Tsunami Detection by GPS

How Ionospheric Observations Might Improve the Global Warning System

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THE TSUNAMI generated by the December 26, 2004, earthquake just off the coast of the Indonesian island of Sumatra killed over 200,000 people. It was one of the worst natural disasters in recorded history. But it might have been largely averted if an adequate warning system had been in place.

A tsunami is generated when a large oceanic earthquake causes a rapid displacement of the ocean floor. The resulting ocean oscillations or waves, while only on the order of a few centimeters to tens of centimeters in the open ocean, can grow to be many meters even tens of meters when they reach shallow coastal areas. The speed of propagation of tsunami waves is slow enough, at about 600 to 700 kilometers per hour, that if they can be detected in the open ocean, there would be enough time to warn coastal communities of the approaching waves, giving people time to flee to higher ground.

INNOVATION INSIGHTS
with Richard Langley

There would be enough time to warn coastal communities.

Seismic instruments and models are used to predict a possible tsunami following an earthquake and ocean buoys and pressure sensors on the ocean bottom are used to detect the passage of tsunami waves. But globally, the density of such instrumentation is quite low and, coupled with the time lag needed to process the data to confirm a tsunami, an effective global tsunami warning system is not yet in place.

However, recent investigations have demonstrated that GPS might be a very effective tool for improving the warning system. This can be done, for example, through rapid determination of earthquake magnitude using data from existing GPS networks. And, incredible as it might seem, another approach is to use the GPS data to look for the tsunami signature in the ionosphere: the small displacement of the ocean surface displaces the atmosphere and makes it all the way to the ionosphere, causing measurable changes in ionospheric electron density.

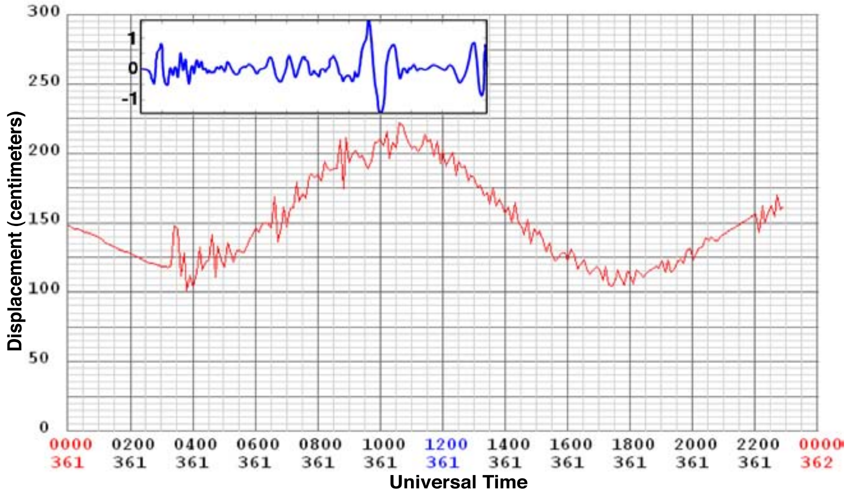
In this month's column, we look in detail at how a tsunami can affect the ionosphere and how GPS measurements of the effect might be used to improve the global tsunami warning system.

"Innovation" is a regular column that features discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who welcomes your comments and topic ideas. To contact him, see the "Contributing Editors" section on page 6.

The December 26, 2004 earthquake-generated Sumatra tsunami caused enormous losses in life and property, even in locations relatively far away from the epicentral area. The losses would likely have never been so massive had an effective worldwide tsunami warning system been in place. A tsunami travels relatively slowly and it takes several hours for one to cross the Indian Ocean, for example. So a warning system should be able to detect a tsunami and provide an alert to coastal areas in its path. Among the strengths of a tsunami early-warning system would be its capability to provide an estimate of the magnitude and location of an earthquake. It should also confirm the amplitude of any associated tsunami, due to massive displacement of the ocean bottom, before it reaches populated areas. In the aftermath of the Sumatra tsunami, an important effort is underway to interconnect seismic networks and to provide early alarms quantifying the level of tsunami risk within 15 minutes of an earthquake.

