Real-Time Detection of Tsunami Ionospheric Disturbances Using a VARION Approach: Results for the 2011 Tohoku-Oki and 2012 Queen Charlotte Island Events

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Outline

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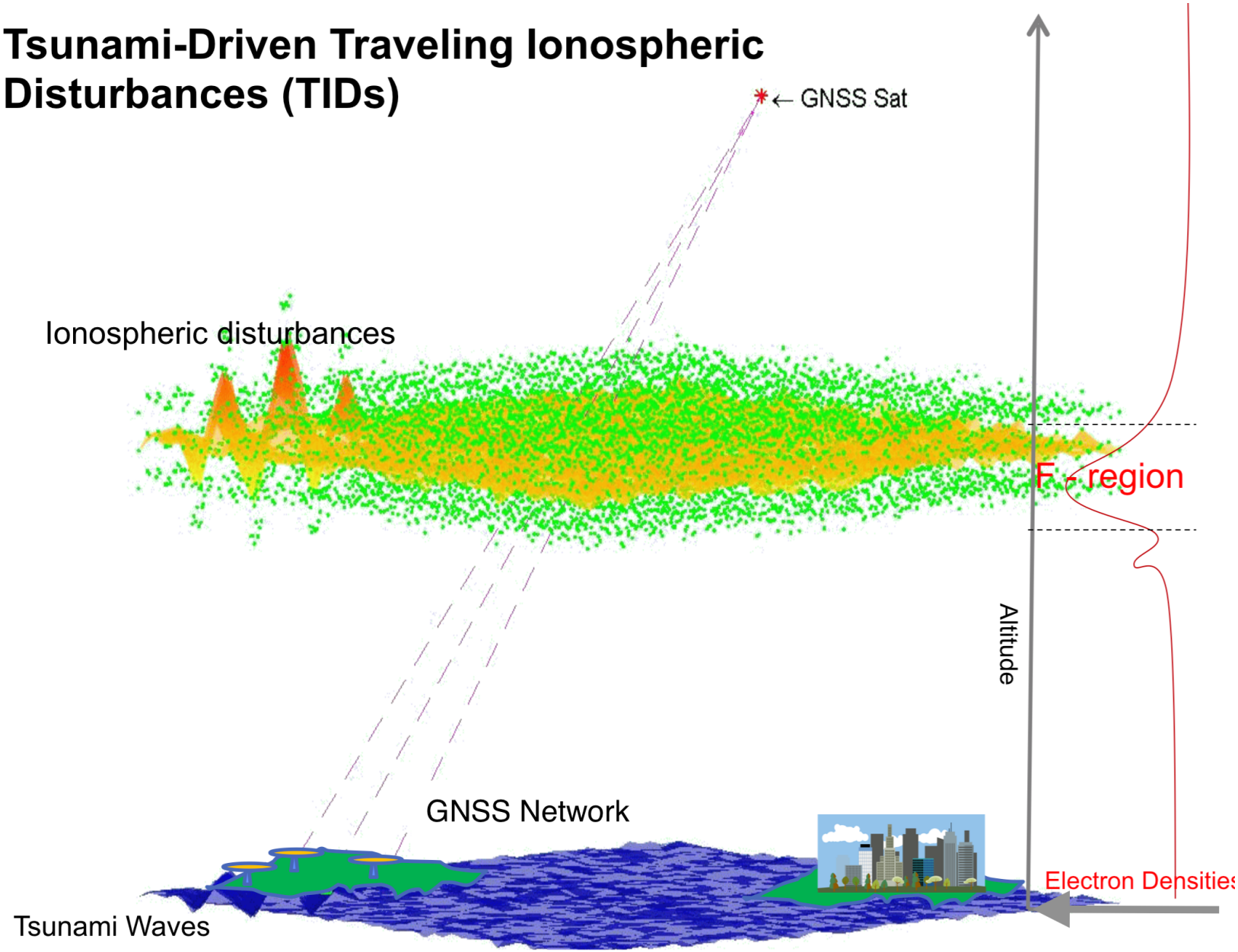
Tsunami-Driven Traveling Ionospheric Disturbances (TIDs)



VARION algorithm - Tsunami Early Warning System

TEC Variations → Post-Processing

- detection of **TEC variations** due to **internal gravity waves** using **GPS signals** has been demonstrated
- **tsunami** has been detected as **traveling ionospheric disturbances** (TIDs) **in post-processing mode**

