Remote Sensing of the Ionosphere and Plasmasphere from Space Using Radiowaves

Anthony J. Mannucci
Jet Propulsion Laboratory
California Institute of Technology
Topics

- Why bother…the scientific context
- Trans-ionospheric and sounding
- Small-scale structure
- Plasmasphere
- Tomography: “fast” and “slow”

- Pseudo-imaging
Where Geospace Science Stands Today

- Characterization of ionospheric behavior has changed dramatically in the past 10 years
  - Including mid-latitudes
- We can now identify large to meso-scale plasma structures that vary over time scales of minutes to hours
- New phenomenology has been discovered

Missing:
- The right observations at the right locations to achieve *understanding* of what is observed

Highest scientific priority:
- Achieving understanding
The expansion of the convection pattern can transport middle latitude plasma to high latitudes.

Here plasma from below 50 degrees magnetic is transported poleward and across the high latitude regions.

This feature would not be easily visible if there were not a high density reservoir from which the plasma were extracted. (where does this come from?)

GPS TEC data
Dusk effect
RF Delay ~ $1/f^2$

$L1 = 1575\, \text{GHz}$

$L2 = 1227\, \text{GHz}$

$1\, \text{TECU} = 10^{16}\, \text{el/m}^2$
\[
 n^\pm_2 = 1 - \frac{2X(1-X)}{2(1-X) - T^2 + \sqrt{T^4 + 4(1-X)^2 Y^2}}
\]

\[
 X = \left( \frac{f_p}{f} \right)^2 = \left( \frac{n_p e^2 / 4 \pi^2 \epsilon_0 m}{f^2} \right)
\]

\[
 Y_T = Y \sin \theta_B; \quad Y_L = Y \cos \theta_B
\]

\[
 Y = \frac{f_R}{f} = \left( \frac{e|B_0| / 2\pi m}{f} \right)
\]

Appleton-Hartree: electromagnetic wave (carrier) propagating in a magnetized plasma, neglecting collisions

\[
 n^\pm_{\text{group}} = 1 + \frac{1}{2} \frac{1}{X + XY|\cos \theta_B|} \left[ X + \frac{3}{4} X \left[ \frac{1}{2} X + Y^2 \left( 1 + \cos^2 \theta_B \right) \right] \right]
\]

Using (6) above
Phase and Range Ionospheric Observables

\[ PI = P_2 - P_1 = 40.3 TEC \left( \frac{f_1^2 - f_2^2}{f_1^2 f_2^2} \right) + b_i^r + b_i^s \]

\[ LI = L_1 - L_2 \]

\[ = 40.3 TEC \left( \frac{f_1^2 - f_2^2}{f_1^2 f_2^2} \right) + n_1 \lambda_1 + n_2 \lambda_2 + b_i^{r'} + b_i^{s'} \]

First-order delays, with interfrequency biases included

- In direct TEC observations (single-difference), phase level is assumed unknown
- Pseudorange level is absolute, except for instrumental biases
- Pseudorange noise \( >> \) carrier phase noise
Examples of Leveling

GPS 22 for Receiver BIL

leveled phase $L_I$

pseudorange $P_I$
Large Ionization Changes During Storms

CHAMP (TEC above 400 km altitude)

Mannucci et al., GRL 2005
New Mid-Latitude Phenomena
Ionospheric Sounding
Probes that gather data along satellite trajectory

- *In situ* probes (e.g., Langmuir probes) on satellites are straightforward, reliable, and provide accurate measurements of both plasma density and structures/irregularities along the satellite path.

- The peak density and its altitude are not known. Indeed the probe could be above or below the F-peak.

- Knowledge of how the F-peak varies in altitude and amplitude is often the key to understanding the large scale behavior of the ionosphere.
Gathering knowledge of the F-peak along the satellite trajectory...

- Satellite track could be above or below the F-peak, particularly as the ionosphere changes with local time, latitude.
- Shown is drawing of an equatorial satellite trajectory such as C/NOFS.

- Space-based sounders that provide the F-peak density profile both above and below the satellite enable a new window on ionospheric measurements.

-- Scientific satellites with in-situ probes must go where the physics is, which is usually to lower altitudes (200 - 500 km), particularly where neutral atmosphere/ionosphere processes are studied.

-- The F-peak information along the trajectory can be readily compared to the other measurements gathered in situ, such as neutral winds, electric fields, currents, ion composition, etc.
Ionospheric Sounding

- Ionospheric sounding from 450 km altitude provides accurate electron density profiles to hmF2
- Determines whether S/C is above or below hmF2
- Advanced space-borne sounder designs exist
- Software for automatic analysis exists
- Low radiated power using DSP

More later in the program…
COSMIC CERTO/Tri-Band Beacon

– 150 MHz, 400 MHz, 1066 \(\frac{2}{3}\) MHz

Bernhardt – COSMIC First Data User’s Meeting, Boulder CO, 2006
LEO-Ground Radio Tomography

Tomographic Image: 23/12/92 14:54 UT
Electron Density ($10^{11}$ m$^{-3}$)

Tomographic Image: 17/11/95 14:07 UT
Electron Density ($10^{11}$ m$^{-3}$)

