A joint variometric approach for real-time analysis of earthquake driven ionospheric disturbances using a Stand-Alone GNSS receiver: the 2015 Chile earthquake case study

M. Ravanelli[1], G. Savastano[1,2], A. Komjathy[2], O. Verkhoglyadova[2], E. B. Shume[2] and M. Crespi[1]

[1] Geodesy and Geomatics Division, DICEA, Sapienza University of Rome
[2] Ionospheric and Atmospheric Remote Sensing Group, Jet Propulsion Laboratory, California Institute of Technology

EGU General Assembly 2018
Vienna - Austria - 8–13 April 2018

Outline

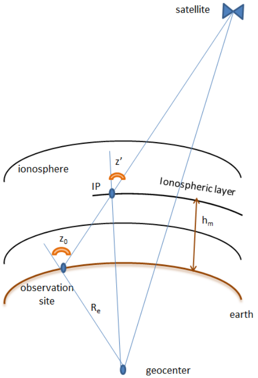
Outline

GNSS and the ionosphere

Another way to use GNSS observables is to compute **total electron content** (TEC) in order to detect ionospheric disturbances caused by earthquakes, volcano eruptions, tsunamis and other kind of natural/man-made hazards

The ionosphere acts like a **dispersive medium** for GNSS signal

$$I_R^S = \pm \frac{A}{f^2} \mathbf{TEC(t)} \quad (1)$$

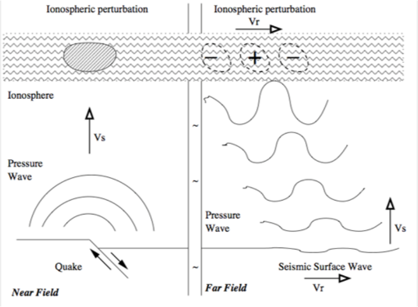


(*Figure from Hoffman et al., 2008*)

Induced ionospheric disturbances

CIDs related to acoustic waves

- atmosphere as **high-pass filter**: only waves with **frequency greater than acoustic cutoff frequency** (about 3.3 mHz) reach the ionosphere
- **strong amplification** during the upward propagation (density decreasing, momentum conservation)
- ionosphere perturbation detectable with GNSS



(*Figure from Garcia et al., 2005*)

Outline

Our work

Aim of the work

Combined application of **VADASE** and **VARION** algorithms on the **real-time scenario** of the 8.3 magnitude earthquake that occurred in Chile on September 16, 2015

VADASE

- **V**ariometric **A**pproach for **D**isplacements **A**nalysis **S**tand-alone **E**ngine
- able to characterize **ground velocities and displacements**, using a stand-alone GNSS receiver **in real-time**

VARION

- **V**ariometric **A**pproach for **R**eal-time **IO**nosphere Observatio**N**
- able to detect **sTEC variations in real-time** using observations coming from a stand-alone GNSS receiver

The VADASE approach

Features

- direct displacements estimation from the **observations of a stand-alone GNSS receiver** (single station approach)
- advantages: no infrastructure, no post-processing, no initialization needed; no clipping as standard seismometers

A patented idea

Since June 2010 VADASE idea was protected by a patent pending, thanks to the support of Sapienza University (patent released in 2014)

The VADASE approach

Methodology

$$\underbrace{\alpha[\lambda\Delta\Phi_r^s]_{L1} + \beta[\lambda\Delta\Phi_r^s]_{L2} =}_{\text{time single–difference ionosphere–free observations}}$$

$$\underbrace{[\Delta\rho_r^s]_{OR} - c\Delta\delta t^s + TZD_{SB}[1/cos(Z_r^s(t+1)) - 1/cos(Z_r^s(t))]}_{\text{known term, computed on the basis of known orbits and clocks}}$$

$$\underbrace{\mathbf{e}_r^s \bullet \Delta\boldsymbol{\xi}_r + c\Delta\delta t_r(t, t+1)}_{\text{terms containing the 4 unknown parameters}} \quad + \underbrace{[\Delta\rho_r^s]_{EtOl} + \Delta p_r^s)}_{\text{known term, from models}} + \underbrace{\Delta m_R^S + \Delta\epsilon_R^S}_{\textit{noise}}$$