Tsunami Early Warning System → Real-Time

- **VARION** algorithm is able to estimate **TEC variations in real-time**

Outline

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**

Metodology

- **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

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

Ionospheric Refraction along the geometric range

$$I_{iR}^{S}(t) = \frac{A}{f_i^2} TEC(t) \quad (3)$$

Algorithm (2/2) - TEC Estimation

Geometry-free Time Single-Difference Observation Equation

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

TEC variations between two consecutive epochs

$$\delta TEC(t+1,t) = \frac{{f_1}^2 {f_2}^2}{A({f_1}^2 - {f_2}^2)}\left[L_{4R}^{S}(t+1) - L_{4R}^{S}(t)\right] \quad (5)$$

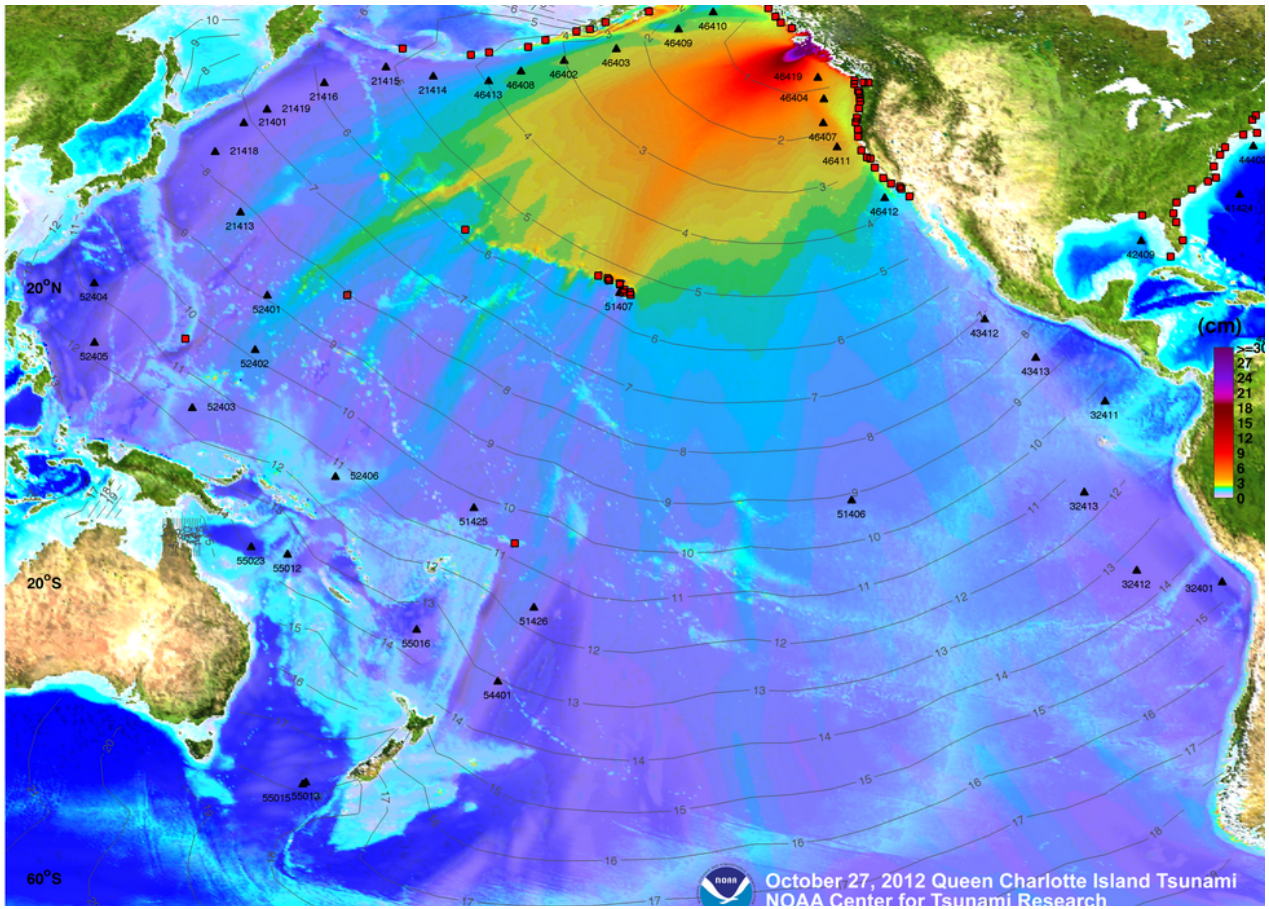
TEC time series $\Rightarrow$ Traveling Ionospheric Disturbances (TIDs)