However, the seismic estimation process cannot quantify the exact amplitude of a tsunami, and so the second step, that of tsunami confirmation, is still a challenge. The earthquake fault mechanism at the epicenter cannot fully explain the initiation of a tsunami as it is only approximated by the estimated seismic source. The fault slip is not transmitted linearly at the ocean bottom due to various factors including the effect of the bathymetry, the fault depth, and the local lithospheric properties as well as possible submarine landslides associated with the earthquake.

In the open ocean, detecting, characterizing, and imaging tsunami waves is still a challenge. The offshore vertical tsunami displacement (on the order of a few cen-



▲ **FIGURE 1** The Sumatra tsunami signal measured at the Cocos Islands by the tide gauge (red) and by the co-located GPS receiver (blue). The tide gauge measures the sea-level displacement (tide plus superimposed tsunami) and the GPS receiver measures the slant *total electron content* perturbation (+/−1 TEC unit) in the ionosphere.

timeters up to half a meter in the case of the Sumatra tsunami) is hidden in the natural ocean wave fluctuations, which can be several meters or more. In addition, the number of offshore instruments capable of tsunami measurements, such as tide gauges and buoys, is very limited. For example, there are only about 70 buoys in the whole world. As a tsunami propagates with a typical speed of 600–700 kilometers per hour, a 15-minute confirmation system would require a worldwide buoy network with a 150-kilometer spacing.

Satellite altimetry has recently proved capable of measuring the sea surface variation in the case of large tsunamis, including the December 2004 Sumatra event. However, satellites only supply a few snapshots along the sub-satellite tracks. Optical imaging of the shore has successfully measured the wave arrival at the coastline (see **PHOTO**), but it is ineffective in the open sea. At present, only ocean-bottom sensors and GPS buoy receivers supply measures of mid-ocean vertical displacement. In many cases, the tsunami can only be identified several hours after the seismic event due to the poor distribution of sensors. This delay is necessary for the tsunami to reach the buoys and for the signal to be recorded for a minimum of one wave period (a typical tsunami wave period is between 10 and 40 minutes) to be adequately filtered by removing the "noise" due to normal wave action.

In the case of the December 2004 Sumatra event, the first tsunami measurements by any instrumentation were only made available about 3 hours after the earthquake. They were supplied by the real-time tide gauge at the Cocos Islands, an Australian territory in the southeast Indian Ocean (see **FIGURE 1** where the tsunami signature is superimposed on the large semidiurnal tide fluctuation). Up until that time, the tsunami could not be fully confirmed and coastal areas remained vulnerable to tsunami damage. This delay in confirmation is a fundamental weakness of the existing tsunami warning systems.

Ionospheric Perturbation. Recently, observational and modeling results have confirmed the existence and detectability of a *tsunamigenic signature* in the ionosphere. Physically, the displacement induced by tsunamis at the sea surface is transmitted into the atmosphere where it produces *internal gravity waves* (IGWs) propagating upward. (When a fluid or gas parcel is displaced at an interface, or internally, to a region with a different density, gravity restores the parcel toward equilibrium resulting in an oscillation about the equilibrium state; hence the term *gravity wave*.) The normal ocean surface variability has a typical high frequency (compared to tsunami waves) and does not transfer detectable energy into the atmosphere. In other words, the Earth's atmosphere behaves as an "analog low-pass filter." Only a tsunami produces propagating waves in the atmosphere. During the upward propagation, these waves are strongly amplified by the double effects of the conservation of kinetic energy and the decrease of atmospheric density resulting in a local displacement of several tens of meters per second at 300 kilometers altitude in the atmosphere. This displacement can reach a few hundred meters per second for the largest events.

