International Monitoring of Ionosphere

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Presentation Outline

1. Background: ionosphere vs. GNSS
2. Challenges in Synergizing Space Weather – GNSS Studies
4. Results Highlight
Remote Sensing of Ionosphere

- HAARP, Alaska
- Millstone, MA
- Arecibo, Puerto Rico
- Jicamarca, Peru
- EISCAT, Svalbard
- Poker Flat, Alaska
- AMISR, Ethiopia
- 武汉, 中国
Growth in Spaced Based Systems

- Navigation
  - GPS
  - GLONASS
  - Beidou
  - Galileo

- Communication
  - C/NOFS
  - Ionosphere & Space Science
  - DNA
  - DORIS
  - CHAMP
  - CITRIS
  - GOES
  - SAC-S
  - SIRIS

- Broadcasting
  - ATS1
  - ATS3
  - ATS6
  - ETSII
  - CRABEX
  - CERTO
  - COSMIC
  - TOPEX

- Weather
  - DNA
  - DORIS
  - CHAMP
  - CITRIS
  - GOES
  - SAC-S
  - SIRIS

- Earth Monitoring
  - C/NOFS
  - Ionosphere & Space Science
  - DNA
  - DORIS
  - CHAMP
  - CITRIS
  - GOES
  - SAC-S
  - SIRIS

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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 impacts GNSS performances
2. GNSS offers an excellent means to study ionosphere
High latitude:
Mainly driven by solar and magnetosphere activities

Low latitude:
Ionosphere internal mechanisms + modulation by solar activities

New Generation of GNSS Space Weather Monitoring Systems
Existing GNSS Space Weather Monitoring Systems

Map and geomagnetic boundaries of interests courtesy of James Secan, Northwest Research Associates, Inc.
Issues

1. Accuracy
   \[(\text{Iono Effects} + \text{Other Errs}) \times h(t) = \text{Observed Effects}\]
   \[\text{Iono Effects} \neq \text{Observed Effects}\]

2. Availability
   Receivers cease to function during strong space weather events. Critical data are lost when needed most.

3. Repeatability
   Receiver processing is irreversible \(\rightarrow\) Iono effects are wiped out during processing

High quality, raw GNSS signals are needed for space weather studies and robust GNSS receiver development
Ascension Island: 3/10/2013, Beidou GEO PRN 5

The graph shows the comparison of SDR S4, Pola S4, SDR $\sigma_\phi$, and Pola $\sigma_\phi$ for PRN 5 and PRN 30 over UTC time from 20 to 25.

- **PRN 5**
  - SDR S4: Blue line
  - Pola S4: Cyan line
  - SDR $\sigma_\phi$: Red line
  - Pola $\sigma_\phi$: Pink line

- **PRN 30**
  - SDR S4: Blue line
  - Pola S4: Cyan line
  - SDR $\sigma_\phi$: Red line
  - Pola $\sigma_\phi$: Pink line
Event Driven Multi-Constellation IF Data Collection System

Space Weather Events

Commercial ISM Receiver
RF Front End 1
RF Front End 2
RF Front End N

Data Collection and Control Server
Space Weather Event Monitoring & Trigger Software
Circular Buffer
Circular Buffer
Circular Buffer

Data Storage

VPN
Data Center at Home Institution

Internet
A Global Scintillation Data Collection Network

Existing Sites
- Fairbanks, Alaska
- Arecibo, Puerto Rico
- Jicamarca, Peru
- Ascension Island
- Hong Kong
- Singapore
- Casey Island
- Kwajalein, Marshall Islands

Magnetic Equator
- 50% Magnetic Latitude
- ±15° Magnetic Latitude
- 90% Auroral Oval

Background map and geomagnetic boundaries of interests courtesy of James Secan, Northwest Research Associates, Inc.
HAARP (Gakona, Alaska)

