Science on the GNSS-seismology interface

The Variometric Approach to GNSS Seismology from Concept to Applications

VADASE and VARION Teams
G. Colosimo, E. Benedetti, M. Branzanti, G. Savastano,
F. Fratarcangeli, M. Ravanelli, M.C. D'Achille, A. Mazzoni,
O. Verkhoglyadova, A. Komjathy,
M. Crespi

EPOS Seismology Workshop - 2017 ORFEUS Annual Workshop

Lisbon, Portugal
25 – 27 October 2017

Outlook

Outline

The main challenge: fast ground motions

Since middle '90s - early 2000s

- algorithms for kinematic post-processing (**one position per epoch**)
- a new idea: using **GPS** to estimate displacements and waveforms due to an earthquake (**GPS Seismology**)
- two approaches, very good for **positioning**:
  Differential Positioning (DP), Precise Point Positioning (PPP)
  drawbacks: infrastructures, post-processing, initialization, L1/L2 needed

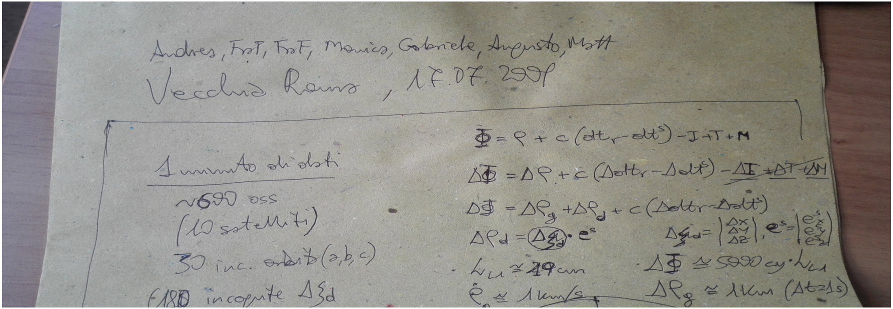
More recently . . . A major challenge to measure with

Real-Time GPS Science Requirements Workshop (September 2007)

- **1 cm** GPS **displacements** accuracy
- in a **global reference frame**
- within **3 minutes** after an earthquake

exploiting advances in receivers technology (high acquisition rate - **10-50 Hz**)

The VADASE concept:
Can we use a GPS just as a seismometer?



The VADASE concept

The goal

Focus on

- (near) **real-time accurate displacements** (**NOT positions**)
- in a **global reference frame**

The idea: keep it fast, keep it simple!

- 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 our University (patent released in 2014)

How does VADASE work?

The brand new *variometric* approach

VADASE:

Variometric **A**pproach for **D**isplacements **A**nalysis **S**tand-alone **E**ngine

Velocities estimation

- **time single-difference** of phase observations between two consecutive epochs
- at least **four satellites required, common to the two epochs**
- **cycle slips** identification and removal (**no need of ambiguity fixing**)
- **epoch-by-epoch velocity** estimation for each couple of consecutive epochs

Displacements estimation

- displacements estimation from **velocity integration**

VADASE model: the *variometric* equation

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

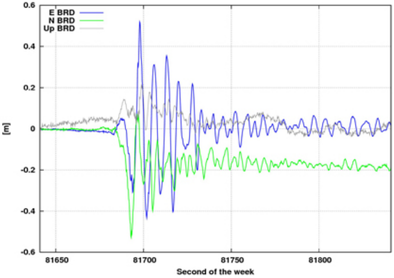
$$= \underbrace{[\Delta\rho_r^s]_{OR} - c\Delta\delta t^s + TZD_{SB}[1/cos(Z_r^s(t+1)) - 1/cos(Z_r^s(t))]}_{\text{known term (orbits, clocks, troposphere model)}}$$

$$+ \underbrace{(\mathbf{e}_r^s \bullet \Delta\xi_r(t,t+1) + c\Delta\delta t_r)}_{\text{terms containing the 4 unknown parameters}} + \underbrace{([\Delta\rho_r^s]_{EtOl} + \Delta p_r^s)}_{\text{small known term (models)}} + \underbrace{\Delta m_r^s + \Delta\epsilon_r^s}_{\text{noise}}$$

