Towards Real-Time Detection of Traveling Ionospheric Disturbances using the VARION Algorithm with GNSS and Geostationary Satellites

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Outline

Objectives

Improve tsunami-TIDs detection

Separate time/space ionospheric variability

Introduction

Introduction to tsunami-induced TIDs detection from the ionosphere

Methodology

Details of the VARION Algorithm

Differences between Medium Earth Orbit and Geostationary Orbits

Results

SAWs detected in the ionosphere – Aug 24, 2017 event

SAWs detected from real-time solutions - May 22, 2018 event

Conclusions and Prospects

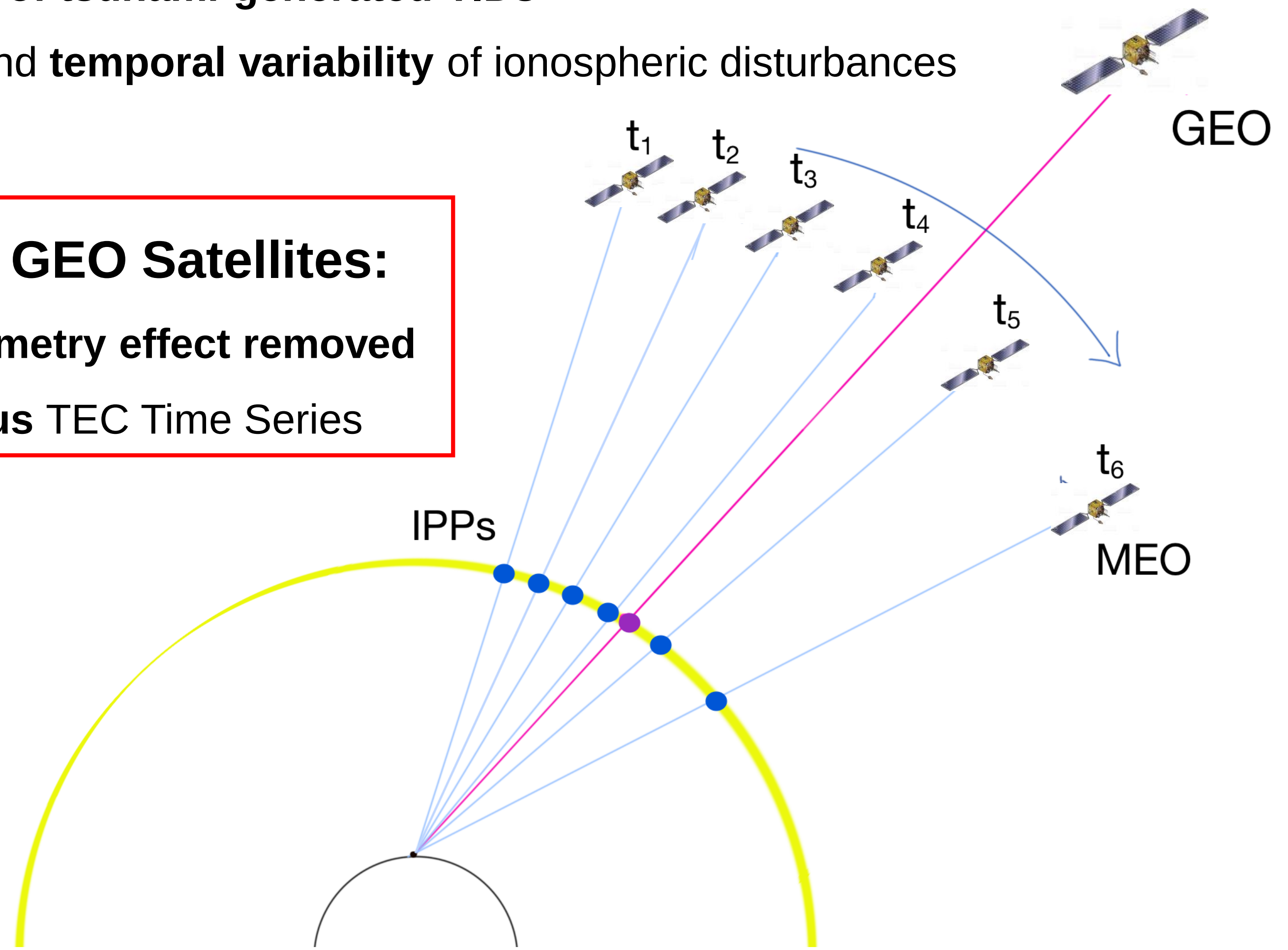
Objectives

Motivation for using geostationary (GEO) satellite to:

- **Improve detection of tsunami-generated TIDs**
- **Separate spatial** and **temporal variability** of ionospheric disturbances

Advantages of using GEO Satellites:

- GNSS satellite **geometry effect removed**
- Provides **continuous** TEC Time Series

