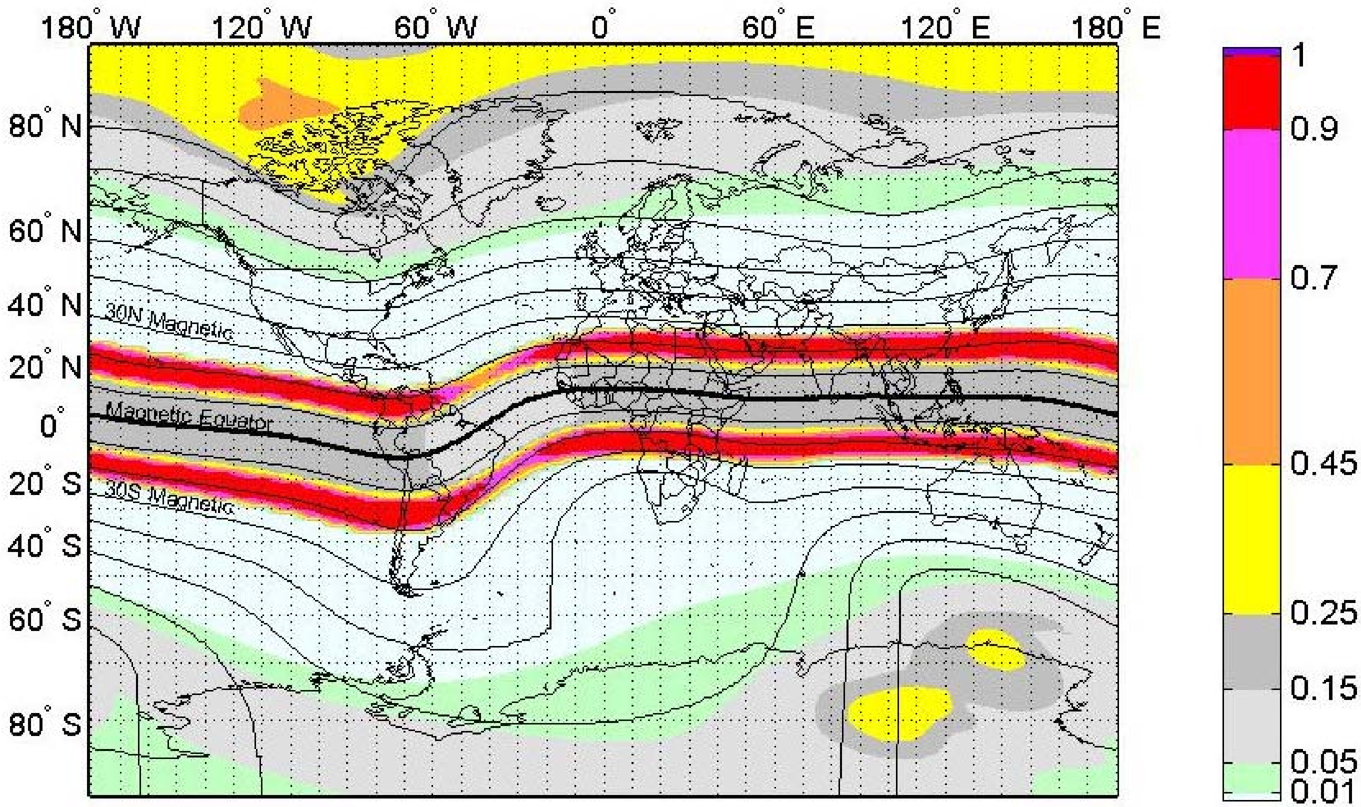
Amplitude Scintillation Depth



Worst Case Fading Depth at L-Band due to Ionospheric Scintillation
Aarons, J, S. Basu, "Ionospheric Amplitude and Phase Fluctuations at the GPS Frequencies," *Proceedings of ION-GPS '94*, Salt Lake City, UT, pp. 1569 – 1578.

