Global Navigation Satellite Systems and Ionospheric Remote Sensing

Jade Morton
Miami University
Our Increasing Dependence on GNSS Services, ....
Global Navigation Satellite Systems & Ionosphere

Ionosphere:
- Dynamic
- Difficult to model
- Introduces error, disruptive

GNSS:
- Passive
- Well defined signals
- Global coverage, distributed

By 2023:
- >160 GNSS satellites
- >400 signals

1. Ionosphere impact GNSS performances
2. GNSS offers an excellent means to study ionosphere
Presentation Outline

1. Ionosphere background
2. First order ionosphere error and TEC
3. Higher order ionosphere error
4. Ionosphere scintillation
Ionosphere Background

\[ \rho = v \Delta t \]

\[ v = \frac{c}{n} \]

\( n \): Reflective index

\( c \): Speed of light

Communication
Surveillance
Navigation

UV radiations

Ionosphere
Ionosphere Refractive Index

Appleton-Hartree Equation:

\[ n_\phi = 1 - \frac{X}{1 - \frac{Y^2 \sin^2 \theta_B}{2(1 - X)} \pm \sqrt{\frac{Y^4 \sin^4 \theta_B}{4(1 - X)^2} + Y^2 \cos^2 \theta_B}} \]

\[ X = \left( \frac{f_p}{f} \right)^2 \quad Y = \frac{f_g}{f} \]

Electron gyro frequency:

\[ f_g = \frac{|eB|}{m_e} \]

Plasma frequency:

\[ f_p = \frac{\sqrt{Ne^2}}{m_e \varepsilon_0} \]
Electron Gyro Frequency

\[ f_g: \text{Rate of electrons cycling along the } B \text{ field line} \]

\[ f_g = \frac{|e|B}{2\pi m_e} \approx 28 \times 10^9 B \approx 1 \text{MHz} \]

\[ 30,000 \text{nT} \sim 3 \times 10^{-5} \text{T} \]
Plasma Frequency

$f_p$: Rate of electron oscillations in a plasma

$$f_p = \frac{1}{2\pi} \sqrt{\frac{N_e e^2}{m_e \varepsilon_0}} \approx 9 \sqrt{N_e} \approx 9MHz$$

Peak ionosphere $N_e$ value: 1 million/cc
Simplified Appleton-Hartree Equation

\[ f_g \approx 1\text{MHz} \rightarrow Y = \frac{f_g}{f} \quad f_p \leq 10\text{MHz} \rightarrow X = \left(\frac{f_p}{f}\right)^2 \]

At GPS frequency, \( f \sim \text{GHz} \): \( X << 1 \) \quad \( Y << 1 \)

\[ n_\phi = 1 - \frac{X}{1 - \frac{Y^2 \sin^2 \theta_B}{2(1 - X)} + \sqrt{\frac{Y^4 \sin^4 \theta_B}{4(1 - X)^2} + Y^2 \cos^2 \theta_B}} \]

\[ n_\phi \approx 1 - \frac{X}{2} \pm XY |\cos \theta_B| - \frac{1}{4} X \left(\frac{X}{2} + Y^2 \left(1 + \cos^2 \theta_B\right)\right) \]

Vacuum \quad 1^{\text{st}} \text{ order} \quad 2^{\text{nd}} \text{ order} \quad 3^{\text{rd}} \text{ order}
Ionosphere Error in GNSS Measurements

\[ n_\phi \approx 1 - \frac{40.3N_e}{f^2} \pm \frac{f_g f_p^2}{2f^3} \left| \cos \theta_B \right| - \cdots \]

\[ n_\rho = n_\phi + f \frac{dn_\phi}{df} \]

\[ I_\phi = \int (n_\phi - 1) dl \]

\[ I_\rho = \int (n_\rho - 1) dl \]

\[ I_\rho = \frac{q}{f^2} + \frac{s}{f^3} + \frac{r}{f^4} + \cdots \quad I_\phi = - \frac{q}{f^2} - \frac{s}{2f^3} - \frac{r}{3f^4} + \cdots \]