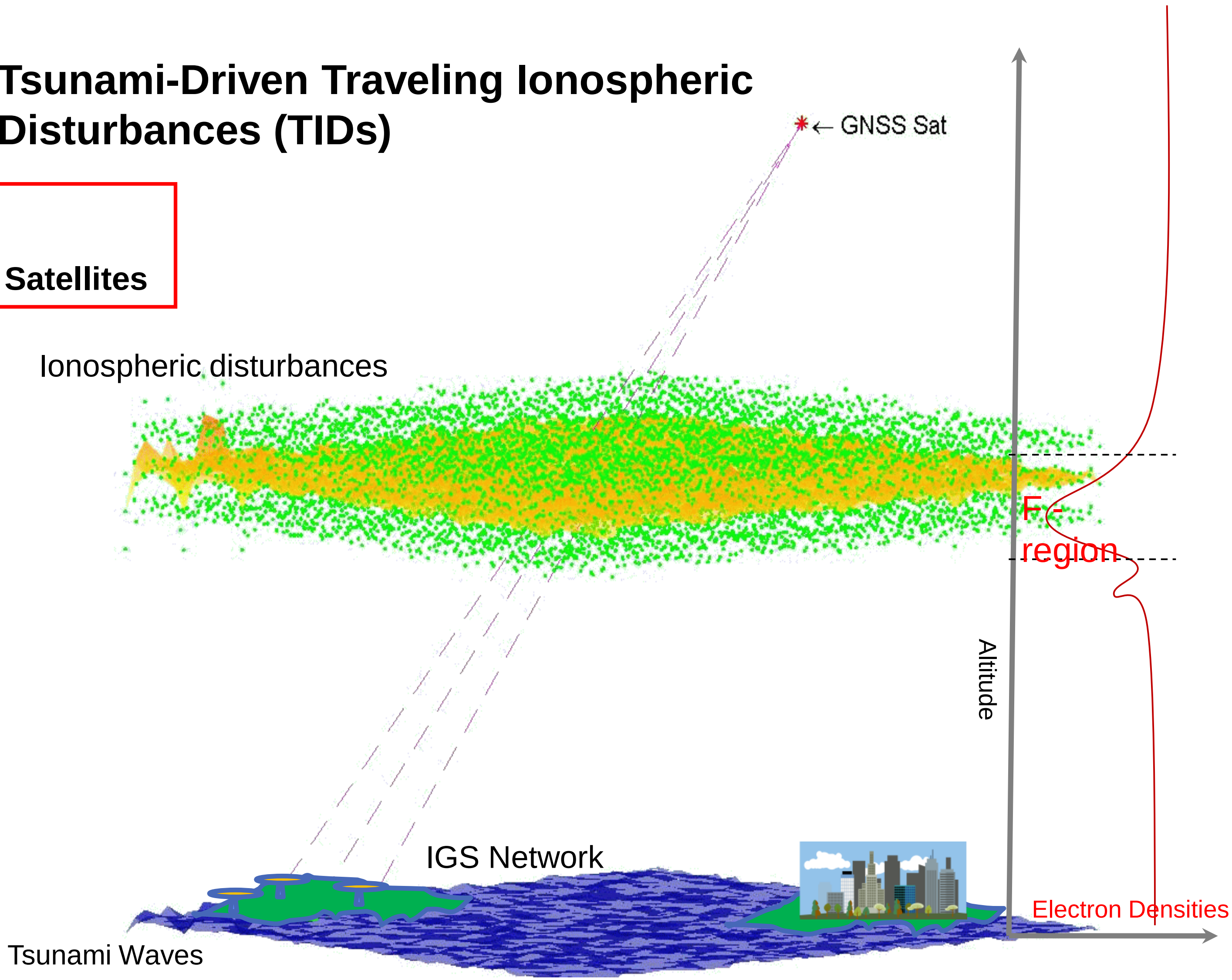


Introduction

Tsunami-Driven Traveling Ionospheric Disturbances (TIDs)

Tsunamis produce **TIDs**

TIDs detectable with **GNSS Satellites**



Methodology

VARION Algorithm for Real-Time TIDs Detection

Idea

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

Methodology

- **Variation of sTEC**
  - **dual-frequency phase observations** (1s, 15s, 30s)
  - **geometry-free combination** to remove geometry, clocks and all **non-dispersive effects**
  - **time single-differences of geometry-free observations (phase ambiguity** removed as for **IFB**, assuming a constant for a given time period)
  - **cycle slips** can be detected as **outliers**
- **Total sTEC determination**
  - **integration** of sTEC variations

Methodology

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

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

Methodology

Algorithm (2/2) - sTEC Estimation

sTEC variations between two consecutive epochs

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

Total derivative of sTEC with respect to t

$$\frac{d\ sTEC(t,s)}{dt} = \frac{\partial sTEC(t,s)}{\partial t} + \frac{\partial sTEC(t,s)}{\partial s}\frac{\partial s}{\partial t} \quad (5)$$

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

$$\Delta sTEC(t_f, t_0) = \int_{sTEC_0}^{sTEC_f} d\ sTEC(t,s) \quad (6)$$

Methodology

- VARION Algorithm for **MEO** satellites:

Total derivative of sTEC with respect to t

$$\frac{d\ sTEC(t,s)}{dt} = \frac{\partial sTEC(t,s)}{\partial t} + \frac{\partial sTEC(t,s)}{\partial s}\frac{\partial s}{\partial t} \tag{5}$$

- VARION Algorithm for **GEO** satellites:

Total derivative of sTEC with respect to t

$$\frac{d\ sTEC(t,s)}{dt} = \frac{\partial sTEC(t,s)}{\partial t} + \cancel{\frac{\partial sTEC(t,s)}{\partial s}\frac{\partial s}{\partial t}} \tag{5}$$

Results No. 1

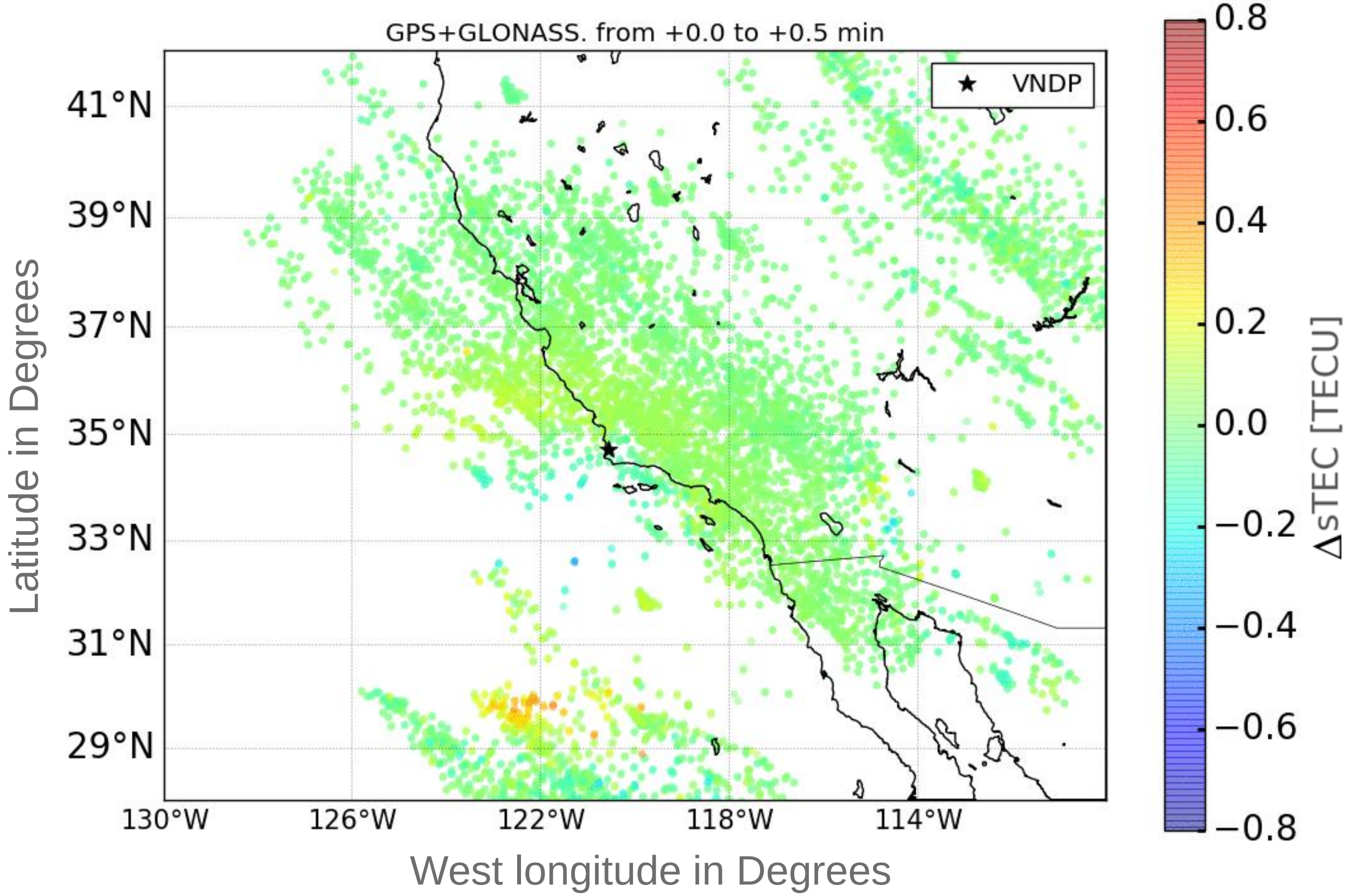
Shock Acoustic Waves Detected in the Ionosphere