At an altitude of about 300 kilometers, the neutral atmosphere is strongly coupled with the ionospheric plasma producing perturbations in the electron density. These perturbations are visible in GPS and satellite altimeter data since those signals have to transit the ionosphere. The dual-frequency signal emitted by GPS satellites can be processed to obtain the integral of electron density along the paths between the satellites and the receiver, the total electron content (TEC).

Within *about 15 minutes*, the waves generated at the sea surface reach ionospheric altitudes, creating measurable fluctuations in the ionospheric plasma and consequently in the TEC. This indirect method of tsunami detection should be helpful in ocean monitoring, allowing us to follow an oceanic wave from its generation to its propagation in the open ocean.

So, can ionospheric sounding provide a robust method of tsunami confirmation? It is our hope that in the future this technique can be incorporated into a tsunami early-warning system and complement the more traditional methods of detection including tide gauges and ocean buoys. Our research focuses on whether ground-based GPS TEC measurements combined with a numerical model of the tsunami-ionosphere coupling could be used to detect tsunamis robustly. Such a detection scheme depends on how the ionospheric signature is related to the amplitude of the sea surface displacement resulting from a tsunami. In the near future, the ionospheric monitoring of TEC perturbations might become an integral part of a tsunami warning system that could potentially make it much more effective due to the significantly increased area of coverage and timeliness of confirmation.

In this article, we'll take a look at the current state of the art in modeling tsunami-generated ionospheric perturbations and the status of attempts to monitor those perturbations using GPS.

Some Background

Pioneering work by the Canadian atmospheric physicist Colin Hines in the 1970s suggested that tsunami-related IGWs in the atmosphere over the oceanic regions, while interacting with the ionospheric plasma, might produce signatures detectable by radio sounding.

In June 2001, an episodic perturbation was observed following a tsunamigenic earthquake in Peru. After its propagation across the Pacific Ocean (taking about 22 hours), the tsunami reached the Japanese coast and its signature in the ionosphere was detected by the Japanese GPS dense network (GEONET). The perturbation, shown in **FIGURE 2**, has an arrival time and characteristic period consistent with the tsunami propagation determined from independent methods. Unfortunately, similar signatures in the ionosphere are also produced by IGWs associated with traveling ionospheric disturbances (TIDs), and are commonly observed in the TEC data. However, the known azimuth, arrival time, and structure of the tsunami allows us to use this data source, even if it contains background TIDs.

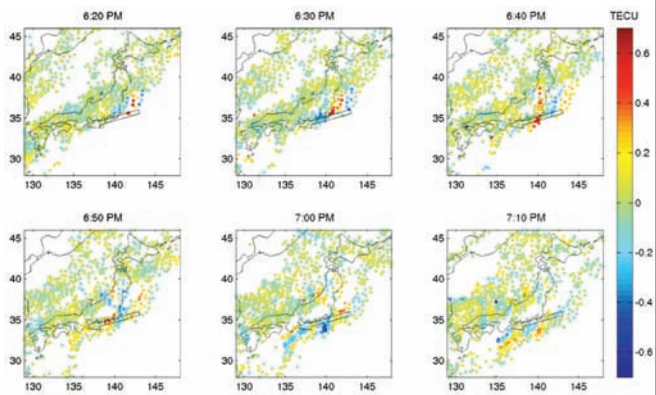
The December 26, 2004, Sumatra earthquake, with a magnitude of 9.3, was an order of magnitude larger than the Peru event and was the first earthquake and tsunami of magnitude larger than 9 of the so-called "human digital era," comparable to the magnitude 9.5 Chilean earthquake of May 22, 1960.

In addition to seismic waves registered by global seismic networks, the Sumatra event produced infragravity waves (long-period wave motions with typical periods of 50 to 200 seconds) remotely observed from the island of Diego Garcia, perturbations in the magnetic field observed by the CHAMP satellite, and a series of ionospheric anomalies.

Two types of ionospheric anomaly were observed: anomalies of the first type, detected worldwide in the first few hours after the earthquake, were reported from north of Sumatra, in Europe, and in Japan. They are associated with the surface seismic waves that propagate around the world after an earthquake rupture (so-called Rayleigh waves).