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

Outline

The boost: European Satellite Navigation Competition 2010



Baja California (Mexico) earthquake 4 April 2010, $M_w = 7.2$

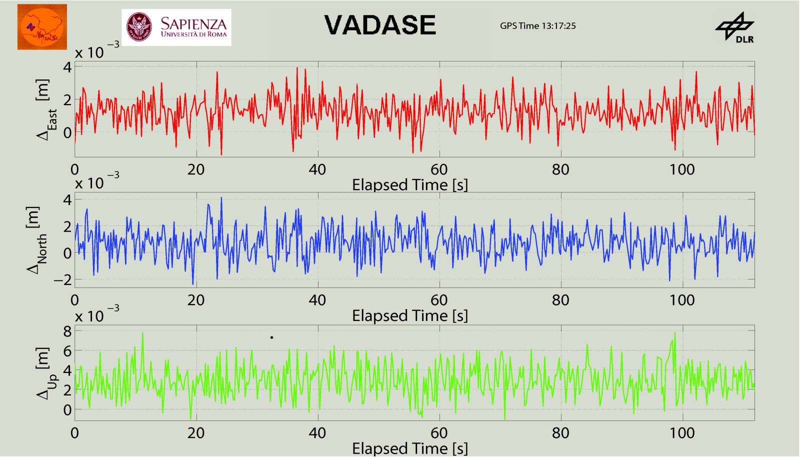
- **VADASE waveforms successfully compared** with solutions from standard approaches
- the results supported VADASE submission for ESNC 2010

VADASE, the winning idea of

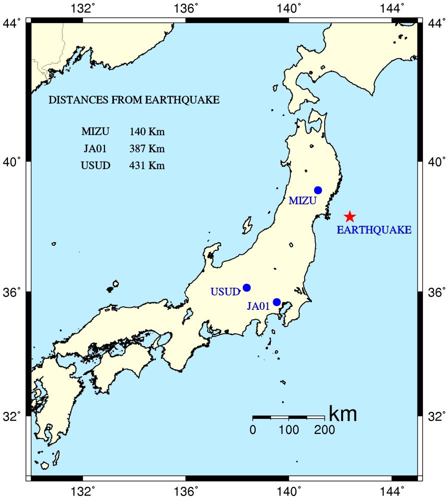
- **DLR Special Topic Prize**
- First Audience Award ($>$ 100 ideas)

Incubation at DLR - March 2011

First VADASE real-time solution within EV network



Tohoku-Oki earthquake - March 11, 2011 ($M = 9.0$)