- Launch date: 24 August 2017, **11:51 a.m. PDT** (daytime)
- Launch site: **Vandenberg Air Force Base**, California
- Rocket: **Falcon 9**
- **Trajectory** of the Rocket almost **Vertical**

Shock Acoustic Waves (SAWs)

- **GPS+GLONASS (MEOs)**
- **731** GNSS stations

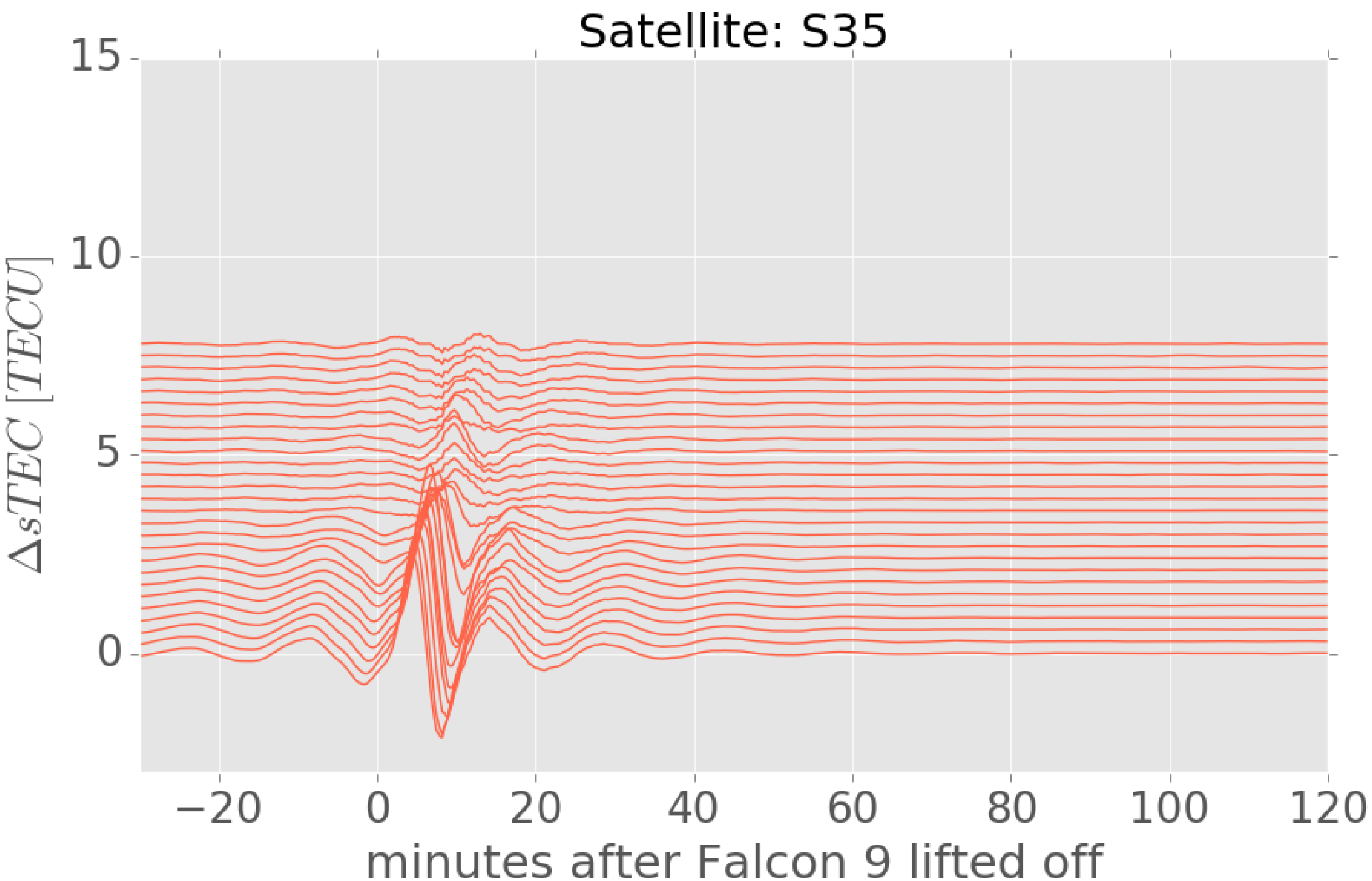
Falcon 9 produced **SAWs detectable** from **MEO Satellites**



