GBAS Ionospheric threat evaluation in the mid-latitude Australian region
Analysis, results and recommendations

Workshop on Ionospheric Data Collection, Analysis and Sharing
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Outline

• Ionospheric Prediction Service (IPS)
• Recap: Challenges for GBAS posed by the ionosphere
• GBAS Iono threat model evaluation for Australia
  – Scope of study
  – Results of analysis
  – Assumptions, limitations, recommendations
• Lessons learned from threat model evaluation
• Ionospheric data sources
• Future directions in ionospheric modelling
Ionospheric Prediction Service (IPS)

- Formed in 1949
- Originally concerned mostly with HF communication
- Now within Australian Bureau of Meteorology
- Today, HF customer base still very important but many other ‘space weather’ customers
- Perform consultancies as well as providing general space weather services and products
- Australian Space Forecast Centre (ASFC) and real time website: http://www.ips.gov.au
- Daily S/W bulletin, web and email/SMS alerts
Ionospheric effects on GPS augmentation

Solar Radio Bursts

(ionospheric delay error due to spatial gradients)

http://www.nap.edu/catalog/12507.html
The solar cycle
Important latitude regimes for GPS effects

**Low latitude/Equatorial region:**
Ionospheric scintillation, plasma bubbles, large TEC gradients, equatorial fountain, sub-equatorial anomalies. Driver of disturbances impacting mid-latitudes, particularly during storm-time.

**Mid-latitude region:**
Mostly smaller gradients, strong diurnal pattern, lower spatial and temporal variability. Affected by strong storms, both from equatorial and high latitude regions.

**High-latitudes/auroral/sub-auroral region:**
Strong gradients around auroral zone. Significant temporal variability on a range of time scales. Big storm response. Driver of disturbances propagating to mid-latitudes, particularly during storm-time.
The Australian Ionosphere

- Predominantly ‘benign’ mid-latitudes
- Under storm conditions, influenced by both equatorial and auroral physics
- Study restricted to latitude range $-40^\circ < \text{lat} < -20^\circ$ reflecting both data availability and ionospheric physics
Anomalous Ionospheric gradients in CONUS
Decorrelation of ionospheric error

GBAS ground station

Ionospheric error ($\delta_1$)

Tropospheric error

Satellite ephemeris errors

Clock errors

Broadcast correction (integrated error)

Ionospheric gradient

Range
Slant ionospheric gradient

\[ \text{SlantIonoGrad} = \frac{\delta_2 - \delta_1}{\text{GrndRange}} \]
Ionospheric Scintillation

- Rapid fluctuations in phase and/or amplitude on GPS signals
- Caused by small scale inhomogeneities in the ionosphere → diffraction screen effect
- Can be severe enough to cause loss of lock on one or more GPS satellites, reducing positioning accuracy
- Clear geographic and diurnal pattern in climatology, closely tied to the occurrence of plasma bubbles

Ionospheric Scintillation – geographic probability

- Occur preferentially after dusk and before midnight (~18-24 Local Time)
- Strongest scintillation occurs in two bands of latitude 5-15 degrees from the geomagnetic equator (sub-equatorial anomalies)
- Also considerable scintillation at high latitudes
- Generally low levels of scintillation at mid latitudes although can at times be significant, especially for high phase sensitivity instruments (e.g., radio telescopes)
Solar radio bursts

Occur during solar active conditions

Can have strong spectral peaks near the GPS L-band frequencies and thus act as a noise source to GPS receivers in the sunlit hemisphere

Result in reduced SNR for GNSS satellite tracking with potential for loss of lock on one or multiple satellites for affected receivers

Resultant GPS Dilution Of Precision (DOP)
GBAS iono threat model

Simplified ionospheric threat model included in the (CONUS certified) Smartpath design for GBAS (Honewell ECM 10023, 2010)
Specifies threat only in terms of ionospheric spatial gradients
2. Methodology

- **Storm identification** - positive phase geomagnetic ‘superstorms’
- **Data sourcing** - dual frequency GPS RINEX data from all available short and long baseline regional CORS networks
- **Network evaluation** - capacity of networks to detect ionospheric gradients based on network geometry
- **Data pre-processing** - standard GNSS algorithms
  - Identification of potential high gradient regions
  - Auto-processing for large gradient events
  - Manual vetting
  - Gradient analysis
  - Context of existing ionospheric threat model