First order ionosphere error: \( q = 40.3 \times \int N_e dl = 40.3 \text{ TEC} \)

Second order ionosphere error: \( s = 7527c \int N_e B_0 \cos \theta_B dl \)

3rd order: \( r = 2437 \int N_e^2 dl + 4738 \times 10^{22} \int N_e B_0^2 \left( 2 + \cos^2 \theta_B \right) dl \)
First Order Ionosphere Error
First Order Ionosphere Error Mitigation

\[ \rho^S_f = r^S_f + \delta r^S_f + T^S_f + c(\delta t^S_{RX} - \delta t^S_f) + I^S_f + c(b^S_{RX,f} + b^S_f) + M^S_f + \epsilon^S_f \]

- Orbit error
- Tropo
- Clock error
- Iono
- Hardware bias
- Multipath

Non-dispersive error
Dispersive error

Differencing measurements from two frequencies:

\[ \Delta \rho^S_f = \Delta I^S_f + c(\Delta b^S_{RX} + \Delta b^S_f) + \Delta \epsilon \]

Differential Code Biases (DCBs)

Global Ionosphere Map (GIM):
- Network of dual frequency receivers distributed around the globe
- Some receiver DCBs are calibrated
- Antenna installations minimize multipath impact
- Multiple measurement epochs are used to solve for TEC and SV DCBs

NGS TEC map:
- National CORS measurements
A TEC Spatial Gradient-Based Algorithm

\[
VTEC_{IPP} = VTEC_0 + \frac{\partial VTEC}{\partial \lambda} \Delta \lambda_{IPP} + \frac{\partial VTEC}{\partial \varphi} \Delta \varphi_{IPP} + O(\Delta \lambda_{IPP}, \Delta \varphi_{IPP})
\]

Zenith(\(\varphi_0, \lambda_0\)) IPP(\(\varphi_{IPP}, \lambda_{IPP}\)) Satellite Signal

Higher order TEC spatial derivatives

\[
\Delta \varphi_{IPP} = \varphi_{IPP} - \varphi_0 \\
\Delta \lambda_{IPP} = \lambda_{IPP} - \lambda_0
\]

\[
STEC_{IPP} = VTEC_{IPP} \times MF
\]

MF: mapping function

\[
I_f^{SV} = 40.3 \frac{STEC_{IPP}}{f^2}
\]
How Sound Is the TEC Spatial Gradient Assumption?

Algorithm Description

\[ \Delta \rho_{SV} = \beta \times MF \times \left( VTEC_0 + \frac{\partial VTEC}{\partial \lambda} \Delta \lambda_{IPP} + \frac{\partial VTEC}{\partial \phi} \Delta \phi_{IPP} \right) + c\left( \Delta b_{RX} + \Delta b_{SV} \right) \]

At time epoch \( k \), there are \( N_k \) satellites in view \( \rightarrow N_k \) equations, \( 4+N_k \) unknowns.

Maximum total number of unknowns from \( K \) epochs: \( 3K+33 \)

Total number of equations: \( \sum_{k=1}^{K} N_k \)