Shock Acoustic Waves

- **WAAS (GEO).** PRN: **135**
- **29** GNSS stations

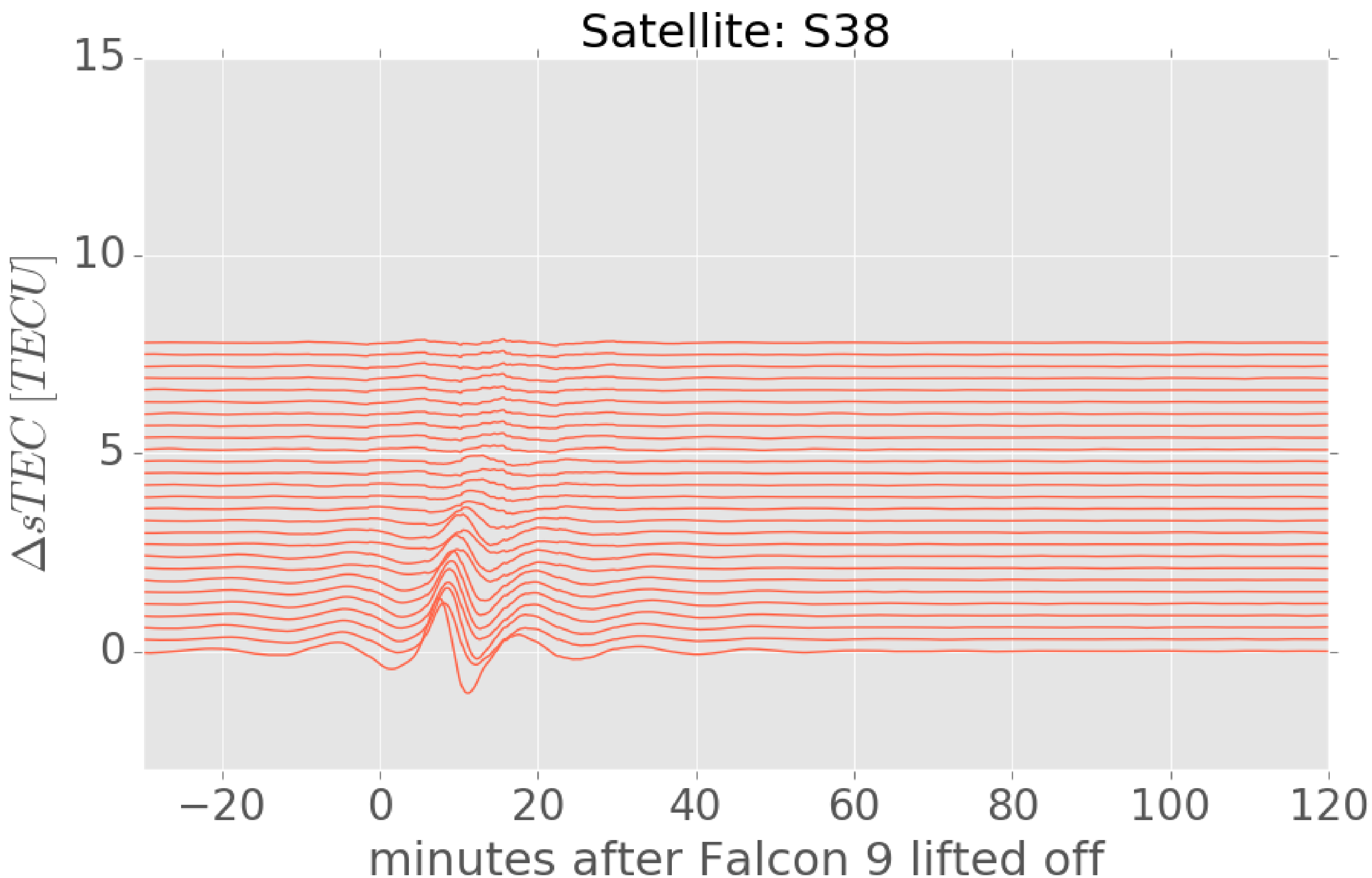
SAWs detected from GEO Satellite



Shock Acoustic Waves

- **WAAS (GEO).** PRN: **138**
- **29** GNSS stations

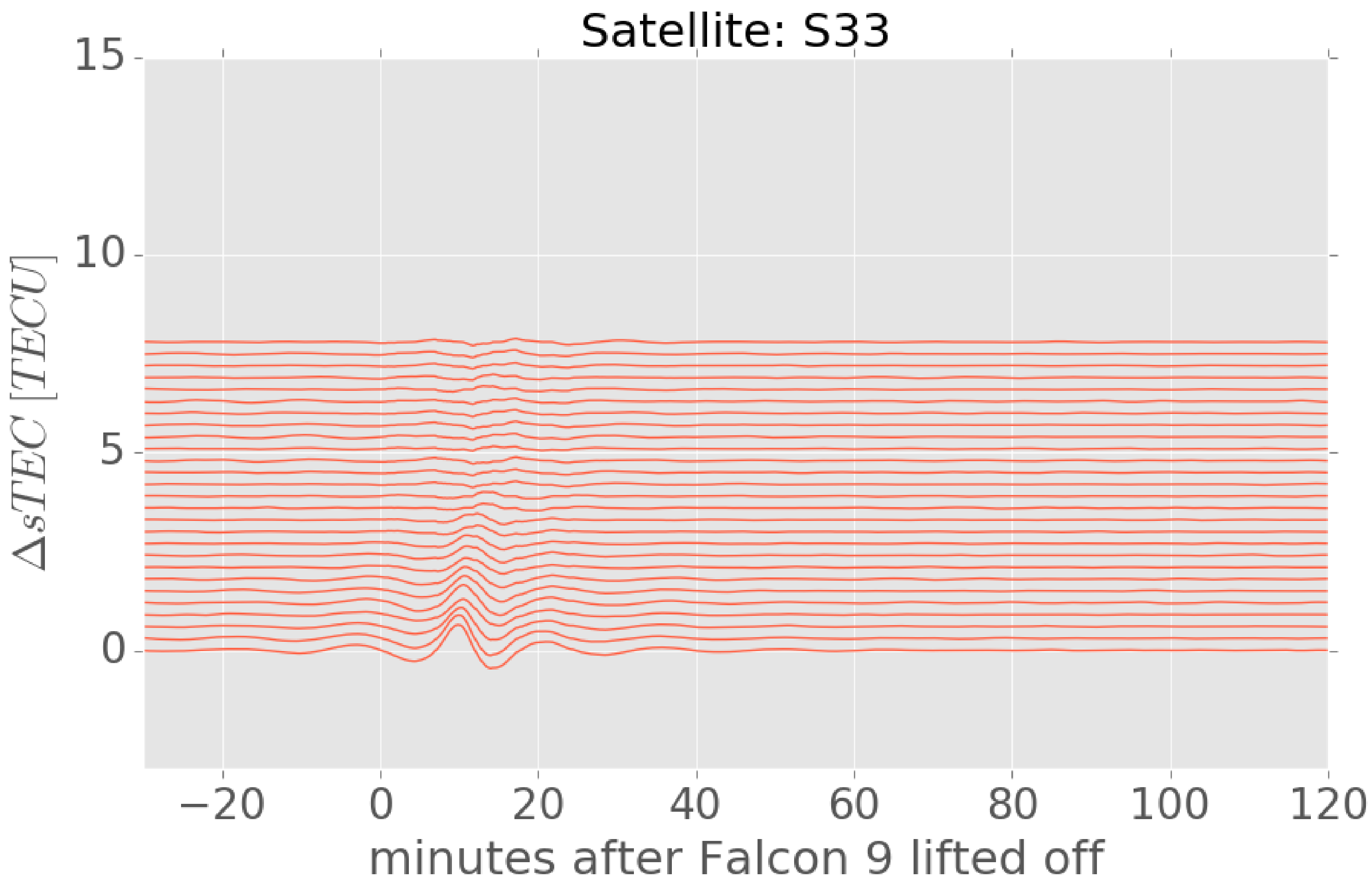
SAWs detected from GEO Satellite