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

Outline

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



Data set

Data set

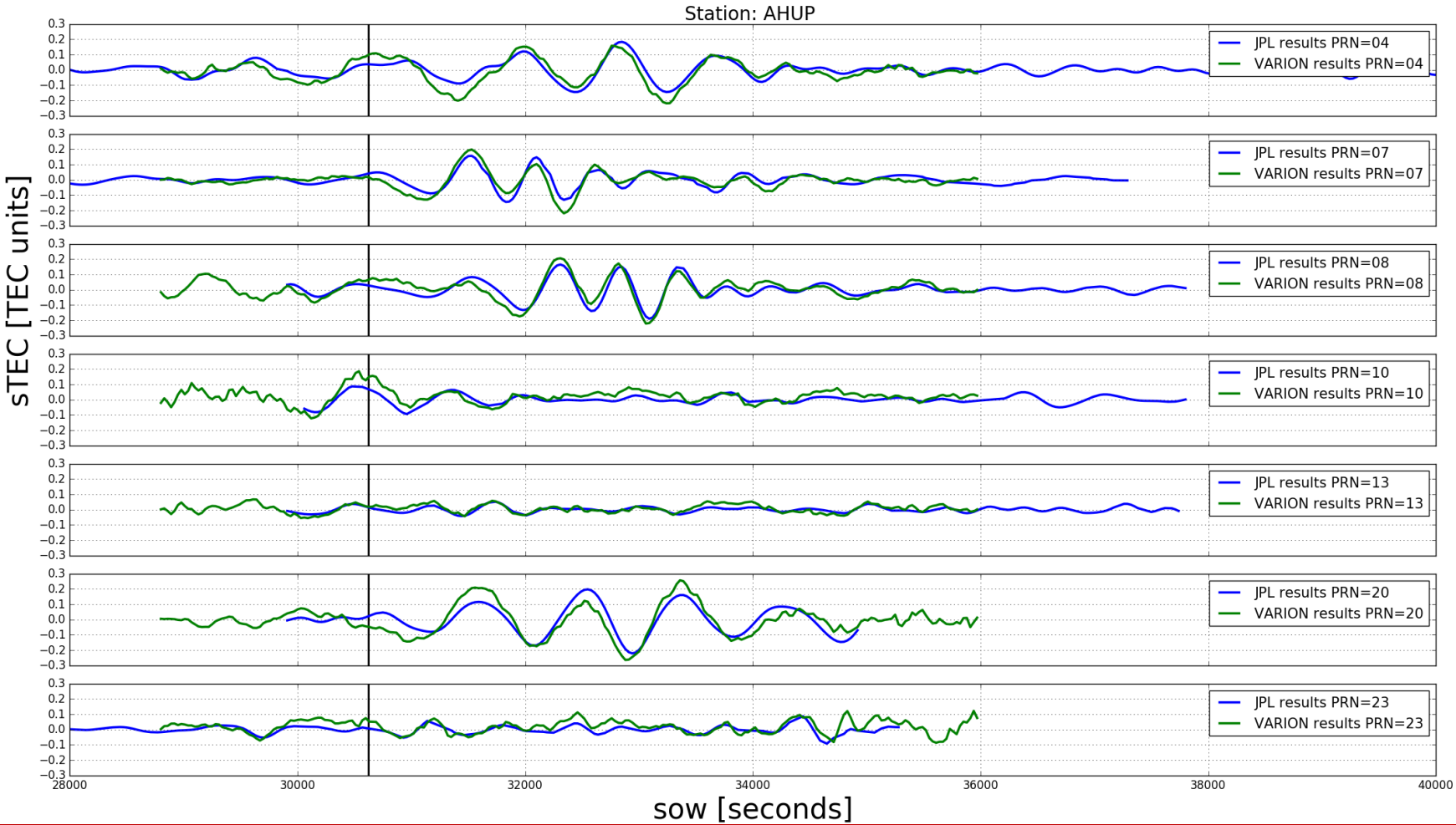
- **52 GPS** stations located in the Hawaii Islands
- **7 satellites** in view from 8:00 to 10:00 UT
- **cut-off elevation angle** of 18 degree

Comparison

- **JPL's results** as reference solution
  - **precise ephemeris**
  - **band-pass filter**: 0.5 to 5 mHz
- **VARION results** as real-time solution
  - **broadcast ephemeris** $\rightarrow$ available in **real-time**
  - **TEC residuals**: 8^{th} polynomial curve

