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

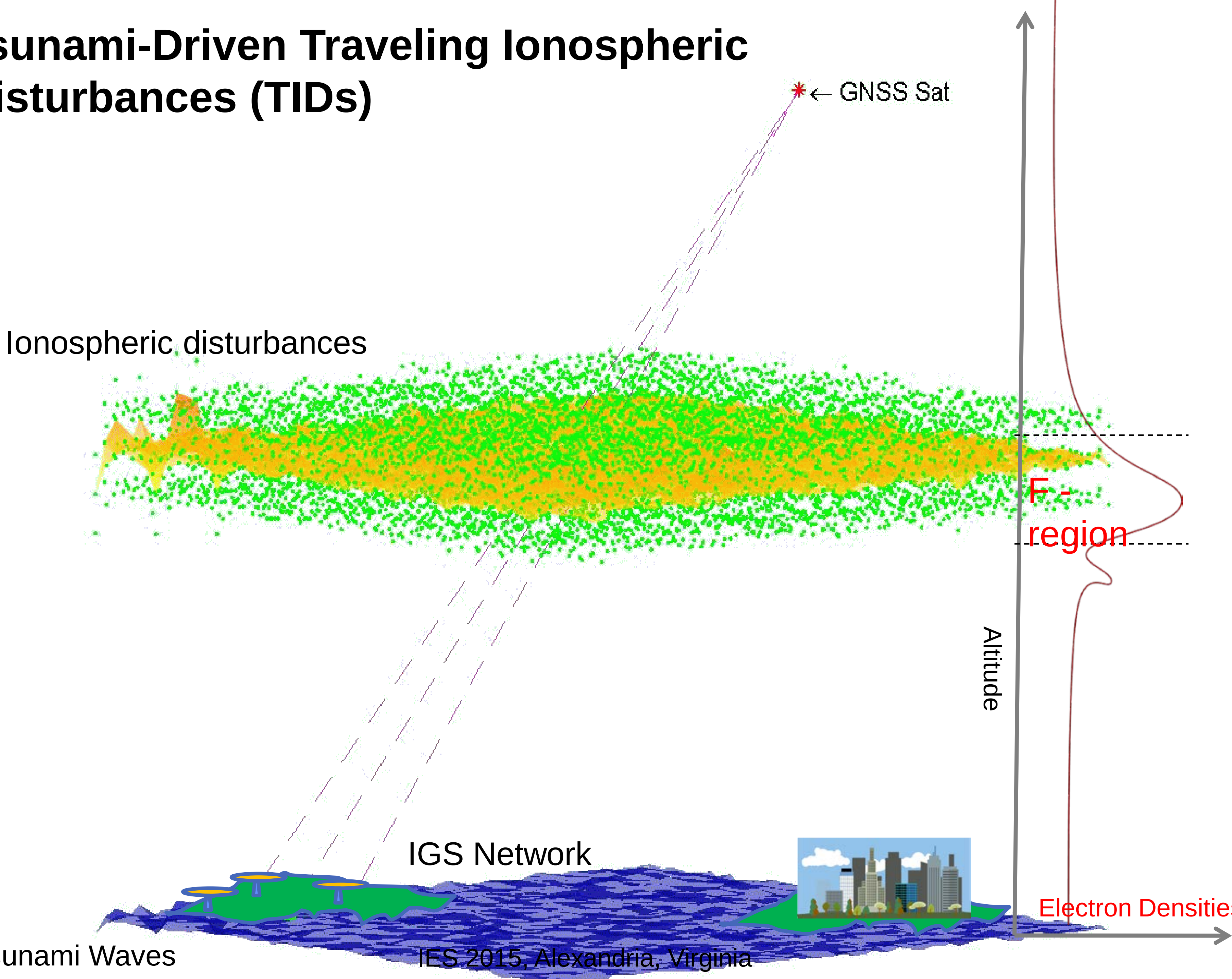
Our Motivation and Constant Reminders to Improve Our Understanding of Natural Hazards

Tohoku-Oki Tsunami, March 11, 2011

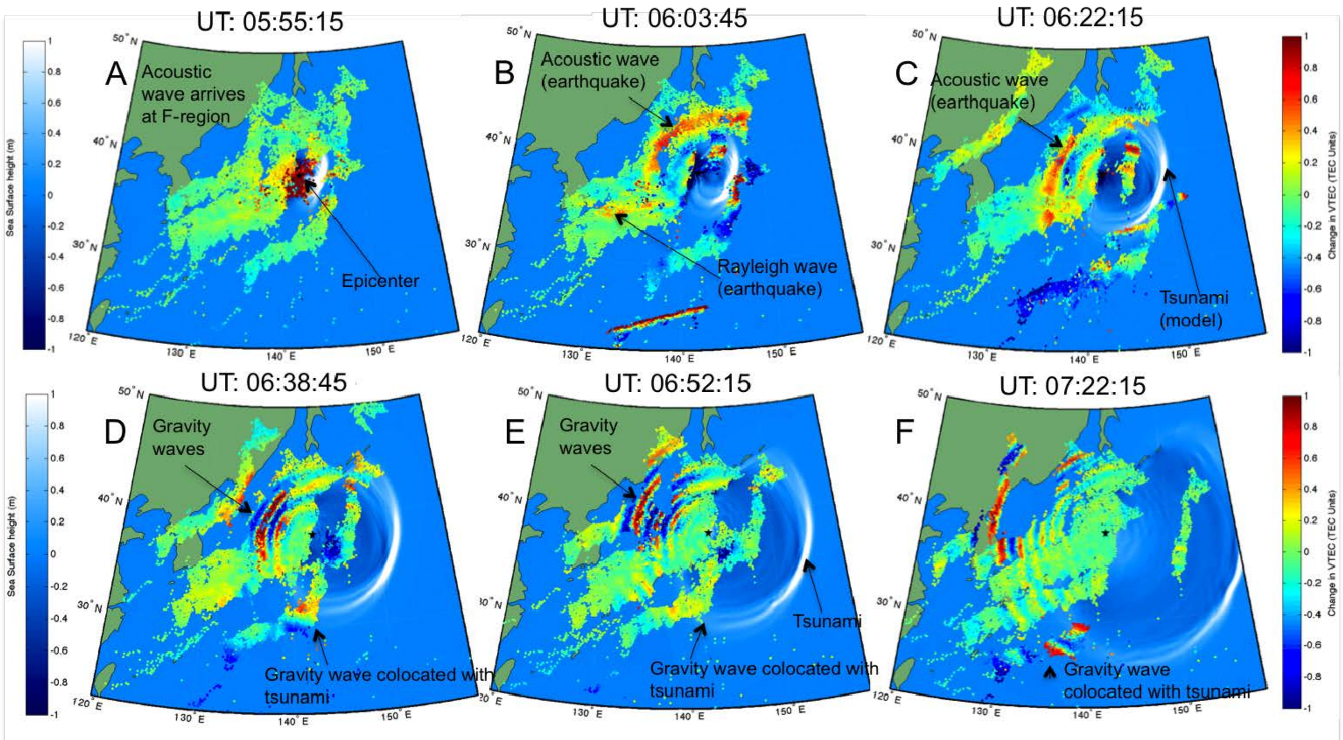
- Magnitude 9.0
- 70 km off shore
- 30 km depth
- Tsunami wave heights up to 15 meters

Nepal (Gorkha) Mw 7.8 Earthquake on Apr 25, 2015

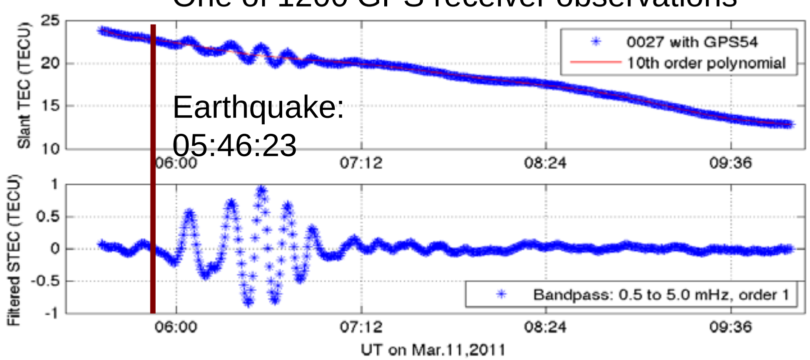
Tsunami-Driven Traveling Ionospheric Disturbances (TIDs)



Tohoku Tsunami Seen in Ionosphere Using GPS Data Compared with JPL's Tsunami Model

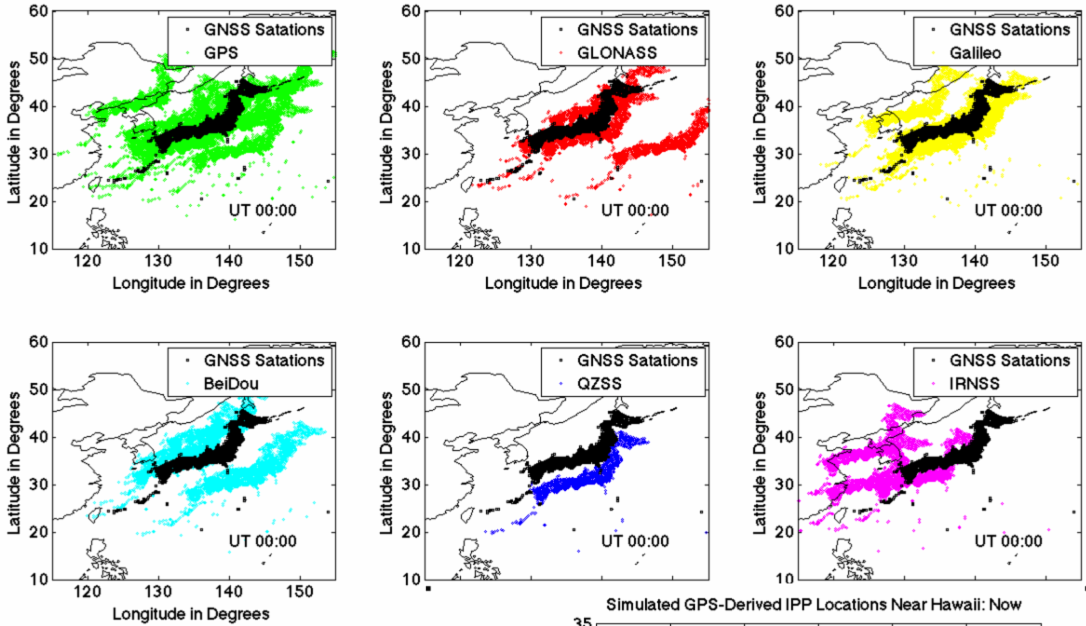


One of 1200 GPS receiver observations



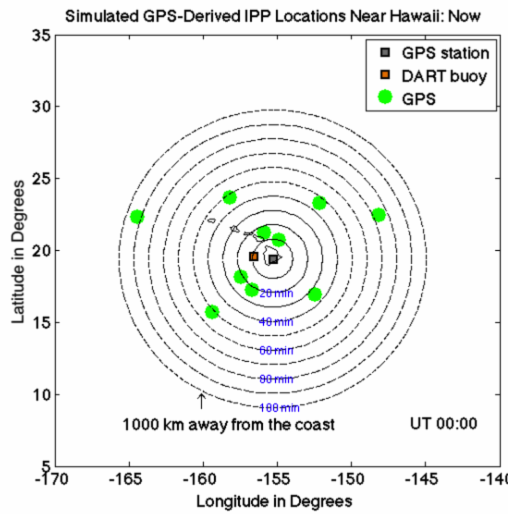
- Earthquakes and tsunamis generate atmospheric gravity waves that propagate vertically, reaching the ionosphere.
- Disturbance to ionosphere is detectable using GPS-derived total electron content (TEC).