Anomalies of the second type were detected above the ocean and were clearly associated with the tsunami. In the Indian Ocean, the occurrence times of TEC perturbations observed using ground-based GPS receivers and satellite altimeters were consistent with the observed tsunami propagation speed. The GPS observations from sites to the north of Sumatra show internal gravity waves most likely coupled with the tsunami or generated at the source and propagating independently in the atmosphere. The link with the tsunami is more evident in the observations elsewhere in the Indian Ocean. The TEC perturbations observed by the other ground-based GPS receivers moved horizontally with a velocity coherent with the tsunami propagation.

▲ **QUICKBIRD SATELLITE IMAGE** of Kalutara Beach on the south-western coast of Sri Lanka showing the receding waters and beach damage from the Sumatra tsunami.



▲ **FIGURE 2** The observed signal for the June 23, 2001, tsunami (initiated offshore Peru). Total electron content variations are plotted at the ionosphere pierce points. A wave-like disturbance is seen propagating toward the coast of Honshu, the main island of Japan.

The amplitude of the observed TEC perturbations is strongly dependent on the filter method used. The four TECU-level peak-to-peak variations in filtered GPS TEC measurements from north of Sumatra are coherent with the differential TEC at the 0.4 TECU per 30 seconds level observed in the rest of the Indian Ocean. (One TEC unit or TECU is 10^{16} electrons per meter-squared, equivalent to 0.162 meters of range delay at the GPS L1 frequency.) Such magnitudes can be detected using GPS measurements since GPS phase observables are sensitive to TEC fluctuations at the 0.01 TECU level. We emphasize also the role of the elevation angle in the detection of tsunamigenic perturbations in the ionosphere. As a consequence of the integrated nature of TEC and the vertical structure of the tsunamigenic perturbation, low-elevation angle geometry is more sensitive to the tsunami signature in the GPS data, hence it is more visible.

The TEC perturbation observed at the Cocos Islands by GPS can be compared with the co-located tide-gauge (Figure 1). The tsunami signature in the data from the two different instruments shows a similar waveform, confirming the sensitivity of the ionospheric measurement to the tsunami structure.

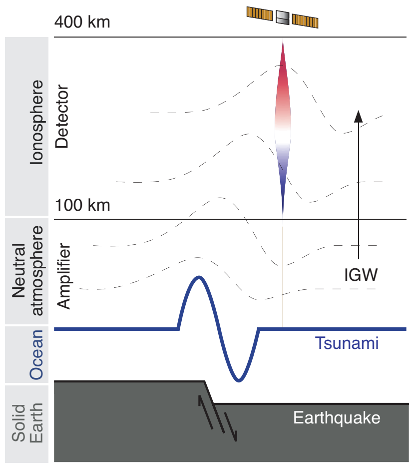
The link between the tsunami at sea level and the perturbation observed in the ionosphere has been demonstrated using a 3D numerical modeling based on the coupling between the ocean surface, the neutral atmosphere, and the ionosphere (see **FIGURE 3**). The modeling reproduced the TEC data with good agreement in amplitude as well as in the waveform shape, and quantified it by a cross-correlation (see **FIGURE 4**). The resulting shift of +/– 1 degree showed the presence of zonal and meridional winds neglected in the modeling. The presence of the wind can, indeed, introduce a shift of 1 degree in latitude and 1.5 degrees in longitude.

Since modeling is an effective method to discriminate between the tsunami signature in the ionosphere and other potential perturbations, the GPS observations can be a useful tool to develop an inexpensive tsunami detection system based on the ionospheric sounding.