Lat: 62.39°, Lon: 145.15°W
Peru: Summer 2013 Deployment

Automatic Scintillation Event Monitoring & Trigger Software

Scintillation Events

Commercial Scintillation Receiver

RF Splitter

Wideband GNSS Antenna

GPS L1/Galileo E1

GLONASS L1

GLONASS L2

Beidou B1

Galileo E5a/5b

GPS L2C

GPS L5

Data collection servers

Storage

Internet connection to Miami University

Timing Signal Splitter

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GNSS Characterization of Ionosphere Events
Peru, 3/11/2013, 13:30 UTC
High Latitude Scintillation Spatial Distribution

Overall scintillation sky map (gridsize = 120*120)

August 2010 – July 2012
HAARP

$S_4 > 0.15$
$\sigma_\phi > 10^\circ$

Magnetic Zenith
Equatorial Scintillation Spatial Distribution

Ascension Island: GPS, Galileo, Beidou
(in process of adding GLONASS results)

March 7, 2013
March 10, 2013
High Latitude Scintillation Seasonal Distribution

Mean sunspot number
Mean event number
Phase scin.
Amplitude & phase scin.
Amplitude scin.
FA WI SP SU FA WI SP SU FA WI SP
2010 2011 2012 2013
Diurnal Pattern

Peru

Alaska

Hours After Sunset

Probability
Adaptive Joint Time-Frequency Analysis
Scintillation Induced Frequency Variation Distributions

High Latitude

Alaska

November 1, 2011
09:11-09:45 UT
PRN 07

Low Latitude

Hong Kong

August 26, 2012
13:36-14:10 UT
PRN 26
High Resolution Drift Velocity Mapping

10/13/2012, HAARP, AK

11:54:17-12:54:17 UTC

09/03/2013, HAARP, AK

Sky View of GNSS Satellite Tracks          Mask Angle 0°
24 hours from UTC 2013-09-03 00:00:00 Gakona, AK

10/13/2012, HAARP, AK

PRN 7
PRN 8
PRN 26
500 (m/s)
Radio Occultation: Singapore Collaboration

GPS
Ionosphere
COSMIC

JAN 1, 2010, 10:46 (UTC)  PRN 32  COSMIC FM1

Ne (1/cm³) x 10⁶

Altitude (km)

0 0.5 1 1.5 2 2.5 3

0 200 400 600 800 1000 1200 1400 1600 1800 2000

GPS
COSMIC Ionosphere

JAN 1, 2010, 10:46 (UTC)  PRN 32  COSMIC FM1

Ne (1/cm³) x 10⁶

Altitude (km)
High Sensitivity GNSS

Diagram of the processing chain:

- **Input**
- **Nav Data Wipe Off**
- **90° Phase Shift**
- **Carrier Generator**
- **Carrier Loop Filter**
- **Carrier Discriminator**
- **Accumulator**
- **Detrend Carrier Phase, Compute $\sigma_\Phi$, Doppler, Detect Cycle Slips**
- **Code Generator**
- **Code Loop Filter**
- **Code Discriminator**
- **L X I & D**
- **E X I & D**
- **P X I & D**
- **Signal Power, $C/N_0, S_4$ index**
- **Compute Bit Error Rate**

Processing steps:
- Input data is processed through various stages to refine and analyze the carrier phase and detect cycle slips.

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Robust Receiver Tracking: Vector Loop vs. Scalar Loop

Conventional Scalar Tracking

Incoming signal

Channel 1

F(S) → G(S)

Range & Range rate Measurement

PVT Solutions

Noise + Interference + Ionosphere impacts + others

Incoming signal

New Robust Vector Tracking

Channel 1

F(S) → G(S)

Doppler Code phase Estimation

PVT Solutions

EKF

Integrity Check

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Ascension Island Data Vector Tracking

VTL
(TI = 1 ms; PLL: 2\textsuperscript{nd} order BW = 15 Hz)

STL
(TI = 10 ms; PLL: 3\textsuperscript{rd} order BW = 3 Hz)

Computation performance is a major challenge!!!
Conclusions

- Space weather will have increasing impact on GNSS applications
  - Efficient and robust GNSS technologies are needed to mitigate space weather effects for assured navigation
- GNSS will be a major enabler for space weather studies
  - Accurate receiver processing algorithms are critical to preserve true space weather signature on GNSS signal parameters
- Many challenges and opportunities
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  – Jicamarca Radio Observatory, Peru
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