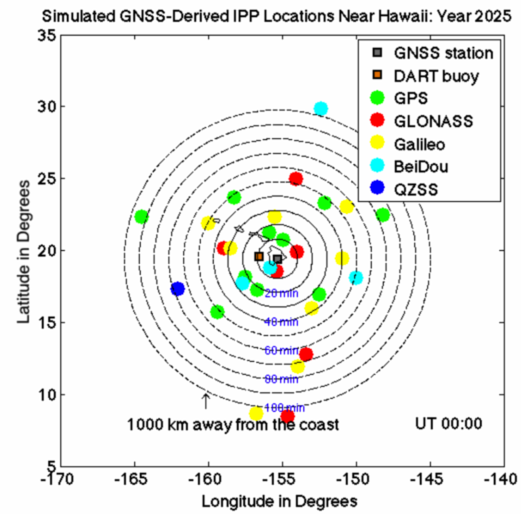
IPPs from Simulated Constellations by 2025

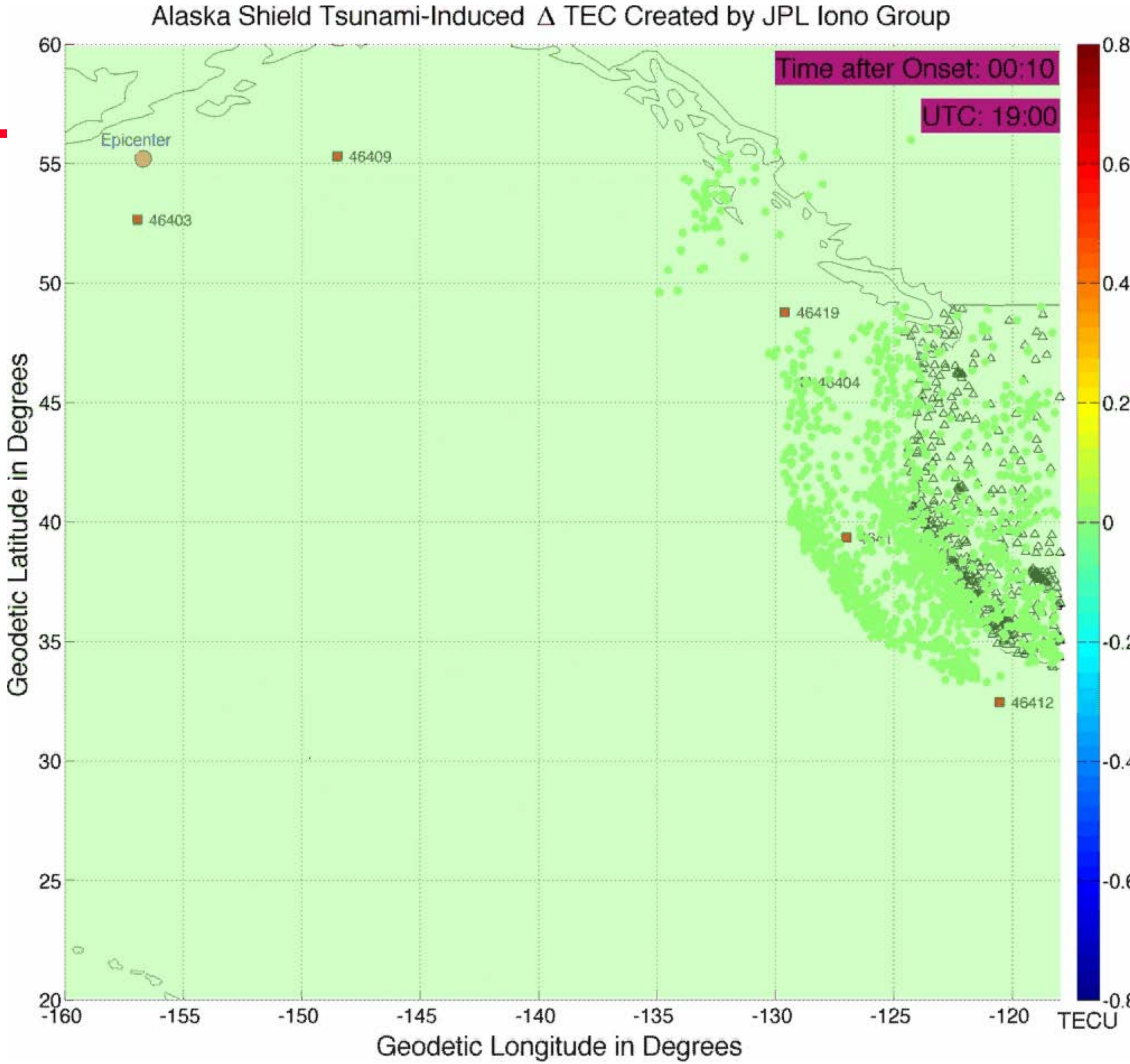


Six different satellite constellations by 2015:

- GPS
- GLONASS
- Galileo
- BeiDou
- QZSS
- IRNSS



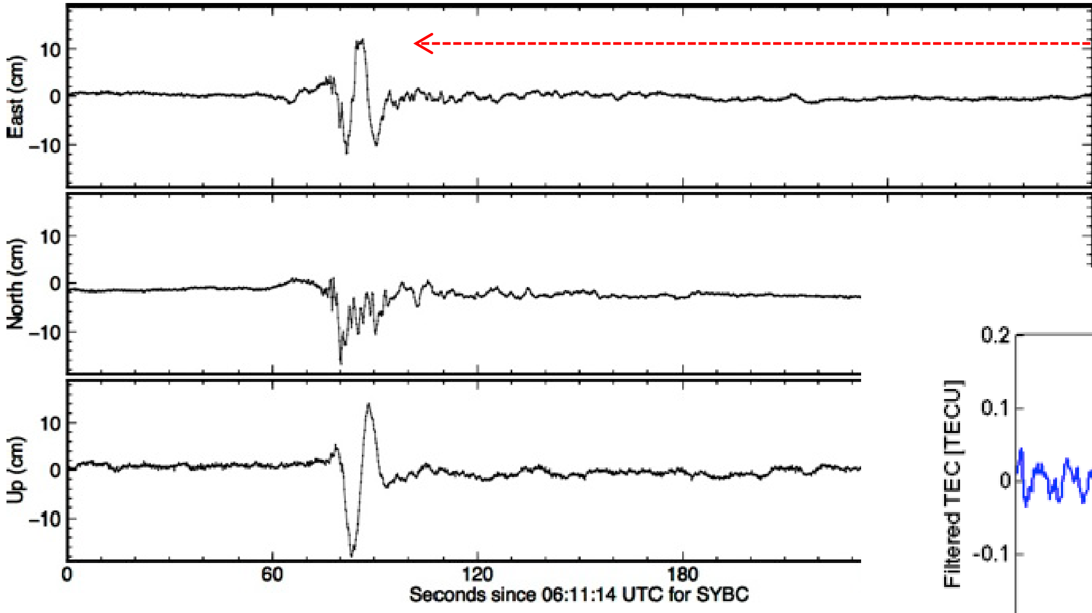




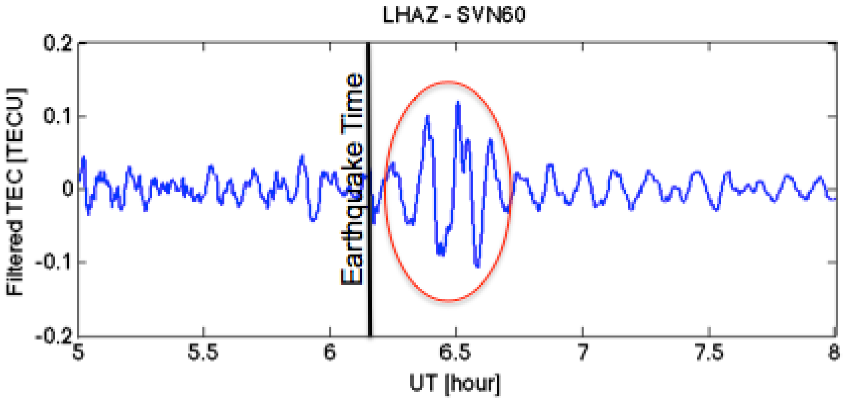
What would be the impact if the1964 Mw 9.2 earthquake were to hit the US today?

Movie to play

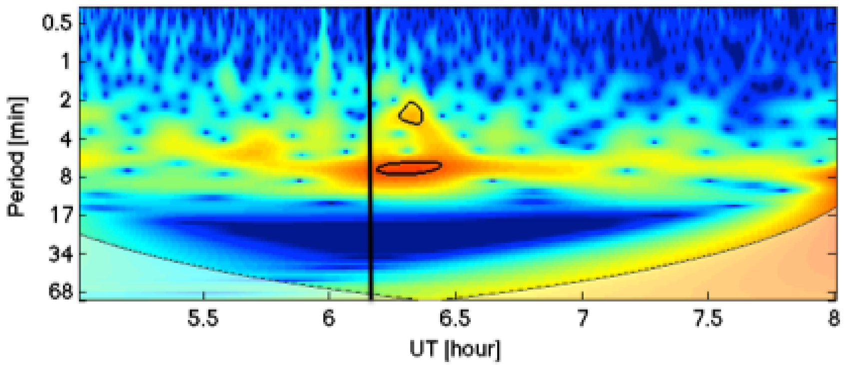
Nepal Mw 7.8 Earthquake Ionosphere Response on April 25