Modeling TEC Perturbations

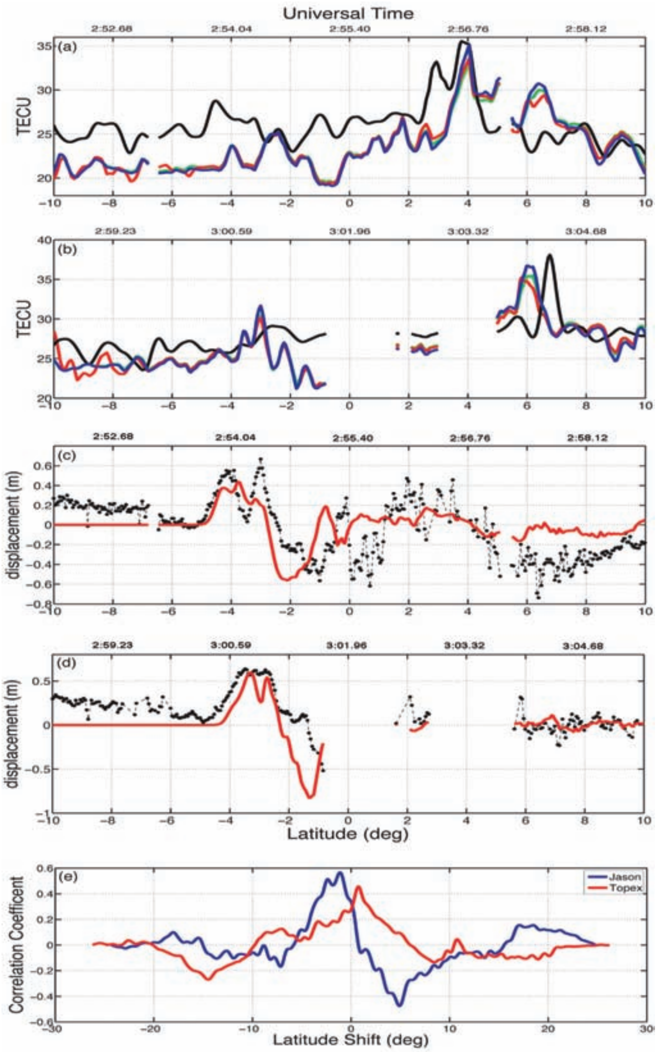
A model to describe the effect of a tsunami on the ionosphere has been developed at the Institut de Physique du Globe de Paris (IPGP), France. It is comprised of three main parts. Firstly, it computes tsunami propagation using realistic bathymetry of, for example, the Indian Ocean. Secondly, an oceanic displacement is used to excite IGWs in the neutral atmosphere. Thirdly, it computes the response of the ionosphere induced by the neutral atmospheric motion resulting in enhanced electron densities. After integrating the electron densities, we obtain modeled (synthetic) TEC data. The modeling steps are as follows:

Tsunami Propagation. Tsunami modeling is an established science and the propagation of tsunamis is generally based on a shallow-water hypothesis. Under this hypothesis, the ocean is considered as a simple layer where the ocean depth, h, is locally taken into account in the tsunami propagation velocity, $v = \sqrt{hg}$, which directly depends on h and the gravity acceleration g. The modeling, usually based on finite differences, solves the appropriate hydrodynamic equations.



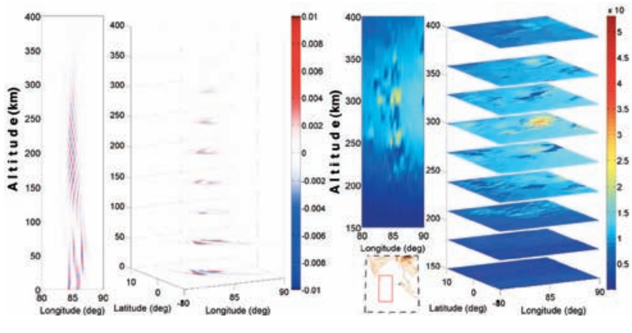
▲ **FIGURE 3** The tsunamigenic earthquake mechanism and transfer of energy in the neutral and ionized atmosphere. The solid Earth displacement produces the tsunami and the sea surface displacement produces an internal gravity wave in the neutral atmosphere, which perturbs the electron distribution in the ionosphere.