Shock Acoustic Waves

- **WAAS (GEO).** PRN: **133**
- **29** GNSS stations

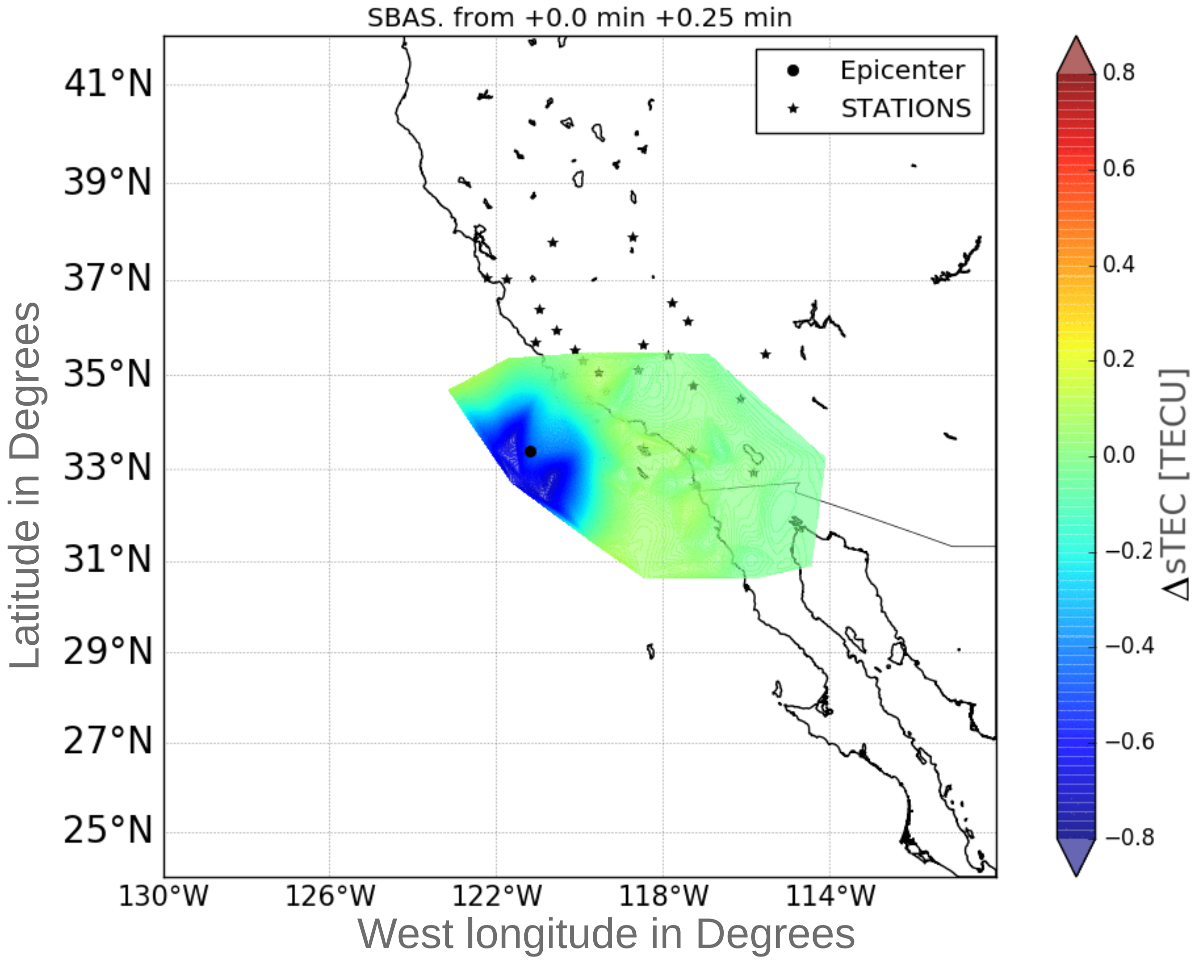
SAWs detected from GEO Satellite



Shock Acoustic Waves

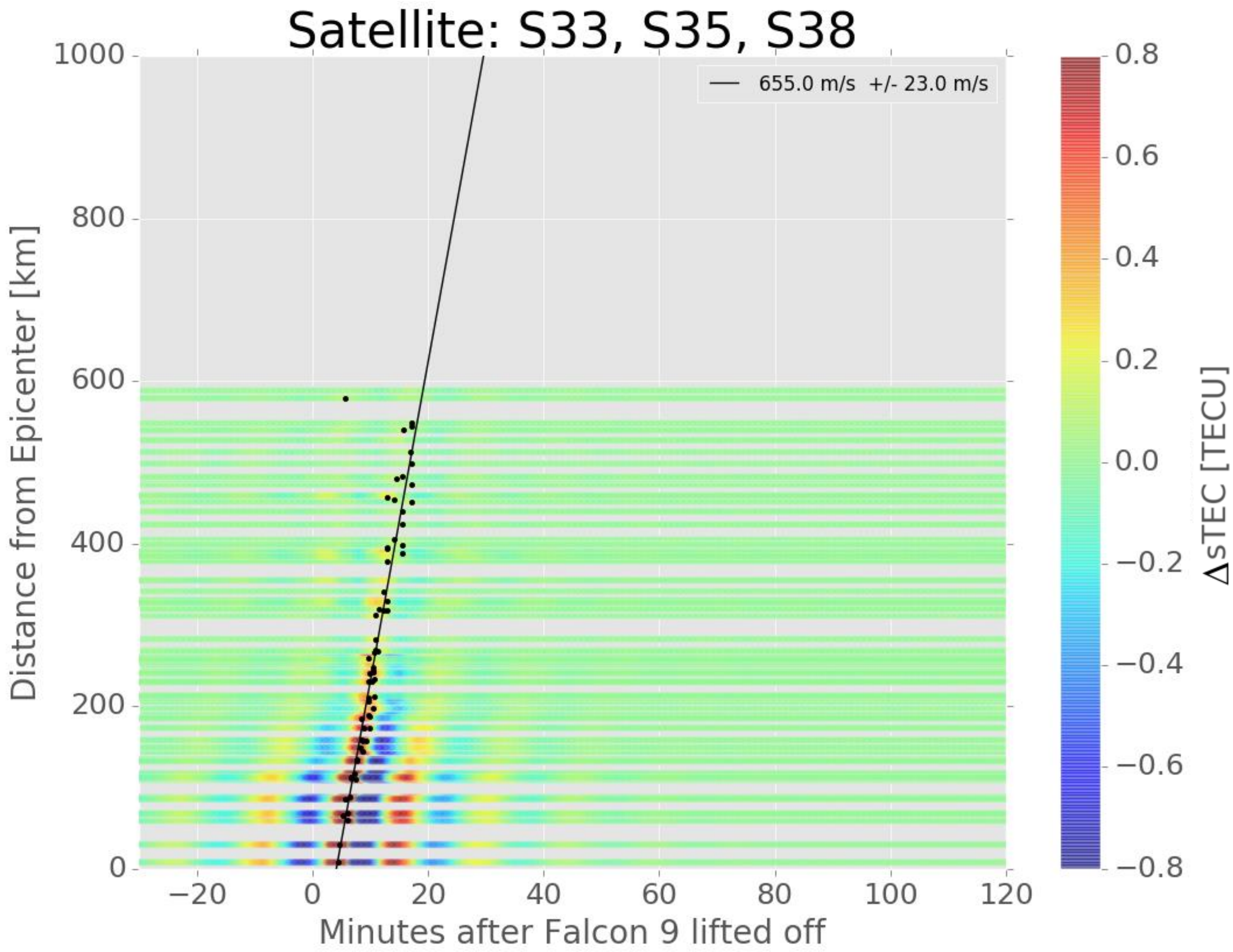
- **WAAS (GEOs).** PRN: **133**, **135**, **138**
- **29** GNSS stations

