Real-Time TEC-Based Tsunami Detection with VARION Algorithm and Stand-Alone GNSS Receivers

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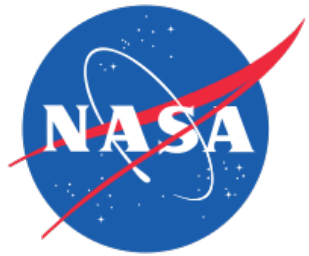

Outline

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Real-Time Detection of Tsunami Ionospheric Disturbances with a Stand-Alone GNSS Receiver: A Preliminary Feasibility Demonstration

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It is well known that tsunamis can produce gravity waves that propagate up to the ionosphere generating disturbed electron densities in the E and F regions. These ionospheric disturbances can be studied in detail using ionospheric total electron content (TEC) measurements collected by continuously operating ground-based receivers from the Global Navigation Satellite Systems (GNSS). Here, we present results using a new approach, named VARION (Variometric Approach for Real-Time Ionosphere Observation), and estimate slant TEC (sTEC) variations in a real-time scenario. Using the VARION algorithm we compute TEC variations at 56 GPS receivers in Hawaii as induced by the 2012 Haida Gwaii tsunami event. We observe TEC perturbations with amplitudes of up to 0.25 TEC units and traveling ionospheric perturbations (TIDs) moving away from the earthquake epicenter at an approximate speed of 316 m/s. We perform a wavelet analysis to analyze localized variations of power in the TEC time series and we find perturbation periods consistent with a tsunami typical deep ocean period. Finally, we present comparisons with the real-time tsunami MOST (Method of Splitting Tsunami) model produced by the NOAA Center for Tsunami Research and we observe variations in TEC that correlate in time and space with the tsunami waves.

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VARION Algorithm for Real-Time TIDs Detection

Idea

- designed in 2015 at **University of Rome "La Sapienza", VADASE team**
- developed and validated in 2016 in collaboration with the **Jet Propulsion Laboratory, Ionospheric and Atmospheric Remote Sensing Group**

Methodology

- **Variation of the sTEC**
  - **double frequencies phase observations** (1s, 15s, 30s)
  - **geometry free combination** (L4), remove the geometry, clocks and all non-dispersive effects
  - **time single differences of geometry free observations** remove **phase ambiguity** and **IFB**, assumed as constant for a given period
  - **cycle slips** detected as **outliers**
- **Total sTEC determination**
  - **Integration** of variations of the sTEC

Algorithm (1/2)

Carrier-Phase observation

$$L_{iR}^{S}(t) = \rho_{R}^{S}(t) + c(\delta t_R(t) - \delta t^{S}(t)) + T_{R}^{S}(t) - I_{iR}^{S}(t) + \lambda_i N_{iR}^{S}(t) + \\ + p_R{}^{S}(t) + m_{iR}^{S}(t) + \epsilon_R{}^{S}(t) \quad (1)$$

Geometry-free Combination Equation

$$L_{4R}^{S}(t) = L_{1R}^{S}(t) - L_{2R}^{S}(t) = -I_{1R}^{S}(t) + I_{2R}^{S}(t) + \lambda_1 N_{1R}^{S}(t) - \lambda_2 N_{2R}^{S}(t) \quad (2)$$

Geometry-free Time Single-Difference Observation Equation

$$L_{4R}^{S}(t+1) - L_{4R}^{S}(t) = \frac{f_1^2 - f_2^2}{f_2^2} \left[I_{1R}^{S}(t+1) - I_{1R}^{S}(t) \right] \quad (3)$$

Algorithm (2/2) - TEC Estimation

TEC variations between two consecutive epochs

$$\delta TEC(t+1,t) = \frac{{f_1}^2 {f_2}^2}{A({f_1}^2 - {f_2}^2)} \left[L_{4R}^{S}(t+1) - L_{4R}^{S}(t) \right] \tag{4}$$

Total derivative of TEC with respect to t

$$\frac{\delta TEC(t,s)}{\delta t} = \frac{\partial TEC(t,s)}{\partial t} + \frac{\partial TEC(t,s)}{\partial s} \frac{\partial s}{\partial t} \tag{5}$$

