Advances in applied ionospheric science for improving single frequency GPS

ION SoCal Briefing
Wednesday, 17 November 2010
W. Kent Tobiska and SWC team

Director, USU Space Weather Center
Space Weather Background
What is Space Weather?

The Sun’s photons, particles and fields that dynamically affect near Earth space and our technology.
Solar flares and coronal mass ejections affect the Earth
At Earth, the photons and geomagnetic disturbances ionize the upper atmosphere and create the ionosphere

http://sol.spacenvironment.net/~ionops/
The space station and space shuttle fly through the upper atmosphere & ionosphere.
Status of Scientific Ionospheric Modeling
Status

- Ionosphere has both a Background State (Climatology) and a Disturbed State (Weather)
- Climatology is Basically Understood
- Weather Involves Storms, Substorms, Plasma Structures, Wave Activity, and Plasma Instabilities
- Main Research Focus is on Weather
Processes requiring modeling

- Storm Enhanced Densities (SED)
- Plasmasphere Refilling
- Neutral Rain
- Sporadic He+ Layer
- Traveling Ionospheric Disturbances
- Wave Coupling with Lower Atmosphere
- Plasma Bubble Effect on Thermosphere
- Scintillation
Research Example:
physics-based Time Dependent Ionosphere Model (TDIM) from USU showing log electron densities for May 5, 2010

The SDO EVE data are used as the solar drivers for this day.
Operations example: Ionosphere Forecast Model (IFM)

- **Physics-based model**
  - Numerical Solution of Ion Gas Continuity, Momentum, and Energy Equations
  - Time-Dependent, High-Resolution, Global Model
  - Ions included: O⁺, H⁺, NO⁺, O₂⁺, N₂⁺
  - Physical processes (field-aligned diffusion, cross-field electrodynamic drifts, thermospheric winds)
  - Neutral composition changes, energy-dependent chemical reactions
  - Ion production (due to solar UV/EUV radiation, starlight, and auroral precipitation)
  - Thermal conduction, diffusion thermal heat flow, and many local heating and cooling processes
  - Displacement between geographic and geomagnetic poles
Physics-based models cannot provide the whole solution, e.g. during storm enhanced densities
Storm Enhanced Densities

- Ionosphere Forecast Model (CONUS)
- GAIM Kalman Filter reconstruction
- 2000 slant TEC values assimilated every 15 min (in 2003)
Global Assimilation of Ionospheric Measurements (GAIM)

- Real-time model/data system readjusts model values to better represent data
  - IFM is the core physics-based model
  - Kalman Filter is used every 15 minutes to assimilate
    - 10,000 slant TEC measurements from ~400 IGS stations for global GAIM runs
    - 10,000 slant TEC measurements from ~400 CORS stations for CONUS GAIM runs
    - Ionosonde, UV airglow radiances, other data can also be assimilated
Global GAIM Gauss Markov
http://spaceweather.usu.edu/

GAIM TEC, NmF2, 3D slice          IGS stations every 15 min.
back to 3 hours
GAIM TEC, NmF2, 3D slice          IFM TEC, NmF2, 3D slice
Global statistical distribution of scintillation

Global Satcom Outage Regions

- Polar Cap Patches
- Auroral Irregularities
- Plasma Depletions
- Equatorial F Layer Anomalies
- Geosat Weather
- Magnetic Equator
- Geosatcom
- Satcom
- Gps

November 17, 2010 Space Weather Center http://spaceweather.usu.edu/
At the equator lower look angles have more scintillation than higher look angles
Scintillation stronger at lower frequencies – historical example