- **$\Delta\xi_r^S$ (t, t + 1) is the epoch-to-epoch displacement, equivalent to velocity**

The VARION approach

Features

- derived from **VADASE**
- sTEC variation estimation from the observations of a **stand-alone GNSS receiver** (single station approach)
- advantages: no infrastructure, no post-processing, no initialization needed

Realization

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

The VARION approach

Methodology

$$\underbrace{L_{4R}^{S}(t+1) - L_{4R}^{S}(t) =}_{\text{time single difference geometry free observation}}$$

$$\underbrace{\frac{f_1^2 - f_2^2}{f_2^2}\left[I_{1R}^{S}(t+1) - I_{1R}^{S}(t)\right]}_{\text{unknown term, sTEC variation}} + \underbrace{\Delta m_R^S + \Delta \epsilon_R^S}_{noise}$$

- **epoch-to-epoch sTEC variations**

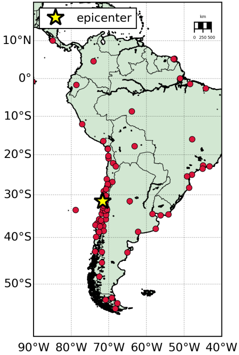
$$\delta sTEC(t+1,t) = \frac{{f_1}^2 {f_2}^2}{A({f_1}^2 - {f_2}^2)}\left[L_{4R}^{S}(t+1) - L_{4R}^{S}(t)\right] \quad (2)$$

(note that this is a total space-time variation)

Outline

Case study: 2015 Chile earthquake

On September 16, 2015, a 8.3 magnitude earthquake was registered in Central Chile, 46 km West of of Illapel, (31.570°S, 71.654°W, depth = 25.0 km), at 22:54:32 UTC



VARION dataset

- to evaluate **sTEC variations**, 89 GPS stations, located in all South American continent, were analyzed
- these GPS permanent stations collected data at 15 and 30 second rate

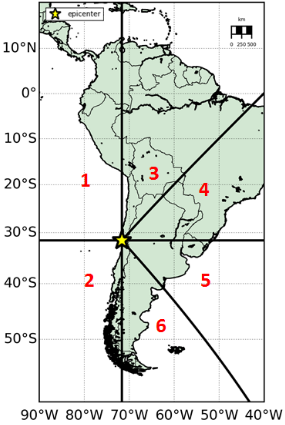
VARION processing

Analysis

The area studied was split into **six regions** making the epicenter the area center:

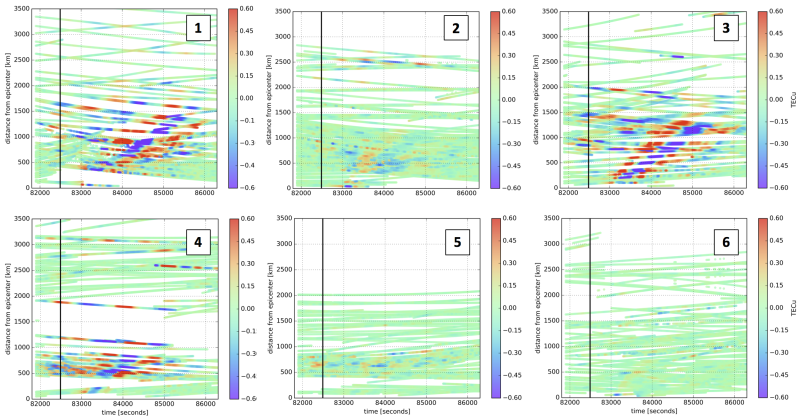
- 1, 2 mainly over the Pacific Ocean
- 3, 4, 5, 6 mainly over land

Results show a strong **asymmetry North-South** in sTEC variations



VARION processing

Hodochrons



VARION processing

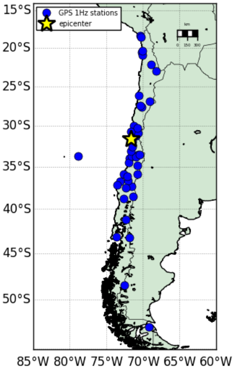
Space-time sTEC variations at the SIPs

Earthquake energy determination involving VADASE

The VADASE algorithm was used to investigate **solid Earth-ionosphere coupling** through a dedicated procedure