Follows original GBAS iono threat analysis
Storm candidate identification

- Major geomagnetic storms list ($Kp > 8$)
- Restriction to positive phase storms in Aus. longitude sector only (using onset time of storm and independent ionospheric observations)
- Reduced list of 8 storms since 2000
7. Ionospheric Storm Analysis

Figure 7.2. Anomalous ionospheric gradient parameters of ionospheric storms in the Australian region in context of the final (Smartpath) GBAS ionospheric threat model. The upper boundary of the threat model is indicated by the solid black line. All observations fall well within the bounds of the threat model.
Data for ionospheric characterisation

What data is required?
From when?
How much?
Data specifics? (sampling rates, network geometries)
Severe GM storms – looking back

Severe geomagnetic storms
(Kp > 8-)

GPS data coverage

regional positive phase storms

Australian Government
IPS Radio and Space Services
The Australian Space Weather Agency
Data for ionospheric characterisation

GNSS data sourcing:

– Requirement for historical data covering the largest ionospheric storms of the previous solar cycle

– Sufficient short baseline GNSS network geometry to enable detection of the full spectrum of ionospheric gradients

– High resolution (1-2s) data
Data for ionospheric characterisation

GNSS data sourcing:
- Standard RINEX data format
- Ionospheric scintillation (ISM or derived from >1Hz GNSS and use of ROTI, DROTI, or comparable parameter)
GNSS Data Sources

- Australia dual frequency GPS (CORS) networks
  - Geoscience Australia (ARGN, SPRGN)
  - Victorian Department of Sustainability and Environment (GPSnet)
  - Queensland Department of Environment and Resource Management (SunPOZ)
  - Landgate, Western Australia
  - National Measurement Institute, Sydney
  - IPS Radio & Space Services, Bureau of Meteorology
  - International GNSS Service (IGS)
  - Land Information New Zealand (PositioNZ)
  - [NSW CORSnet]
Network Geometry

• GPS data limitations in Australia

→ greater emphasis on evaluating capacity of individual networks and network combinations to detect ionospheric gradients in present study

→ Analyse distribution of inter-station spacings and network geometry to confirm gradient detection capacity
GPS network map (old)
GPS network map (SE detail)
Example of ionospheric coverage
Under-sampled network

GNSS satellite

Ionosphere

Ionospheric gradient

Ionospheric ERROR ($\delta_1$)

Ionospheric gradient

Ionospheric ERROR ($\delta_2$)

IPP1, IPP2

Minimum inter-station spacing
Closely-spaced network

Ionosphere

GNSS satellite

Note: As separation $\rightarrow 0$, gradient observations dominated by Rx bias and measurement noise
Threshold inter-station spacing for gradient detection

Threshold station separation for iono gradient detection

Max Iono Delay

30m (185 TECU)
25m (154 TECU)
20m (123 TECU)
15m (92.6 TECU)
10m (61.7 TECU)
5m (30.9 TECU)
ARGN – national long baseline CORS

Very poor capacity to detect large ionospheric gradients, even for the largest events.
SunPOZ - State CORS Queensland

GPS Network Geometry :: gradient detection [SunPOZ]

Maximum slant tropo delay = 5.0m
- All links available
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- Best 4 links removed
- Best 5 links removed
- Best 6 links removed

Gradient [mm/km]

Azimuth [degree]

Qld
NSW
SunPOZ

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Some assumptions

1) Longitudinal invariance in storm response
2) Anomalous gradient occurrence exclusively during superstorms
3) Study period 2000-2008 representative
4) Restricted region of applicability
A1. Longitudinal ‘invariance’ of ionospheric response

- Ionosphere described more strongly by latitude than longitude.
- Although there are longitude sectors with unique characteristics (e.g., CONUS) these are very broad local time sectors.
- IPS experience does not suggest any major difference in ionospheric characteristics between the East and West coasts of Australia.
A2. Validation of storm selection

The largest anomalous ionospheric gradients in the Australian mid-latitude region occur during geomagnetic “superstorms” (as identified by threshold level of Kp), more specifically those storms that have a positive phase in the Australian longitude sector.

