Ionospheric Storm Monitoring with GNSS

Anthea J. Coster, MIT Haystack Observatory

Outline

MOVIE
Introduction
Review Atmospheric Measurements
History
Storm time electric fields
Global Space Weather Events
Definition:

TEC = Total Electron Content \( (10^{16} \times \text{el/m}^2) \)
GPS samples the ionosphere and plasmasphere to an altitude of ~20,000 km

TEC is a measure of integrated density in a 1 m² column

1 TEC unit = $10^{16}$ electrons m⁻²
Space Weather

- Definition:

  - “Conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can affect performance and reliability of space-based and ground-based technological systems.”

---

*National Space Weather Program Strategic Plan, NSF*
Northwest Territories, Canada
West Texas 15 Sept 2000
near El Paso Texas

(from astronomy picture of the day)
Space Weather
Why do we care?

Never before has our society depended so much on radio waves that can be disrupted by the effects of the Sun’s activity on the Earth.
Space Weather
Space Weather - Scintillation

Wave front:
- uniform phase
- uniform amplitude

Incident wave

SV velocity $v_s$

Ionosphere

Irregularities

Wave emerging from below irregularities:
- non-uniform phase
- quasi-uniform/non-uniform amplitude

Diffraction/interference pattern

Plasma drift $v_p$

Ground
Space Weather - Scintillation
Outline

Introduction

Review Atmospheric Measurements

History

Storm time electric fields

Global Space Weather Events
Atmospheric Propagation

From Attila Komjathy, JPL
Illustration of Atmospheric Effects

TROPOSPHERE

IONOSPHERE

RADAR

TOTAL REFRACTION
ERROR IN ELEVATION

OBSERVED BEARING

TRUE BEARING

TROPOSPHERE

IONOSPHERE

RADAR

TOTAL REFRACTION
ERROR IN RANGE

OBSERVED RANGE

TRUE RANGE
Index of Refraction in the Ionosphere

\[ n^2 = 1 - \frac{X(1-X)}{(1-X) - \frac{1}{2} Y_T^2 \pm \left( \frac{1}{4} Y_T^4 + (1-X)^2 Y_L^2 \right)^{\frac{1}{2}}} \]

\[
X = \frac{\omega_N^2}{\omega^2} \quad Y = \frac{\omega_H}{\omega} \quad \omega_N = \left( \frac{Ne^2}{\varepsilon_0 m_e} \right)^{\frac{1}{2}} \quad \omega_H = \frac{e|B|}{m_e}
\]

\[ \omega = \text{the angular frequency of the radar wave,} \]

\[ Y_L = Y \cos \theta, \quad Y_T = Y \sin \theta, \]

\[ \theta = \text{angle between the wave vector } \bar{k} \text{ and } \bar{B}, \]

\[ \bar{k} = \text{wave vector of propagating radiation,} \]

\[ \bar{B} = \text{geomagnetic field,} \quad N = \text{electron density} \]

\[ e = \text{electronic charge,} \quad m_e = \text{electron mass,} \]

and \( \varepsilon_0 = \text{permittivity constant.} \)
Ionospheric Range Correction

\[ n \approx (1 - \frac{\omega^2}{\omega_N^2})^{\frac{1}{2}} \approx 1 - \frac{\omega^2}{2\omega_N^2} \approx 1 - \frac{AN_e}{f^2} \]

\[ \Delta R_{ion} (meters) = \frac{40.3}{f^2} \int_0^R N_e \, dr \]

<table>
<thead>
<tr>
<th>TEC</th>
<th>S-Band</th>
<th>L-Band</th>
<th>UHF</th>
<th>VHF</th>
<th>Elev</th>
<th>Mapping Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2.4 m</td>
<td>12 m</td>
<td>104 m</td>
<td>787 m</td>
<td>90°</td>
<td>x 1</td>
</tr>
<tr>
<td>110</td>
<td>5.1 m</td>
<td>26 m</td>
<td>223 m</td>
<td>1.7 km</td>
<td>20°</td>
<td>x 2.12</td>
</tr>
</tbody>
</table>
Ionospheric Parameters

GPS can be used to measure

Ground-Based Receivers

• Total Electron Content
• Scintillation Parameters: $S_4$ and $\sigma_{\phi}$

Space-Based Receivers

• Electron Density Profiles
• Scintillation Parameters: $S_4$ and $\sigma_{\phi}$
Total Electron Content (TEC) Estimation
Dual-Frequency Measurements
Outline