VADASE dataset

- high rate GPS data (1 Hz)
- VADASE computes the **estimated receiver velocities** for the East, North and Up components



Earthquake energy determination involving VADASE

Methodology

1. compute earthquake duration through **F-test of equality of variances**

Our F-test compares the ratio of the velocity sample variances before and after the earthquake under the hypothesis that they are equal

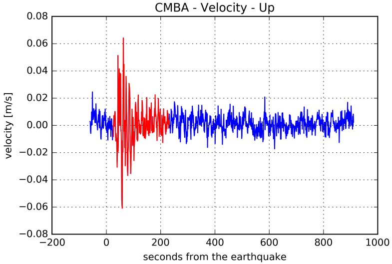
$$F = \frac{S^2_{after}}{S^2_{before}} < 1.84 \quad (3)$$

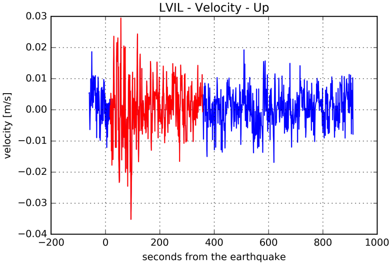
Where this condition is **false**, the earthquake is occurring

Earthquake energy determination involving VADASE

Methodology

1. compute earthquake duration through **F-test of equality of variances**



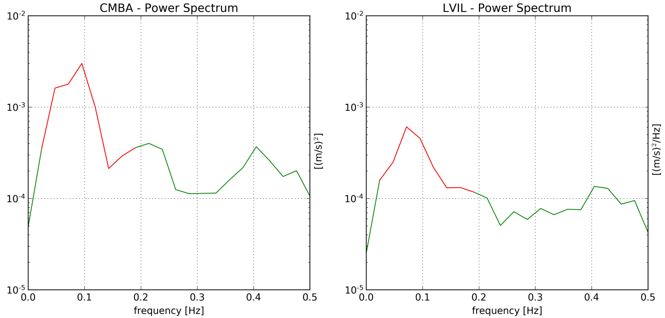


Earthquake energy determination involving VADASE

Methodology

2. calculate **Power Spectrum Density** (PSD) on this duration

It describes the distribution of power into frequency components

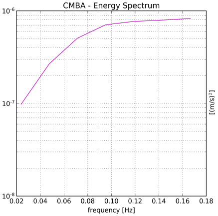


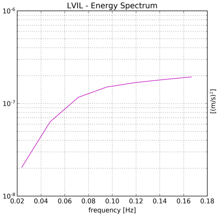
Earthquake energy determination involving VADASE

Methodology

3. integration in the frequency domain of Power Spectrum Density in order to obtain the earthquake **energy** per unit mass [J/kg]

Results show a greater energy in the north-placed stations within 250 km from the epicenter



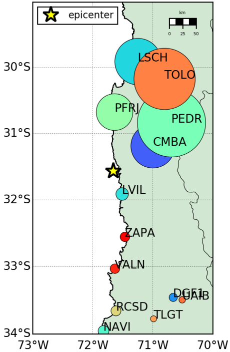


	Station	Distance from epicenter	Energy
		km	J/kg
North	CMBA	76.91	8.27 e^{-7}
	PFRJ	99.33	1.44 e^{-6}
	TOLO	176.021	1.00 e^{-6}
South	LVIL	40.56	1.93 e^{-7}
	ZAPA	110.74	1.70 e^{-7}
	VALN	161.71	2.36 e^{-7}

Earthquake energy determination involving VADASE

Methodology

3. integration in the frequency domain of Power Spectrum Density in order to obtain the earthquake **energy** per unit mass [J/kg]



CID directivity is caused by the **different energy** released by the earthquake in both directions

Outline

Conclusions and prospects

- **dual variometric approach**, represented by the application of VARION and VADASE algorithms useful for the comprehension of **earthquake induced ionospheric events** in real-time processing mode

Outlook

- applications on **other kind of natural/man-made hazard ionospheric pertubation** such as volcanic eruptions and geomagnetic storms
- other factors, such as the geologic structure of the crust, play an important role in the CID and should be considered as the subject of further studies

Thanks for your kind attention