TEC time series $\Rightarrow$ Traveling Ionospheric Disturbances (TIDs)

$$\Delta TEC(t_f, t_0) = \int_{t_0}^{t_f} \delta TEC(t,s) \tag{6}$$

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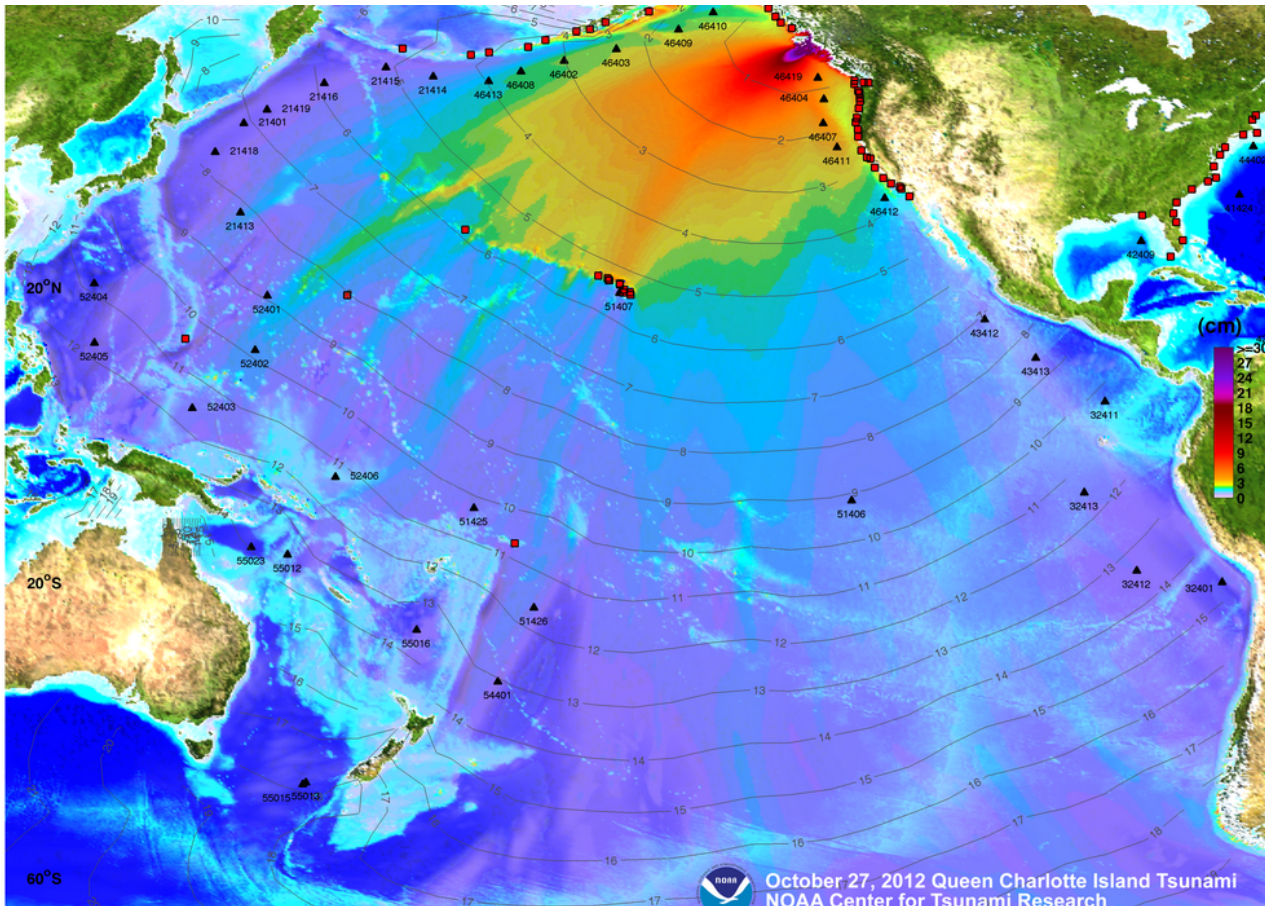
Haida Gwaii 2012 Earthquake and Tsunami Event

