Space Weather Effects on GPS Systems

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Outline

- Space Weather Effects on GPS
  - Solar Radio Bursts
  - Relevant Phenomenology
  - Delay and Total Electron Content

- Scintillation
  - Equatorial Impacts
  - DMSP/SSUSI Scintillation Maps

- IDA4D Data Assimilation

- Polar Cap GPS Scintillation
Why Care About Space Weather?

Each of the next 5 years is expected to have higher solar activity than any year since 2003. So if you are used to space weather being a non-factor in your operations, that is about to change.

March 7, 2012 – The sun unleashed an X5.4-class solar flare, the largest in 6 years. A warning shot at the beginning of the new solar maximum?
Space Weather Effects

X-Rays, EUV, Radio Bursts
- SATCOM Interference
- Radar Interference
- HF Radio Blackout
- Geolocation Errors
- Satellite Orbit Decay

Scintillation
- Degraded SATCOM
- Dual-Frequency GPS Error
  - Positioning
  - Navigation
  - Timing

SEP Events
- High Altitude Radiation Hazards
- Spacecraft Damage
- Satellite Disorientation
- Launch Payload Failure
- False Sensor Readings
- Degraded HF Comm (high latitudes)

Geomagnetic Storms
- Spacecraft Charging and Drag
- Geolocation Errors
- Space Track Errors
- Launch Trajectory Errors
- Radar Interference
- Radio Propagation Anomalies
- Power Grid Failures
Effects of Solar Radio Bursts on GPS

- Sun produces radio waves during solar flare eruptions
- Reduces the signal-to-noise ratio of relatively weak GPS signal
- Solar radio waves cover a broad frequency range and interfere with frequencies L1, L2 (among many other) channels used by GPS

GPS SNR

Carrano et al. 2009
Atmospheric Effects on GPS Ranging

- Refraction lengthens the path of the wave compared to a geometric line of sight.
Error-Producing Time Delays

\[ \rho = R + c(t_u - \delta t + \delta t_D) \]

- \( \rho \) is pseudo-range
- \( R \) is actual range
- \( c \) is the speed of light
- \( t_u \) is the receiver clock offset
- \( \delta t \) is the satellite clock offset
- \( \delta t_D = \delta t_{atm} + \delta t_{noise\text{-}resolution} + \delta t_{mp} + \delta t_{hw} \)

- Concentrate on \( \delta t_{atm} \) which is a group delay due to the ionosphere and troposphere
- Signal information delayed (e.g. PRN code and navigation data)
- Carrier phase advanced
Atmospheric Delays

- \( \delta t_{\text{atm}} = \delta t_{\text{trop}} + \delta t_{\text{iono}} \)

- Physical reason for delays is refraction due to changes in indices of refraction for ionosphere and troposphere

\[
S = c \quad t_{\text{atm}} = \int_{SV}^{\text{User}} n \, ds + \int_{SV}^{\text{User}} dl
\]

\( \Delta S \) is the path length difference due to refraction by the Ionosphere or Troposphere

\( \omega_{pe}^2 \) = plasma frequency

Can be equated with total electron content (TEC)
Ionospheric TEC maps (left), 60 TECU → 10 m (33 ns delay)

- During geomagnetic storms, TEC values can increase by more than 100% (effectively doubling the error)
- Ionospheric storms occur within first hours of a geomagnetic storm
- TEC “walls” (Dehel, 2004); TEC falls by 130 TECu over 50 km; 30 m GPS delay; walls move 100 to 500 m/s
Ionospheric Scintillation Affects GPS and Other RF Signals

- Scintillations ("twinkling") in GPS signals arise from spatial and temporal variations in the ionosphere.
- These ionospheric variations occur under quiet and disturbed conditions.
- They are difficult to forecast accurately.
Lines of sight all pass through regions of depleted ionospheric electron density

Depleted regions known as bubbles (equatorial spread F)
Equatorial Region Space Weather Impacts

Special Sensor Ultraviolet Spectrographic Imager (SSUSI) Daily Summary Image

- Degraded SATCOM
- Dual-Frequency GPS Error
  - Positioning
  - Navigation
  - Timing

Scintillation

- South Atlantic Anomaly
- Bubbles
- Ionization Arcs
- Orbit gaps
SSUSI imagery shows locations of irregularities

• 2D tomographic inversion is performed for each altitude vs. longitude slice, 12 combined to make 3D profile
• 3D grid (12x24x30), 5 deg lat., 0.33 deg lon., 20 km alt. resolution
Mesoscale Ionosphere Model – Assimilate SSUSI, GPS, SCINDA Data

- Model assimilates SSUSI, GPS, and SCINDA data using Kalman Filter
- 20° lat. x 15° lon., available at all longitudes
- Background ionospheric physics and propagation model eliminates data gaps
- Fixed grid, updates every 15 minutes
Ionospheric Data Assimilation Four Dimensional (IDA4D)

- Global 3D time-evolving imaging of the ionosphere electron density
  - Gauss Markov Kalman Filter predicts forward in time
- Solves for log of electron density
  - Guarantees positivity
  - Errors are more log normal distribution
- Completely irregular horizontal grid, vector of vertical grid points
  - User selectable
  - High resolution where desired
  - Can be dynamically chosen based on data
Polar cap GPS scintillation is a typical occurrence often caused by ionization patches immersed in convection flow. It interferes with increasing human activity at high latitudes.

Present simulated GPS scintillation based on ICI-2 Langmuir probe measurements of F-region density fluctuations.

Finding: Scintillation for this case caused primarily but F-region gradient drift waves.

NEW RESULT: Scintillation fluctuations mimic TEC fluctuations which leads to position error and scientific uncertainty.
ICI-2 Langmuir Probe Data

- ICI-2 sampled F-region density with sufficient resolution (<10 m) for phase screen modeling of GPS scintillation
Summary

- Solar max is approaching – ionospheric disturbances will likely increase interference with GPS (signal fading and precision errors)
- Ionosphere affects GPS through time delays associated with TEC gradients and scintillation associated with ionospheric irregularities
- GPS susceptible to scintillation particularly at low latitudes
- Satellite UV (SSUSI) imagery can map irregularities
- APL data assimilation models (IDA4D) can identify scintillation over regions of interest
- New models at APL reveal sources of polar cap GPS scintillation and positioning errors

Purpose: To discuss impacts of space environment on DoD and IC systems, and the applications and requirements for sensors and algorithms to mitigate these impacts and enhance operations

2012 Theme: *Operating through solar max*

- Lessons learned from last solar max

Confirmed Keynote Speakers:

- Brig. Gen. Coffin (*Deputy Commanding General for Operations, USASMDC/ARSTRAT*)
- Dr. Fred Lewis (Director Air Force Weather)
- Ms. Aurea Rivera (Senior Intelligence Engineer, NASIC)

Open to US Citizens with a Secret clearance

SCI sessions

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