Neutral Atmosphere Coupling. A tsunami is an oceanic gravity wave and its



▲ **FIGURE 4** Satellite altimeter and total electron content (TEC) signatures of the Sumatra tsunami. The modeled and observed TEC is shown for (a) Jason-1 and for (b) Topex/Poseidon: data (black), synthetic TEC without production-recombination-diffusion effects (blue), with production-recombination (red), and production-recombination-diffusion (green). The Topex/Poseidon synthetic TEC has been shifted up by 2 TEC units. In (c) and (d), the altimetric measurements of the ocean surface (black) are plotted for the Jason-1 and Topex/Poseidon satellites, respectively. The synthetic ocean displacement, used as the source of internal gravity waves in the neutral atmosphere, is shown in red. In (e), the cross-correlations between TEC synthetics and data are shown for Jason-1 (blue) and Topex/Poseidon (red).

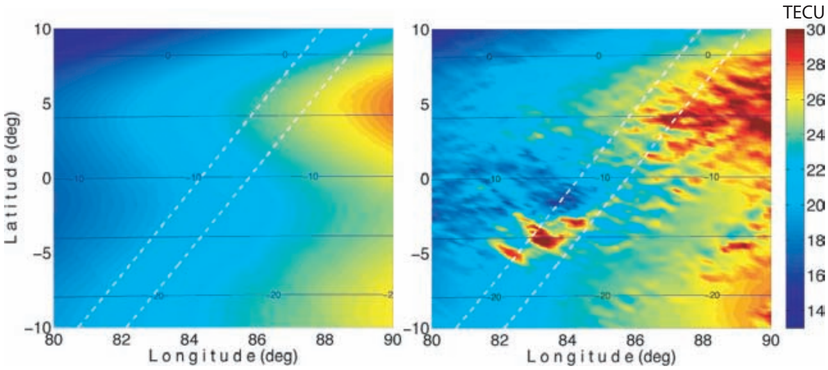
propagation is not limited to the oceanic surface; as previously discussed, the ocean displacement is transferred to the atmosphere where it becomes an internal gravity wave. This coupling phenomenon is linear and can be reproduced solving the wave propagation equations, nominally the continuity and the so-called Navier-Stokes equations. These equations are solved assuming the atmosphere to be irrotational, inviscid, and incompressible. The IGWs are, indeed, imposed by displacement of the mass under the effect of the gravity force, contrary to the elastic waves generated by compression (for example, sound waves), so the medium can be considered incompressible. **FIGURE 5** (left) shows the IGWs produced by the Sumatra tsunami. The inversion of the velocity with altitude (wind shear) is a typical structure of IGWs.



▲ **FIGURE 5** Internal gravity waves (IGWs) generated by the Sumatra tsunami and the response of the ionosphere to neutral motion at 02:40 UT (almost two hours after the earthquake). On the left, the normalized vertical velocity induced by tsunami-generated IGWs in the neutral atmosphere is shown. On the right, the perturbation induced by IGWs in the ionospheric plasma (in electrons per cubic meter) is shown, with the maximum perturbation at an altitude of about 300 kilometers. The vertical cut shown in these profiles is at a latitude of −1 degree.

Neutral-Plasma Coupling. The tsunamigenic IGWs are injected into a 3D ionospheric model to reproduce the induced electron density perturbations. In essence, the coupling model solves the hydromagnetic equations for three ion species (O_2^+, NO^+, and O^+). Physically, the neutral atmosphere motion induces fluctuations in the plasma velocity by way of momentum transfer driven by collision frequency and the Lorentz term associated with Earth's magnetic and electric fields. Ion loss, recombination, and diffusion are also taken into account in the ion continuity equation. Finally, the perturbed electron density is inferred from ion densities using the charge neutrality hypothesis. The International Reference Ionosphere model is used for background electron density; SAMI2 (a recursive acronym: SAMI2 is Another Model of the Ionosphere) is used for collision, production, and loss parameters; and a constant geomagnetic field is assumed based on the International Geomagnetic Reference Field. **FIGURE 5** (right) shows the perturbation induced in the ionospheric plasma by the tsunamigenic IGW following the Sumatra event. The perturbation is strongly localized to around 300 kilometers altitude where the electron density background is maximized.