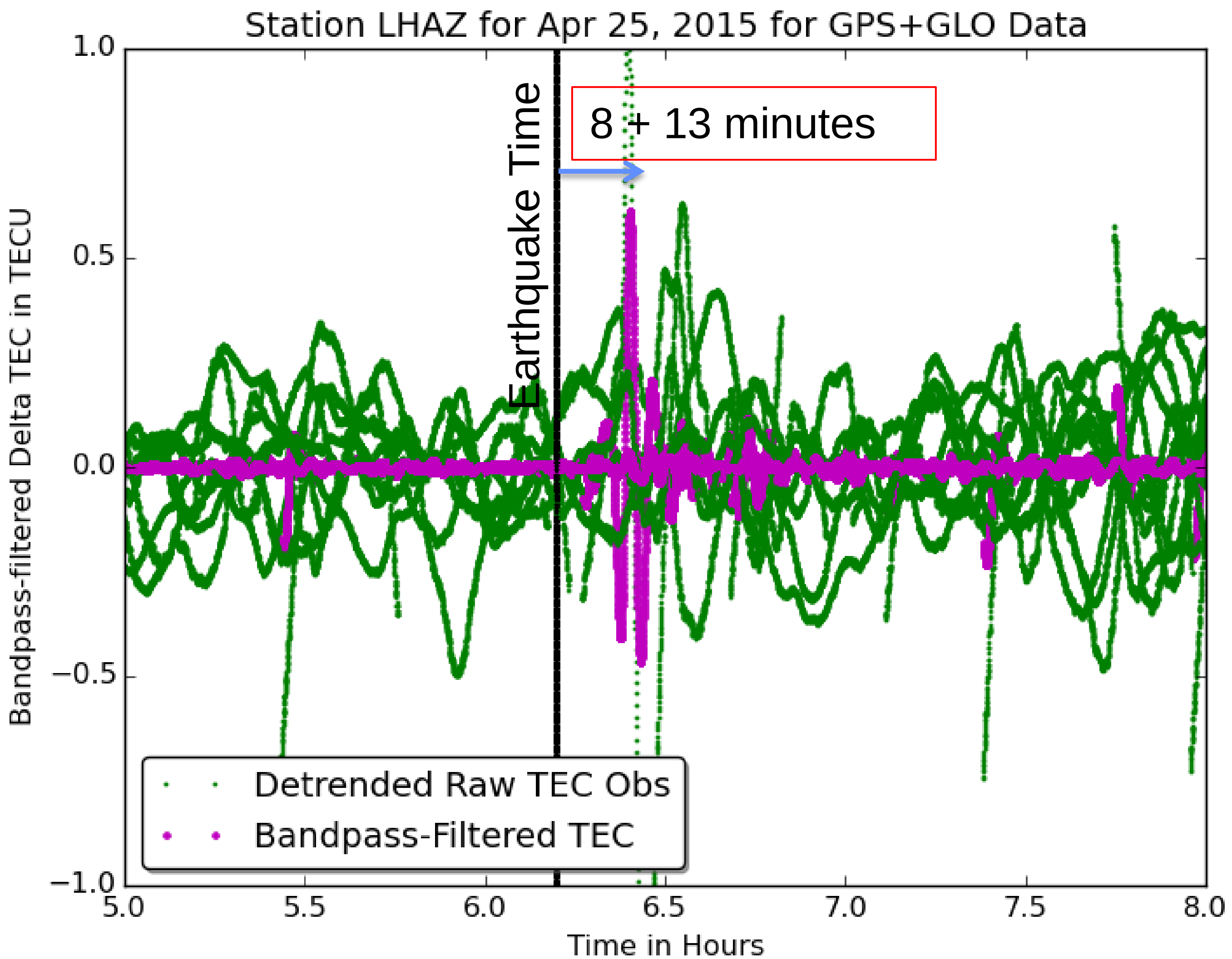
- 1-sec PPP solution at LHAZ
- Surface displacement at 10 cm level



- GPS + GLONASS data processed, all satellites utilized and plotted
- 1-sec data analyzed – filtered for acoustic waves

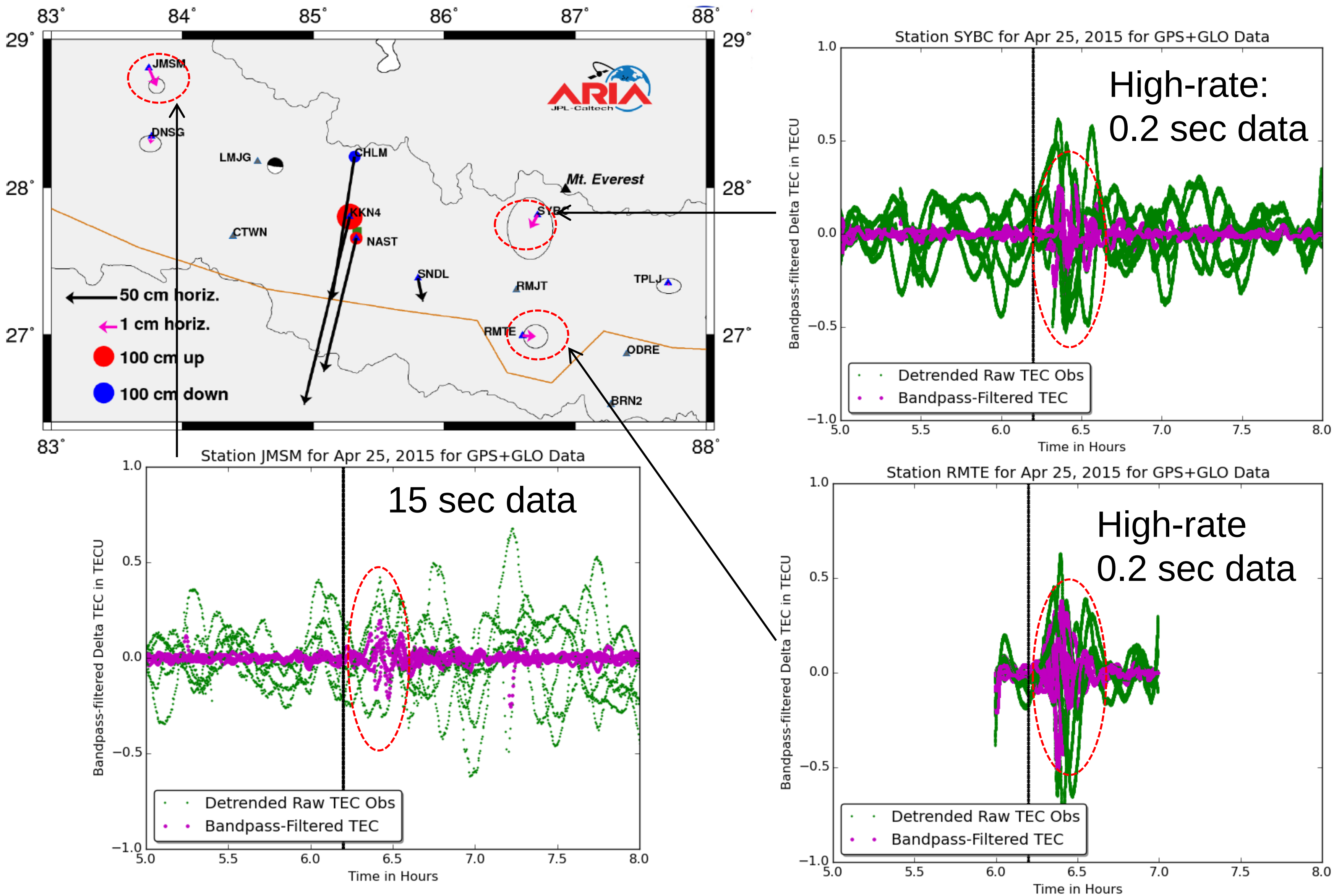


Nepal Mw 7.8 Earthquake Ionosphere Response on April 25

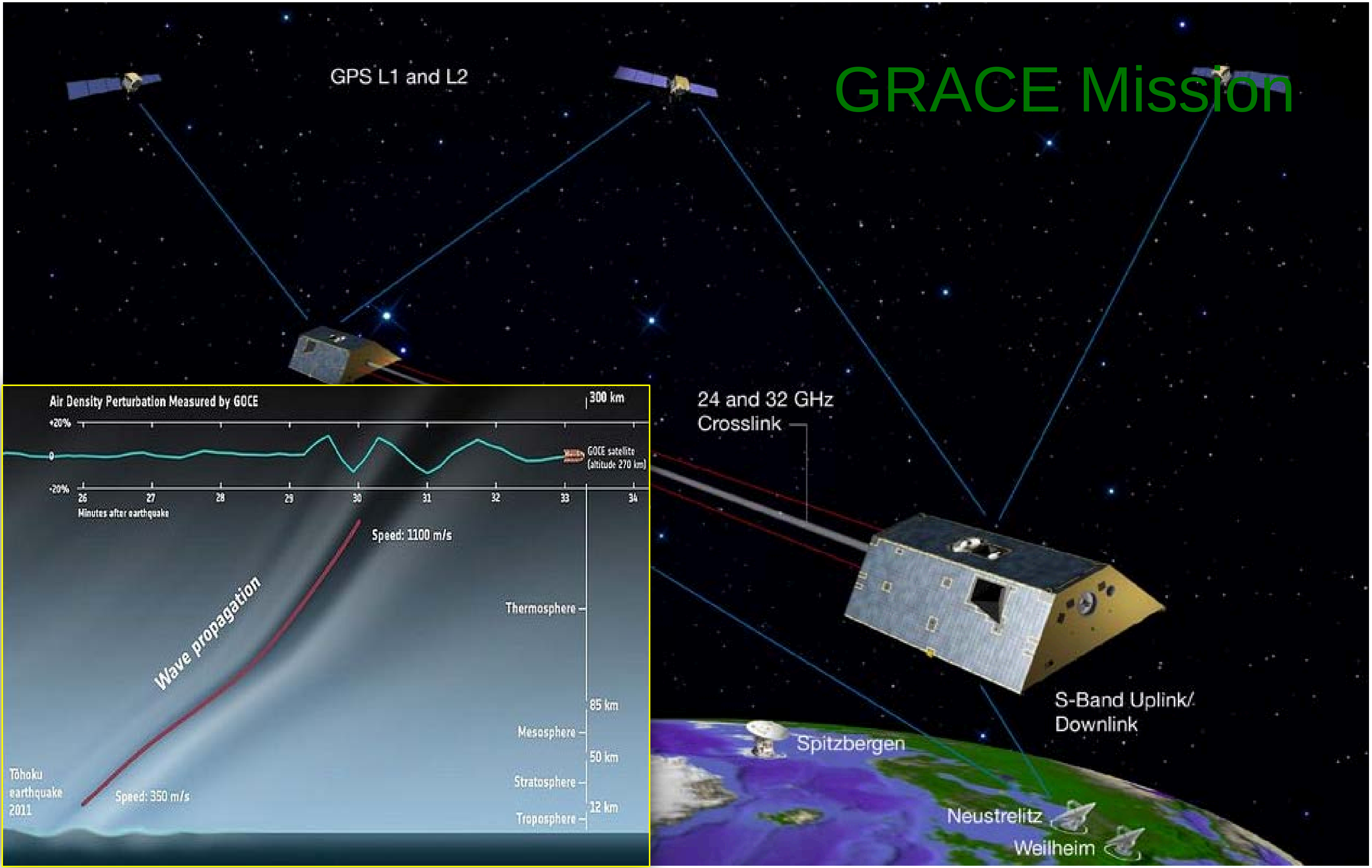


- IGS site LHAZ is located about 650 km from the EQ epicenter
- It takes about 8 minutes for acoustic waves to reach the ionosphere and about 13 minutes to travel 650 km (wave velocity is ~800 m/s at 350 km)