Amplitude Scintillation "Bands"



Example output from WBMOD scintillation model: amplitude Scint. index, S4, for September 15, assuming SSN = 150 (≈ peak of solar cycle), Kp =1 (quiet ionosphere), Local Time = 9:00 pm everywhere

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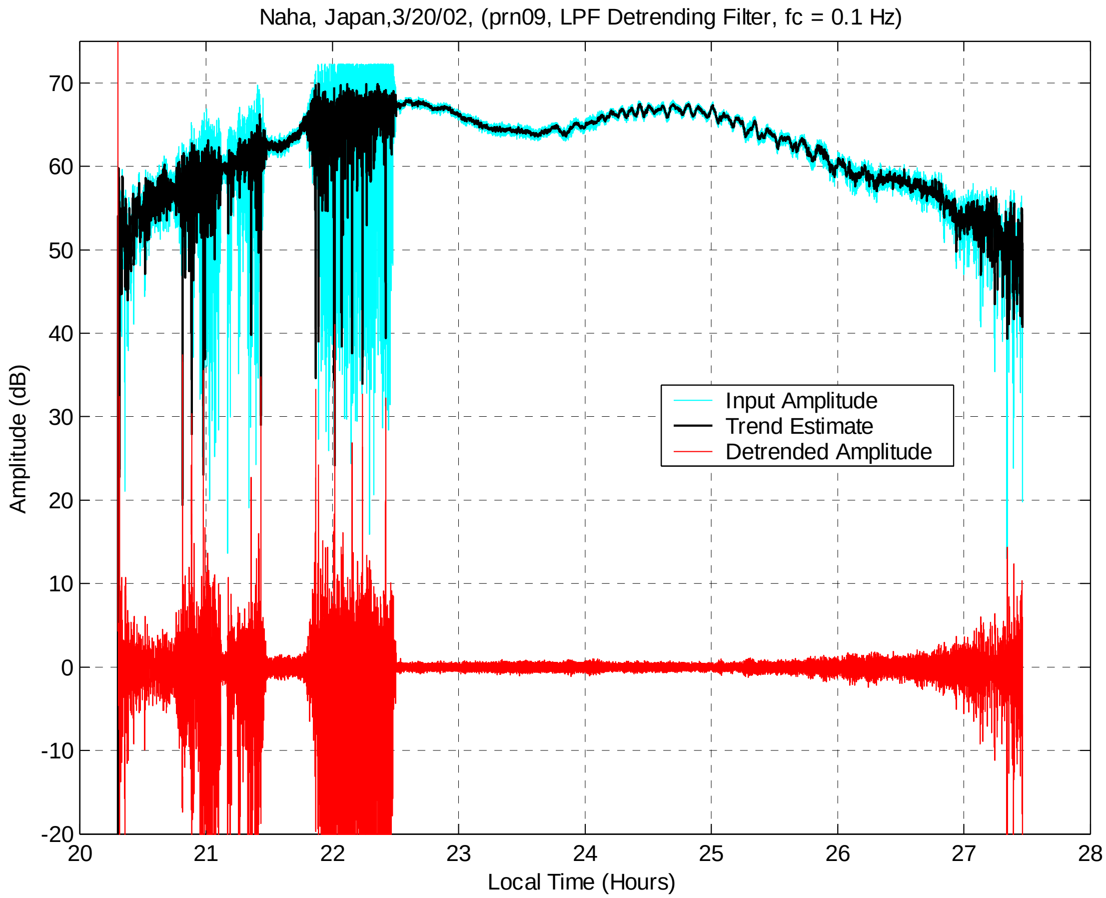
Example Amplitude Scintillation Effect