Gravity Waves Signatures on GPS Signals

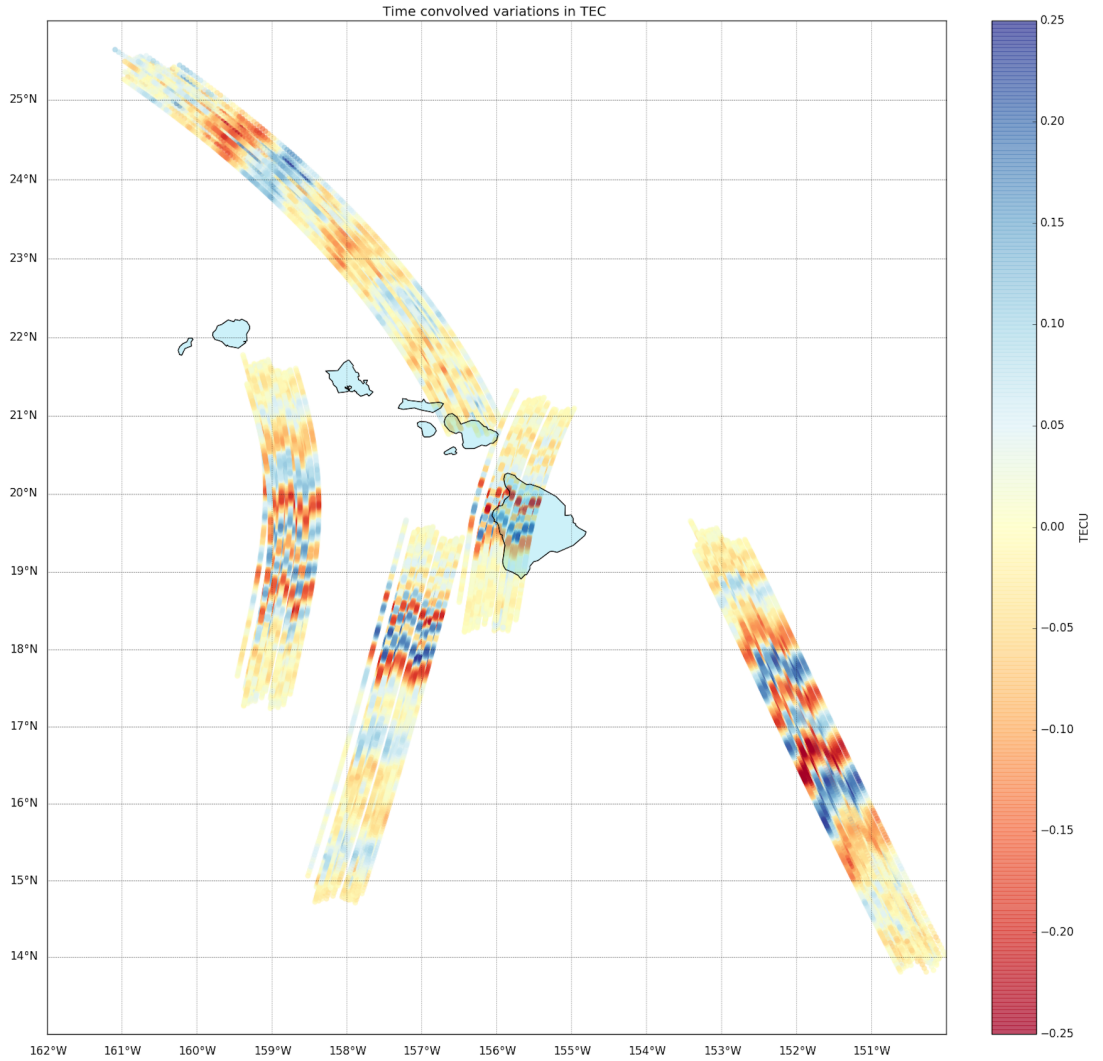
- **TEC comparison** between two independent algorithms