Nepal Mw 7.8 Earthquake Ionosphere Response on April 25



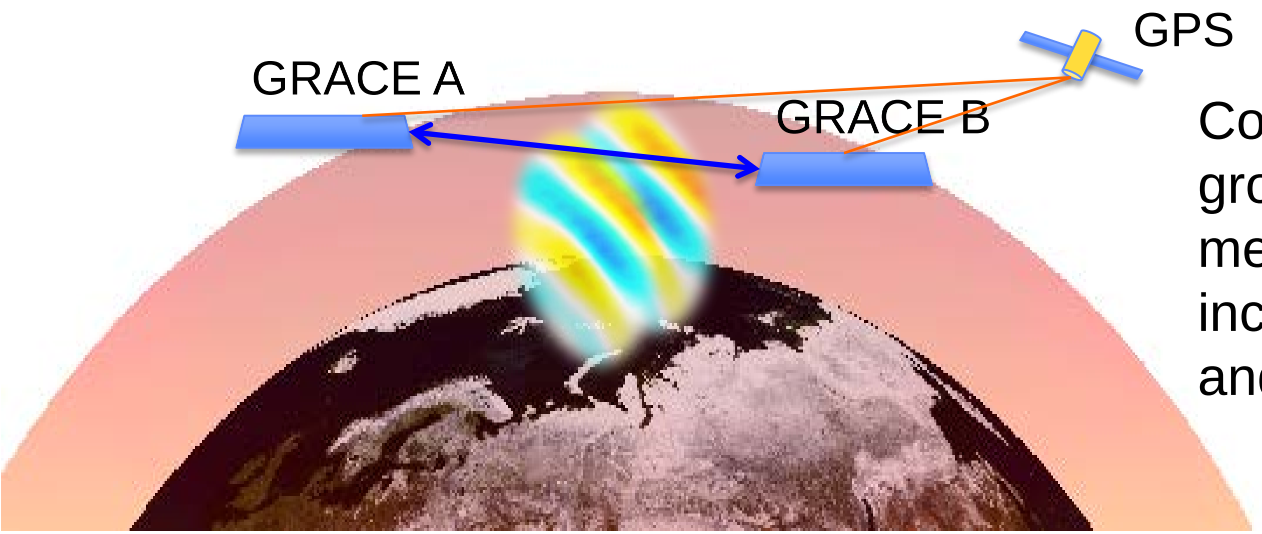
Space-Based Detection Capabilities



Space-Based Natural Hazards Remote Sensing in the Ionosphere

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



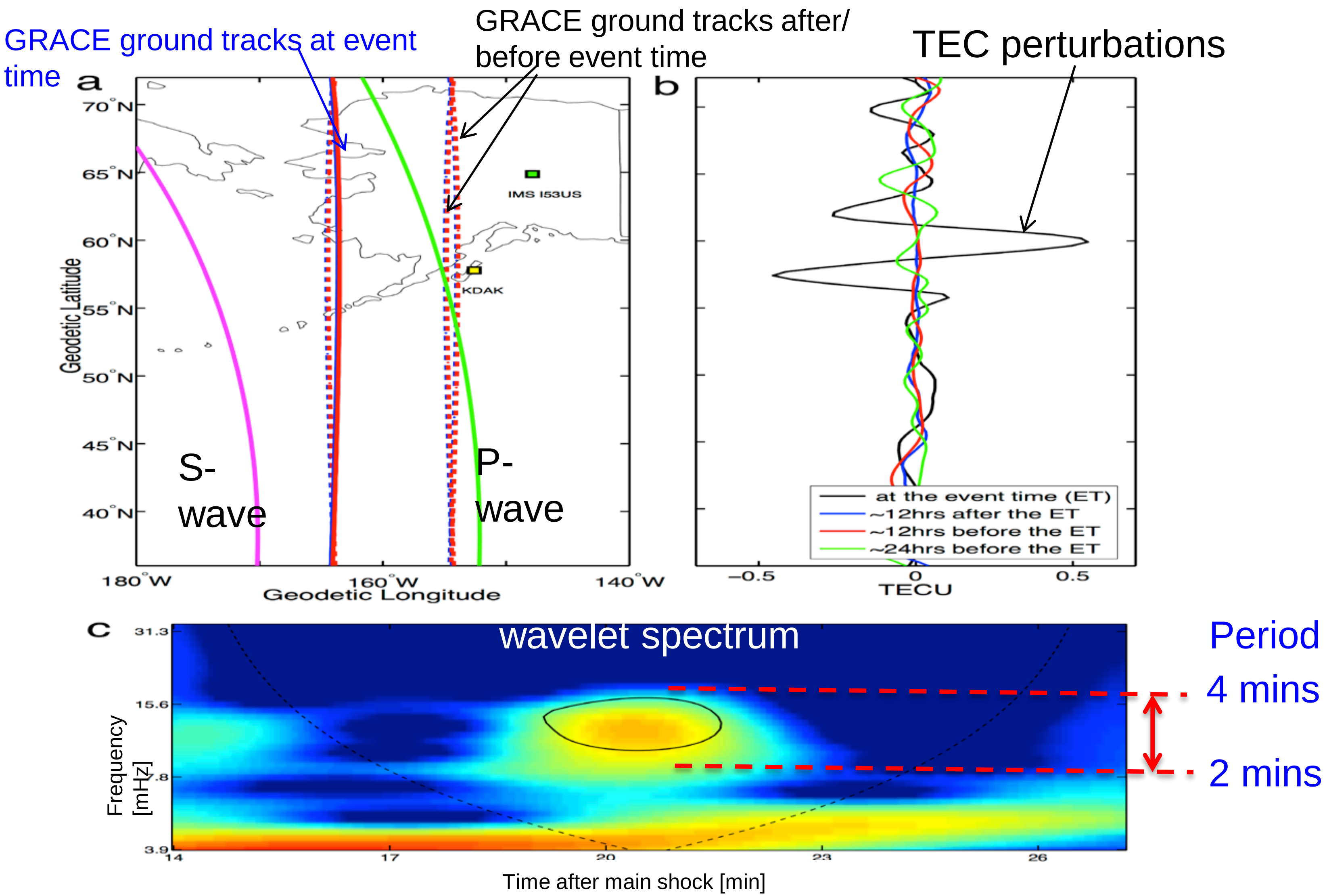
Comparisons with ground-based measurements, which include: GPS, seismic, and infrasound data

Observation Equations:

Relative acceleration: $$a_d = \frac{1}{2}\rho' C_d A V_r^2 \hat{V}_r$$

Phase advance: $$\delta\tau_p = -\frac{40.3 \cdot TEC}{f^2}$$

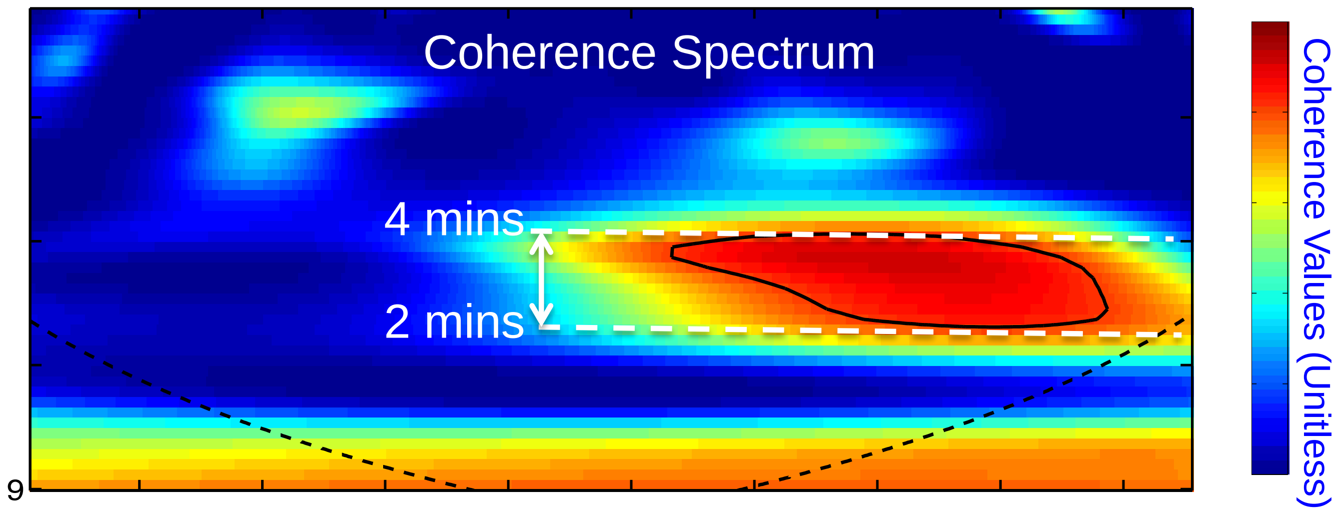
Space-Based TEC Observations



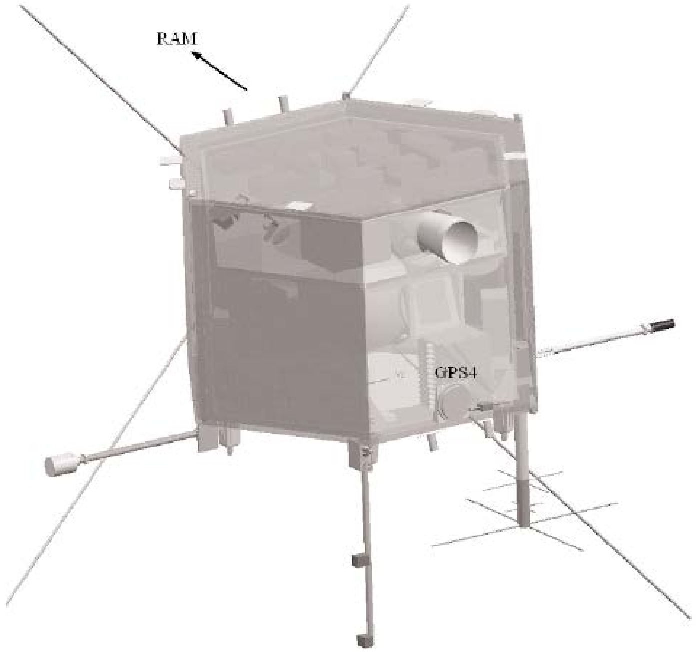
Space-Based Neutral Air Density Observations

