Recent Developments in Understanding Natural-Hazards-Generated TEC Perturbations: Measurements and Modeling Results

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Introduction

• Natural hazards generate waves in the thermosphere and ionosphere that may be detected using ground and space-based GPS observations.
• There is an abundance of current and future GNSS signals that we can use in a real-time and post-processing modes.
• Our objective has been to use GNSS ground-based and space-based GPS measurements to develop new technologies for e.g., augmenting natural hazards early warning systems.
• Our goal is improved understanding of wave propagation properties, acoustic and gravity wave velocities, directions, etc.
  • Physics-based modeling and observational evidence.
  • Differentiate between disturbances generated in situ versus those arising from natural hazards.
• Recent examples of ionospheric disturbances generated by:
  • Earthquakes and tsunamis using ground-based and space-based GPS data,
  • High-latitude plasma irregularities using high-rate RO measurements
Tohoku-Oki Tsunami, March 11, 2011

- Magnitude 9.0
- 70 km off shore
- 30 km depth
- Tsunami wave heights up to 15 meters

Nepal (Gorkha) Mw 7.8 Earthquake on Apr 25, 2015
Tsunami-Driven Traveling Ionospheric Disturbances (TIDs)
Earthquakes and tsunamis generate atmospheric gravity waves that propagate vertically, reaching the ionosphere.

Disturbance to ionosphere is detectable using GPS-derived total electron content (TEC).
IPPs from Simulated Constellations by 2025

Six different satellite constellations by 2015:

- GPS
- GLONASS
- Galileo
- BeiDou
- QZSS
- IRNSS
What would be the impact if the 1964 Mw 9.2 earthquake were to hit the US today?
Nepal Mw 7.8 Earthquake Ionosphere Response on April 25

- GPS + GLONASS data processed, all satellites utilized and plotted
- 1-sec PPP solution at LHAZ
- Surface displacement at 10 cm level
- 1-sec data analyzed – filtered for acoustic waves
IGS site LHAZ is located about 650 km from the EQ epicenter.

It takes about 8 minutes for acoustic waves to reach the ionosphere and about 13 minutes to travel 650 km (wave velocity is ~800 m/s at 350 km).
Nepal Mw 7.8 Earthquake Ionosphere Response on April 25
Space-Based Detection Capabilities

GRACE Mission

Air Density Perturbation Measured by GOCE

Wave propagation

Tibetan earthquake 2011

Troposphere

Stratosphere

Mesosphere

Thermosphere

Spitzbergen

Neustrelitz

Weilheim

S-Band Uplink/Downlink

24 and 32 GHz Crosslink

GPS L1 and L2
GRACE very-high-precision inter-satellite measurements are used for:

- detecting ionospheric TEC perturbations,
- retrieving neutral air density perturbations and
- analyzing ionospheric and atmospheric perturbations and interpretation

### Observation Equations:

**Relative acceleration:**

\[ a_d = \frac{1}{2} \rho' C_d A V_r^2 V_r \]

**Phase advance:**

\[ \delta \tau_p = -\frac{40.3 \cdot TEC}{f^2} \]
Space-Based TEC Observations

GRACE ground tracks at event time

GRACE ground tracks after/before event time

TEC perturbations

S-wave

P-wave

Wavelet spectrum

Period

4 mins

2 mins
Space-Based Neutral Air Density Observations

GRACE observations

GITM simulations

Coherence Spectrum

Coherence Values (Unitless)
CASSIOPE Satellite GAP Observations

- CASSIOPE is a multi-task Canadian satellite which was to launched into a high inclination orbit in September 2013
- GAP-A antennas (4): high precision navigation and attitude determination (mounted on zenith-facing side)
- GAP-O antenna (1): occultation (mounted on the anti-ram side)
At higher $H$, $\sigma_\phi$ is getting smaller as the irregularities length scales get smaller and less varied.