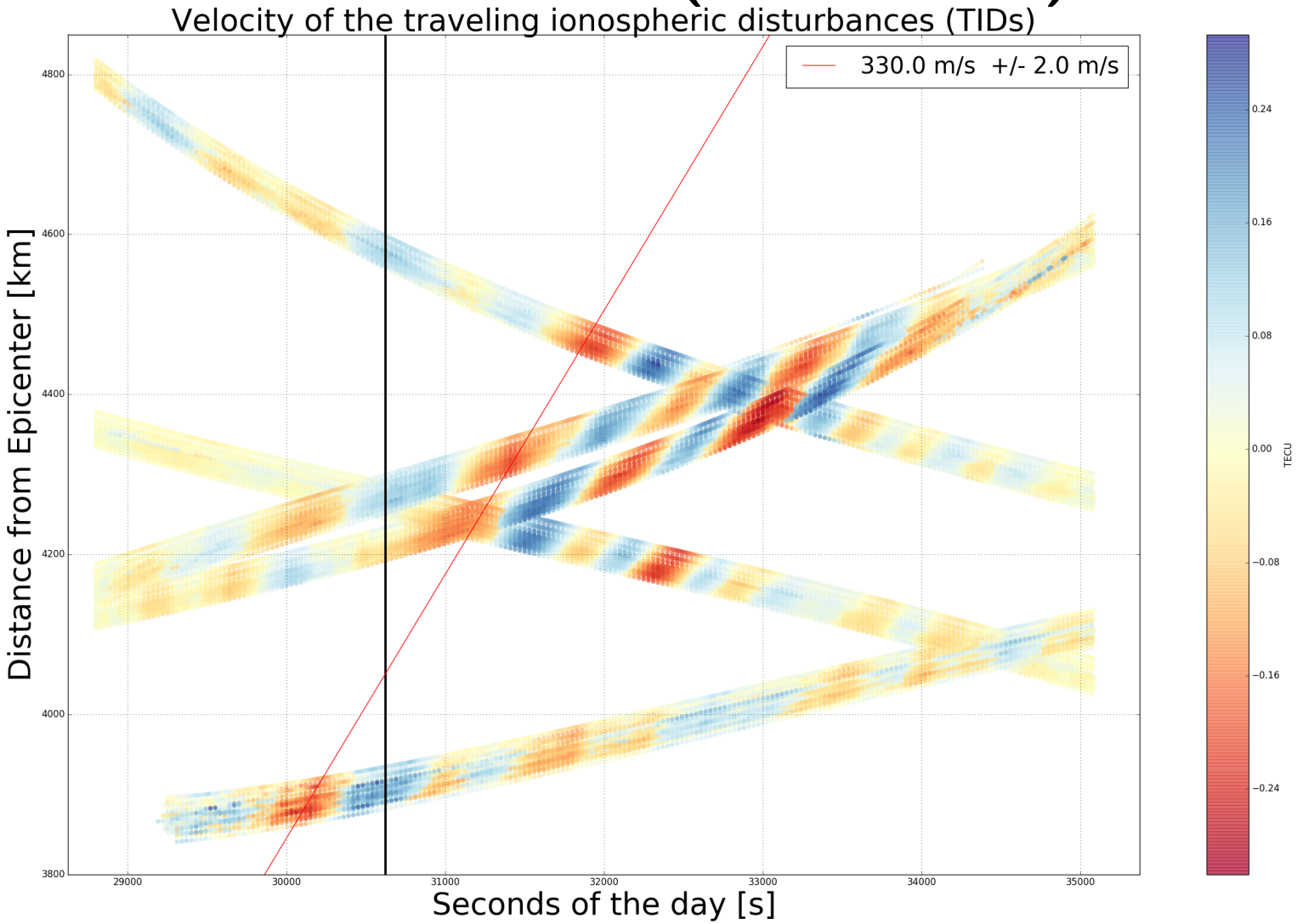
Time Convolved Variations in TEC

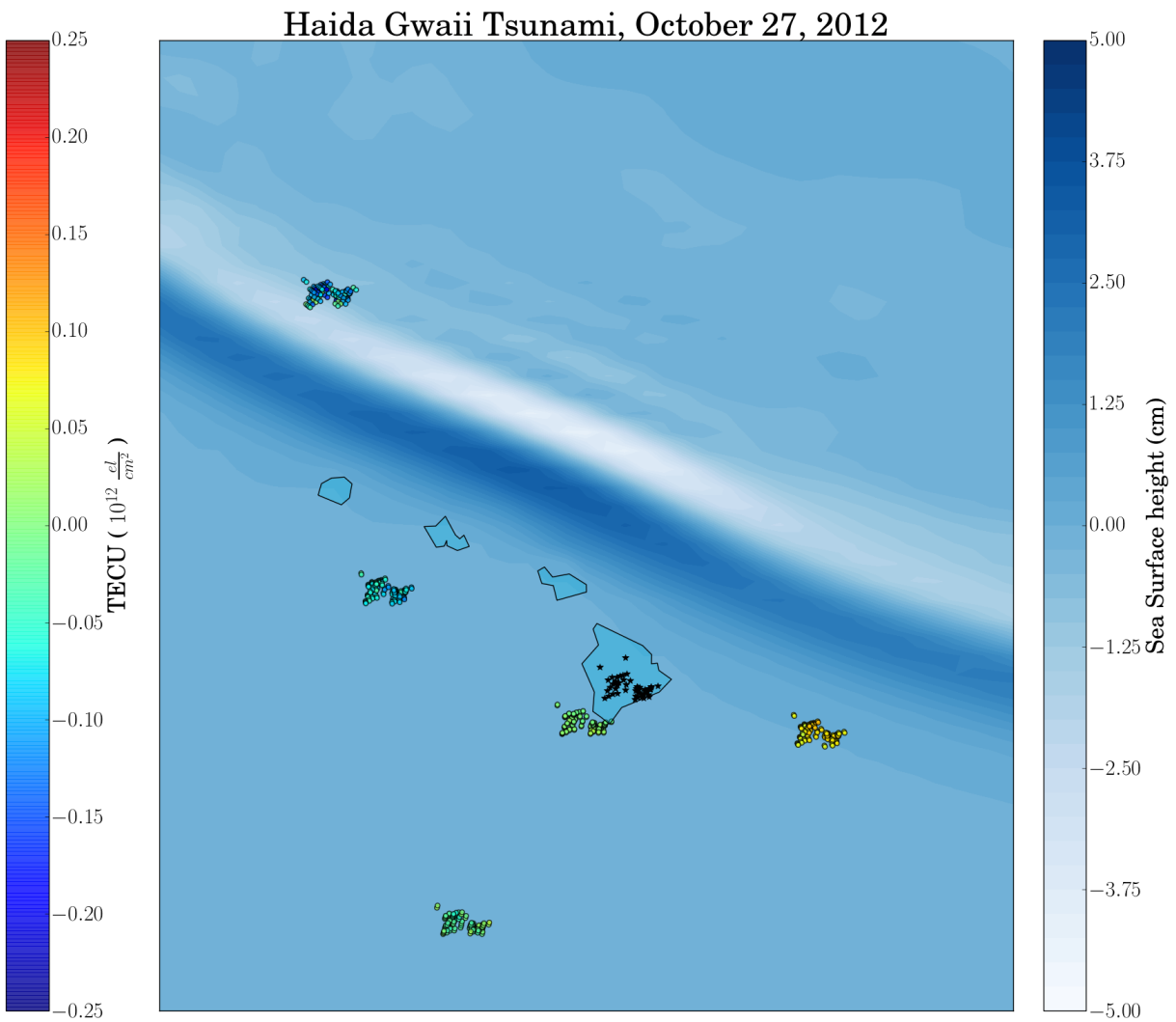
Processing

- **52 GPS** stations