The resulting electron density dynamic model described above allows us to compute a map of the perturbed TEC by simple vertical integration (see **FIGURE 6**). In addition to the geometrical dispersion of the tsunami, the TEC map shows horizontal heterogeneities in the electron density perturbation that are induced by the geomagnetic field inclination. The magnetic field plays a fundamental role in the neutral-plasma coupling, resulting in a strong amplification at the magnetic equator where the magnetic field is directed horizontally. The isolated perturbation appearing more to the south is probably induced by the full development of the IGW in the atmosphere. Recent work



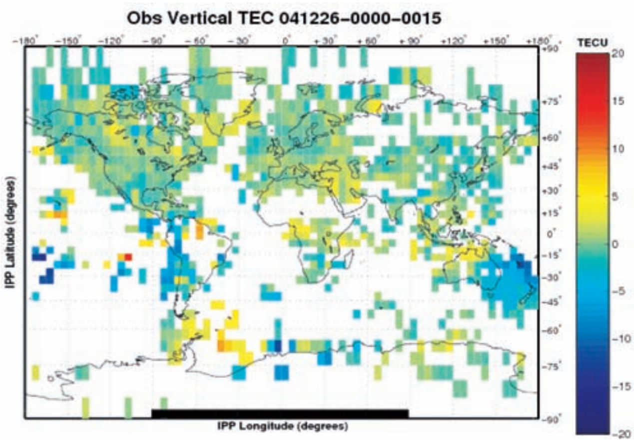
▲ **FIGURE 6** The signature of the Sumatra tsunami in total electron content (TEC) at 03:18 UT (right) compared with the unperturbed TEC (left). The TEC images have been computed by vertical integration of the perturbed and unperturbed electron density fields. The broken lines represent the Topex/Poseidon (left) and Jason-1 (right) trajectories. The blue contours represent the geomagnetic field inclination.

also explains this second perturbation as induced by the role of the magnetic field in the neutral-plasma coupling.

GPS Data Processing

To validate our model, we use ground-based GPS receivers to look for the ionospheric signal induced by tsunamis. Prior research has shown post-processed results detecting a tsunami-generated TEC signal using regional GPS networks such as GEONET in Japan (about 1,000 stations) or the Southern California Integrated GPS Network (about 200 stations). Those studies benefited from the very high density of GPS receivers in the regional networks, so that, for example, no forward modeling was needed to help initially identify the characteristics of the tsunami-generated signal.

High-Precision Processing. More than 1,300 globally-distributed dual-frequency GPS receivers are available using publicly accessible networks, including those of the International GNSS Service and the Continuously Operating GPS Stations coordinated by the U.S. National Geodetic Survey. Most researchers estimate vertical ionospheric structure and, simultaneously, treat hardware-related biases as nuisance parameters. In our approach for calibrating GPS receiver and satellite inter-frequency biases, we take advantage of all available GPS receivers using a new processing technique based on the Global Ionospheric Mapping software developed at the Jet Propulsion Laboratory (JPL). **FIGURE 7** shows a JPL TEC map using 1,000 GPS stations. This new capability is designed to estimate receiver biases for



▲ **FIGURE 7** The total electron content (TEC) between 01:00 and 01:15 UT on December 26, 2004, at ionosphere pierce points (IPPs) provided by a global network of more than 1,000 GPS tracking stations. To highlight variations, a five-day average of TEC has been subtracted from the observed TEC.

all stations in the global network. We solve for the instrumental biases by modeling the ionospheric delay and removing it from the observation.