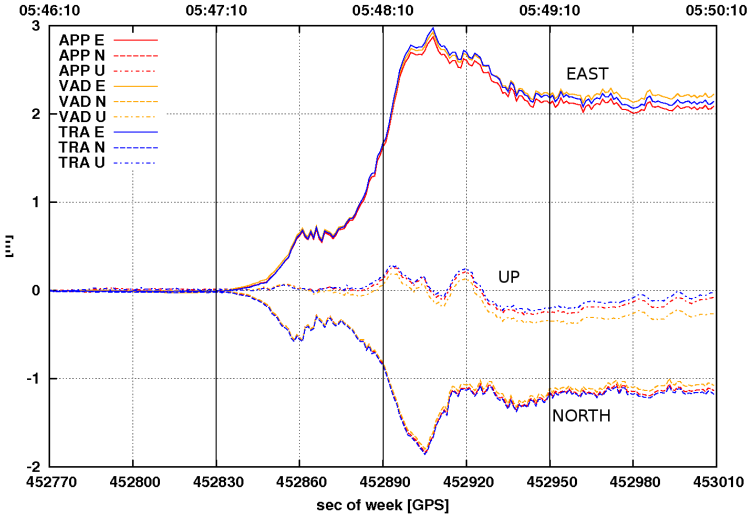


What is new

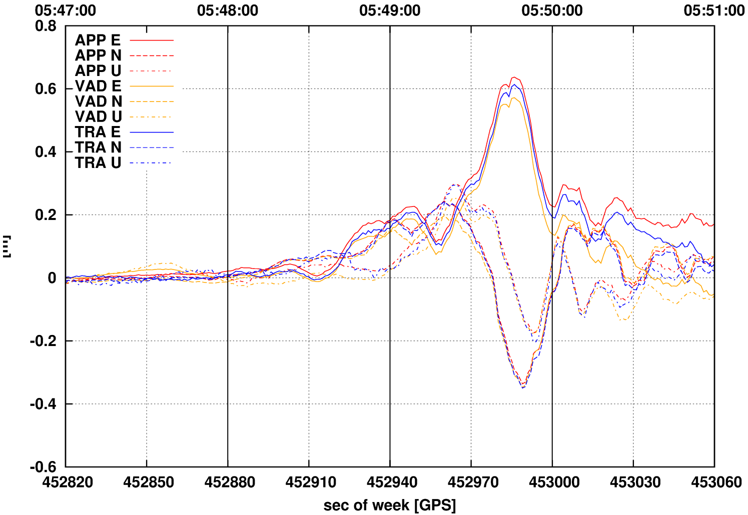
- VADASE provided the **first displacements computation**
  - **[IGSMAIL-6358]** - March 11, 04:13:35 PST 2011
  - solutions published on the **Tohoku-oki Event Supersite Website** - March 12, 2011
- **comparison** with other sw (DP: Track - PPP: APP)

Cover story
GIM International
vol 25, 5, May 2011

Tohoku-Oki earthquake - MIZU



Tohoku-Oki earthquake - USUD



Tohoku-Oki earthquake - VADASE vs. Track & APP

VAD - TRA		μ [m]	σ [m]	RMSE [m]	ρ
MIZU	East	0.015	0.033	**0.036**	**1.00**
	North	0.040	0.027	**0.048**	**1.00**
	Up	-0.088	0.075	**0.115**	**0.90**
USUD	East	-0.030	0.044	**0.054**	**0.96**
	North	-0.003	0.020	**0.020**	**0.99**
	Up	-0.019	0.037	**0.042**	**0.91**

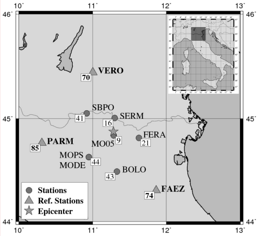
VAD - APP		μ [m]	σ [m]	RMSE [m]	ρ
MIZU	East	0.051	0.049	**0.071**	**1.00**
	North	0.024	0.021	**0.032**	**1.00**
	Up	-0.065	0.051	**0.082**	**0.97**
USUD	East	-0.057	0.064	**0.086**	**0.91**
	North	-0.009	0.016	**0.018**	**0.99**
	Up	-0.025	0.038	**0.045**	**0.90**

Emilia earthquake - May 20, 2012 ($M = 6.1$)

What is new

- application to a **"small" earthquake**
- **comparison** with:
  - other sw (DP: BERNESE, TRACK - PPP: APP, CSRS)
  - **high cost accelerometer (Strong Motion)**
- **first VADASE L1 solution** (Klobuchar ionosphere model)