Estimation **Source Location**
Computation **TEC Gradients**



Shock Acoustic Waves

Estimation of **Horizontal Phase Velocity** using GEO Satellites



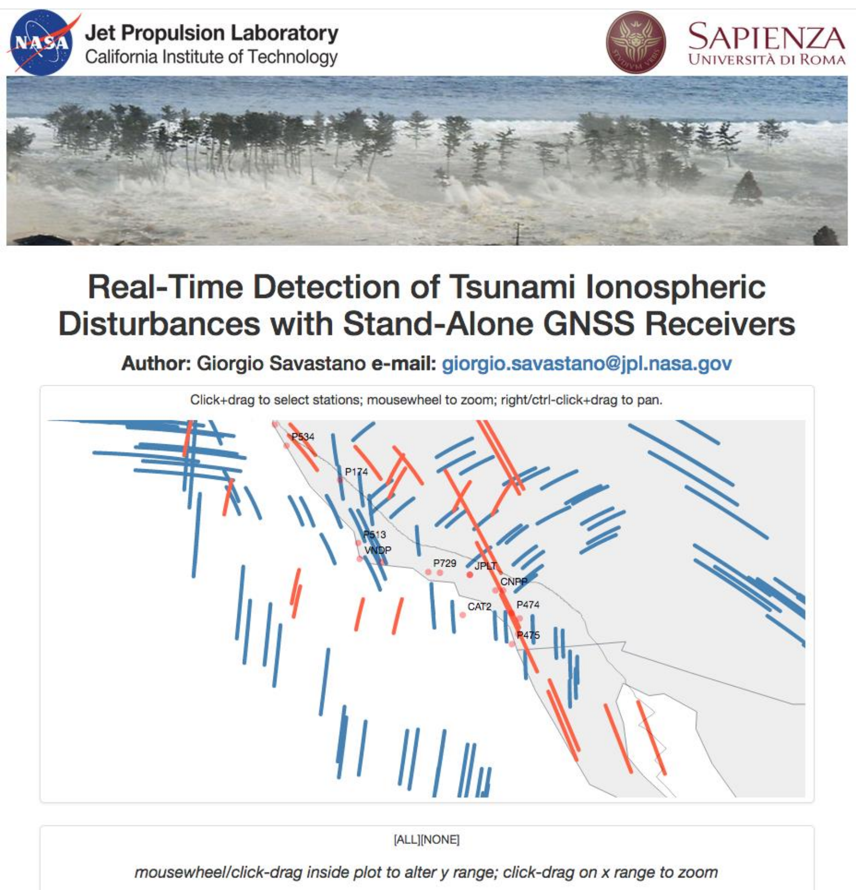
Results No. 2

Shock Acoustic Waves Detected in the Ionosphere from Real-Time Solutions

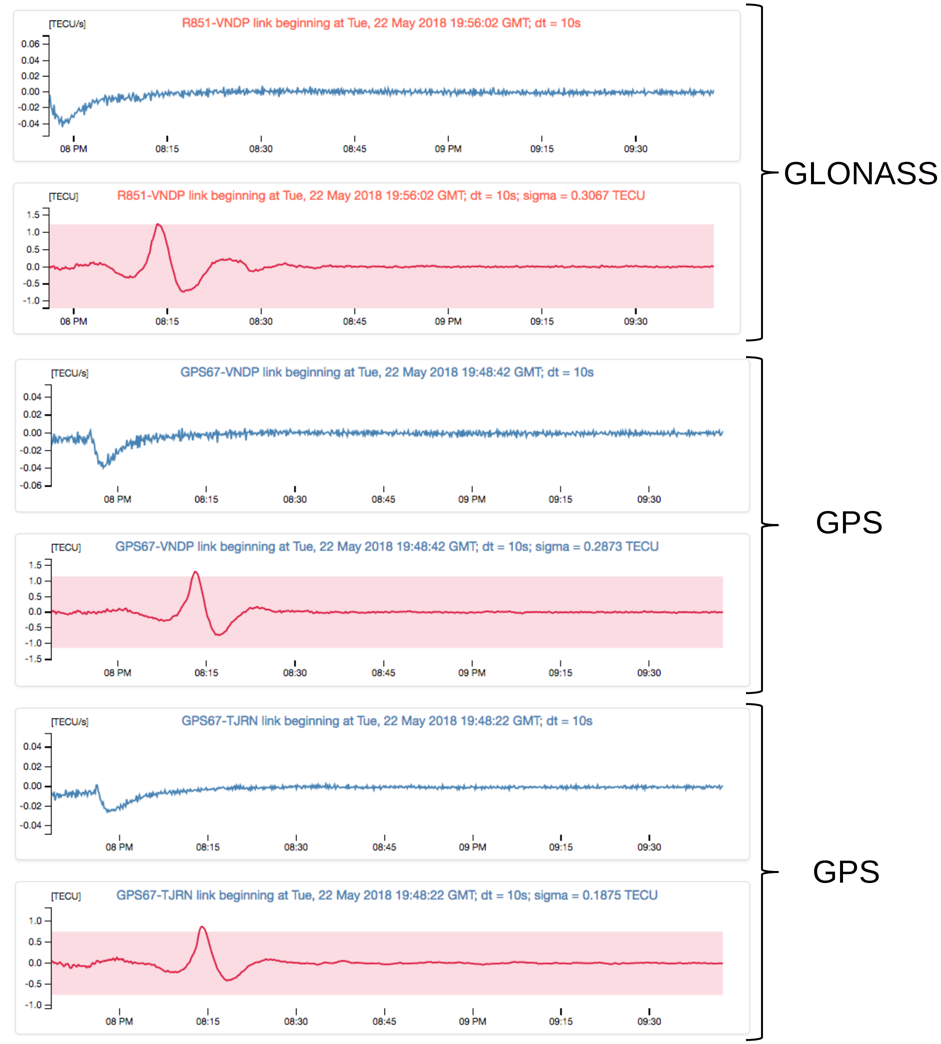
- Launch date: 22 May 2018, **12:47 p.m. PDT** (daytime)
- Launch site: **Vandenberg Air Force Base**, California
- Rocket: **Falcon 9**
- **Trajectory** of the Rocket almost **Vertical**