- **5 satellites** in view
- from 8:00 to 10:00 UT



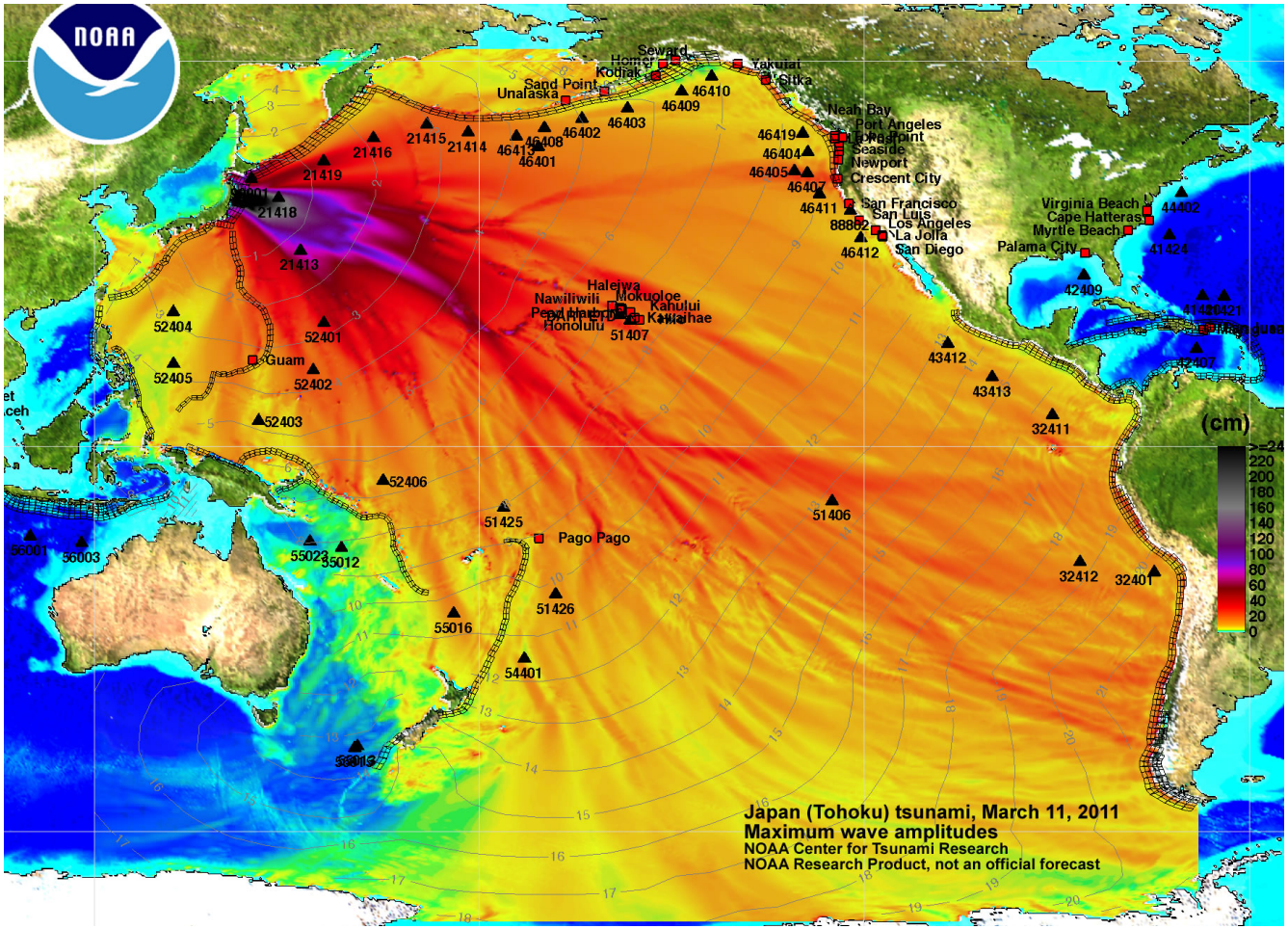
Distance Versus Time Plot (Hodochron)