Bernhardt et al., Physics of Plasmas 1998

Remote Sensing Using Radiowaves
© 2008 California Institute of Technology. Gov’t Sponsorship Acknowledged
Irregularity Measurements

Straus, Anderson and Danaher, GRL 2003

October 18, 2007 Remote Sensing Using Radiowaves
© 2008 California Institute of Technology. Gov’t Sponsorship Acknowledged

AJM/JPL 16
COSMIC

- Successful launch April 14, 2006
- Six satellite constellation
- Initial configuration: single orbital plane
- Final configuration:
  - 800 km altitude
  - Separate orbital planes
  - 72 degrees inclination
- JPL-designed receiver
- Broad-Reach Engineering built
- Near real-time feed to NOAA
COSMIC GPS Limb Sounding: Critical Sensor Data

Low-Earth Orbiter

GPS

COSMIC coverage

Electron Density Profile

3000 profiles/day

October 18, 2007

Remote Sensing Using Radiowaves
© 2008 California Institute of Technology. Gov’t Sponsorship Acknowledged
Occultation Geometry

Geometry of an acquisition

Transmitter

occulting GPS

1 Hz

ground station
Recev

neutral atmosphere

ionosphere

Bending angle

50 Hz

EARTH

occulting GPS calorating GPS

Remote Sensing Using Radiowaves
© 2008 California Institute of Technology. Gov't Sponsorship Acknowledged

October 18, 2007

AJM/JPL
Comparison of Calibrated Slant TEC Measurements for June 26, 2006

- An example of comparison of calibrated TEC between JPL and UCAR
- There appears to be a 2-3 TECU bias between JPL and UCAR slant TEC
- Negative TEC, differences between UCAR and JPL elevation cutoff angles
- Similar data volumes between JPL and UCAR

Elev cutoff angle differences?

Good match

Calib. Different
Historic examples of Abel electron density profiles

**GPS/MET Profile**
(Compared to Millstone hill radar)

**Oersted Profile**
(Compared to nearby ionosonde)

**SAC-C Profile**

**IOX Profile**

Comments:
- ISR meas. are at 42.6 N, 288.5 E, 1995-05-05-03:40 UT
- Occultation tangent point is at 41.6 N, 282 E
- Occultation time is 1995-05-05-03:22 UT
- ISR profile from 320 us mode of operation

**Graphs**
- Electron Density (m⁻³)
- Height, km
- ISR vs GPS/MET
- Height vs Electron Density (m⁻³)
- Oersted vs Nearby Ionosonde
- SAC-C vs Millstone Hill Radar
- IOX vs Nearby Ionosonde
Comparison of UCAR and JPL Abel Profiles
June 26, 2006

UCAR and JPL Abel profiles usually agree well.
Validating UCAR and JPL Abel Profiles Using Arecibo ISR Measurements for June 26, 2006

- E-region error in naive Abel profiles: negative electron densities
- Spacecraft not yet in final orbital altitudes so Abel inversions more difficult
- JPL smoothed, UCAR unsmoothed profiles

Arecibo calibrated profiles are courtesy of Prof M. Kelley and V. Wong of Cornell University
E-Region From GPS/MET 1995

Date 1995-05-04
UT: 1125
LT: 0712
Lat -55N, Lon 296E

Date 1995-05-04
UT: 1928
LT: 0122
Lat -36N, Lon 88E
3000 Profiles/Day

Hajj 2006 Constellation, 24 Hours

Number Of Occultations

Latitude

No. Occultations Per (100x100) km²

Latitude
Plasmasphere

GPS Transmitter (20,230 km)  RF Delay ~ $1/f^2$
L1 = 1575 GHz
L2 = 1227 GHz

1 TECU = $10^{16}$ el/m²

TOPEX (1330 km)

Ionosphere

SAC-C (715 km)
CHAMP (400 km)

Ground Based GPS Receiver
JASON TEC Above Satellite

![Graph showing magnetic latitude vs. biased TEC](image)
GPS Equatorial Plasmasphere Measurements

- TEC from 1336 km upward using JASON upward viewing antenna
- Blackjack receiver
- ±5 degrees in magnetic latitude
- Restricted elevation angle (> 40 deg)
- Average vertical TEC per pass in equator
- Pass repeat every 100 minutes
April 2002 Geomagnetic Storm

Equatorial TEC from 1336 km -- April 17 2002 Storm

Six AM TEC
Six PM TEC

TEC Units

Days Since April 12, 2002

April 12
April 17

Dst Index (nT)

Dst Index

October 18, 2007

Remote Sensing Using Radiowaves

© 2008 California Institute of Technology. Gov’t Sponsorship Acknowledged
Space-based GPS Tomography

Yizengaw et al., GRL 2006
Summary

• Radio techniques have been used for decades to measure electron density
• With COSMIC and other satellites, constellation deployments likely to continue
• Instrument development: new GPS signals
  • Steerable antennas
• Algorithm development continues
  • Radiowaves a major source of data for Assimilation models
  • Improved tomographic or Abel inversions
• Advanced sounding will be covered later