GRACE observations

GITM simulations

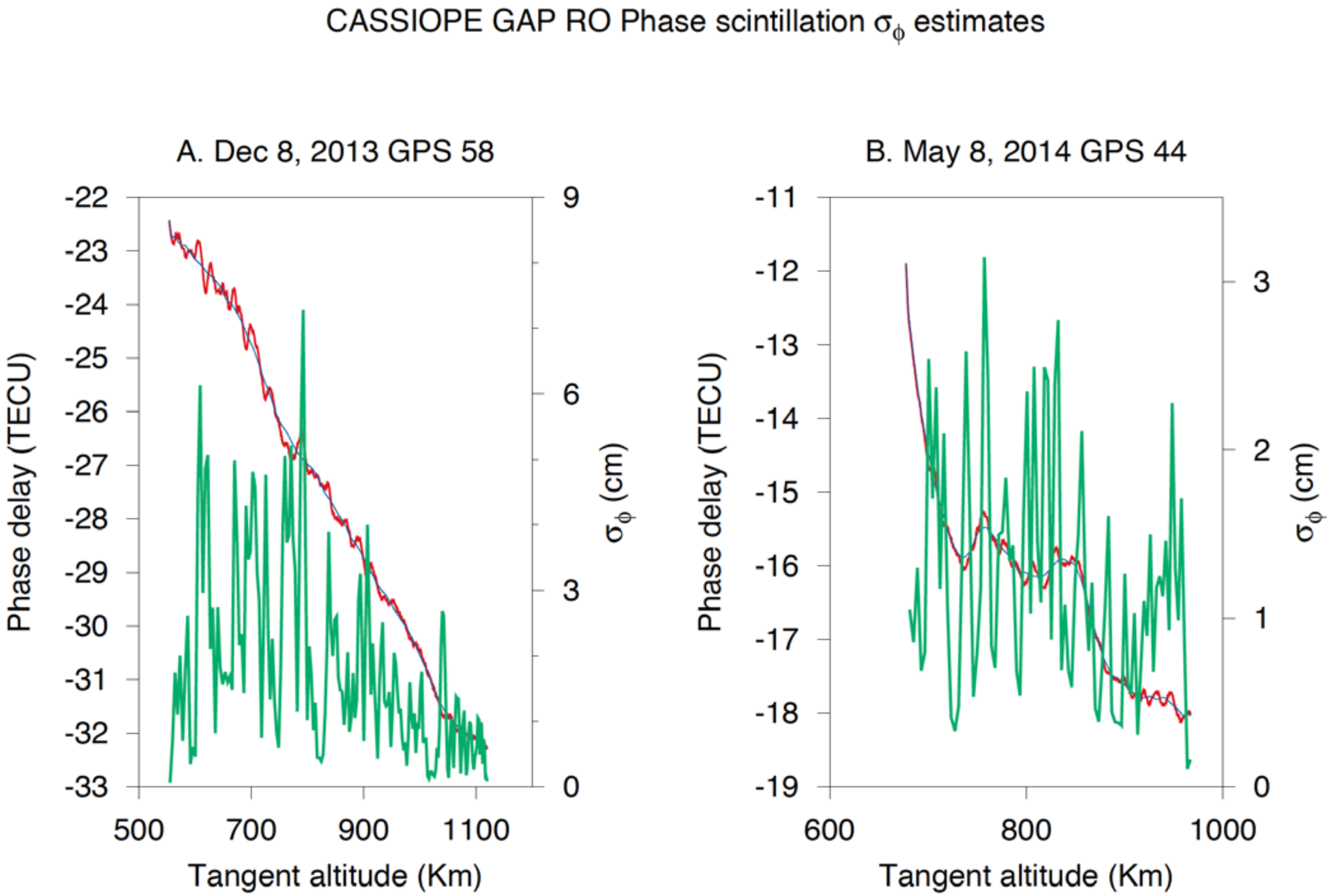


CASSIOPE Satellite GAP Observations



- 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)

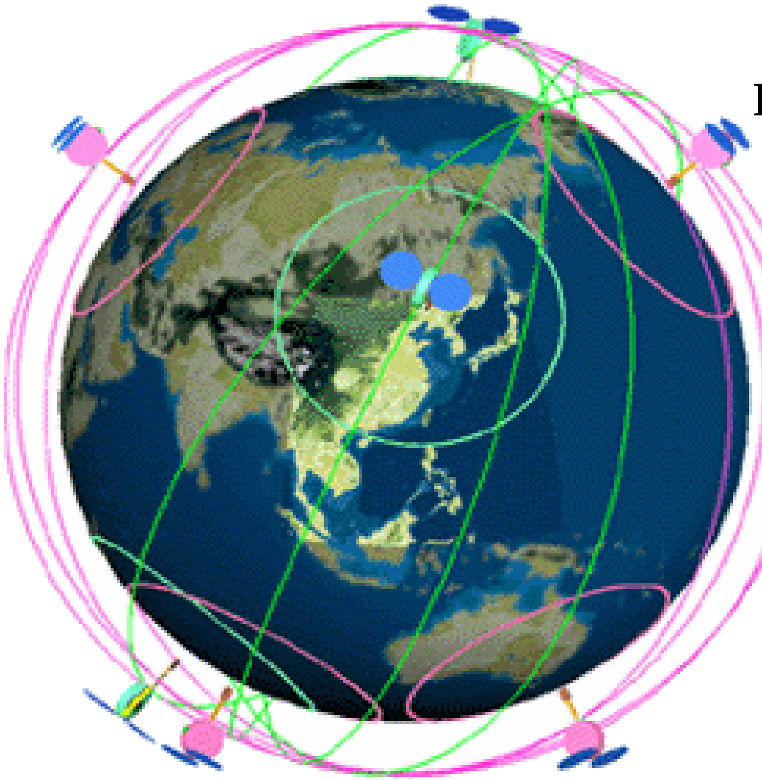
Phase Scintillation Using RO Data

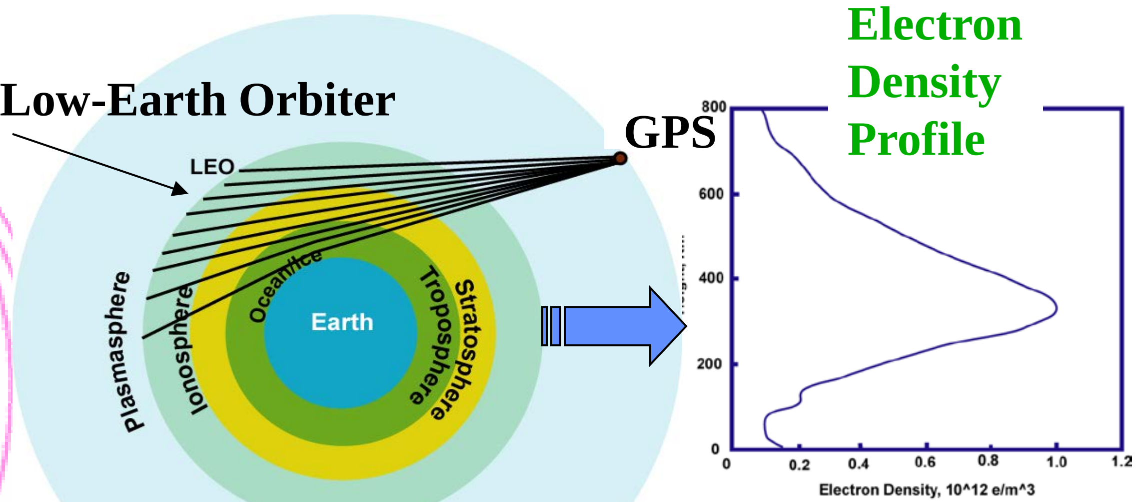


- Auroral oval max 16 cm; Polar cap max 3 cm
- Strong phase scintillations > 12cm in the E region & F region < 600 km

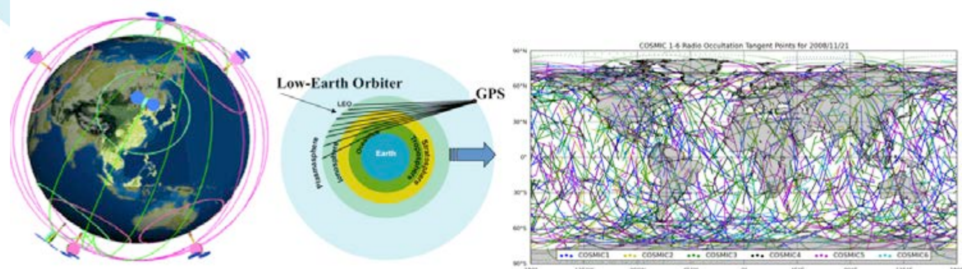
At higher *H* , σ_ϕ is getting smaller as the irregularities length scales get smaller and less varied

COSMIC
Ionospheric Weather Constellation

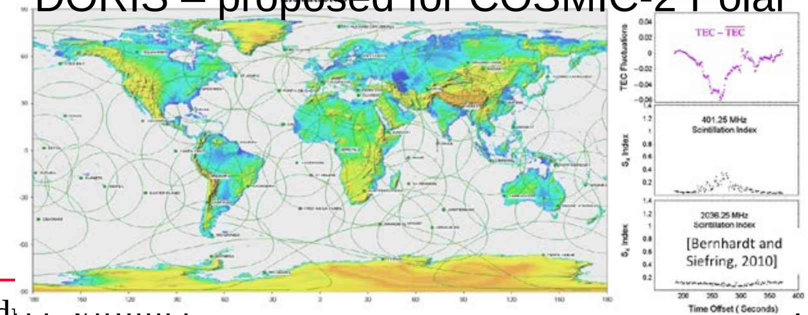




Space – COSMIC Radio Occultation, DMSP SSUSI



DORIS – proposed for COSMIC-2 Polar



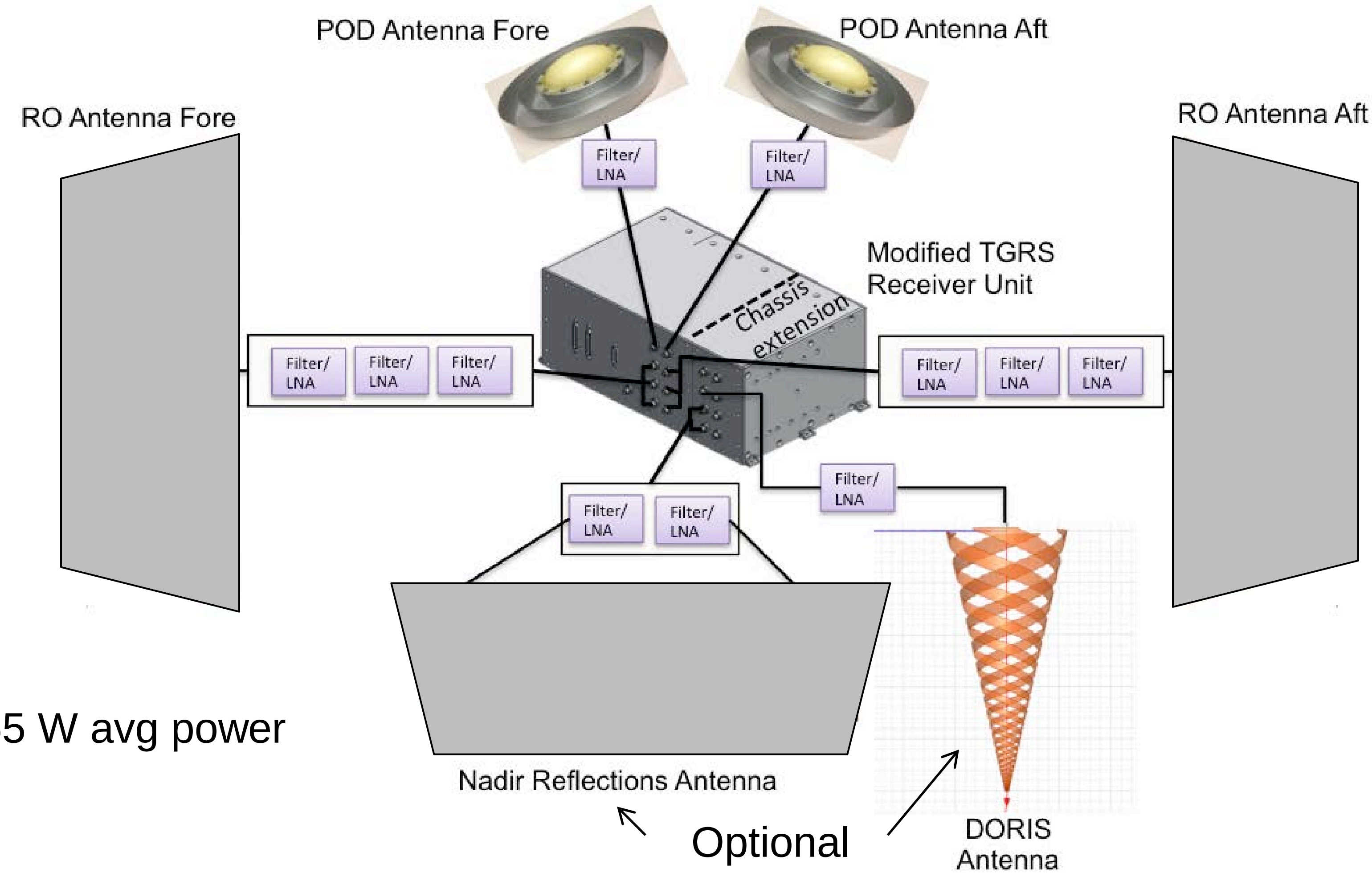
Six-satellite COSMIC constellation
Launched April 14, 2006