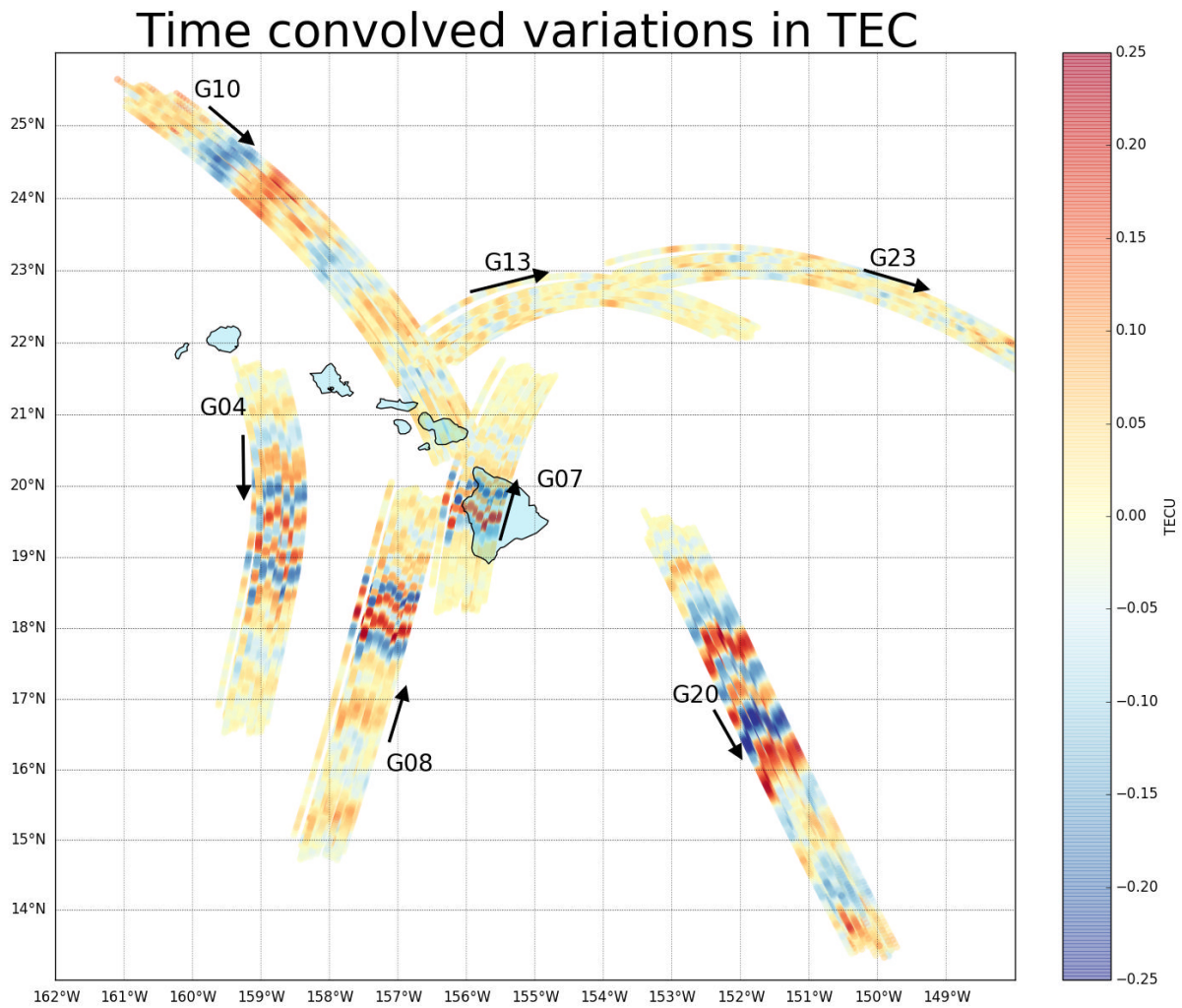
- **Mw 7.8 earthquake** at 2012-10-28 03:04:08 UTC
- **Tsunami** arrived at the Hawaii Islands in approximately 5:30 h