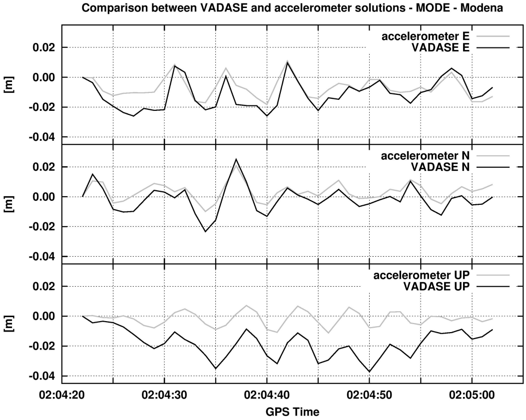
Overall results

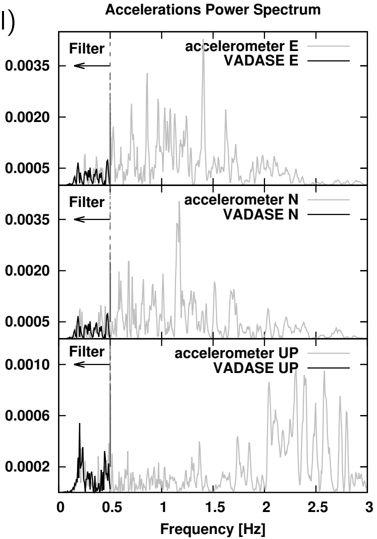


- **reference solutions agreement**: within **1 cm** in horizontal and **1.5 cm** in height
- VADASE L3 - reference solutions: within **1.1 cm** in horizontal and **1.5 cm** in height
- **VADASE L1** - VADASE L3 and reference: within **1.7 cm** in horizontal and **1.8 cm** in height

Emilia earthquake - VADASE vs. Strong Motion

GPS - Strong Motion comparison (40 s interval)
GPS receiver (1 Hz) - Strong motion (100 Hz)





Application to low-cost Galileo L1 receivers

Receiver

E1 observations collected through NV08C-EVK-CSM evaluation Kit

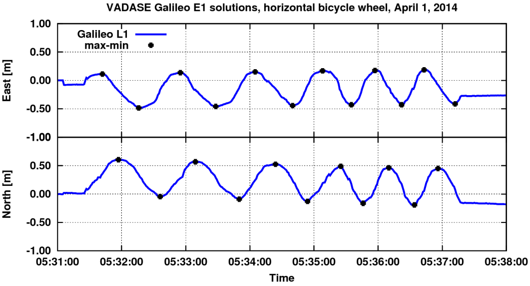
Navigation Message

- still not created by the receiver
- taken from a MGEX permanent station

Receiver motions

- stationary
- oscillations
- circular motion

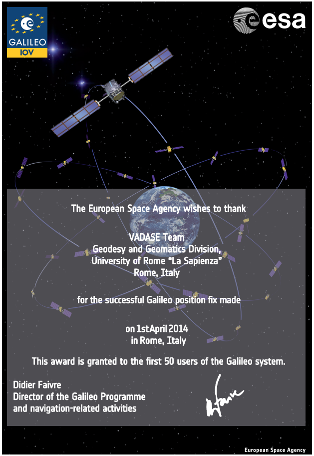
Low-cost Galileo L1 - circular motion



Bicycle wheel diameter

- manually measured **0.62 m**
- average oscillation amplitude (max-min in East and North) **0.63 m**

European Space Agency award
Fix certification for VADASE Galileo solutions



ESA fix certification

VADASE Team was recognized as **one within the first 50 companies/institutions worldwide** having made a ***fix*** with Galileo

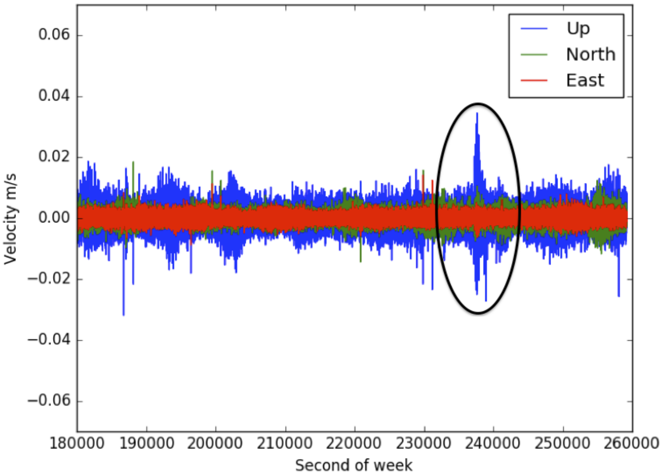
Outline

VADASE known problems

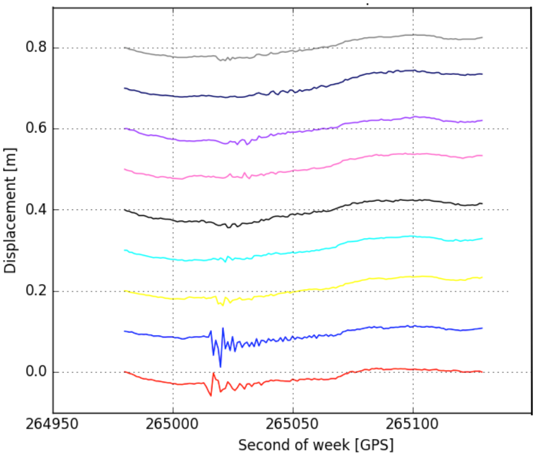
Real-time variometric solutions **might be impacted** by two different effects:

- **spurious spikes** in the velocities due to outliers
  (displacements, obtained by velocities integration, are severely corrupted)
- **common trends** in the displacements of near stations (approx. 100 km)
  (mainly due to broadcast orbit and clock errors)

VADASE known problems - Spurious spikes



VADASE known problems - Common trends



New VADASE improvements

- **VADASE–LOO:**
  receiver autonomous outliers detection, based on Leave-One-Out Cross Validation
- **A–VADASE:**
  network augmentation strategy to filter common trend out, based on **median filter, not impacting waveforms**

the two **improvements are combined** (1st VADASE–LOO, 2nd A–VADASE) for the complete reliable **real-time solution A–VADASE–LOO**

- **A–VADASE–LOO: real-time coseismic displacement estimation**,
  based on a suitable testing procedure
  (equal solution noise before and after the earthquake)

Meinong Earthquake, Taiwan

Features

- M 6.4
- 2016-02-05 19:57:27 UTC

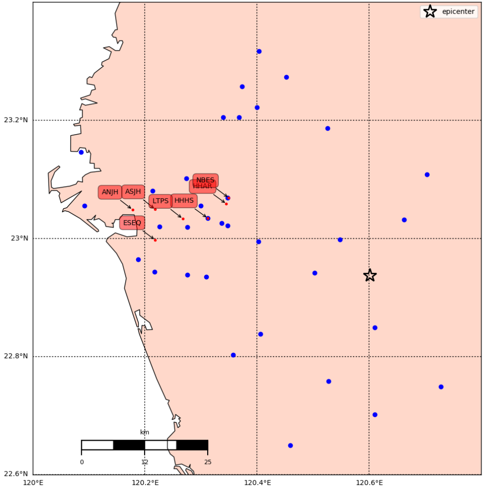
Goals

- **waveforms**
- **coseismic displacements**
- **S waves velocity**

VADASE outputs

- 3D velocities (East, North, Up)
- integrated displacements

GPS permanent network & data



Data set

GPS receivers:

- **34** dual frequency
- **7** single frequency

obs rate: **1 Hz**

time interval: **300 sec**

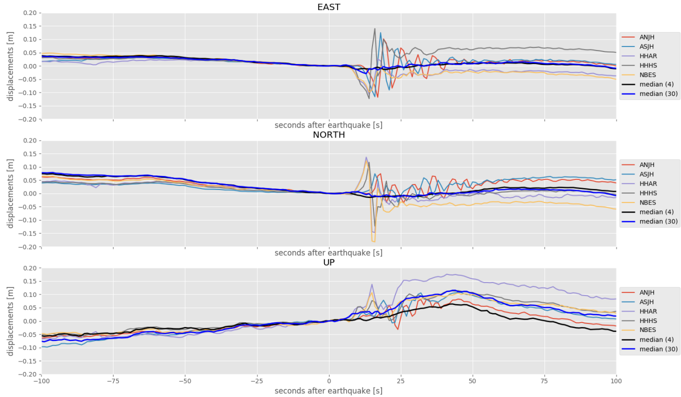
broadcast orbits and clocks

used L1 observations only

Common trend estimation & removal

Common trend estimation

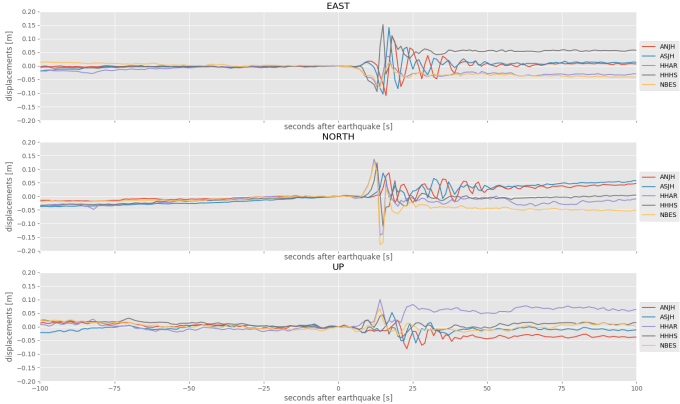
- real-time median (epoch-by-epoch)