NSF NASA USAF NOAA NSPO ONR

GNSS Receiver Payload and COSMIC-2/FORMOSAT-7

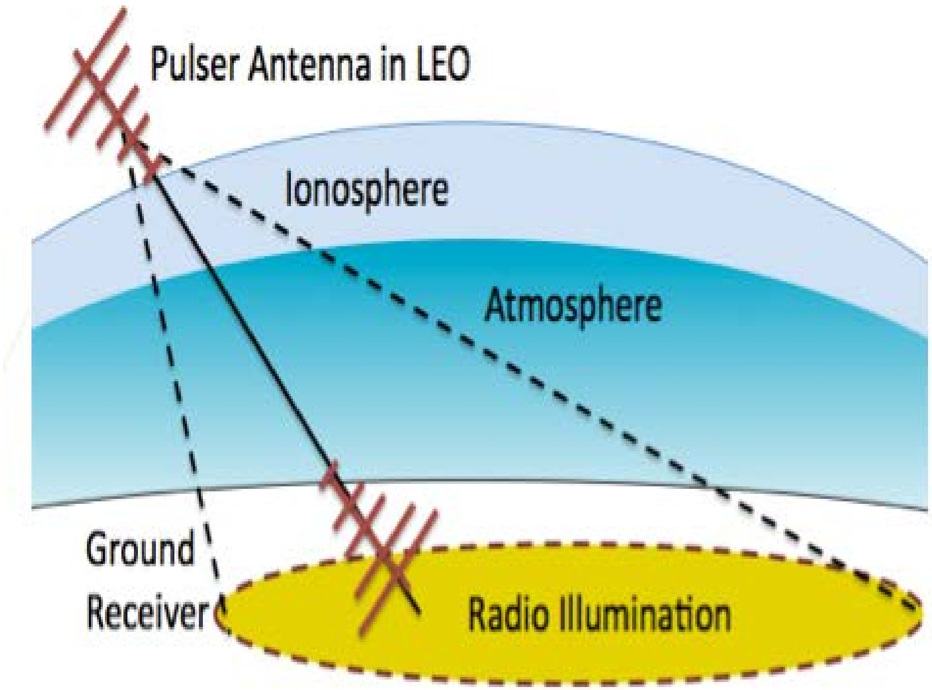
TriG GNSS Radio Occultation System → TGRS-Reflections and DORIS (RAD)

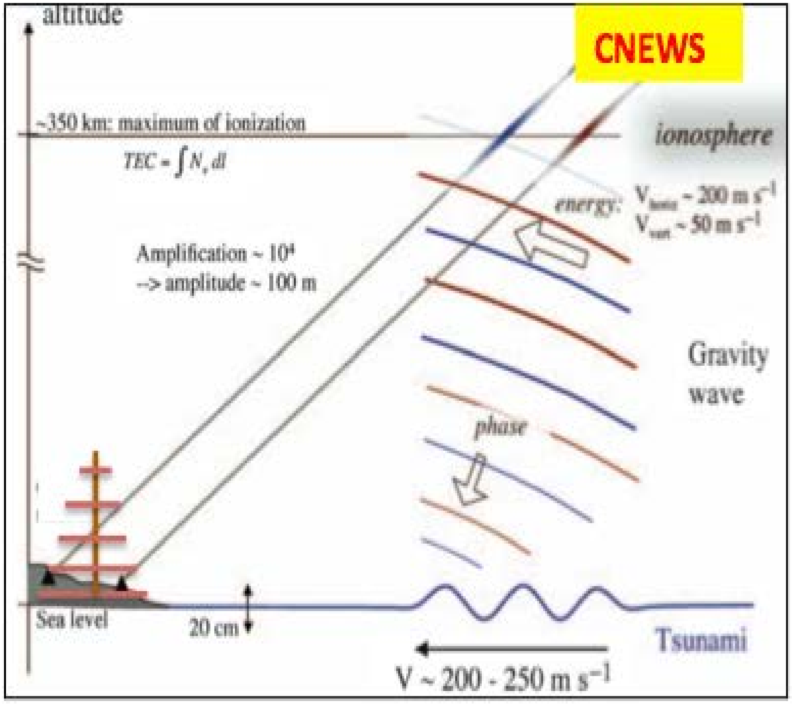
Equatorial/6 Sats/Launch 2016 **Polar/6 Sats/Launch 2018**

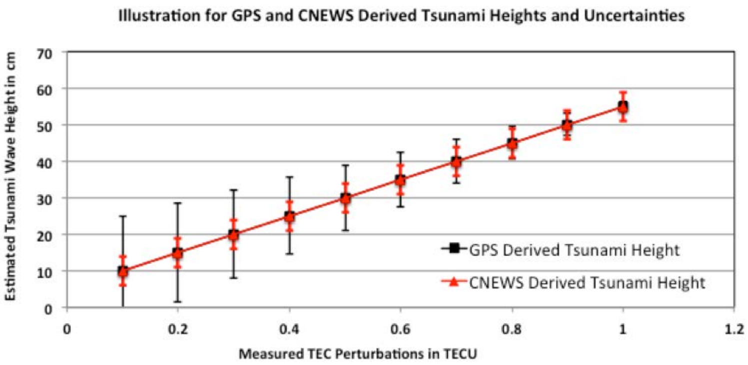


65 W avg power

CubeSat for Natural-Hazard Estimation With Ionospheric Sciences (CNEWS)







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

Conclusions

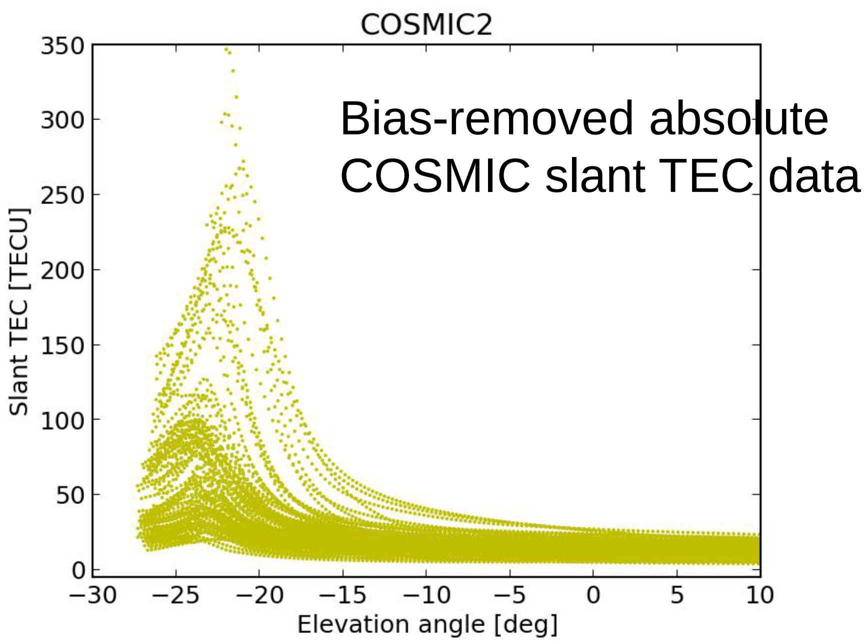
- New space-physics applications using ground-based or space-based GPS data include investigations of:
  - Various natural hazards that may be observed using TEC data from ground and space-based GPS observations.
  - Tsunamis, earthquakes, volcanic eruptions, meteor impacts, industrial explosions generating 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.