\[
\begin{bmatrix}
g_{SV(1)}^{g_k} & g_{SV(1)}^{g_k} \Delta \lambda_{IPPk} & g_{SV(1)}^{g_k} \Delta \phi_{IPPk} & 1 & \delta_{1,1} & \cdots & \delta_{1,m} & \cdots & \delta_{1,32} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
g_{SV(n)}^{g_k} & g_{SV(n)}^{g_k} \Delta \lambda_{IPPk} & g_{SV(n)}^{g_k} \Delta \phi_{IPPk} & 1 & \delta_{n,1} & \cdots & \delta_{n,m} & \cdots & \delta_{n,32} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
g_{SV(N_k)}^{g_k} & g_{SV(N_k)}^{g_k} \Delta \lambda_{IPPk} & g_{SV(N_k)}^{g_k} \Delta \phi_{IPPk} & 1 & \delta_{N_k,1} & \cdots & \delta_{N_k,m} & \cdots & \delta_{N_k,32} \\
\end{bmatrix}
\begin{bmatrix}
x_k \\
y_k \\
z_k \\
\Delta b_{RX} \\
\Delta b_{PRN1} \\
\vdots \\
\Delta b_{PRN32} \\
\end{bmatrix}
= \frac{1}{c}
\begin{bmatrix}
\Delta \rho_k^{SV(1)} \\
\vdots \\
\Delta \rho_k^{SV(n)} \\
\vdots \\
\Delta \rho_k^{SV(N_k)} \\
\end{bmatrix}

\beta = 40.3 \frac{f_{L2}^2 - f_{L1}^2}{f_{L1}^2 f_{L2}^2} \quad g = \frac{\beta}{c} \times MF \quad x = VTEC_0 \quad y = \frac{\partial VTEC}{\partial \lambda} \quad z = \frac{\partial VTEC}{\partial \phi} \quad \delta_{n,m} = \begin{cases} 
1 & \text{if } m = SV_n \\
0 & \text{otherwise}
\end{cases} \]
SV and RX DCB Estimation

DCB(32 GPS Satellites) compared with GIM

- Receiver's DCB
  - With First Order TEC Gradients: 6.591ns
  - With Second Order TEC Gradients: 6.809ns
  - DCB from GIM: 6.787ns
Sparse Network TEC and DCB Estimation

\[
\frac{\Delta \rho_k^{SV(n)}}{c \times g_k^{SV(n)}} = x_k + y_k \Delta \lambda_{IPPk(i)}^{SV(n)} + z_k \Delta \phi_{IPPk(i)}^{SV(n)} + \frac{\Delta b_{RX(m)} + \Delta b_k^{SV(n)}}{g_k^{SV(n)}}
\]

\(n = 1, 2, \ldots, N\): SV index for all SVs in view by the network
\(m = 1, 2, \ldots, M\): RX index in network
\(i = 1, 2, \ldots, I\): IPP index for all RX-SV pairs
Total number of difference equations between 2 IPPs: \(I(I-1)/2\)
TEC Spatial Gradients From A Sparse Network

- Sunrise
- Sun in the central area
- Noon time
- Sunset

UT (hour)

TEC Gradient (TECU/degree)

Latitudinal Gradient
Longitudinal Gradient
Gradient Magnitude
On-Going Efforts in First Order Error Estimation

1. Use of multi-constellation GNSS measurements
2. Joint GNSS receiver and incoherent scatter radar experiments
3. Performance evaluations at diverse geographical locations
4. Introduce IPP height as a new variable
5. Introduce vertical Ne profile dependency
6. Introduce RX DCB as a time-varying quantity
7. Impact on PPP performance evaluation
Higher Order Ionosphere Error
Rough Estimation of Iono Error

**TEC**: 60 units (1 unit = $10^{16}$ el/m$^2$)

$q = 40.3TEC \
1^{\text{st}} \text{order}: \quad \frac{q}{f^2} = 10m$

**$B_0$**: ~ 30000nT   **TEC**: 60 units

$s = 7527c \int N_e B_0 \cos \theta_B dl \leq 7527cB_0 \int N_e dl = 7527cB_0TEC \
2^{\text{nd}} \text{order}: \quad \frac{s}{f^3} \approx 1cm$

**$B_0$**: ~ 30000nT   **TEC**: 60 units   **Uniform Ne in $\Delta L$**: 100km

$r_1 = 2437\int N_e^2 dl \approx 2437N_e^2\Delta L \approx 2437\frac{TEC^2}{\Delta L} \
3^{\text{rd}} \text{order}: \quad \frac{r_1}{f^4} \approx 1mm$

$r_2 = 4738 \times 10^{22} \int N_e B_0^2 (2 + \cos^2 \theta_B) dl \leq 10^{26} B_0^2 TEC \
\frac{r_2}{f^4} \approx 0.01mm$
How To Accurately Estimate Higher Order Error?