Real-Time VARION-GDGPS

- GPS+GLONASS 20 minutes IPP tracks



- Raw [TECU/s] and Filtered [TECU] Solutions



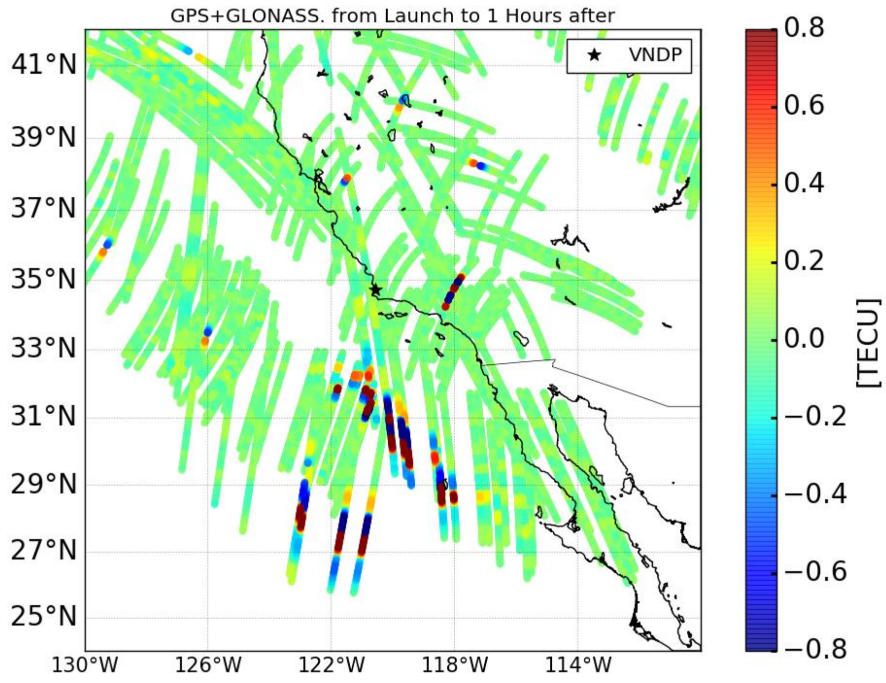
Validation of Real-Time Solutions

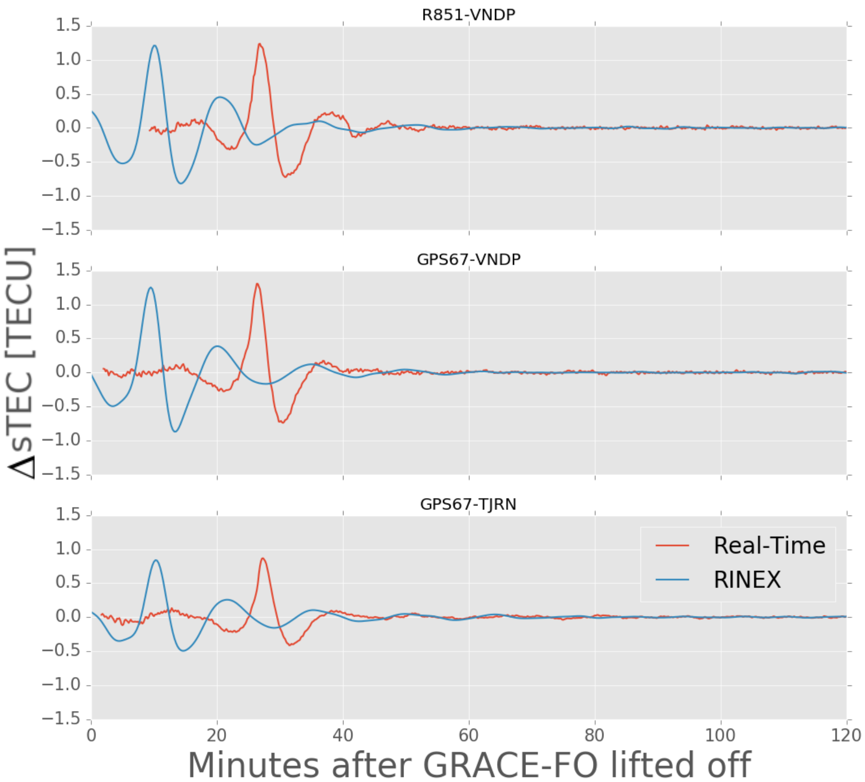
1 Hour of Real-Time IPP tracks:

- **TEC Perturbations** localized in the **South**

Real-Time vs RINEX TEC Solutions:

- Correlation in **Amplitude** and **Period**
- **Phase** shifted (15 min **time delay**)





