Decadal Survey RFI: Combining Ground-Based and Spaceborne Data for Detecting and Monitoring Ionospheric Signatures Generated by Natural Hazards

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Natural hazards, including earthquakes, volcanic eruptions, and tsunamis, have been significant threats to humans throughout recorded history. The Global Positioning System (GPS) satellites have become primary sensors to measure signatures associated with such natural hazards. These signatures typically include GPS-derived seismic deformation measurements, co-seismic vertical displacements, and real-time GPS-derived ocean buoy positioning estimates. Another way to use GPS observables is to compute the ionospheric total electron content (TEC) to measure and monitor post-seismic ionospheric disturbances caused by earthquakes, volcano eruptions, and tsunamis.

Earthquakes are known to generate electron density irregularities in the ionosphere and TEC variations through atmospheric acoustic waves. There are three types of atmospheric waves typically generated by earthquakes: (1) direct acoustic waves generated near the epicenter; (2) gravity waves generated by a tsunami; (3) secondary acoustic waves excited by the Rayleigh surface wave outside the epicenter area. GPS measurements are well suited to monitor ionospheric activities associated with earthquakes both in the epicenter area (i.e., using dense local GPS networks) and outside of it (i.e., using global GPS networks) with sufficient spatial and temporal resolution to infer key properties such as velocity, direction, and magnitude of traveling ionospheric disturbances (TIDs).

Volcanic eruptions also generate TEC perturbations triggered by acoustic and gravity waves. At ionospheric heights, coupling between neutral particles and free electrons induces electron density fluctuations. TEC fluctuations have been used to estimate explosive energy of a volcanic eruption. Although indirect, using TEC perturbations is becoming increasingly important because of the lack of other reliable means to measure energy content.

Tsunamis have been observed to generate traveling ionospheric disturbances due to internal gravity waves. Such TIDs are distinguishable from TIDs caused by other sources (such as geomagnetic activity or tropospheric weather) by the fact that tsunami-driven TIDs match the period, velocity, and propagation direction of the ocean tsunamis causing them.

Key Challenges:

The *key challenges* the community faces will be to elucidate the mechanics of tsunamigenic earthquakes through a combination of ground-based GNSS receivers and spaceborne assets. This knowledge will aid both the assessment and mitigation of natural hazards and the response to extreme events. The research community will be challenged to quantify the coupling between earthquakes, tsunamis, and tsunami-generated ionospheric TEC perturbations. The ionosphere-based measurements of natural hazards such as earthquakes and tsunamis are surprisingly useful because 1) surface, acoustic, and gravity wave propagation in the upper atmosphere is well-understood using first-principle-based physics models, 2) they may be observed before tsunami arrival at coastlines due to low-elevation measurements and 3) they provide dense measurements of the tsunami signature as opposed to isolated data points from buoys or tsunameters. The combination of ground-based and spaceborne measurements will allow scientists to characterize earthquake-tsunami coupling processes and *better understand tsunami generation or their earthquake sources*. Furthermore, researchers will need to map the spatial extent of both the earthquake and the tsunami-induced TIDs in 3-dimensions by relying on the *ionosphere as a common medium*.

Determining earthquake moment magnitudes (Mw) using ground-based measurements leads to large uncertainties. Due to the complexities of interpreting seismometer measurements and epistemic uncertainties in critical parameters such as Earth structure, the uncertainties in Mw may persist for months and years after the events, such as Mw 8.8 to 9.2 estimates for the Tohoku-Oki event, Mw 8.3 ± 3.3 for the 1964 Alaska earthquake. Tsunamis are predominantly generated by earthquakes. Earthquake-induced landslides and volcanic eruptions are other sources of tsunamis. Seismic data have been the primary measurements for tsunami studies. For earthquake-generated tsunamis, the earthquake magnitude is related to the tsunami energy but the relationship is not yet well understood.