Common trend estimation & removal

Common trend removal

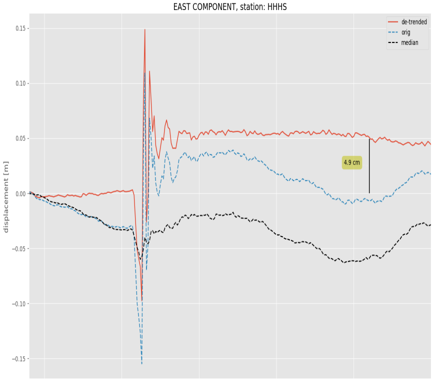
- real-time median removed from displacements

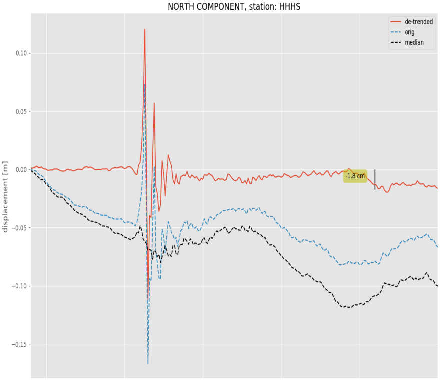


Coseismic displacements estimation - HHHS site

Estimated cosismic displacement

East: +4.9 cm North: -1.8 cm

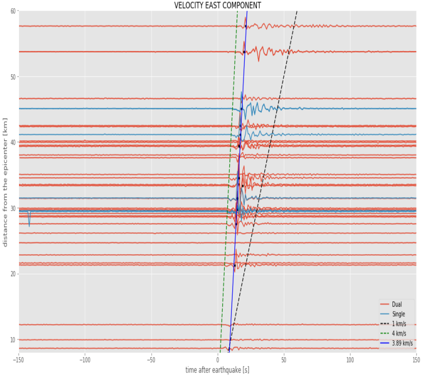


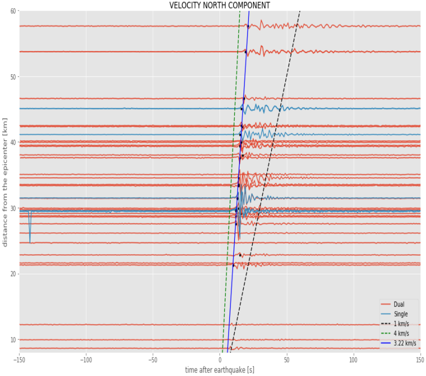


S waves velocity estimation

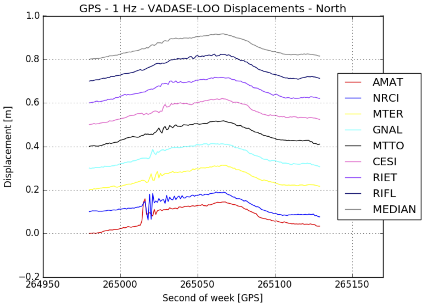
S waves velocity

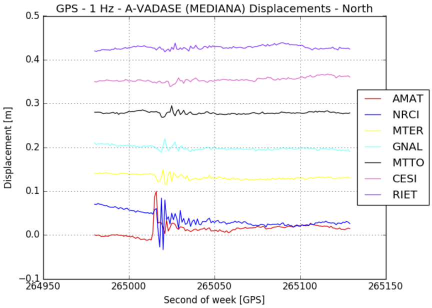
3.6 km/s





Amatrice earthquake - Aug 24, 2016 ($M = 6.0$)