B field:
International Geomagnetic Reference Field (IGRF) model, 11th Generation

$$s = 7527c \int NeB_0 \cos \theta_B dl$$

Question:
How good is the model in ionosphere?
IGRF Model Validation

Low Earth Orbit Satellite-Based Magnetometers (100 - 1000 km)
Over 600 GB satellite measurements analyzed

**MAGSAT** (NASA)
300-600 km altitude
November 2, 1979 – May 6, 1980.

**Orsted** (Danish Meteorological Institute)
630 – 860 km altitude
March 1999 – Present

**SAC-C** (Argentine Commission on Space Activities)
702 km altitude
January 23, 2001 – December 4, 2004

**CHAMP** (Germany)
350-450 km altitude
May 15, 2001 – Present

**DEMETER** (France)
660 – 715 km altitude
August 11, 2004 - Present
11th Generation IGRF Validation Results

Relative misfit from IGRF 11 - All

Relative RMS misfit (%)

# data points

0.2 0.4 0.6 0.8 1 1.2

0.9 1 1.1 1.2 1.3 x 10^5
Ne Profiles

Arecibo 1.5MW VHF/UHF Incoherent Scatter Radar Ne profiling up to 2200km
Multiple ISR Measurements

Over 1 decade of data
Daily
Seasonal
Solar activities
Geographical
Ionosphere Radio Occultation

JAN 1, 2010, 10:46 (UTC)

PRN 32
COSMIC FM1

Ne (1/cm³) vs. Altitude (km)
Higher Order Error Spatial Behavior

**Jicamarca**
- 3 December 2002
- 10:11 AM (local), Kp 2

**Arecibo**
- 11 April 1989
- 5:04 PM (local), Kp 2

**Millstone**
- 17 October 2002
- 12:30 PM (local), Kp 2
Geomagnetic Activity Impact

![Graph showing geomagnetic activity impact on Millstone and Arecibo.

- Millstone - South 10°
- Arecibo - South 10°

Second order error (cm)

Local time

0:00 8:00 16:00 0:00 8:00 16:00

NGS Washington DC 05/22/13
Ionospheric Scintillation
Iono. Scintillation Conceptual Description

SV velocity \( v_s \)

Wave front:
- uniform phase
- uniform amplitude

Incident wave

Ionosphere

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

Irregularities

Diffraction/interference pattern

Plasma drift \( v_p \)

Amplitude fading
Random phase fluctuation

Ground
High latitude:
Mainly driven by **solar and magnetosphere** activities

Low latitude:
Ionosphere internal mechanisms
+ modulation by solar activities

Strong Equatorial Scintillation: Simultaneous Deep Fading and Large Phase Fluctuation

03/18/2001 8:45-9:30PM

C/N0 (dB-Hz)

Time (s)  C/N0 (dB-Hz)

Carr Phase (cycles)

Time (s)  Carr Phase (cycles)
Conflicting Demands on Scintillating GNSS Signal Tracking

Input

Carrier wipeoff

Code wipeoff

Correlators

Error functions

Filters

Plants

Carrier discriminator

Carrier loop filter

Carrier generator

Carrier tracking

Code discriminator

Code loop filter

Code generator

Code tracking

Integration time $T_I$

Discriminator type $\Delta(\theta)$

Filter BW $B$

Short

High dynamics

Wide

Long

High sensitivity

Narrow

$\leftarrow$ Tracking parameters

High carrier dynamics

Deep signal fading
Research Objectives

- **Data Collection:** Establish high quality scintillation event monitoring and data collection stations at both high and low latitude scintillation zone.