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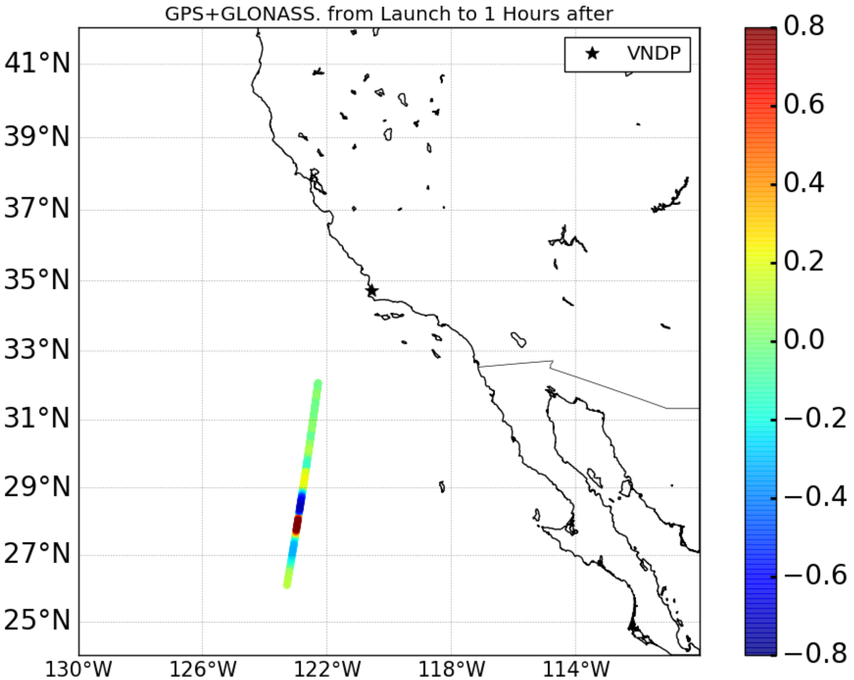
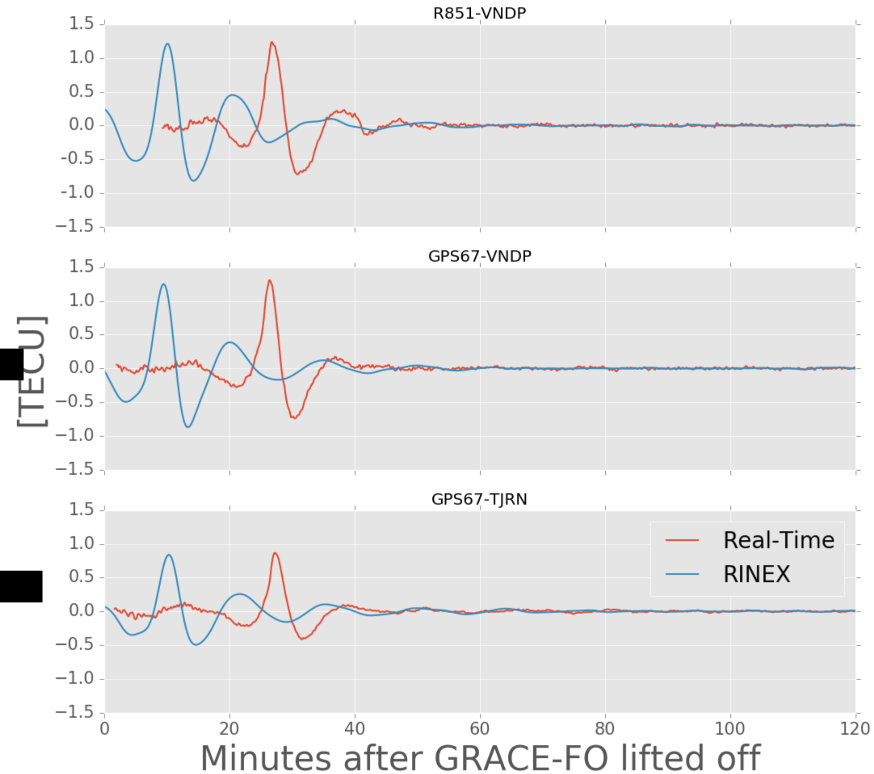
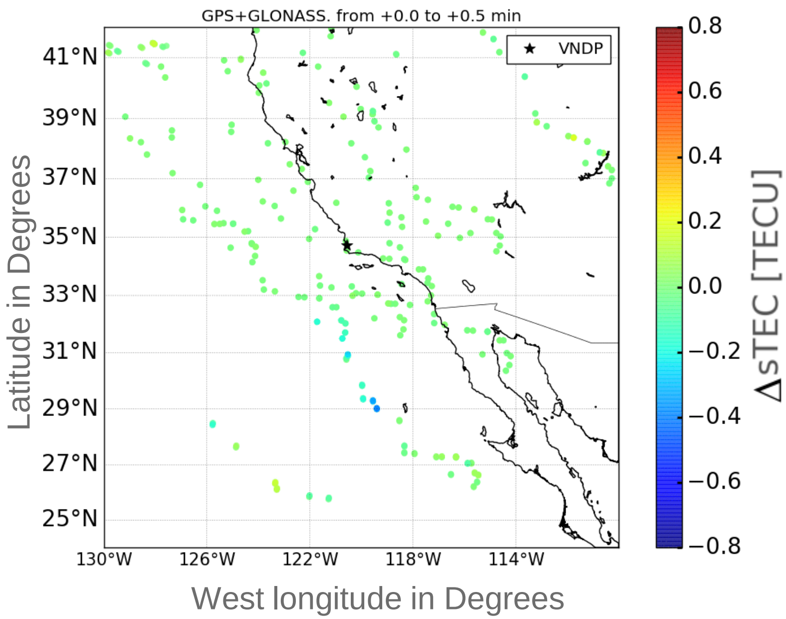




Validation of Real-Time Solutions

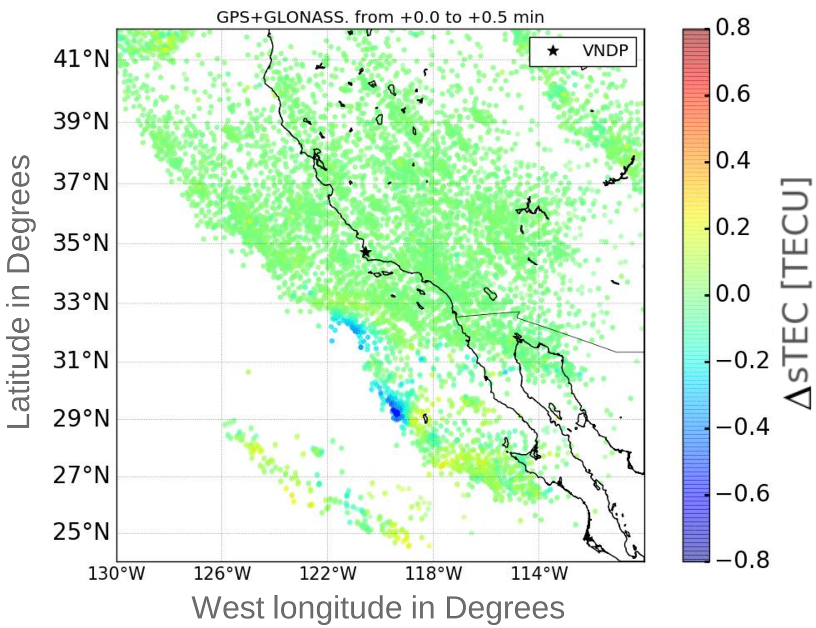
- **TEC Perturbations Detected** from **Real-Time TEC Solutions**
- **Correlation** in **Time, Space** and **Amplitude**

Real-Time Solutions



- **GPS+GLONASS**
- **17** Stations

Post-Processed Solutions



- **GPS+GLONASS**
- **900** Stations

Conclusions and Prospects

Conclusions

- Demonstrated ability to **detect Shock Acoustic Waves (SAWs)** using GEO Satellites
- Demonstrated possibility to **estimate source location** and **horizontal phase velocity** of SAWs using GEO Satellites

Future Work

- Detect **Tsunami-TIDs** from the Ionosphere using **GEO** and **MEO Satellites**

Acknowledgments

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- **Michele Vallisneri** for his great help in implementing the **VARION Webpage**
- **Byron Iijima** and **Larry Romans** for their help with the **real-time stream of data**