Towards Observing Tsunamis in the Ionosphere Using GPS TEC Measurements

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Tsunamis have been a significant threat to humans living in coastal regions throughout recorded history. The recent tsunami of September 29, 2009 was a tragic reminder of this fact, as the waves caused over 180 deaths on the islands of Samoa, American Samoa, and Apia in the south Pacific. Recent modeling results and observations have demonstrated that the ionospheric signature of an ocean tsunami can potentially be detected as a traveling ionospheric disturbance (TID) produced by internal gravity waves propagating upward in the atmosphere [*e.g., Occhipinti et al.*, (2006, 2008), *Hickey et al.,* (2009), *Mai and Kiang* (2009]. These tsunamigenic TIDs have been demonstrated to be present in ionospheric total electron content (TEC) measurements using ground-based GPS radio signals [e.g., *Artru et al.,* (2005)] and satellite-based altimeter radar [*Occhipinti et al.,* (2006)].

There are many remaining unanswered questions regarding the reliability of detecting tsunamigenic TIDs, including how to distinguish them from regular TIDs of non-tsunamigenic origin, as well as factors affecting the propagation of internal gravity waves into the ionosphere. Recent models show that the magnitude of variations in electron density in the ionosphere due to a tsunamigenic internal gravity wave can depend heavily on the local orientation of the magnetic field [e.g., Occhipinti et al., (2008)], as well as the direction of propagation of the tsunami itself, with meridianol (north-south) propagating waves producing much larger perturbations in TEC than waves propagating zonally (east-west) [*Hickey et al.,* (2009)]. Such nuances may influence our ability to detect tsunamigenic TIDs, and should be thoroughly explored via data analysis of multiple events.

We present ongoing research analyzing ground-based GPS TEC observations during multiple known tsunami events. Specifically, fluctuations in TEC correlated in time, space, and wave properties with ocean tsunamis are observed in TEC estimates processed using JPL's Global Ionospheric Mapping (GIM) system (*e.g., Komjathy et al.,* 2005). Results are discussed in terms of the degree to which a tsunamigenic TID is observed in each case, and the possible causes for failing to observe them.

Comparisons between observations and results from theoretical models of tsunamigenic ionospheric wave propagation are also discussed for specific cases. The Method Of Splitting Tsunami (MOST) model for sea-surface waveform of a tsunami [*Titov and Gonzalez,* 1997] has been produced for multiple major tsunami events around the world by the group at the NOAA Tsunami Research Center, and can be used as an input to the ocean-atmosphere-ionosphere coupling model of *Hickey et al.,* (2009). This model yields estimates of the expected variation in ionospheric electron density as observed in TEC, which can be compared to real observations of GPS TEC from ground-based dual frequency receivers. Initial model runs for the American Samoa 2009 tsunami event indicate that, given the known ocean tsunami waveform observed by tidal gauges and Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys, as well as MOST models of the ocean surface waveform, a detectable variation in vertical TEC of ~1.5% should occur. Review of actual TEC data does reveal TEC variations of the appropriate order of magnitude soon after the seismic event took place, and up to 10 minutes before the ocean tsunami was observed at a tidal gauge in Pago Pago, American Samoa. (See Figures 1 and 2).

This ongoing research will be discussed in terms of the reliability of detecting tsunamigenic TID's, as well as the potential for implementing such detection techniques into the operational tsunami warning system using real-time data in the future.

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Figures:

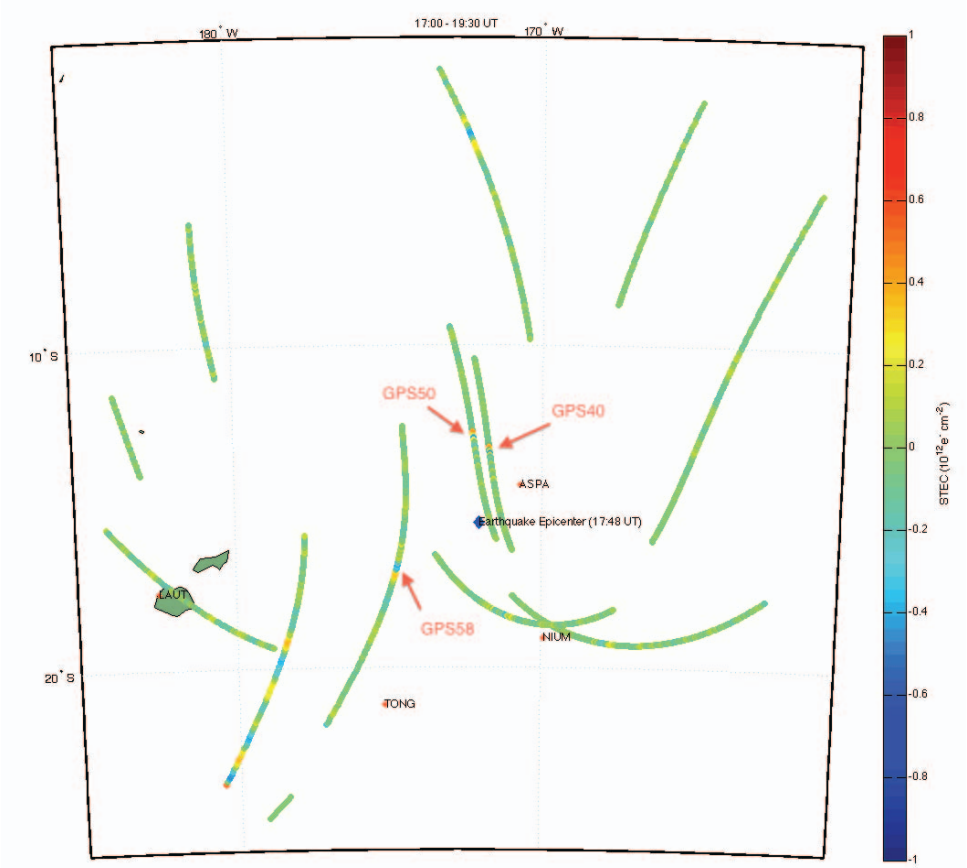

Figure 1. Tracks of the variations in GPS TEC measurements observed from the American Samoa, Pago Pago (ASPA) GPS ground station during the time between 17:00 and 19:30 UT on September 29, 2009. Small variations of ~1 TECU peak-to-peak are thought to be associated with the tsunami.

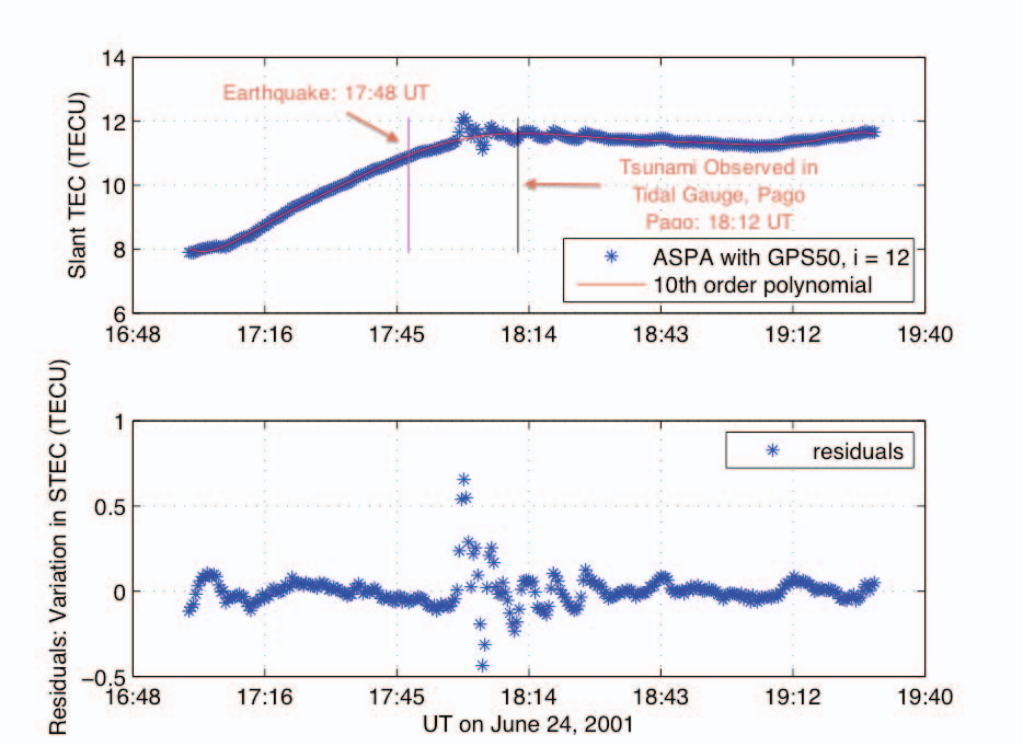

Figure 2. **(Top)** Time series of slant TEC observations between the ASPA (American Samoa, PAgo Pago) GPS ground station and GPS satellite vehicle number 50. The red fit-line shows a 10^{th} order polynomial fit to the data. The magenta vertical line shows the time of the seismic event, and the black vertical line shows the time at which the ocean tsunami was first observed in tidal gauge data at Pago Pago. Note the ionospheric signature of the tsunami was observed ~10 minutes earlier. **(Bottom)** Difference between the TEC data and the polynomial fit. Note the ~1 TECU peak-to-peak disturbance.