How to catch a tsunami wave by monitoring the ionosphere

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*Supported by Centre national d'études spatiales (CNES) and Agence National de la Recherche (ANR)

Introduction

- Conventional tsunami early warning systems are limited
- As tsunamis waves propagate across an ocean, they couple with the atmosphere at ocean surface, generating waves called internal gravity waves (IGW)
- The IGW impact on the ionosphere can be monitored with GNSS
- Our aim is to discriminate the tsunami imprint from other phenomena

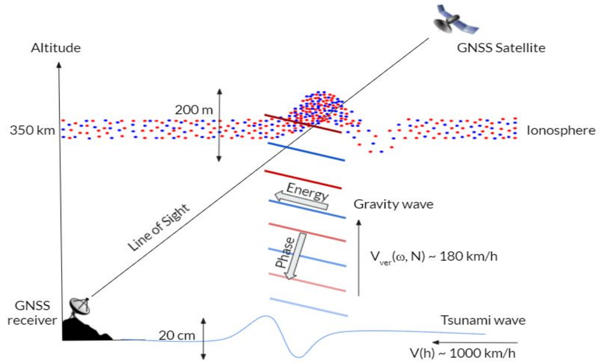

Figure 1. Schematic illustration of tsunami-induced gravity waves and their interaction with the ionosphere (Adapted from Artru et al. 2005). h, ω and N are the ocean depth, the wave angular frequency and Brunt-Väisälä frequency, respectively.

The case of a 2-cm tsunami

The tsunami produced by the 2012 7.8Mw Haida Gwaii Earthquake (Canada) reached Hawaii with an amplitude of 2cm

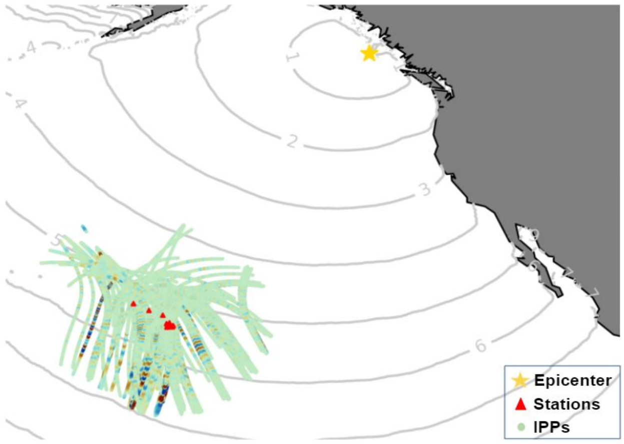

Figure 2. Map showing the epicenter of the 2012 7.8Mw Haida Gwaii Earthquake, the GNSS receivers located at Hawaii archipelago, the subsequent tsunami traveling times, and the intersection between satellites line of site with the ionospheric layer (IPPs) at 350 km altitude.

Monitoring procedure

- In order to identify the signature of tsunami-induced gravity waves in the ionosphere using the GNSS systems, the procedure illustrated in the flowchart (**Fig. 3**) is followed
- GNSS data source: UNAVCO (Miklius, A. 2004), and CDDIS (Noll, C. 2010)

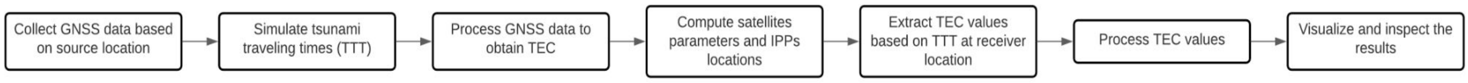

Figure 3. Flowchart outlining the processing steps followed in the analysis to identify tsunami-induced TEC signatures.

