Analysis of GPS TEC TIDs
Launched by the 2011 Tohoku Earthquake

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• At ionospheric heights, the motion of the neutral gas in the AGW sets the ionosphere into motion.

• The waves displace the isoionic contours, resulting in a travelling ionospheric disturbance (TID).

• Traditionally, TIDs observed in the $F$ region have been classified into two categories
  - Medium Scale TIDs (MSTIDs)
  - Large Scale TIDs (LSTIDs)

• Confusion: In past 10 yrs, another class of TIDs has been identified – *electrobuoyancy waves*. Unfortunately, they have been labelled “MSTIDs”, which has confused the community.
• Large-Scale Traveling Ionospheric Disturbances (LSTID)
  ▸ Amplitude: \( \sim 20\% \)
  ▸ Wavelength: 300 - 5,000 km
  ▸ Propagation velocity: 300 - 1000 m/s, equatorward
  ▸ Occurrence: Geomagnetic activity (Kp) dependence

• Medium-Scale Traveling Ionospheric Disturbances (MSTID)
  ▸ Amplitude: \( \sim 10\% \) (0.5 - >1.5 TECU)
  ▸ Wavelength: 100-300 km, Propagation velocity: 50-300 m/s

### Classification of Gravity Waves/TIDs

<table>
<thead>
<tr>
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<th>Medium Scale</th>
<th>Large Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>10-60 min</td>
<td>1-5 hr</td>
</tr>
<tr>
<td>( V_H ) (m/s)</td>
<td>50-300</td>
<td>300-1000</td>
</tr>
<tr>
<td>( \lambda_H ) (km)</td>
<td>100-300</td>
<td>300-5000</td>
</tr>
</tbody>
</table>

Electrobuoyancy Waves? (Erroneously called “MSTIDs”)
A magnitude 9.0 earthquake occurred on March 11, 2011 at 05:46:23 UT near the northeast coast of Honshu, Japan.

Figure shows the NOAA simulations of the 2011 Tohoku tsunami source and water heights over a tsunami travel time (TTT) map.

According to these simulations, the tsunami reached the west coast of the United States about 10 to 11 hours after the earthquake.
TIDDBIT Sounder - Peru

4.605 MHz, O-mode

Tsunami TIDs

Lurin

Huaura
Galvan et al. [2011] studied ionospheric perturbations caused by the Tohoku earthquake and tsunami. Perturbations were found in TEC near the epicenter of the 2011 earthquake.

Makela et al. [2011] presented observations of the airglow signature of GW, resulting from the 11 March 2011 Tohoku earthquake off the eastern coast of Japan.
GPS Data Analysis

- ~4000 GPS receivers throughout the continental United States

- Provides a 2D spatial map of TEC perturbations, which can be used to calculate TID parameters, including horizontal wavelength, phase speed, and period.

- The work presented in this paper demonstrates a technique for the study of ionospheric perturbations that can affect navigation, communications and surveillance systems.
• Near-field waves appear as spherical wave fronts
  ➢ Example: Thunderstorm

• Far-field waves appear as plane waves
  ➢ Example: Tsunami above the West Coast of US from the 2011 Tohoku Tsunami

• Develop algorithms to extract coherent wave features in 2D maps of GPS TEC perturbations

• Augmented 3D FFT algorithms to extract parameters of all extracted waves
TIDs in GPS TEC over the Western US

(a) 15:30 UT

(b) 16:40 UT

(c) 17:10 UT

(d) 18:10 UT
A subset of GPS data was selected covering the Western United States of ~4°x4° in latitude and longitude.

Within this region, a 2 hour time window was selected from 17:03:30 to 19:03:30 UTC, representative of the TID passing through this region.

A 3D FFT was calculated for this 3D “block,” and the data are zero padded to provide interpolation in the frequency domain.
From the $k_x$ vs. $k_y$ “slice” of the maximum value of the FFT, we computed the horizontal wavelength and azimuth of the wave.

From the FFT of the third dimension (i.e., time) we estimate the wave period.

<table>
<thead>
<tr>
<th>Wave Parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Period</td>
<td>15.1 min</td>
</tr>
<tr>
<td>Horizontal Wavelength ($\lambda_H$)</td>
<td>194.8 km</td>
</tr>
<tr>
<td>Phase Speed ($\nu_p$)</td>
<td>215.0 m/s</td>
</tr>
<tr>
<td>Azimuth ($\theta$)</td>
<td>105.2°</td>
</tr>
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</table>
• Used GPS receivers to image TIDs over the US
• Quantitative characterization of the occurrences of TIDs over CONUS
• 11 March 2011 Tohoku tsunami.
• The tsunami propagated across the Pacific to the West Coast of the US over a ten-hour period
• Corresponding TIDs were observed in ionospheric TEC measurements.
• The period of the wave was 15.1 minutes with a horizontal wavelength of 194.8 km, phase velocity of 233.0 m/s, and an azimuth of 105.2° (propagating in the direction of the tsunami wave).
• Consistent with TID observations in airglow measurements from Hawaii earlier in the day, and other GPS TEC observations.
• Observations of long range propagation of TIDs have significant implications for advancing our understanding of TID sources including earthquakes, tsunamis, large explosions, etc