Example of Amplitude Scintillation on PRN09 at Naha, Japan, on March 20, 2000

Ref.: El-Arini, Conker, Ericson, Bean, Niles, Matsunaga, Hoshinoo, ION-GPS-2003

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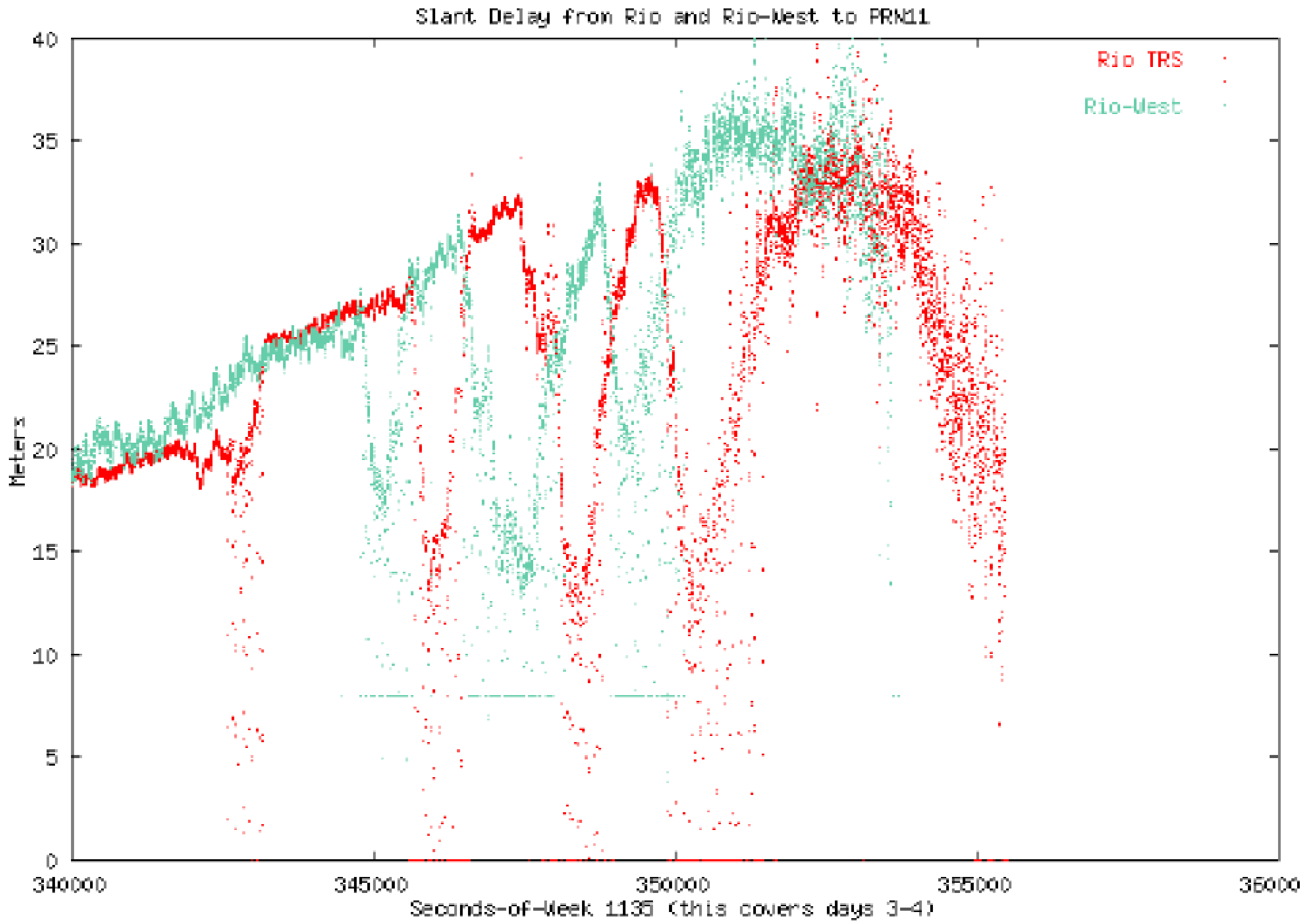
Example of Depletions

(Data recorded in Brazil by Tom Dehel, FAA, Jan. 2002)



The South American Ionosphere

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- **Generating reliable ionospheric delay corrections in most of South America presents a very difficult challenge**
  - **Steep, time-variable gradients due to the equatorial anomalies**
  - **Narrow depletions that a ground network of reference station might not observe reliably**
  - **Algorithm research has so far not produced a satisfactory solution for single-frequency SBAS**
- **Scintillation will cause receivers to lose lock on multiple satellites signals at certain times**

The South American Ionosphere

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- **The ionospheric delay estimation difficulties will disappear (for all practical purposes) once dual-frequency signals are available to civil users (GALILEO, Modernized GPS with L5, GPS III)**

- **Scintillation will remain**
  - **L5 (1176.45 MHz) will be somewhat more sensitive to scintillation than L1 (1575.42 MHz), but the signal will also be better than L1 (C/A)**
  - **Building robustness to scintillation in the receiver design is an active area of research**
  - **Loss of a few satellites does not necessarily imply losing positioning service, particularly when more satellites are in view (GALILEO + GPS = 18 satellites in view on average)**

Useful References

- Conker, R. S., M. B. El-Arini, C. Hegarty, T. Hsiao, "Modeling the Effects of Ionospheric Scintillation on GPS/SBAS Availability," Radio Science, Vol. 38, No. 1, January, 2003.
- Davies, Kenneth, *Ionospheric Radio*, Peter Peregrinus Ltd., 1990.
- El-Arini, M. B., W. Poor, R. Lejeune, R. Conker, J.P. Fernow, K. Markin, "An Introduction to Wide Area Augmentation System and its Predicted Performance," Radio Science, V. 36, N. 5, pp. 1233-1240, September-October 2001.
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- Hargreaves, J.K., *The Solar-Terrestrial Environment*, Cambridge University Press, 1992.
- ICAO Navigation System Panel, "Ionospheric Effects on GNSS Aviation Operations," December 2006.

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