Ionospheric Warning System

The currently implemented tsunami warning system uses seismometers to detect earthquakes and to perform an estimation of the seismic moment by monitoring seismic waves. After a potential tsunami risk is determined, ocean buoy and pressure sensors have to confirm the tsunami risk. Unfortunately, the number of available ocean buoys is limited to about 70 over the whole planet. With the existing system, it may take several hours to confirm a tsunami when taking into account both the propagation time (of tsunamis reaching buoys) and data-processing time. On the other hand, the proposed ionosphere-based tsunami detection system may only require the propagation time and data-processing delays of only up to about 15–30 minutes. GPS receivers are able to sound the ionosphere up to about 20 degrees away from the receiver location, and a dense GPS network can therefore increase the coverage of the monitored area.

The fundamental idea behind a detection method is that we need to separate tsunami-generated TEC signatures from other sources of ionospheric disturbances. However, the tsunami-generated TEC perturbations are distinguishable because they are tied to the propagation characteristics of the tsunami. Tsunami-related fluctuations should be in the gravity-wave period domain and cohere in geometry and distance with the earthquake epicenter (for example, they show up in data on multiple satellites from multiple stations and, with increasing distance from the epicenter, at a rate related to tsunami propagation speed).

The coupled tsunami model described earlier can also be used to compute a prediction for the tsunami-generated TEC perturbation based on the seismic displacement as an input parameter to the model. The model prediction may be used as a detection aid by indicating the location of the tsunami wave front with time. This permits us to focus our detection efforts on specific locations and times, and will allow us to discriminate signal from noise.

The model also provides information on the expected magnitude of the TEC perturbation. This provides further value in filter discrimination. Cross-correlations can be performed on nearby observations using different satellites and stations to take advantage of tsunami-related perturbations being coherent in geometry and distance from the epicenter. Once the signal is detected in data from multiple satellites and stations, we can "track" and image the tsunami during its propagation in space and time.

The goal of our research is to assess the feasibility of detecting tsunamis in near real time. This requires that GPS data be acquired rapidly. Rapid availability of ground-based GPS data has been demonstrated via the NASA Global Differential GPS System, a highly accurate, robust real-time GPS monitoring and augmentation system.

Conclusions

Earlier research using GPS-derived TEC observations has revealed TEC perturbations induced by tsunamis. However, in our research, we use a combination of a coupled ionosphere-atmosphere-tsunami model with large GPS data sets. Ground-based GPS data are used to distinguish tsunami-generated TEC perturbations from background fluctuations. Tsunamis are among the most disrupting forces humankind faces. The December 26, 2004, earthquake and resulting tsunami claimed more than 200,000 lives, with several hundreds of thousands of people injured. The damage in infrastructure and other economic losses were estimated to be in the range of tens of billions of dollars. To help prevent such a global disaster from occurring again, we suggest that ionospheric sounding by GPS be integrated into the existing tsunami warning system as soon as possible.

Acknowledgments

This article is based on the paper "Three-Dimensional Waveform Modeling of Ionospheric Signature Induced by the 2004 Sumatra Tsunami" published in *Geophysical Research Letters.* ⊕

GIOVANNI OCCHIPINTI received his Ph.D. at the Institut de Physique du Globe de Paris (IPGP) in 2006. In 2007, he joined NASA's Jet Propulsion Laboratory (JPL), California Institute of Technology, as a postdoctoral fellow to continue his work on the detection and modeling of tsunamigenic perturbations in the ionosphere. He will soon take up the position of assistant professor at the University of Paris and IPGP. His scientific interests are focused on solid Earth-atmosphere-ionosphere coupling.

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PHILIPPE LOGNONNÉ is the director of the Space Department of IPGP, a professor at the University of Paris VII, and a junior member of the Institut Universitaire de France. His science interests are in the field of remote sensing and are related to the detection of seismic waves and tsunamis in the ionosphere. Also, he participates in several projects in planetary seismology.

FURTHER READING

■ Ionospheric Seismology

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■ Ionospheric Effects on GPS

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■ Real-time GPS Data Collection and Dissemination

NASA Global Differential GPS System *<http://www.gdgps.net>*