Coseismic displacements

East = -0.2 cm , North = +3.6 cm , Up = -3.8 cm

VADASE status

VADASE main features - www.vadase.eu

Able to reliably estimate **velocities and displacements**

- in **real-time (broadcast products)**
- using a **stand-alone GNSS receiver**
- in a **global reference frame (ITRF)**
- from **high-rate** (1 Hz or more) **dual and single frequency phase observations** (low-cost GNSS receivers too)
- with an **accuracy within 1-2 centimeters**
- over **intervals up to few minutes**

Able to **work, in real time**

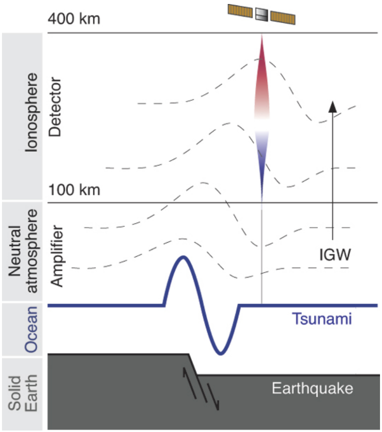
- in **stand-alone GNSS receiver firmware**
- in **centralized GNSS network processing center**

From Academy to Industry: Leica VADASE

September 2, 2015 - Leica Geosystems released Leica VADASE, **GNSS monitoring solution integrated into a stand-alone geodetic GR series receiver**

Outline

From VADASE to VARION: fast iono TEC variations



(Figure by Giovanni Occhipinti)

Tsunami TIDs

- atmosphere as low-pass filter
- **tsunami** waves transmitted as Gravity Waves into the atmosphere (**period lower than buoyancy period** (5 min at sea level))
- **strong amplification** during the upward propagation (density decreasing, energy conservation)
- **perturbations in the electron density** due to Gravity Waves
- TEC perturbations **detectable by GPS**

The VARION concept

The goal

Focus on

- **real-time accurate sTEC variation**

A new idea, a known approach

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

The realization of the 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**

How does VARION work?

A second brand new *variometric* approach

VARION:
Variometric **A**pproach for **R**eal-time **I**onosphere **O**bservatio**N**

sTEC variation estimation

- **dual frequency** phase observations
- **geometry-free combination** (L4 - removal of geometry, clocks and all non-dispersive effects) time single differences between two consecutive epochs
- **each satellite** common to the two epochs provides **one epoch-to-epoch sTEC variation**
- **cycle slips** identification and removal (**no need of ambiguity fixing**)

Total sTEC variation estimation

- **epoch-to-epoch sTEC variation integration**

VARION model: the *ionospheric variometric* equation

$$\underbrace{[\lambda\Delta\Phi_r^s]_{L1} - [\lambda\Delta\Phi_r^s]_{L2} = \left[L_{4r}^{\ s}(t+1) - L_{4r}^{\ s}(t)\right]}_{\text{time single–difference geometry–free observation}} =$$

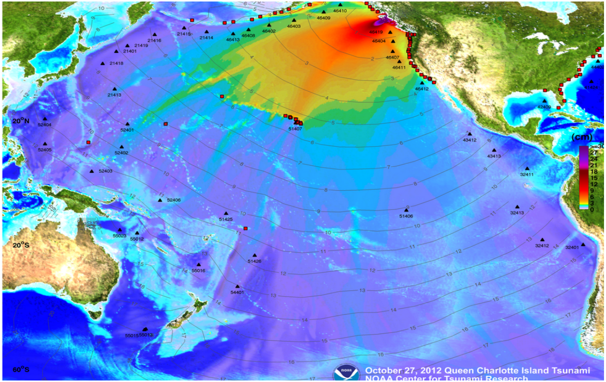
$$\underbrace{\frac{f_1^2 - f_2^2}{f_2^2}\left[I_{1r}^{\ s}(t+1) - I_{1r}^{\ s}(t)\right]}_{\text{unknown term, sTEC variation}} + \underbrace{\Delta m_r^s + \Delta\epsilon_r^s}_{\text{noise}}$$

