Static vs Real-Time Coseismic Offset Comparison: The Test Case of 30 October, 2016 Central Italy Earthquake

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Abstract: The knowledge of coseismic deformations due to earthquakes represents the fundamentals on which studies on seismic cycle and fault source mechanism are based on. Geodetic methods, in particular the recent developments of GNSS monitoring, are the only onescapable of providing the displacements of reference sites due to the occurrence of significant seismic events. Usually the detection of seismic offsets is done by comparing coordinates estimated before and after the earthquake. Here, considering the test case of the 30 October, 2016 central Italy seismic event, we show that it is possible to achieve such offsets also in real-time through the application of the new functionalities of the VADASE (Variometric Approach for Displacements Analysis Stand-alone Engine) approach. The comparison between the seismic offsets coming from the two approaches (static and real-time) is shown and discussed; the mean overall agreement is at the level of about half centimetre.

I. Introduction

On August 24 2016 at 1:36 GMT a large earthquake (M_w 6.0) struck Accumoli and Amatrice (Rieti, central Italy) causing major destruction of ancient villages and 299 fatalities. It was the beginning of the largest seismic sequence recorded in Italy since the Irpinia event (M_w 6.9, November 23 1980), that hit the central sector of the Apennines among Lazio, Umbria, Marche and Abruzzi regions, and is still ongoing at the moment of writing this manuscript, after more than six months. The central Apennines area is characterized by a complex extensional tectonics generat-

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ing slow crustal deformations (at the few mm/yr level) and is affected by repeated seismic sequences. The 2016 sequence occurred on a NW-SE trending normal rupture, manifestation of this extensional tectonic regime, ongoing since the Late Pliocene ([Falcucci et al., 2016] and reference therein). RCMT solutions evidence the tensional feature of seismic sources well in agree with the tectonic style of the area ([Pondrelli et al., 2016]). Two months later than the first event, known as the Amatrice event, two other large events occurred, on October 26, M_w 5.9 near Castel Sant'Angelo sul Nera (Macerata) and on October 30, M_w 6.5 near Norcia (Perugia), the largest magnitude of the sequence. Till now, the Italian Istituto Nazionale di Geofisica e Vulcanologia (INGV) recorded about 57400 earthquakes, 9 with $M \geq 5.0$, about 1100 with $3.0 \leq M < 5.0$ and the remaining with magnitudes below 3.0 (seismic data archive http://iside.rm.ingv.it). In the following we have considered only the 30 October, 2016 earthquake as capable of generating both offsets in GNSS coordinate time series and significant waveforms in high rate GNSS data.

Table 1. *Earthquake*

Date Yr-m-d	2016-10-30
Time (UTC) h:m:s	06:40:19
Magnitude M_w	6.5
Province	Perugia
Depth (km)	9
Latitude °N	42.83
Longitude °E	13.11

The rapid development of GNSS networks in Italy, installed with different aims thanks to the efforts of various Institutions, provides great advances in geodynamical studies. The data of all these networks, over 900 raw-data files per day for a mean geometric inter-distance of about 20 km over the whole country, are currently archived and processed at INGV ([Devoti et al., 2014]). Therefore before and during the seismic sequence, several continuous GPS stations were already operating, mostly at 30s sampling rate,only few at 1s. Soon after the first large event, some GPS markers belonging to the CaGeoNet non-permanent network ([Galvani et al., 2012]) were re-occupied to measure the coordinates after the shocks and then estimate the seismic source parameters by the inversion of coseismic offsets ([Cheloni et al., 2016]). Some stations, set up at higher sampling rates than standard 30s (1s, 0.05s), also recorded the dynamic displacements due to the main-shocks ([Avallone et al., 2016]). The importance of coseismic offset estimation at the very early stage of a seismic crisis relies on a rapid seismic-source parameters evaluation, potentially useful to imagine the development of a seismic sequence, the possible activation of nearby faultsand generally to give immediate response to Civil Protection needs.