- **Ionosphere Characterization:** Develop accurate signal parameter estimation techniques to characterize scintillation behavior for ionosphere research and GNSS receiver development.

- **Receiver Algorithms:** Develop robust GNSS tracking algorithms to ensure continuity and accuracy of navigation solutions during space weather events.
Existing GNSS Space Weather Monitoring Systems Issues

1. Commercial GNSS receivers are designed for PNT solutions. They are not optimized for remote sensing applications.

2. Space weather events are *Nuisances* for PNT. Receiver signal processing will hide them → Measurements are not true representation of physical processes in space.

3. Receiver design and signal processing are proprietary. Users have no knowledge of specific processing used.

4. Receivers break down during strong space weather events. Critical data cannot be collected when needed most.

High quality, raw GNSS RF data are needed for Ionosphere studies and robust GNSS receiver development
HAARP (Gakona, Alaska)

Lat: 62.39°, Lon: 145.15°W

Operation Center
HF Heating Array
Ant 1
Ant 2
Ant 3
Science Pad 3
Ant 4
1km
3km
½ km
North
Scintillation Event Trigger Example

11/01/2010  GPS PRN29

UTC
C/N₀ (dB-Hz)

-8
-6
-4
-2
0

RX 1
RX 2
RX 3

UTC
S₄

0
0.05
0.1
0.15
0.2

S₄ threshold
Multi-Constellation GNSS → Spatial Observability

05/19/2013
HAARP, Alaska
(62.39°N, 145.15°W)
24-hour satellite path
A New Global GNSS Space Weather Data Collection Network

- Established/Approved Sites
- Potential Future Sites

**Background map and geomagnetic boundaries of interests courtesy of James Secan, Northwest Research Associates, Inc.**
Strategic Site Selection for Collaborative Research

- EAR, Indonesia
- HAARP, Alaska
- AMISR, Ethiopia
- Arecibo, Puerto Rico
- Jicamarca, Peru
High Latitude Scintillation Spatial Distribution

August 2010 – July 2012
HAARP
$S_4 > 0.15$
$\sigma_\phi > 10^\circ$
High Latitude Scintillation Temporal Distribution

The diagram shows the percentage distribution of scintillation events over different UTC hours. The x-axis represents UTC hours ranging from 0 to 24, while the y-axis represents the percentage. The histogram peaks around UTC hours 14, indicating the highest occurrence of scintillation during this period.
Event Duration Distribution

Mean = 8.8 minutes
Std = 12.3 minutes

Amplitude Scintillation
Mean = 3.6 min
Std = 4.8 min

Phase Scintillation
Mean = 9.6 min
Std = 12.9 min
Phase

Amp. & phase

Amplitude
Scintillation Impact on PPP

Hong Kong

08/31/2012

Scintillation intensity

positioning error / cm

satellite number

LT / hour

UTC / hour

E

N

U

Satellite Number

S

4

φ / rad

0.1

0.2

0.3

0.4

0

10

20

30

-30

-20

-10

0

10

20

30
Robust Receiver Tracking: Vector Loop vs. Scalar Loop

Conventional Scalar Tracking

EKF Integrity Check

New Robust Vector Tracking

Incoming signal

Channel 1

\( F(S) \)

\( G(S) \)

Range & Range rate Measurement

PVT Solutions

Doppler Code phase Estimation

PVT Solutions

\((\hat{f}_D, \hat{\tau})\)

\((\rho_1, \dot{\rho}_1)\)

\((\rho_j, \dot{\rho}_j)\)
Ascension Island Strong Scintillation Vector Tracking

Computation performance is a major challenge!!!
Ionospheric Scintillation On-Going Efforts

- Deployment enhancement
- Data analysis on GLONASS, Galileo, and Compass signals
- Multi-frequency scintillation analysis
- Accurate signal parameter estimation algorithms
- Real time receiver processing
- Scintillation tomography
- Global scintillation climatology
- Joint experimental campaign with other remote sensing instruments