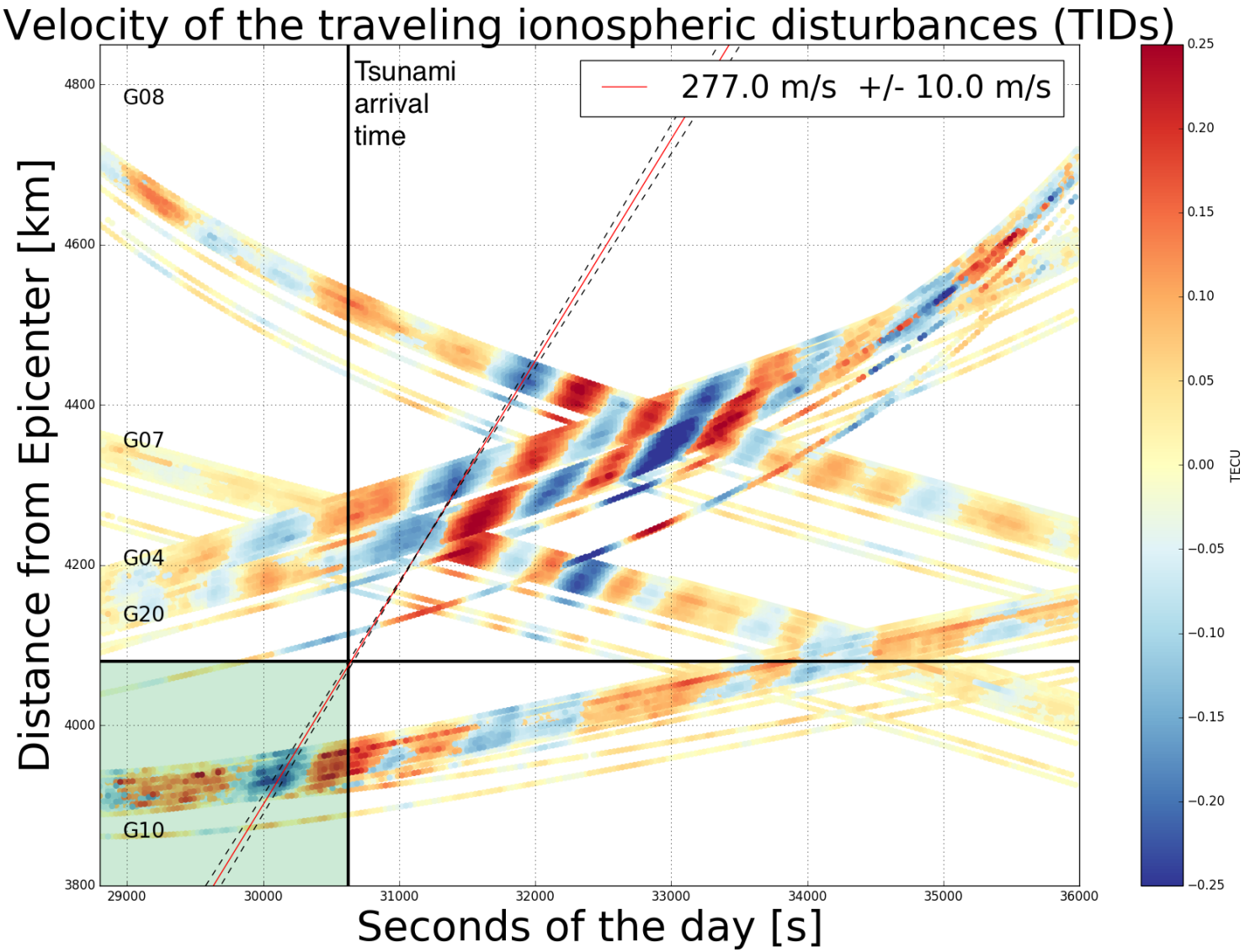


Time Convolved Variations in TEC

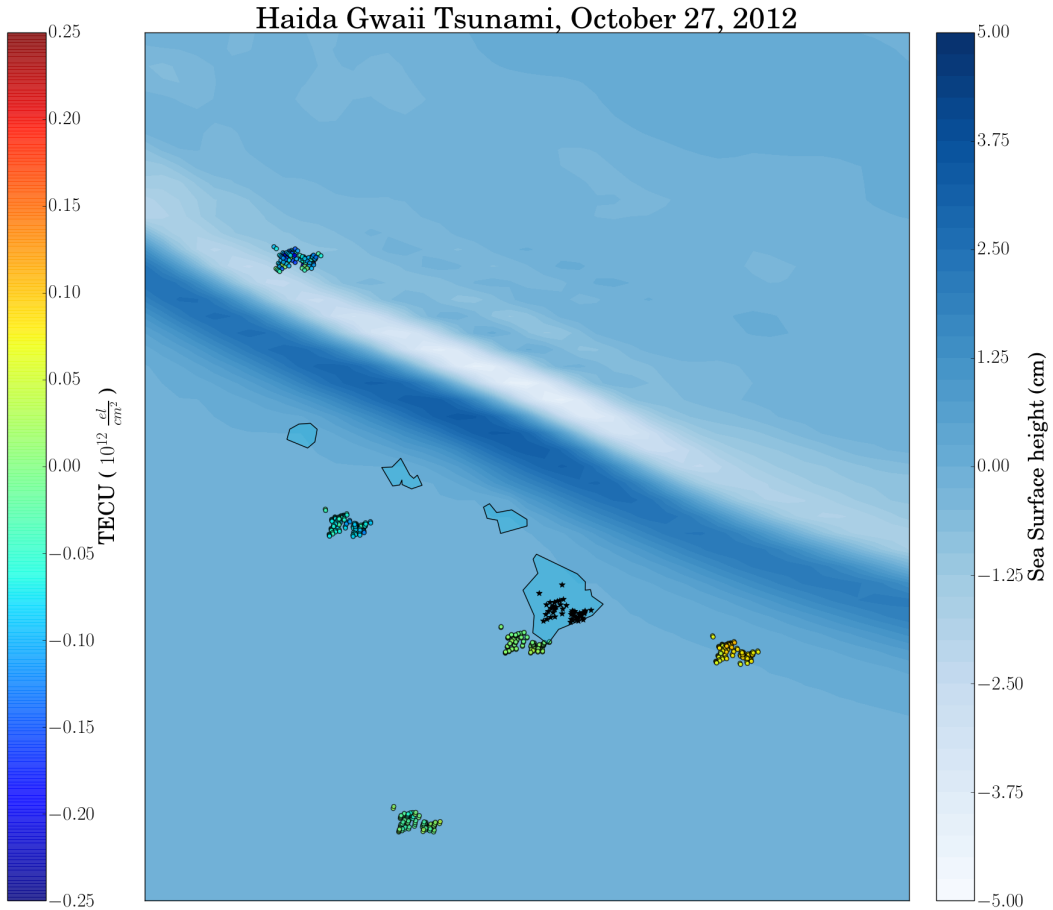
Processing

- **56 GPS** stations
- **7 satellites** in view
- from 8:00 to 10:00 UT



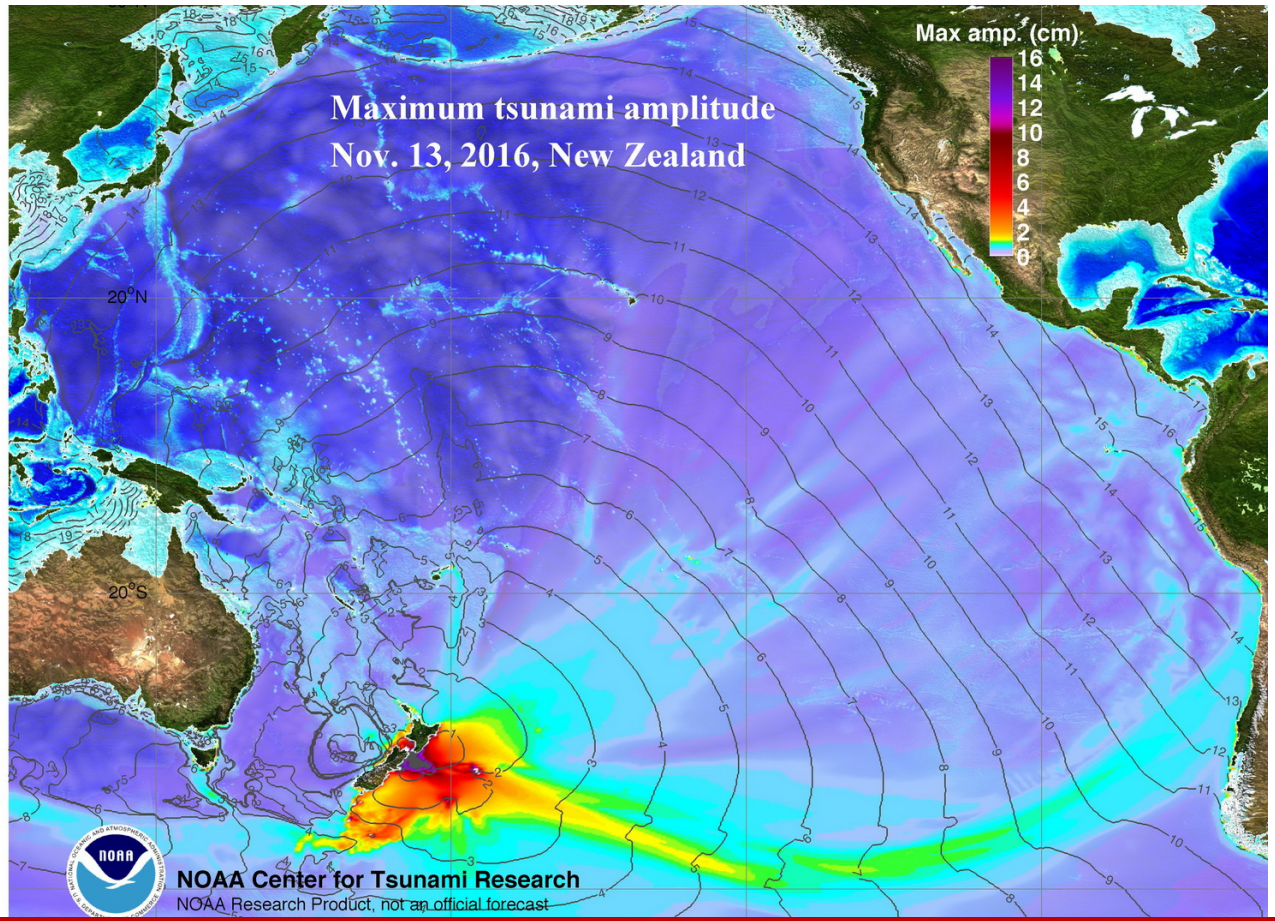

Velocity of the traveling ionospheric disturbances (TIDs)