II. Static estimation

The static offset estimation is based on the analysis of the available GPS data, in the form of 24-hours 30s sampling rate RINEX files, processed by three different analysis groups, using different software (BERNESE, http://www.bernese.unibe.ch; GAMIT, http://www.gpsg.mit.edu/ simon/gtgk and GIPSY, http://gipsy.jpl.nasa.gov/orms/goa). We refer to [Devoti et al., 2017] for a more detailed description of the three processing approaches, usually devoted to estimate velocity and strain rate fields. The static offsetswere computed from three distinct time series of stations located around the epicenters from the linear model:

$$x_i(t) = x_i{}^0 + r_i \cdot t + \alpha_i \cdot \sin(\omega t + \varphi_i) + \Delta x_i \cdot H(t_j) \quad (1)$$

where x_i are the Cartesian coordinates at epoch t of each site (i = 1,2,3), are the coordinates at epoch t_0, the rates, α and φ are the amplitude and phase of periodical signals (mostly annual) and H is the Heaviside step function, used to estimate the coordinate offsets (Δx_i) at a given epoch t_j .

We have estimated the three sets of independent coseismic displacements by limiting the time series up to 15 days before and only 3 days after each event, to minimize the effects of early postseismic displacements, commonly observed in a wide range of seismic events causing deformations up to several centimeters, depending on the magnitude and the driving mechanism. The three independent coseismic offset estimates are then combined to obtain a final field of validated displacements, following the procedure described in [Devoti, 2012] and first applied in [Serpelloni et al., 2012]. The combination allows to obtain a final revised solution, with efficient outlier detection obtained after cross-checking independent solutions, and realistic estimates of the displacement uncertainties. The combined offsets after the Amatrice ([Cheloni et al., 2016]), Castel Sant'Angelo sul Nera and Norcia earthquakes (INGV Working Group "GPS Geodesy (GPS data and data analysis center)", 2016) are fully available at http://ring.gm.ingv.it.

III. Real-time (High Rate) estimation

On the other hand the real-time offset estimation is based on the analysis of the GPS 1Hz data with the VADASE approach. Generally the real-time VADASE solutions can be impacted by two different effects, which can severely mask the actual phenomena: spurious oscillations in the estimated velocity due to outliers in GNSS observations, resulting in false displacements and trends in the displacements mainly due to broadcast orbit and clock errors. Two strategies were defined in order to solve these problems; they were described in Sections III.1 and III.2.

III1. VADASE Leave-one-out

A strategy to detect outliers in the observations during the real-time estimation was defined on the basis of the Leave-One-Out Cross Validation (LOOCV) ([Brovelli et al., 2008]).

Standard techniques for outliers detection as the well known Baarda data snooping, do not generally supply statistical tests of proper power, due to the low redundancy of the epoch by epoch solution; on the contrary, LOOCV is more powerful, at the cost of n-repeated least squares epoch by epoch solutions (being n the number of satellite common in view in two consecutive epochs), which are however still feasible from the computational point of view (VADASE-LOO). Therefore if n is the number of variometric equations, where the number of the set of equations depends on the number of satellites common to the two epochs, the Leave-one-out-LOO method applied to VADASE algorithm involves the iterative application of the algorithm using all the satellites except one, different in each iteration. The satellite left out is considered outlier on the basis of statistical test.

III2. Augmented VADASE

Discrete integration of 3D estimated velocities obtained of VADASE–LOO was often impacted by trends. It was clearly identified a strong spatial correlation of these trends among close GNSS stations (within 100 km) due to the common errors in the satellite broadcast orbits and clocks. For this reason it was introduced a new strategy, called augmented strategy (A–VADASE) in order to filter out these trends. The approach used to filter the trend is based on the computation of the statistical index of the spatial median of the displacements epoch by epoch considering all station involved in the phenomena.