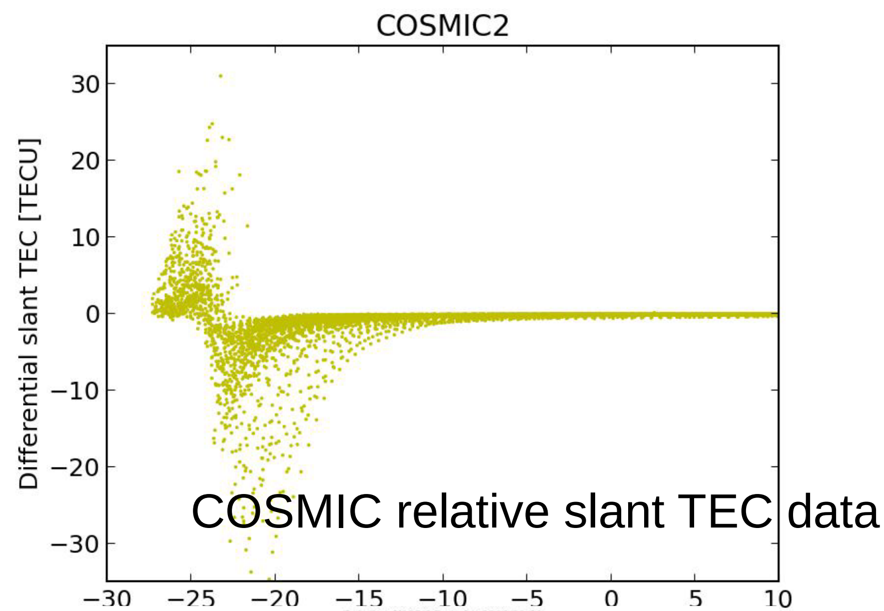
BACKUP SLIDES

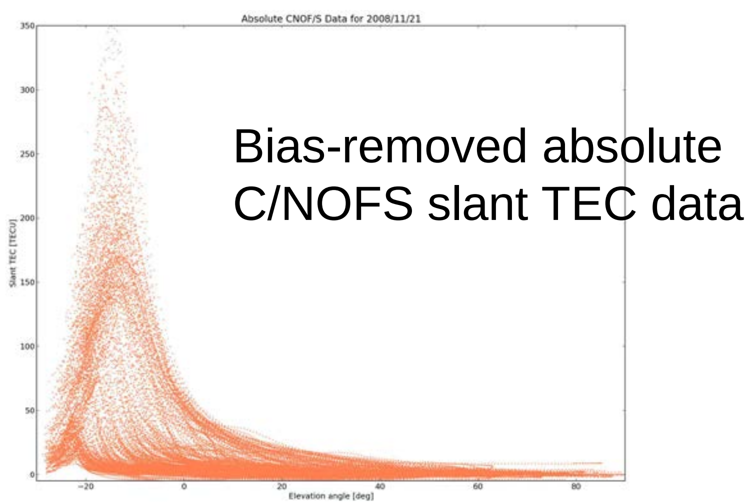
GITM Modeling and Simulations

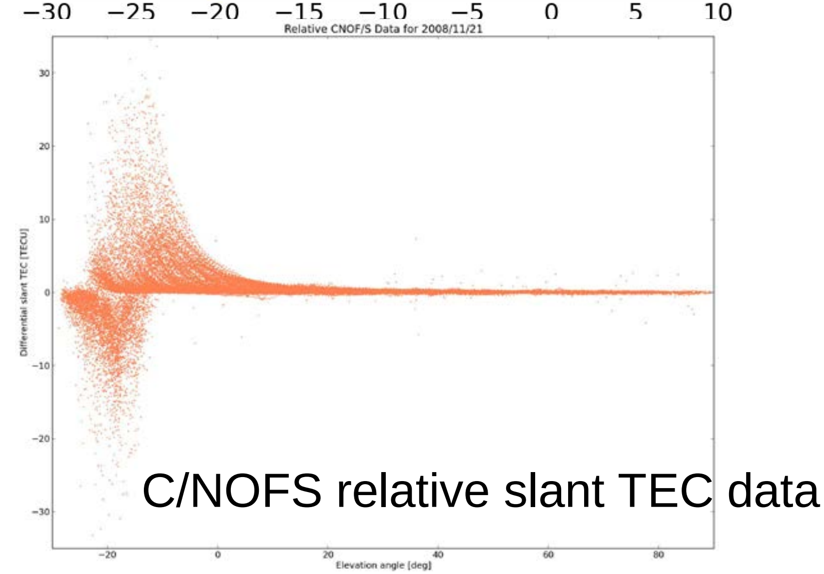
Movie to play

Absolute (Calibrated) and Relative COSMIC and C/NOFS TEC Data for Nov 21, 2008



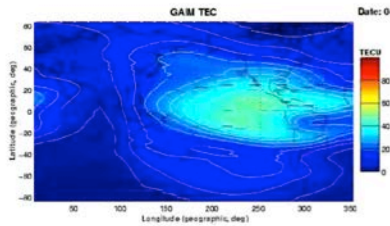


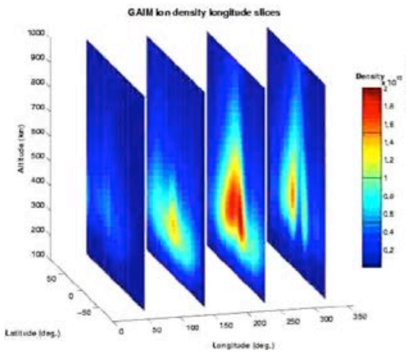


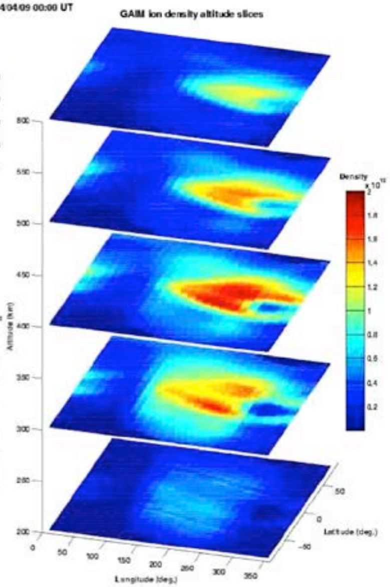


Nowcasts – Multi-Resolution and Multiple Data Sets

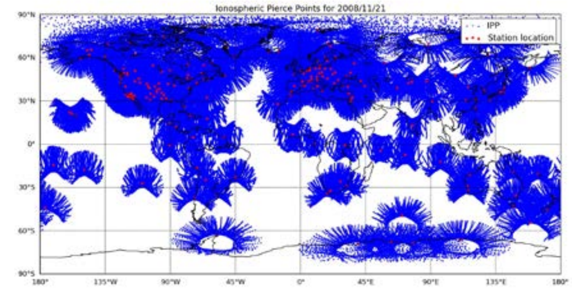
GAIM: Global electron density grids – continuously updated





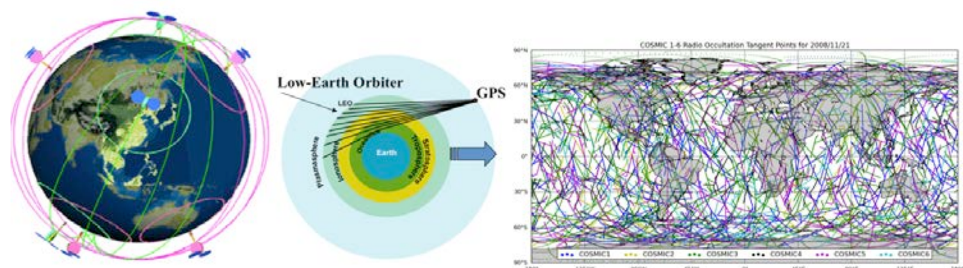


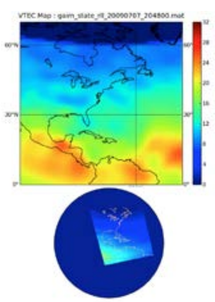
Ground-based: GPS TEC



+ Ionosonde global network

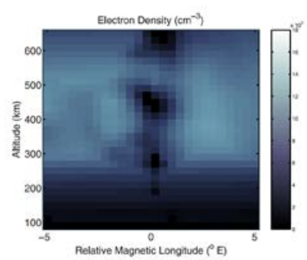
Space – COSMIC Radio Occultation, DMSP SSUSI





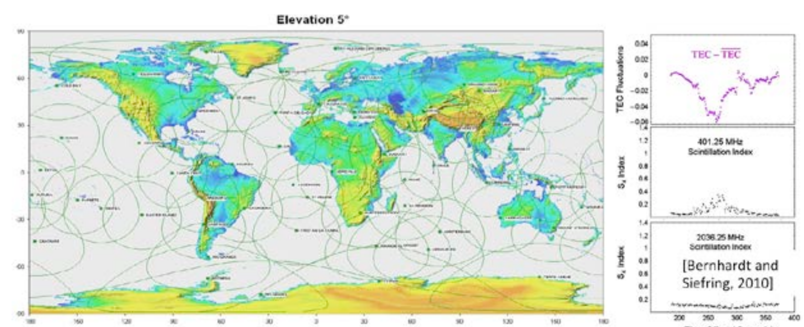
Nested grid GAIM
High resolution locally

Tomographic inversion of GUVI/SSUSI data

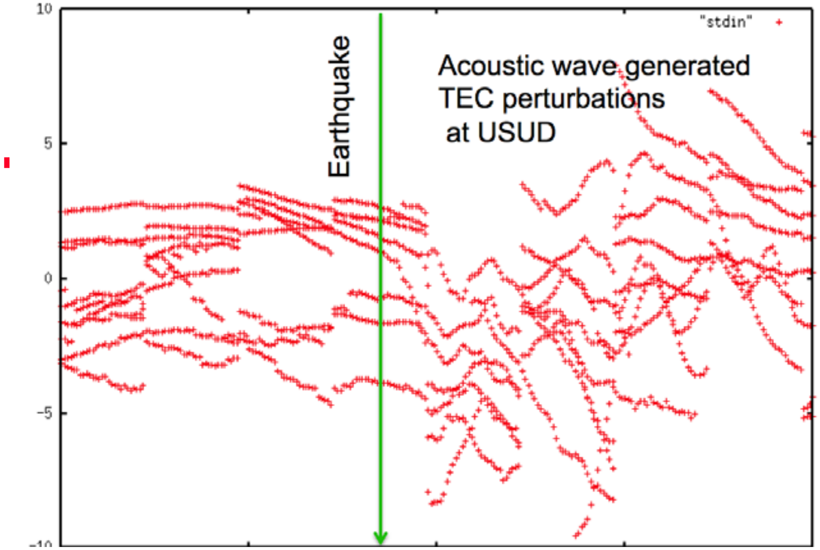


Comberiate et al., GRL 2006

DORIS – proposed for COSMIC-2 Polar

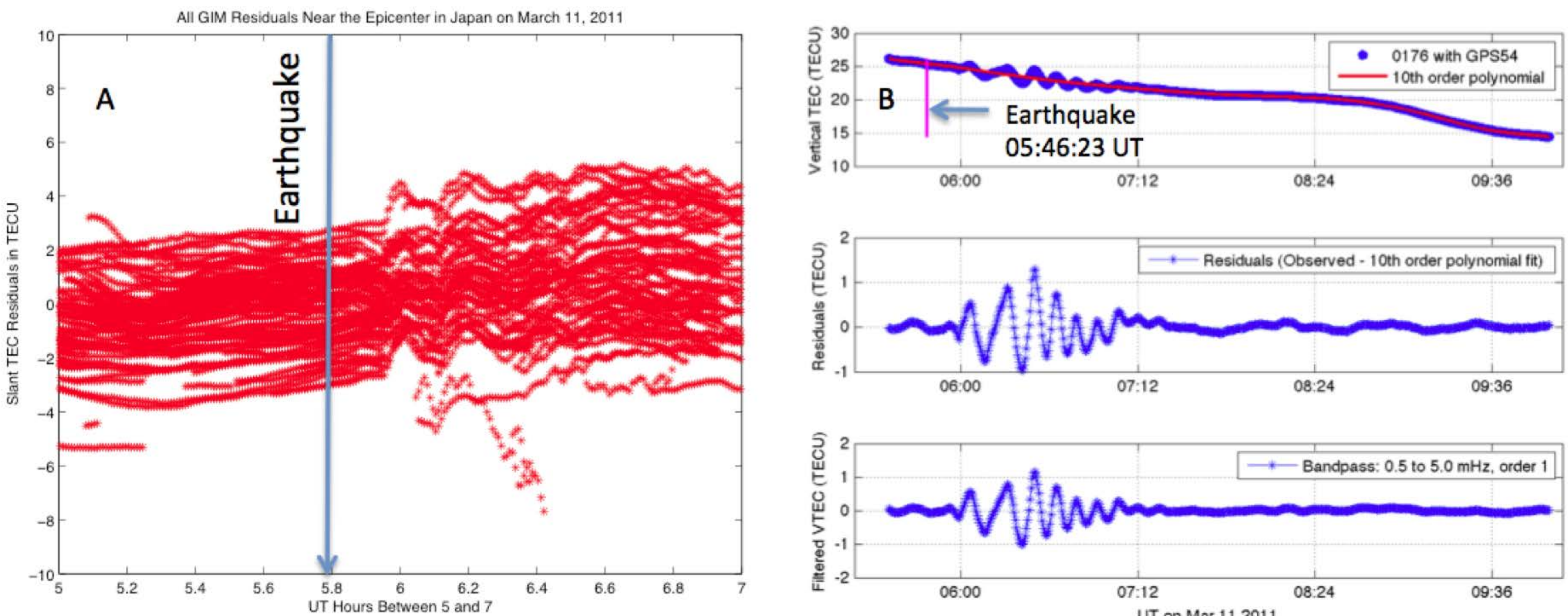


NASA's GDGPS R&D role is highly valuable and gratefully acknowledged



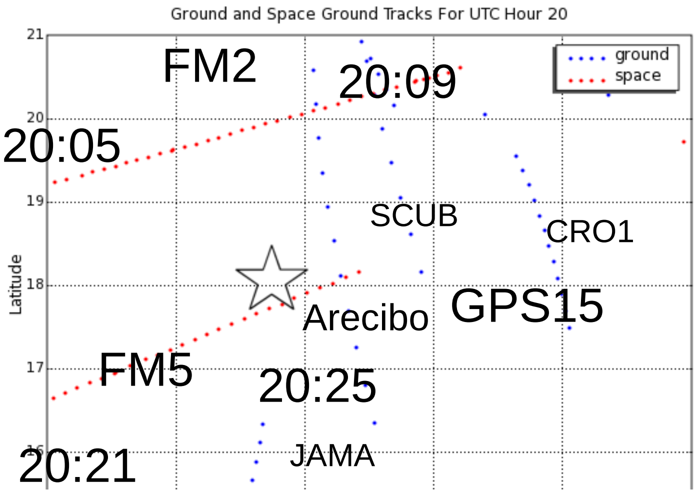
Real-Time GAIM TEC Residuals for Tohoku Earthquake on March 11, 2011