Tsunami arrival time
277.0 m/s +/- 10.0 m/s
G08
G07
G04
G20
G10
Distance from Epicenter [km]
Seconds of the day [s]
TECU

Queen Charlotte Island (Haida Gwaii) 2012 event



New Zealand 2016 Earthquake and Tsunami Event

- **Mw 7.8 earthquake** at 2016-11-13 11:02:56 UTC
- **Tsunami** arrived at the Gambier Islands in approximately 6:00 h



Real-Time VARION Processing - Galileo

Data Stream from files

- PRN=E201, Station: GAMB
- obs rate: **1 Hz**

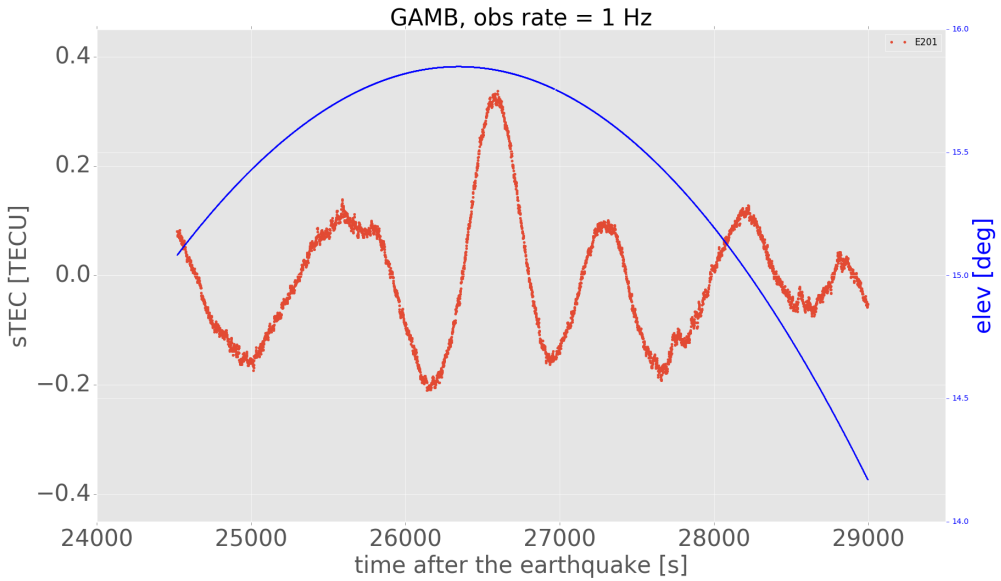
Real-Time Implementation

- **VARION** Algorithm

FIR filter - High Pass filter

I **Transitory** Phase:

- $\simeq$ **35 min** (2048 epochs)



Outline

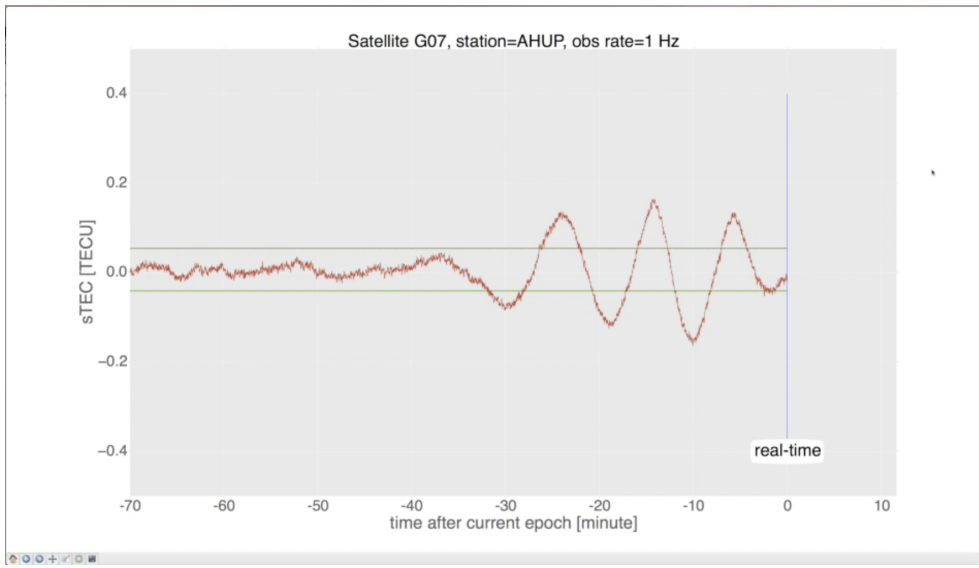
Real-Time VARION Implementation

Data Stream from files

- PRN=7, Station: AHUP
- obs rate: **1 Hz**

Real-Time Implementation

- **VARION** Algorithm



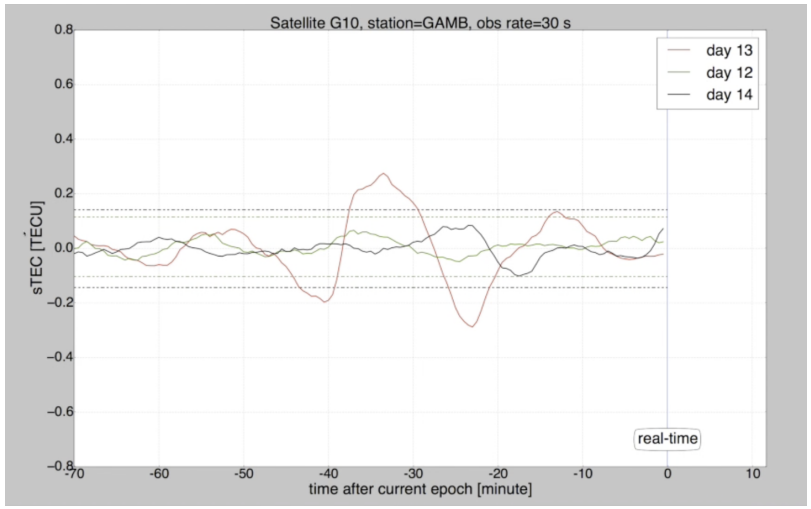
Real-Time VARION Implementation

Data Stream from files

- PRN=10, Station: GAMB
- obs rate: **30 s**

Real-Time Implementation

- **VARION** Algorithm



Outline

Tsunami Early Warning System - Ground-GNSS observations

Real-Time Capabilities

- **VARION** algorithm $\Rightarrow$ **sTEC** time series
- 5σ **confidence level** $\Rightarrow$ **sTEC background noise**
- **broadcast ephemeris** $\Rightarrow$ IPPs **distance** from the epicenter
- **pre-computed tsunami propagation database (NOAA)** $\Rightarrow$ **tsunami** characteristics

Goals

- **Real-Time Tsunami TIDs Detection**
- **Risk Assessments and Maps**
- implement VARION in a **real-time GNSS system**

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Thanks for your attention