III3. VADASE results

The 30 October, 2016 earthquake was recorded by a number of GPS stations belonging to the Rete Integrata Nazionale GPS (RING), SmartNet ItalPoS and Rete Regione Lazio around the damaged area. The RINEX data at 1Hz were available; regard the navigation data, the daily broadcast ephemeris file for GPS, free online distributed by CDDIS–Nasa's Archives of Space Geodesy Data, were used.

Map of the GNSS station distribution was shown for 30 October, 2016 earthquake (Fig. 1). The distances among the GNSS stations and the epicentre was reported (Tab. 2).

The observation data were processed with VADASE algorithms (VADASE–LOO and A–VADASE) in order to quantify the coseismic displacements and to depict the waveforms. The 3D velocities (in East, North and Up component) were computed with VADASE-LOO for the earthquake. The possible outliers were removed

Table 2. *GNSS Stations distances from the epicentre of the 30 October, 2016 earthquake.*

Station	distance [km]
ARQT	14.57
FOL1	34.05
MTER	40.41
MTTO	45.94
GNAL	46.48
TERI	49.12
RIET	54.15
CONI	55.63
TOD3	56.72
FRMO	61.97
ROPI	62.11
GRAM	64.48
BARS	70.66
CAOC	71.13
PSAN	93.58

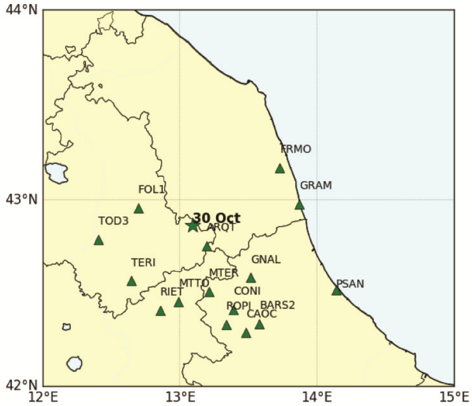


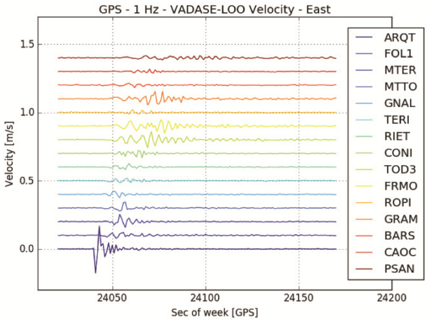
Figure 1. *GNSS stations map - 30 October 2016*

and the trends of the 3D velocities, in the 150 second interval over the mainshocks were displayed in Fig. 2. The earthquake signatures were clearly evident in the 150 second interval time series of the 3D velocities.

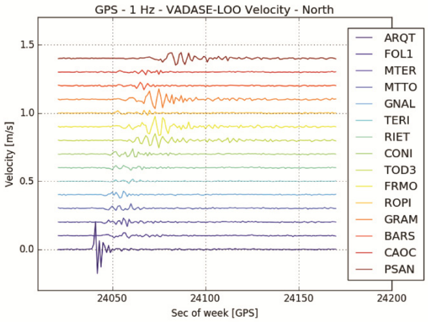
In order to reconstruct the occurring receivers motion, 3D velocities, obtained by VADASE-LOO, were integrated, within the selected interval. Displacements obtained by integrating 3D velocities were displayed in Fig. 3. Well known is that this (discrete) integration is very sensitive to estimation biases, due to the possible mismodeling of different intervening effects (such as multipath, residual clock errors, orbit errors, and atmospheric errors) which accumulate over time and display their signature as a trend in the coseismic displacements themselves ([Brazanti et al., 2013]); in fact slight trends were shown in all coseismic displacements (Fig. 3).

In order to remove a spatial correlation of these trends among close GNSS stations, A-VADASE strategy was applied. The median of the displacements epoch by epoch considering all the stations, involved in the earthquake, was computed and it was subtracted at VADASE-LOO solutions for each station to filter out these trends. The detrented coseismic displacements, called A–VADASE–LOO, are displayed in Fig. 4.