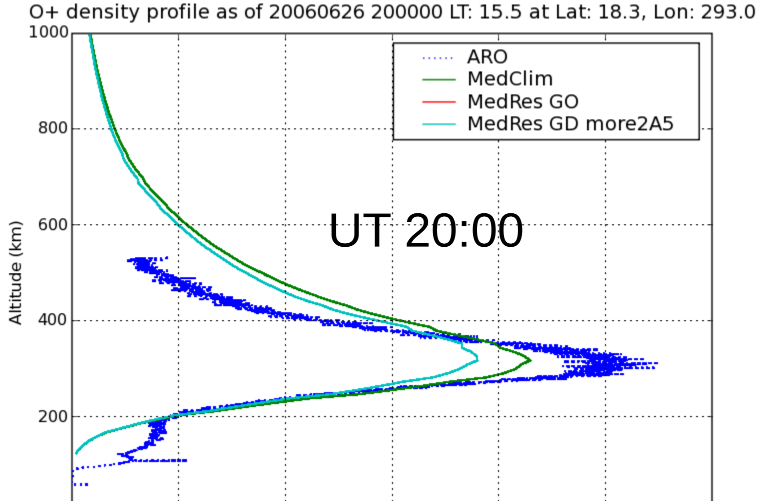
GAIM: Global Assimilative Ionosphere Model
GIM: Global Ionospheric (TEC) Maps

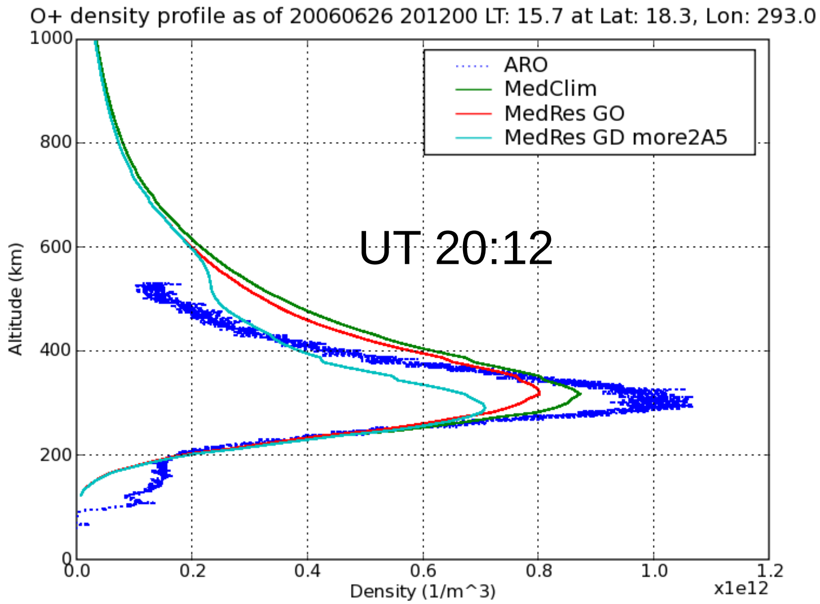


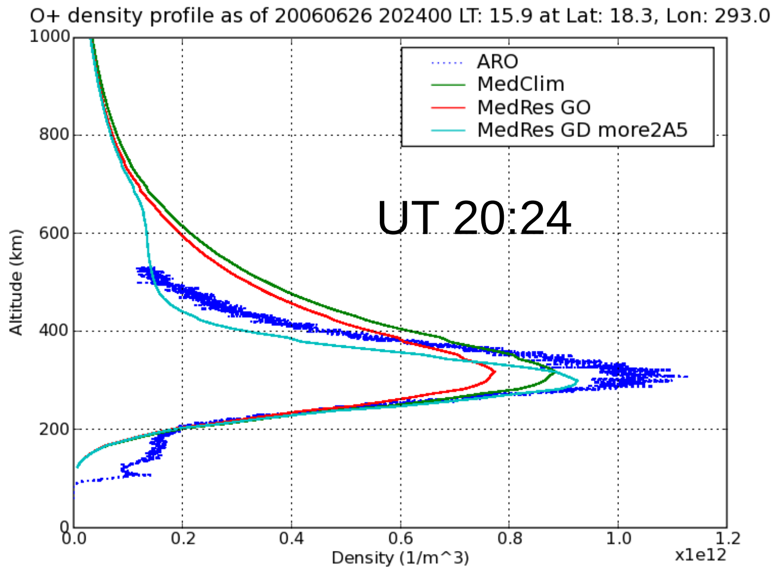
GIM residuals (a) and band-pass filtered slant TEC measurements. Panel (b) indicates an example for filtered TEC observations.

Arecibo ISR Case Study for June 26, 2006

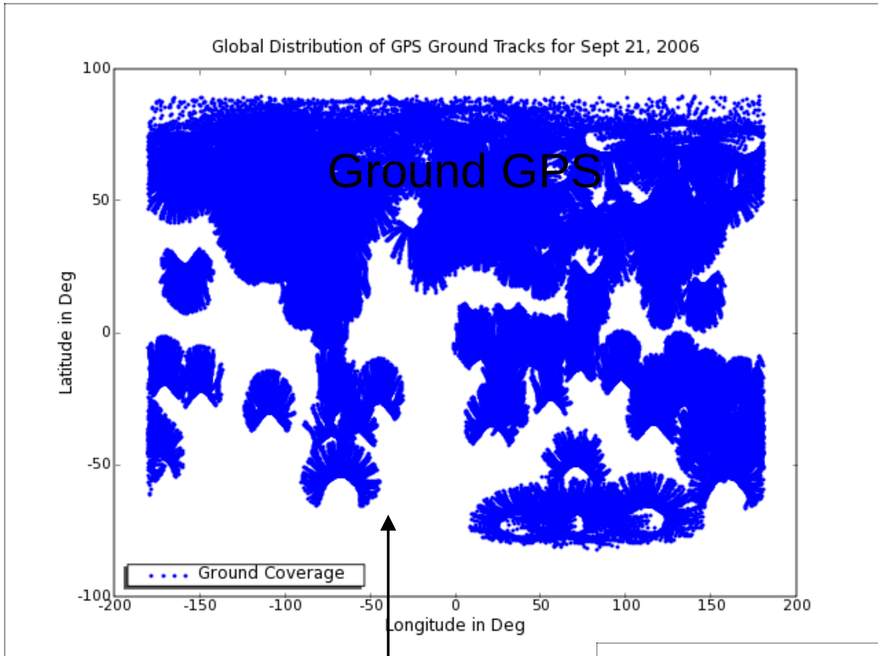


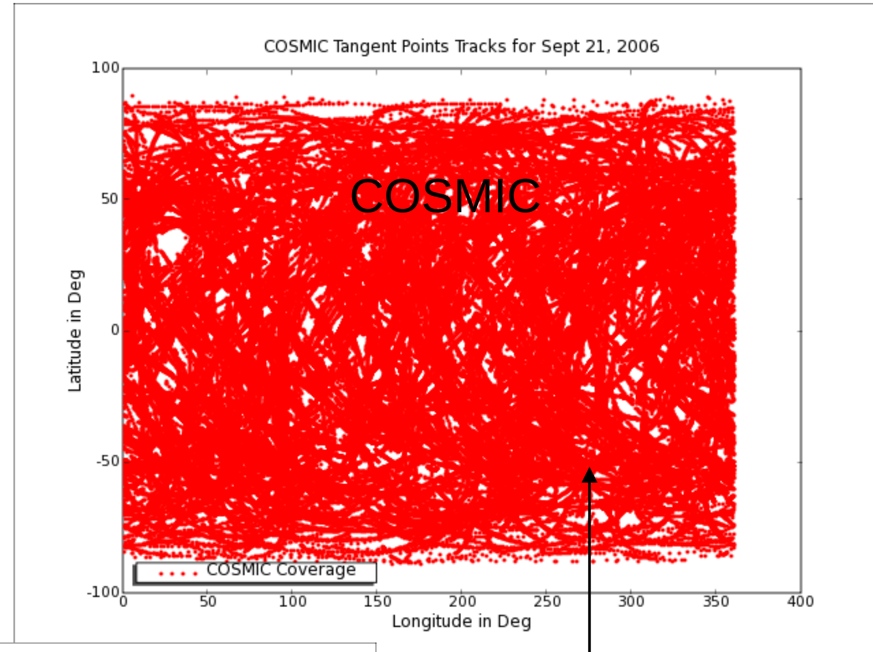


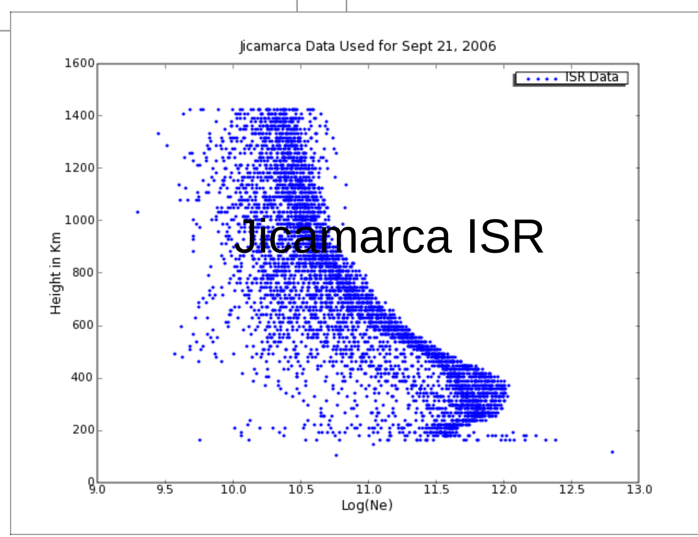




Ground-Based GPS, COSMIC and Jicamarca ISR Coverage for Sept 21, 2014







dense but
unevenly distributed
coverage

less dense yet
evenly distributed
coverage

An Example of COSMIC Impact on Profile Shape