Timeliness:

Many fatalities occur when small earthquakes followed by larger tsunamis go undetected. Accuracy in determination of the tsunami scale – a quantitative representation of the tsunami potential destructive force – is critical. It serves as a threshold for issuing a tsunami warning to affected areas. Earthquake source modeling can be improved using joint inversions of land-based estimates of co-seismic deformation from GPS, near-shore wave gauges, along with novel GPS ionosphere-derived tsunami measurements. The expected results include better earthquake source estimation, initialization of tsunami propagation in near-source coastline, and improvement in inundation forecasts by a factor of 2 as the increase in earthquake magnitude is proportional to the square of the propagation speed. Understanding the relationship of seismic waves to tsunami generation is critical and timely to developing future systems capable of increasing warning time and reducing fatalities as well as material damage.

Why space?

To help decrease the uncertainties in estimating earthquake moment the community will need to leverage the experience with ground-based GPS ionospheric TEC measurements that was gained over the years. The researchers will need to demonstrate that tsunami wave amplitudes and propagation speeds observed by *TID measurements can be inverted using a physics-based model*. For better understanding of earthquake to tsunami energy transfer and its source, and to increase the spatial and temporal coverage over the oceans, a successful inversion will require the use of *spaceborne measurements*. To take advantage of the growing number of low Earth orbiters (LEOs) including the current Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) and upcoming COSMIC-2 constellations and additional NASA remote sensing spacecraft, the community will need to process and analyze the ionospheric radio occultation measurements and spaceborne airglow measurements for investigating earthquake- and tsunami-generated TEC perturbations.

Increasing the temporal and spatial coverage over the oceans using the combination of ground-based GPS and spaceborne ionospheric measurements will help quantify our understanding of the relationship between earthquakes and the subsequent tsunamis. Combining ground-based and spaceborne measurements will make it possible to quantify energies for smaller and therefore more frequent events. Such capability is imperative to understand and quantify the wave coupling of earthquakes and tsunamis to the ionosphere. Researchers will gain a better understanding of errors affecting the tsunami wave heights and vertical surface displacements that have direct impact on the coupling mechanism to the ionosphere.

Responses to the Questions:

a. Is there a capability gap?

Scientists have recently come to the understanding that seismic data alone are unable to provide the level of accuracy required for tsunami modeling and energy transfer estimates. Other ground-based techniques exist to estimate tsunami energy including the use of coastal GPS data and tsunameters. Atmospheric and ionospheric disturbances are promptly generated by earthquakes and tsunamis and contain important geophysical signals on earthquake-tsunami coupling. *However, there exists no other measurement system that is capable of substantially contributing to simultaneously estimating both seismic radiation energy and tsunami energy using spaceborne measurements*. The combination of ground-based and spaceborne measurements provides a unique opportunity to study the spatial extent of seismic events while reducing systematic errors in simultaneously estimated seismic and tsunami energies. Other ground-based measurement techniques either contribute to estimating seismic or tsunami energies but not both.

b. Linking space-based observations with other observations;

Researchers must increase the spatial and temporal measurement coverage over e.g., the Pacific region to investigate coupling between earthquake- and tsunami-generated ionospheric signatures. Up to date no researchers have attempted to use both ground-based and spaceborne measurements to establish a link between acoustic and gravity-wave-generated TEC perturbations associated with the same earthquake and tsunami events.

c. Scientific and Societal Benefits

Earthquakes, tsunamis, and volcanoes are among the most disrupting forces faced by humankind, often endangering heavily populated coastal areas. The tsunami of March 11, 2011 in Japan caused over 10,000 fatalities. The Chilean tsunami of February 27, 2010 and the Samoa tsunami of Sep 29, 2009 caused hundreds of deaths, and the Sumatra tsunami of 2004 took the largest toll of human life on record, with approximately 228,000 casualties attributed to the waves. These tsunamis had a major impact on public consciousness as they made their way across the oceans, affecting distant islands and coasts up to 24 hours after the earthquake. To better prepare society for the consequences of multiple natural hazards, it is our responsibility to help develop early warning systems for which researchers are expected to provide invaluable contributions over the next decade.

d. The science communities that would be involved

Exploring new measurements techniques will be paramount to monitor extreme events, including storms, heat waves, earthquakes and volcanic eruptions. This will represent a major improvement to the current state of knowledge, and one that can be potentially applied to early warning systems in the case of tsunamis, volcanoes, explosions, and other events. Furthermore, the increased temporal and spatial coverage provided to users using spaceborne measurements will be expected to enable scientists in the natural hazards area to estimate the size of inundation, tsunami run-ups and storm surges.