Solar Maximum Conditions at Ascension Island: UHF and L-Band

(After Groves, AFRL, 2000)
PBMOD real-time modeled scintillation

http://sol.spacenvironment.net/~ionops/
Global_Scintillation.html

PBMOD L-band                S4 key          PBMOD UHF band

November 17, 2010         Space Weather Center http://spaceweather.usu.edu/
Creating an Accurate Real-time Ionosphere: the Utah State University Space Weather Center
<table>
<thead>
<tr>
<th>Position</th>
<th>Members/Consultants</th>
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<tr>
<td>5 Faculty Members</td>
<td>• PI — Robert W. Schunk</td>
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<td>• Jan J. Sojka</td>
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<td>• Ludger Scherliess</td>
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<td>• Lie Zhu</td>
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<td>• Larry Gardner</td>
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<tr>
<td>3 Senior Level Scientists</td>
<td>• Director — W. Kent Tobiska</td>
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<td>• Director Strat. Develop. — Herbert C. Carlson</td>
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<td>• Research Scientist — TBD</td>
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<td>1 Executive Admin. Asst.</td>
<td>• Shawna Johnson</td>
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<td>1 Senior Software Engineer</td>
<td>• Eric Hunsaker</td>
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<td>1 Website Designer/Tech Ed.</td>
<td>• Jared Fulgham</td>
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<td>4 Students</td>
<td>• David Hansen, Layne Pedersen, Jennifer Meehan, Landry Heaton</td>
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<td>Total SWC</td>
<td>• 15 of 20 positions filled</td>
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<td>1 GPS Consultant</td>
<td>• Don Rice</td>
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What is the USU Space Weather Center’s role?

**Vision:** Provide operational SpWx for 21st Century challenges

**Mission:** Provide global real-time data to reduce SpWx risks

**Project Milestones:**

- **Product releases:**
  - *SpaceWX* iPhone public education app (v1.2) released (Aug 2009)
  - v1.3 (Nov 2009); v1.4 (May 2010); v1.5 (Jul 2010); v1.6 (Nov 2010)

- **Product demos:** Global HF radio propagation & reduced GPS uncertainty

- **System start-ups:**
  - GAIM Global uses 400 GPS stations & 10,000 measurements every 15 minutes to create accurate real-time ionosphere
  - GAIM Continental U.S. (CONUS) has high spatial resolution

- **Facility completion:** Space Weather Center facility in USU SER building
USU SWC Product Development
iPhone app *SpaceWx*
The iPhone *SpaceWX* app

- The first real-time space weather application for smart phones
- 1514 app purchases as of 01 November 2010 in 41 countries
- $2K revenue generated for product expansion so far
- Highlighted in *Space Weather Journal* October 2010
- 16 institutional partners, 112 data sets in v1.6
HF improvements
September 7 2005: NOAA issued space weather warning

- A powerful X17 solar flare had erupted – 4th largest ever
- Katrina rescue communications were likely to be affected such that U.S. disaster relief workers would lose reliability of their backup communication system

Hurricane Katrina 2005/08/29  Solar flare 2005/09/07  SWC HF comm maps
The ionosphere at low and high latitudes can be disrupted by large scale variations which interfere with communications.
DoD, FEMA, and amateur radio operators can use point-to-point HF links in real-time, and soon, forecast modes

Logan-Tokyo 8.831 MHz link Nov 14, 2010 at 03:14 UT
September 7, 2005 1931 UT:

- A major solar flare occurs
- The event creates a complete radio blackout on the sunlit hemisphere
- A Chicago to Hong Kong flight on a polar route forced to divert to Anchorage at a schedule penalty of 180 minutes and additional fuel
- Per incident-plane costs for route diversions start at $250,000
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ATC LOC FCAST @ 17946 kHz

HF signal strength example: UA 8844

- SMA
- LGT
- NYC
- KEF
- GAN

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Space Weather Center
http://spaceweather.usu.edu

November 17, 2010
6000 planes over U.S. every minute, every morning – better geolocation allows them to fly
Where is my iPhone?

- Severe disruption of GPS can occur from solar flares and geomagnetic storms and the uncertainty grows significantly.
GPS improvements
Primary GPS Position Errors

The position errors are a result of:

<table>
<thead>
<tr>
<th>Source</th>
<th>Effect (m)</th>
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<tbody>
<tr>
<td>Ionospheric effects</td>
<td>±5</td>
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<tr>
<td>Signal arrival, C/A code</td>
<td>±3</td>
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<tr>
<td>Ephemeris errors</td>
<td>±2.5</td>
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<tr>
<td>Satellite clock errors</td>
<td>±2</td>
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<tr>
<td>Multipath distortion</td>
<td>±1</td>
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<tr>
<td>Tropospheric effects</td>
<td>±0.5</td>
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</tbody>
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- Of these, ionospheric and tropospheric effects are most variable.
- Errors from ionospheric disturbances are largest if strong gradients exist so that each satellite path has wildly different delays.
Other sources of error include:

- **Geometry:** poor satellite distribution may increase errors, e.g. in the far north where satellites are only seen to the south.
- **Limited view:** mountains or buildings produce poor satellite distribution geometry.
- **Multipath:** reflections from objects (particularly artificial metallic objects) produce multiple receptions of the same signal.

These conditions are often found in cities (the “urban canyon” effect).