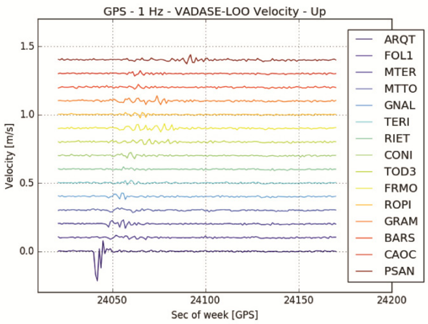
Both the velocities, the displacements and the detrended displacements of the GNSS stations are sketched in function of the distance of the epicentres. The ve-



(a) *East*

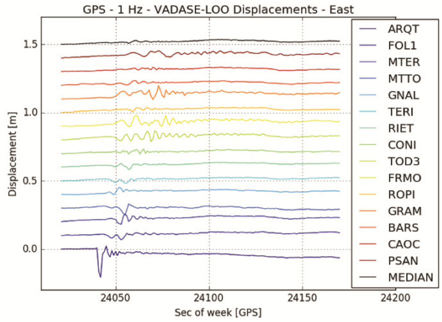


(b) *North*

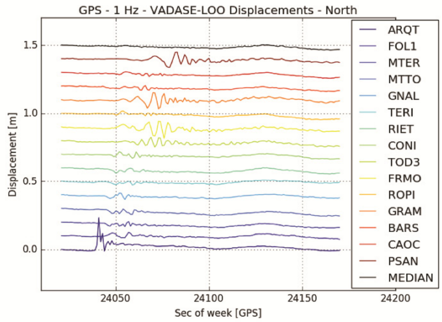


(c) *Up*

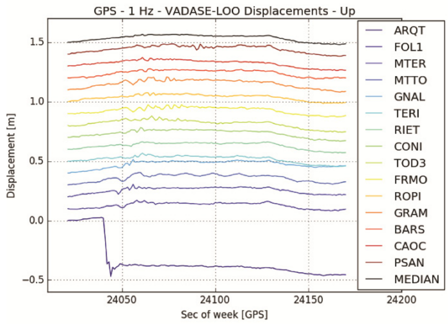
Figure 2. *Estimated velocity by VADASE–LOO in the 150s interval on 30 October 2016, GPS time*



(a) *East*



(b) *North*



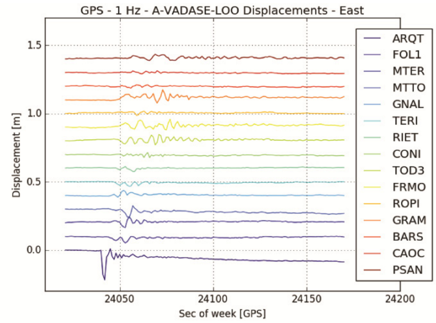
(c) *Up*

Figure 3. *Estimated displacements by VADASE–LOO in the 150s interval on 30 October 2016, GPS time*

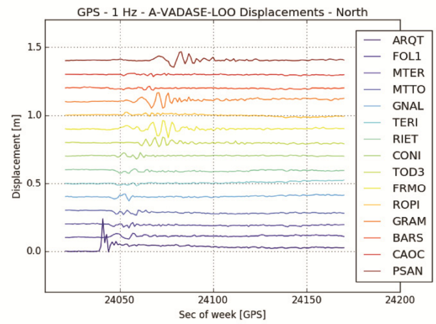
locities, the displacements and the detrended displacements of the GNSS stations nearest to the epicentre are lowest outlined but the spacing among the trends is the some, it is not respect the real distance from the epicentres.

Starting from the A–VADASE–LOO displacements, the VADASE coseismic displacements were computed as differences of average between two moving windows of 30x30 size immediately before and immediately after the earthquake mainshock applying at the two windows a statistical test, based on the hypothesis of a constant mean level noise of the VADASE velocity estimates over few minutes.