Haida Gwaii Tsunami, October 27, 2012
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−0.25
TECU (10^{12} $\frac{el}{cm^2}$)
5.00
3.75
2.50
1.25
0.00
−1.25
−2.50
−3.75
−5.00
Sea Surface height (cm)

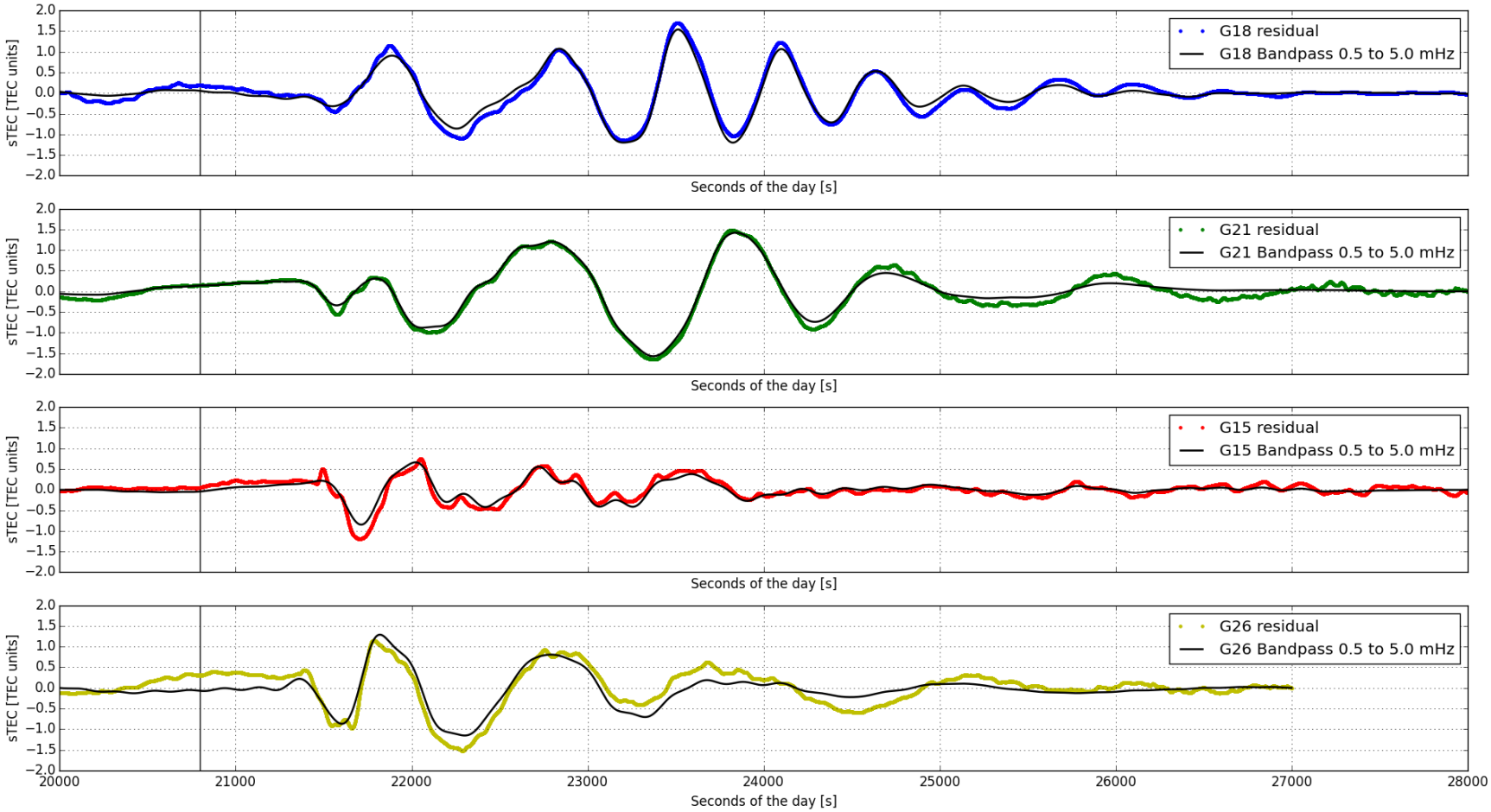
Tohoku-oki 2011 Earthquake and Tsunami Event