- **Auroral oval**
  - Max 16 cm;
  - Polar cap
  - Max 3 cm

- **Strong phase scintillations**
  - $>12$ cm in the E region & F region
  - $<600$ km
COSMIC
Ionospheric Weather Constellation

Low-Earth Orbiter
GPS

Space – COSMIC Radio Occultation, DMSP SSUSI

Six-satellite COSMIC constellation
Launched April 14, 2006

DORIS – proposed for COSMIC-2 Polar

May 12-14, 2015
IES 2015, Alexandria, Virginia
GNSS Receiver Payload and COSMIC-2/FORMOSAT-7

TriG GNSS Radio Occultation System
Equatorial/6 Sats/Launch 2016

TGRS-Reflections and DORIS (RAD)
Polar/6 Sats/Launch 2018

65 W avg power
CubeSat for Natural-Hazard Estimation With Ionospheric Sciences (CNEWS)

- Total Electron Content (TEC) uncertainty: \(0.02\) TECU
- Sensitivity estimates of geomagnetic field and TEC after de-dispersion of HF/VHF; Geomagnetic field measurements uncertainty: 50 nT
Conclusions

• New space-physics applications using ground-based or space-based GPS data include investigations of:
  • Various natural hazards that may be observed using TEC data from ground and space-based GPS observations.
  • Tsunamis, earthquakes, volcanic eruptions, meteor impacts, industrial explosions generating atmospheric waves that we can use to learn about wave propagation properties.
  • Using NASA’s real-time ground-based GDGPS system and RO data to observe natural hazards to augment existing tsunami early warning systems.
  • Irregularity scales and phase scintillation characteristics as functions of the solar wind and magnetospheric forcing.
  • Large length scales and more intense phase scintillations are prevalent in the auroral oval compared to the polar cap.
  • Space climate and real-time space weather applications using data assimilation
  • NASA HQ and NASA ROSES Grant (NNH07ZDA001N-ESI) are gratefully acknowledged.
Absolute (Calibrated) and Relative COSMIC and C/NOFS TEC Data for Nov 21, 2008

Bias-removed absolute COSMIC slant TEC data

Bias-removed absolute C/NOFS slant TEC data

C/NOFS relative slant TEC data

COSMIC relative slant TEC data

Elevation angle [deg]
Nowcasts – Multi-Resolution and Multiple Data Sets

GAIM: Global electron density grids – continuously updated

Ground-based: GPS TEC + Ionosonde global network

Space – COSMIC Radio Occultation, DMSP SSUSI

Nested grid GAIM
High resolution locally

Tomographic inversion of GUVI/SSUSI data

Comberiate et al., GRL 2006

DORIS – proposed for COSMIC-2 Polar

IES 2015, Alexandria, Virginia

May 12-14, 2015
NASA’s GDGPS R&D role is highly valuable and gratefully acknowledged

Real-Time GAIM TEC Residuals for Tohoku Earthquake on March 11, 2011

GAIM: Global Assimilative Ionosphere Model
GIM: Global Ionospheric (TEC) Maps

GIM residuals (a) and band-pass filtered slant TEC measurements. Panel (b) indicates an example for filtered TEC observations.
Arecibo ISR Case Study for June 26, 2006

Ground and Space Ground Tracks For UTC Hour 20

Arecibo

GPS15

FM2

20:09

20:05

SCUB

CRO1

FM5

20:25

20:21

JAMA

O+ density profile as of 20060626 201200 LT: 15.7 at Lat: 18.3, Lon: 293.0

UT 20:00

UT 20:12

UT 20:24
Ground-Based GPS, COSMIC and Jicamarca ISR Coverage for Sept 21, 2014

Ground GPS

COSMIC

Jicamarca ISR

dense but unevenly distributed coverage

less dense yet evenly distributed coverage
An Example of COSMIC Impact on Profile Shape

1. UT 15:36

2. UT 15:48

3. UT 16:36

COSMIC UT 15:30