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

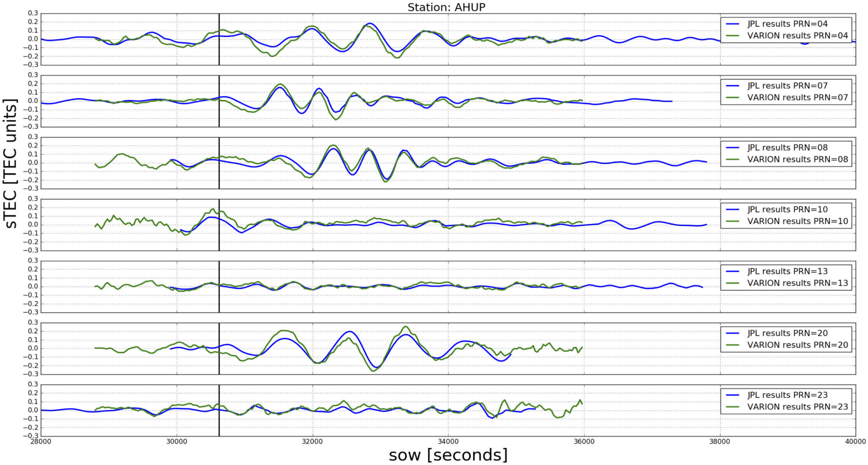
is the epoch-to-epoch sTEC variation
(note that this is a total space-time variation)

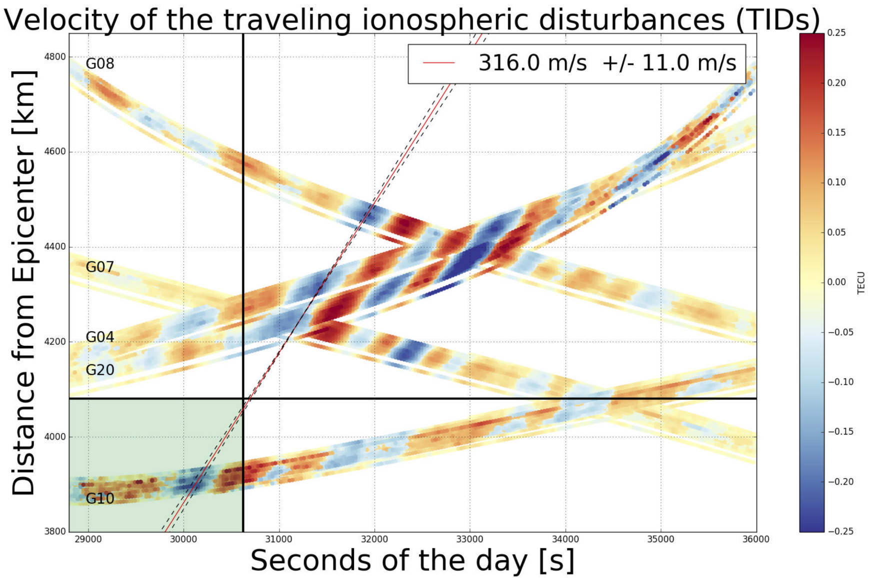
Haida Gwaii quake/tsunami - Oct 28, 2012 ($M = 7.8$)

Tsunami arrived at the Hawaii Islands in approximately 5:30 h



VARION vs. JPL post-processing solution




Velocity of the traveling ionospheric disturbances (TIDs)
316.0 m/s +/- 11.0 m/s
G08
G07
G04
G20
G10
Distance from Epicenter [km]
Seconds of the day [s]
TECU
4800
4600
4400
4200
4000
3800
29000
30000
31000
32000
33000
34000
35000
36000
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−0.25

Outline

Conclusions and prospects

Variometric approach was demonstrated light and effective for real-time solutions:

- **VADASE for fast ground motions**
- **VARION for fast variations of ionospheric TEC**

VADASE

- **was already** implemented in the **receivers firmware (Leica GR Series)**
- **is ready** to be used with **low-cost L1-only receivers**
- **is ready** to be used in a centralized **GNSS network processing center**
- **need to be fully extended to new GNSS constellations**

VARION

- is **under implementation in the NASA's Global Differential GPS system (GDGPS)**
- **need to be refined and fully extended to new GNSS constellations**

Thank you very much for your kind attention

www.vadase.eu