- **Mw 9.0 earthquake** at 2011-03-11 05:46:24 UTC,



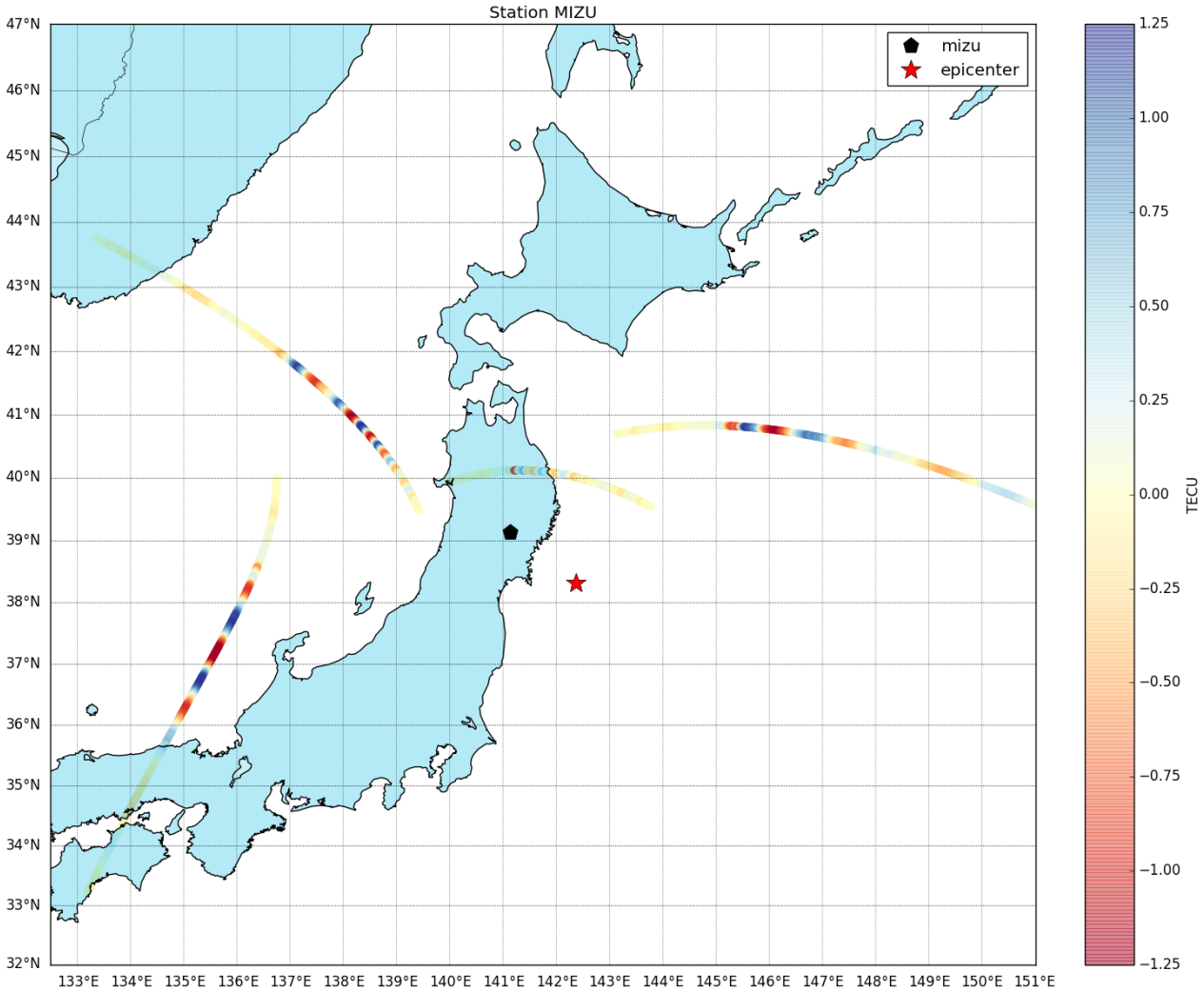
TEC Variations on GPS Signals

PRN=(15, 18, 21, 26), station=MIZU, freq=1 Hz



Time Convolved Variations in TEC

4 satellites in view from 1 station (MIZU)



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