GNSS Multi-scale studies of the ionosphere and plasmasphere

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Outline

- GPS Signal Structure
- Other GNSS Constellations
- GPS Ionospheric Observations
- TEC Based Scientific Studies of the Ionosphere and Plasmasphere
- Scintillation Based Scientific Studies of the Ionosphere
- Summary
GPS Satellite Signal Structure

Carrier:
- Doppler
- Range

Code modulation:
- Identifies SV
- Spread power
- Range

Navigation data
- SV orbit
- Error correction
- SV health

GPS signal
Range Measurements

Transmitted at SV:

Pseudorange:

\[ \rho = c (t_r - t_s) \]

Carrier phase:

\[ \phi = \frac{\lambda}{2\pi} (\phi_r - \phi_s) + N \lambda \]

Received at RX:
• Not necessarily implemented in all receivers
Ionospheric Range Correction

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

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

\[ TEC_{Si,Rj}(range) = \frac{f^2 \Delta R_{ij}^{\text{ion}}(meters)}{40.3} + \varepsilon_{\text{range}} + (SB_i + RB_j) \]
Constellations - Signals

**GPS**

**Glonass**

**Galileo**

**Compass**

**QZSS-Japan**

**IRNSS - India**
Total Electron Content (TEC) Dual-Frequency Measurements: Processing Issues

Processing Problem 1:
- The pseudo-range TEC observation is noisy. Several to 10’s of TECU ($10^{16}$ el/m²)
- The phase TEC is precise (~0.05 TECU) but there is an unknown phase ambiguity for each satellite-receiver pair

Solution: Phase averaging
- Average the phase (carrier) against the range (code) to resolve unknown phase ambiguity
- Implies need for continuous phase arcs over the time period -- NO cycle slips

Processing Problem 2:
- Detect and fix phase cycle slips
- If cannot fix, then flag
- *This must be done for any precise TEC investigation*
- Not easy – several different methods

Processing Problem 3:
- Satellite and Receiver Biases

Example: Open GNSS Processing Codes: GPSTK (ARL:UT)
Problem 3: GPS Biases

- GPS delay difference between two frequencies provides TEC
- Delay differences are also introduced by the satellite and receiver
- Satellite biases are determined by IGS community and are fairly stable
- Receiver biases are determined by individual user and most users estimate one bias over a 24-hour period.
TEC Based Studies of the Ionosphere and Plasmasphere

- Observations
  - Ground GPS slant TEC
  - Satellite based GPS radio occultations (RO) TEC
  - Satellite based GPS slant zenith (positive elevation angle) RO TEC

- Methods
  - Single receiver studies
  - Vertical TEC maps
  - GNSS tomographic imaging
  - Ionospheric data assimilation
  - Plasmaspheric imaging
  - Filter the TEC to look for waves and perturbations - Traveling ionospheric disturbances (TIDS)

- Scientific Studies
  - Global ionospheric storms
  - Polar cap patches
  - Storm enhanced density
  - MI coupling
  - Sudden stratospheric warming
  - TIDS
    - Tsunamis
    - MSTIDS
  - Equatorial plumes
  - E-region equatorial densities and conductances – equatorial spread-F
  - Auroral E-region densities and conductances – electrodynamics
  - Sharp density gradients during storms
  - Using TEC to estimate other state variables and drivers
TEC Observation Types
Vertical TEC Maps
Tomographic Imaging
Ionospheric Data Assimilation Four Dimensional (IDA4D)
- 2012 day 69
  - 1 hour of coverage
- Orange – GPS receiver sites
- Pink diamonds – GPS occultations
- Pink dashes GPS slant zenith TEC
Plasmaspheric Imaging
Traveling Ionospheric Disturbances (TIDS): Historical TID Data 29 July 1991

Two TI 4100 receivers separated ~ 25 km in MA P. Doherty and A. Coster
TIDS: Interferometry Imaging
Afraimovich, 2009

4 GPS stations
Separated by ~ 100 km
Time delays between them
Model as 2D waves
Spatial wave numbers, period

IMPT: Filtering GPS TEC can
Lead to false waves due to satellite
Motion ~50-100 m/s

At low enough elevation angles static
Spatial gradients can look like waves

Need to use a high enough elevation
cutoff and perhaps background data
assimilation or tomographic imaging to
understand the larger scales
Nighttime MSTID Observations (TEC, Airglow)
[Saito et al., 2001]
Several authors have used increasingly sophisticated models of the ULF wave fields in the ionosphere to explain and predict the impact on GPS signals (e.g., Poole and Sutcliffe, 1987; Pilipenko and Fedorov, 1995; Waters and Cox, 2009).
Scintillation Based Studies of the Ionosphere

**Observations**
- Ground GPS statistical parameters of phase ($\phi$) and amplitude ($S_4$)
- Ground GPS high-rate (50-100 Hz) observations of phase and amplitude
- Satellite based GPS radio occultations (RO) statistical and high rate observations

**Methods**
- All high rate observations (and statistical parameters derived from them) must be carefully filtered
- Must have continuous phase over time period being filtered
- Filter out satellite motion effect and low frequency refraction
- High pass filtering
- For phase scintillations need to have a low noise clock (oven controlled crystal oscillators OXCO)
- Or need to find a satellite that is not scintillating and subtract it off (remove common receiver clock errors)

**Scientific Studies**
- Equatorial Spread F / Bubbles
- Occurrence statistics
- Geographical location, intensity
- Duration
- Physics of irregularities that cause scintillations

**High latitudes**
- Relation to auroral processes all sky imagers
- MI coupling
- Patches / Structuring
- Understanding of physical processes the produce scintillations
Space Weather - Scintillation

Incident wave
Wave front:
uniform phase
uniform amplitude

SV velocity $v_s$

Ionosphere

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

Irregularities

Plasma drift $v_p$

Diffraction/interference pattern

Ground
Space Weather - Scintillation
Study of GPS phase scintillations and ASI May 20, 2010

ASI and phase scintillations 02:35 – 02:50
May 20, 2010
Detailed Comparison of PRN 30 Fluctuations at ~ 24 UT
Poker Array: 7 CASES GPS Scintillation Receivers: December 8, 2013: 2620-2680 seconds after 3 UT

- Velocity Estimation (on ground geographic East-North
  - Magnitude = 1,184 m/s
  - Direction = 160 degrees
- Ellipse of ground diffraction pattern
  - Ratio of major / minor axis: 3.3
  - Angle of ellipse from East: 32

Sky Plot at Poker Flat on 8 Dec 2013 0330−0430 UT

Basu et al., Interplanetary magnetic field control of drifts and anisotropy of high-latitude irregularities, *Radio Sci.*, V 26 (4), 1991
Ionospheric irregularities during a substorm event: Observations of ULF pulsations and GPS scintillations

GNSS observations can be used in a variety of ways to probe the ionosphere and plasmasphere. Both ground-based and space-based receivers are useful. Processing the raw GPS signals to either TEC or Scintillation observations is not trivial. Need to use good established techniques, be careful, check for quality, and ensure results are sensible. GNSS satellite and receiver biases are still an issue. Magic Number: Get absolute Vertical TEC < 1 TECU. The biggest issue for GNSS tomography or data assimilation is lack of satellite coverage. Typical receiver only sees 10-12 satellites, all receivers in a region ~ 100-200 km wide see the same satellites, lack of high latitude coverage, new constellations will help, new methods / receivers / arrays that can obtain observations from all constellations. Still a lot of “undiscovered country.” Scientific uses, combining with other IT data sources, dense arrays – what is the best way to analyze the data.