Introduction

Review Atmospheric Measurements

History

Storm time electric fields

Global Space Weather Events
Solar Flare of 14 July 2000

Biggest Solar Storm in Nine Years

Caused very large magnetic storm and ionospheric effects
GPS Loss of Lock at Millstone Hill

Local Westward Ion Velocity at Millstone Hill

Zenith TEC Over Millstone Hill

Loss of Lock on GPS L2 signal
TEC Disturbances on 15 July 2000
Wide Area Distribution of 'Raw' Information

Distributed networks of sensors yield global physics unattainable with single-point measurements

[Coster et al, 2003]
GPS Total Electron Content Map

Illustration of Storm Enhanced Density
Wide Area Distribution of 'Raw' Information

Distributed networks of sensors yield global physics unattainable with single-point measurements.

Example: Global GPS-derived ionospheric mapping during geomagnetic disturbances.

[Coster et al, 2003]
IMAGE Data of Plasmasphere
Inner Magnetosphere – Low Latitude View

May 30, 2003 01:00 UT  TEC [10,100],TECu

Plume

Bulge

Enhanced Eq Anomaly

TEC Hole
Storm-time Electric Fields

- Cross-tail electric fields energize and inject particles into the inner magnetosphere forming the disturbance Ring Current

- Strong penetration eastward electric field uplifts equatorial ionosphere
  - Equatorial anomaly enhanced

- Radial/Poleward Polarization Jet Electric Fields form (Sub Auroral Polarization Stream). As the Polarization Stream overlaps the outer plasmasphere
  - Storm-Enhanced Density (SED)
  - Detached plasmas/plasma tails
Plasmasphere / Ring Current Interactions

April 17, 2002
NASA IMAGE

SAPS Channel

Plasmasphere Erosion Plume

(Merged image courtesy J. Goldstein)
Common Features observed in TEC during geomagnetically disturbed conditions

- SED Plume Base
- Cusp Region ~ local Noon
- Sharp Gradients
- SAPS
- TOI

[Map showing various features and color coding for total electron content (TECU)]
GPS TEC Map from 20-Nov-2003 19:00:00 to 20-Nov-2003 19:20:00

Log10(TEC)
Northern Europe and American Sector SED Plumes
20 Nov 2003 18:20 UT
26 Sep 2011

North Pole

19:00-19:30 UT
Kp = 6.3

20:00-20:30 UT
Kp = 6.3

21:00-21:30 UT
Kp = 6.3

22:00-22:30 UT
Kp = 5.3

South Pole
Location of Base of Plume stays fixed in longitude

17 March 2013

18:00-19:20 UT
Conjugacy Examples

GPS TEC Map from 02-Oct-2001 11:00:00 to 02-Oct-2001 11:30:00
Conjugacy Examples
Conjugacy Examples
TOTAL ELECTRON CONTENT 17/Mar/2013 19:15:00.0 to 17/Mar/2013 19:20:00.0
Median Filtered, Threshold = 0.10
Nighttime MSTID Observations (TEC, Airglow) [Saito et al., 2001]
Japan Tsunami Makes Waves in More Than Just the Ocean
GPS TEC change – no warming

- GPS TEC (Total Electron Content) data show large-scale picture of ionospheric behavior
- Before the warming, TEC change is 10-20% from mean and vertical drift is small
- The mean is Jan 1-14, 2009
GPS TEC during warming: morning sector

- During stratwarming, TEC increases in excess of 50-100% in the morning
- Large upward drift at Jicamarca
- The magnitude of increase is similar to effects of severe geomagnetic storms
24-hour satellite path for GPS (Green) and GLONASS (Red)

GLONASS orbit plane inclination: 65°

COMPASS

GALILEO

European Geostationary Navigation Overlay Service
SUMMARY

Over the last 10 years, global GPS TEC maps have provided a paradigm shift in the way we study the ionosphere/plasmasphere/magnetosphere.

GPS has played a key role in system science studies of the atmosphere, but I think we are only at the beginning. How we combine GNSS observations with other data sets is the key to the future.

New discoveries are there buried in the data.
From the Sun to the Earth
Magnetosphere
Ionosphere
Atmosphere
Coupling