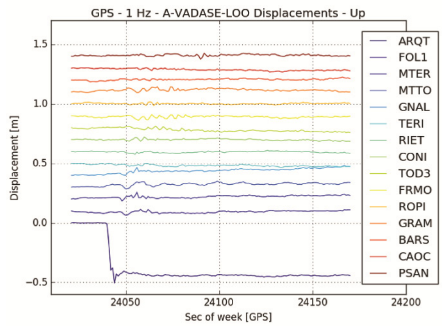
The VADASE coseismic displacements were compared with the official ones supplied by INGV (Tab. 3); on average the differences are in the order of 0.4 cm (Tab. 4).



(a) *East*



(b) *North*



(c) *Up*

Figure 4. *Estimated displacements after trend removing by A–VADASE–LOO in the 150s interval on 30 October 2016, GPS time*

Table 3. *Coseismic dispalcements - 30 October, 2016 earthquake*

Station	A-VADASE-LOO [cm]			INGV [cm]		
	East	**North**	**Up**	**East**	**North**	**Up**
ARQT	-2.88	4.98	-43.29	-4.35	5.26	-44.67
FOL1	0.17	1.85	1.43	-1.73	0.09	-0.36
MTER	0.18	-0.95	0.67	-0.14	-0.97	0.29
MTTO	-2.70	-1.30	-0.40	-0.98	-1.20	0.12
GNAL	2.19	-0.33	1.09	0.94	-0.29	0.48
TERI	-0.86	0.59	0.00	-1.50	-0.84	0.07
RIET	0.84	0.18	0.00	-0.82	-1.08	0.10
CONI	-0.30	-0.88	0.80	0.11	-0.21	0.70
TOD3	-0.20	-0.50	-3.10	–	–	–
FRMO	1.80	-0.40	0.00	0.81	0.67	0.73
ROPI	-0.78	0.52	0.66	-0.05	-0.19	0.31
GRAM	1.69	2.29	0.69	1.17	0.39	0.37
BARS2	0.27	-0.58	1.08	-0.01	-0.01	0.78
CAOC	-0.73	0.86	-0.27	0.03	-0.03	0.43
PSAN	0.80	0.10	1.50	0.30	-0.07	-0.01

Table 4. *Differences between coseismic dispalcements - 30 October, 2016 earthquake*

Station	Differences [cm]		
	East	**North**	**Up**
ARQT	1.48	-0.28	1.39
FOL1	1.91	1.76	1.79
MTER	0.31	0.01	0.38
MTTO	-1.72	-0.10	-0.52
GNAL	1.25	-0.04	0.61
TERI	0.65	1.43	-0.07
RIET	1.66	1.26	-0.10
CONI	-0.41	-0.67	0.10
TOD3	–	–	–
FRMO	0.99	-1.07	-0.73
ROPI	-0.74	0.71	0.35
GRAM	0.53	1.90	0.32
BARS2	0.27	-0.57	0.30
CAOC	-0.76	0.89	-0.70
PSAN	0.50	0.17	1.51
average	0.42	0.39	0.33

VI. Conclusions

The knowledge of coseismic deformations due to earthquakes represents the fundamentals on which studies on seismic cycle and fault source mechanism are based on. Two approaches (static and real-time), based on the GNSS monitoring, can be used to compute the coseismic displacements. The first approach is based on the processing of 30s GPS data with three different software (BERNESE, GAMIT and GIPSY) and on combination of the independent estimated displacements in order to obtain a final solution; the latter is based on the analysis of 1 Hz GPS data with the A–VADASE–LOO strategy as differences of average between two moving windows of 30x30 size immediately beforeand immediately after the earthquake mainshock applying at the two windows a statistical test, based on the hypothesis of a constant mean level noise of the VADASE velocity estimates over few minutes.

The VADASE coseismic displacements were compared with the official ones supplied by INGV; on average the differences are in the order of 0.4 cm.

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Regione Abruzzo (http://gnssnet.regione.abruzzo.it),
ITALPOS (http://it.smartnet-eu.com) and
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