Discriminating a 2cm tsunami in the ionosphere

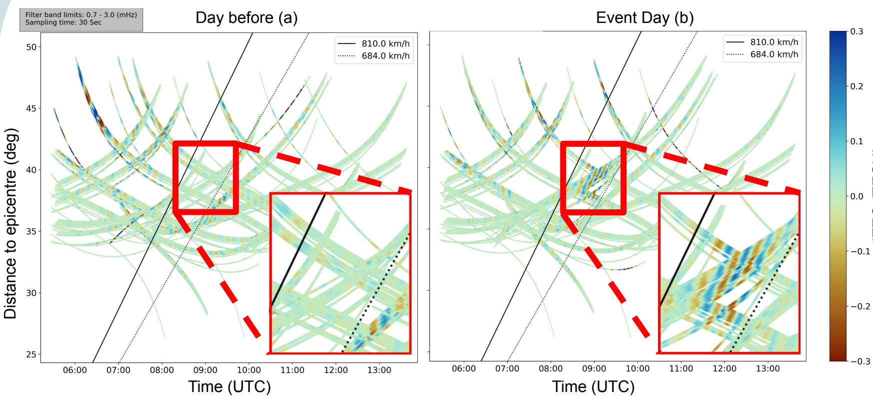

Figure 4. Hodochrones (distance vs time plots) for the event day (b) and day before (a) overplotted with lines starting at the event time with velocities (slops) of 190 m/s (dotted line) and 225 m/s (solid line) that approximate the velocity of the tsunami. The colorbar indicates the value of the processed (detrended with polynomial of degree 10 and filtered with limits 0.7 and 3 mHz) slant TEC. It presents the Haida Gwaii event results, where one can see a propagating pattern in the event day that's consistent with the tsunami speed (b) and absent from the day before (a).

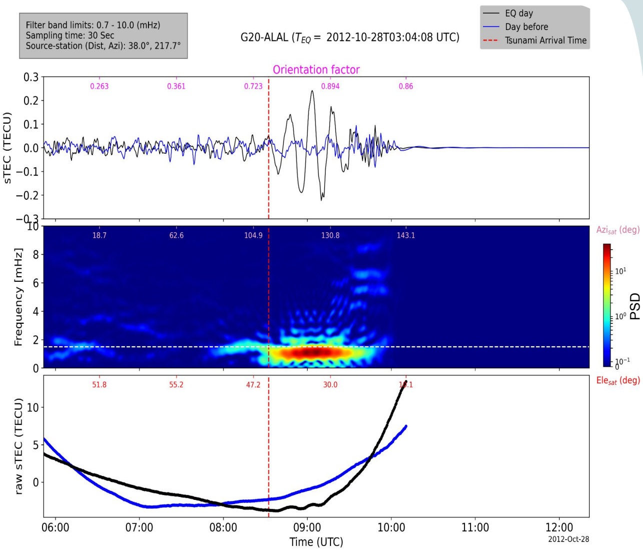

Figure 5. Waveform plots for satellite-station pair time series. Top panel: processed TEC time series of the event day (black) and one day before (blue) overplotted with the tsunami arrival time (dashed vertical red line). Middle panel: spectrogram of the event day TEC time series overplotted with a horizontal line (dashed white) at 1.5 mHz, indicating the expected dominant frequency of the tsunami IGW signature. Bottom panel : raw TEC time series on the event day (black) and the day before (blue). The satellite used here is #20 of the GPS constellation, and the station is ALAL located on Hawaii island. One can see a wave pattern following the expected tsunami arrival time that is non-present the day before. The spectrogram puts the wave peak frequency 0.3mHz below expected. There are no artifacts in the raw data, and the orientation factor depicted on the top axis of the top panel indicates favorable tsunami IGW detection conditions.

Hodochrones (**Fig. 4**) (Artru et al. 2005):

- Highlight gravity waves (low-pass filtering < 3mHz)
- Search for propagating features originating from the earthquake epicentre (hodochrone plots)
- Assess that the wave characteristics are consistent with the tsunami (same speed)
- Discriminate from other phenomena (should be present only near the expected time, so not the day before)

Waveforms (**Fig. 5**) (Rolland et al. 2010):

- Search for wave pattern after the expected tsunami arrival time and ensure its non-existence in the day before
- Inspect the spectrogram to confirm that the pattern is within the expected frequency limits of the tsunami
- Ensure the raw data don't possess artifacts (gaps, jumps)
- Assess the favorability of detection (orientation factor (Grawe and Makela 2015), satellite elevation and azimuth)

Conclusions

- Monitoring the ionosphere for tsunami-induced gravity waves has the potential to complement the conventional tsunami early-warning systems. It can provide a way to detect tsunamis and estimate their amplitude in areas that lack such conventional systems (e.g., open oceans)
- Global navigation satellite system (GNSS) constellations present a reliable and cheap platform to continuously observe and investigate the ionosphere for perturbations that may result from surface disturbances such as tsunamis in an almost real-time fashion
- Once a detection confirmed, the next step is to invert the identified signature to retrieve the tsunami wave height, the quantity usable by tsunami early warning systems

References

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