- Additional work at IPS on validating this assumption
- Ionospheric gradient index derived for this validation, and used to automatically process/analyse four years of short-baseline GPS data to confirm association of anomalous gradients with superstorms
Anomalous gradient event detection using gradient index

Ionospheric slant gradient detection
SunPOZ 2004

Day of year (2004)

Averaged slant gradient [mm/km]
Max Ionospheric gradient index during storms (2002-2005)
A3. Representative study period

This study covering the period 2001 – 2008 is representative of the full range of ionospheric gradients that may occur in the Australian region.

- Qualified. Representative of regional anomalous ionospheric gradients over last solar cycle
- Likely representative of anomalous ionospheric gradients in the Australian region
- Recommend ongoing monitoring of anomalous ionospheric conditions for further confidence (eg CONUS experience)
A4. Region of applicability

• Results limited to Australian longitude sector, mid-latitudes (-40° < glat < -20°)
• Southern boundary: Dictated by archive data coverage (poor short-baseline coverage in Tas)
• Northern boundary: Dictated by archive data coverage, as well as the unique ionospheric physics of the equatorial zone.
• Studies of the impact of the equatorial ionosphere on GBAS-like systems is ongoing in other states
• Recommend advance iono monitoring for northern Australia for future certification of GBAS
Extra slides

- Extra slides follow
Real-time regional TEC model

- IPS has developed a Kalman Filter driven real-time TEC modelling capability

- The model uses Spherical Cap Harmonic Analysis (SCHA) for spatial mapping of TEC

- The filter states are the SCH basis co-efficients, the GPS Rx biases and a plasmaspheric TEC scaling factor.

- Utilises data from > 60 GPS sites across the region, along with ~8-10 ionosondes, with capacity to expand further
Kalman Filter

- Optimal solution for the discrete linear state estimation problem
- Widely used in many areas including GNSS trajectory tracking
- Relatively small computational processing overheads

Linear System
\[ z = Hx \]

State Vector \( x \)
Covariance \( P \)
Measurements \( z \)
Error covariance \( R \)

Innovation \( \nu = z - Hx \)
Kalman Gain \( K = PH^T(HPH^T+R)^{-1} \)
State Update \( x^+ = x + K\nu \)
3D Model Development

• A full 3D ionosphere + plasmasphere real time model is currently under development.

• Model driven by a range of input data, including:
  – ground based GPS
  – Ionosonde vertical soundings
  – Ionosonde oblique soundings
  – LEO satellite GPS
  – LEO satellite radio occultation (RO) observations

• The current approach uses the NeQuick2 ionospheric profiler as a base vertical model, with free model parameters constrained by the real time input data and mapped in 2D using SCHA.
So what about the next solar activity cycle?
A low solar cycle

- Cycle 24 is forecast to be a relatively low solar cycle (peak SSN ~ 60-90)
- In which case there are likely to be less geomagnetic storms, however the intensity of major storms is not well correlated with the peak of the solar cycle, ie major storms are still likely
- Some examples:

The largest SRB (~1 million SFU) occurred near solar minimum

The Carrington event occurred during a rather unremarkable solar cycle
Space Weather

Solar Active Region

Coronal Mass Ejection (CME)

1-3 days propagation through solar wind

Reaches ACE satellite ~ 1 hour upstream (1-hour warning)

Shock hits geomagnetic field (observed on ground)

Geomagnetic storm develops (observed real time)

Ionospheric storm develops (observed real time)
IPS Extreme SpWx Event Alert Service

- Under development at IPS
- Very high alert threshold (minimise false positives)
- Driven by growing demand for advance warning of extreme space weather events from various critical industries (e.g., power networks, pipelines, SES)
- Implemented as a chain of alerts Sun-Earth during S/W event development, each building on the previous, with increasing probability estimates
- To provide sufficient lead time for industries to build awareness, prepare, and ultimately take action to minimise impact of extreme space weather events
- Output can be tailored to GBAS/aviation requirements such as ionospheric storm-front and gradient monitoring