They may be aggravated by space weather but are not a primary concern to us.
Addressing GPS Position Errors

- **Dual frequency GPS** can compensate for ionospheric effects but are expensive (> $5K)
- **Satellite-based augmentation services (SBAS)**, e.g. WAAS in the USA; most current GPS chipsets receive SBAS information
- **Ground-based augmentation services (GBAS)**: regional VHF information, used by higher-end single-frequency receivers
- **Assisted GPS (A-GPS)**: similar to GBAS with additional hints provided via the cell network to smart phones
- **Wi-Fi localization**, used by smart phones; mostly aimed at “urban canyon” areas with high wi-fi access point densities
GPS Position Errors at BLO in 2003

- Diagonal lines: satellite sidereal period versus UT day (3m 56s / day)
- Ionospheric conditions produce horizontal features (single freq. unit)
GPS Position Errors from geometry

Carrier-to-noise ratio (CNR) from River Heights near Logan, Utah
- mountains east of town (45–170° azimuth, to 13° elevation)
- lesser obstructions (180–270° azimuth) are rooftop and trees
- considerable signal strength variation near the mountains and roofline due to multipath can be seen in the data (single frequency unit)
Quiet ionosphere has GPS uncertainty at River Heights

- Position dilution of precision (PDOP) is a dimensionless estimate of uncertainty dependent on satellite geometry; it is not strongly affected by WAAS availability.
- Estimated Position Error (EPE) in meters includes all available information about the position uncertainty (single frequency unit).
- WAAS reduces the daily variation from 6-12 meters to 3-5 meters.
Disturbed ionosphere has greater GPS uncertainty at BLO

- X17 flare on September 7 2005 at 1740 UT.
- Loss of position due to signal outage twice between 1730 and 1800 UT may be due to Type II and Type IV solar radio emissions (bursts) near this time (single frequency unit).
- Large, often periodic variations in vertical position, and smaller variations in horizontal position, starting an hour or two after the storm commencement and lasting for up to several hours can occur.
- Large, sudden change in vertical position and vertical position errors between onset and peak of very large x-ray flares (X-class) can occur.
- Dropout of GPS data due to high levels of solar radio noise lasting from a few seconds to several minutes can occur.
Single frequency GPS data at Colorado Springs during quiet conditions

• 3 days shown in left panel.
• Scatter plot for
  • L1 uncorrected (green)
  • L1+Klobuchar correction (red)
  • L1+L2 dual frequency (blue)
• Horizontal, vertical (N), vertical (E) 1-sigma error scatter in right 3 panels
• Klobuchar correction in single frequency (L1) mode has same variable scatter as uncorrected signal but is readjusted absolutely closer to dual frequency solution
• **OUR GOAL IS TO REDUCE SCATTER AND ACHIEVE CLOSER ABSOLUTE POSITION ACCURACY**
Correction maps

Klobuchar correction       GAIM correction

Klobuchar GPS Correction Map       GAIM Corr 2010/284 248.0E Lon

UTC Hour, 11 Oct 2010       UTC Hour

Correction, m

2 3 4 5 7.5
Improving GPS Position Errors

• **Motivation:**
  • Single frequency devices are ubiquitous in consumer, miniaturized, and legacy devices/systems
  • Ionosphere correction, which is the largest uncertainty, can be corrected in a relatively straightforward manner for single frequency devices using an actual, real-time ionosphere (GAIM) for slant TEC signal delay calculations rather than a climatological ionosphere (Klobuchar)

• **Method:**
  1. Demonstrate that the GAIM ionosphere can correct the signal delay
  2. Demonstrate a method of universal, quick access to GAIM data for real-time corrections to GPS signals
GAIM-IONEX hi-lat

![Graph showing STEC and VTEC comparison for CLGY station.](image-url)
GAIM-IONEX mid-lat
GAIM-IONEX conclusions

• GAIM has very good agreement with IONEX at mid-latitudes ($\Delta$TEC<0.5 TECU) and reasonable agreement at higher latitudes ($\Delta$TEC~1-2 TECU)
  o GAIM slightly modifies GPS TEC data to fit the model
  o GAIM can be tuned to weight bins that are close in time and location to actual TEC measurements; add hi-lat improvements
  o This will result in GAIM being essentially identical to GPS TEC network solutions, will provide global accuracy outside network, and provides a strong candidate method for demonstrating that the GAIM ionosphere can be used to correct the signal delay

• GAIM has forecast advantage not possible with IONEX
  1. Demonstration in Q1 2011 to show reduction in single frequency scatter using real-time GAIM data
  2. Demonstration in Q1 2011 to show universal, rapid retrieval of GAIM data for single frequency corrections