Global Navigation Satellite Systems Seismology for the 2012 M_w 6.1 Emilia Earthquake: Exploiting the VADASE Algorithm

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INTRODUCTION: THE STATE OF THE ART AND OUR CONTRIBUTION

The Global Positioning System (GPS) has been repeatedly proven to be a powerful tool to estimate coseismic displacements and waveforms, with accuracies ranging from few millimeters to few centimeters. These promising results were achieved following two main strategies: differential positioning (DP) and precise point positioning (PPP; Bock *et al.* [1993], Kouba [2003], Larson *et al.* [2007], Larson [2009], Ohta *et al.* [2012], Xu *et al.* [2012], and Hung and Rau [2013]). In particular, both the modeling of fault rupture and the seismic moment estimation could benefit from GPS-derived displacements, because GPS is not affected by the saturation problems experienced by seismometers located near the epicenters of strong earthquakes. Thanks to the robustness of the GPS-derived displacement waveforms, in the last years some authors (Bock *et al.*, 2000; Langbein and Bock, 2004; Blewitt *et al.*, 2006; Bock and Genrich, 2006) addressed the problem to retrieve them in real time, with accuracies of a few centimeters, from GPS high-rate observations (1 Hz or more). In this context, the Variometric Approach for Displacements Analysis Standalone Engine (VADASE) has been proposed (Colosimo *et al.* [2011a], Colosimo [2013]). The approach is based on time single differences of carrier phase observations continuously collected using a standalone GPS receiver and on standard GPS broadcast products (orbits and clocks) that are available in real time. Therefore, one receiver works in standalone mode and the epoch-by-epoch displacements (equivalent to velocities) are estimated. Then, they are summed over the time interval when the earthquake occurred to retrieve displacements. Because VADASE does not require either additional technological complexity or a centralized data analysis, in principle, it can be embedded into the GPS receiver firmware and therefore can work in real time. Moreover, differently from DP and PPP, VADASE does not require phase ambiguity solving and it is also able to work with single-frequency data only.

The effectiveness of VADASE was already proved through the application to the catastrophic Tohoku-Oki earthquake (USGS M_w 9.0, 11 March 2011, 05:46:24 UTC) when variometric approach solutions were obtained immediately after the availability of data at International Global Navigation Satellite Systems (GNSS) Service (IGS) permanent stations (Group on Earth Observations [GEO], 2011). Then, these solutions were compared with the well-estabilished strategies in GNSS Seismology (DP and PPP) and an high level of agreement was found (for more details please refer to Colosimo *et al.* [2011b] and Branzanti *et al.* [2013]). As regards a short recall about the fundamentals of VADASE and its current implementation, please consider the summary outlined in the Appendix A.

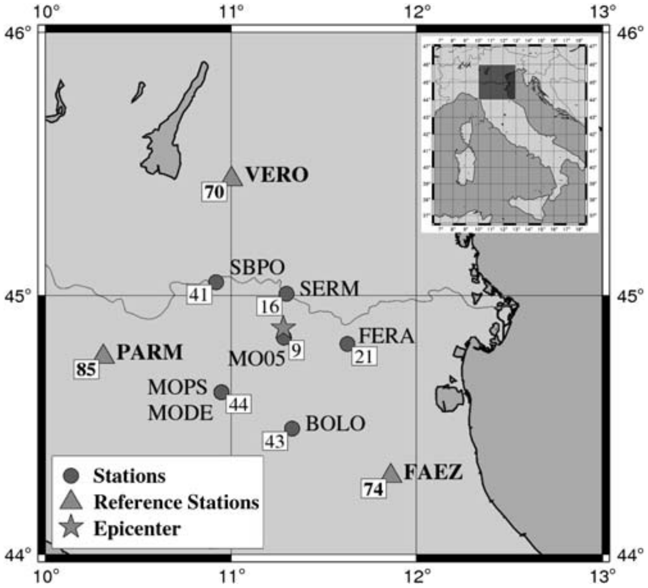
Here, we present VADASE application to the Emilia earthquake (Pondrelli *et al.* [2012] M_w 6.1, 20 May 2012, 02:03:51 UTC) characterized by a moment magnitude of 6.1 and a focal depth of 11.4 km, with northwest–southeast-striking reverse mechanism. For detailed informations about this earthquake, please refer to Pondrelli *et al.* (2012) and references therein.

This work is motivated by four goals: (1) perform a thorough comparison between VADASE and credited software in case of small earthquake displacements (unlike the large ones occurred during the already analyzed Tohoku-Oki event), (2) evaluate the accuracy level of VADASE when processing L1 observations only, (3) show the usefulness of VADASE in retrieving coseismic displacements for low-acquisition rates, and (4) compare VADASE results to collocated accelerometer solutions. Therefore, after a general introduction about the applied GPS data processing strategies outlined in GPS Data Processing section, in 1 Hz Dual Frequency Data section we present VADASE L3 solutions obtained with 1 Hz sampling rate data collected at seven permanent stations of Italian Positioning Service (ItalPoS) network and the comparison with other software results on the same input data.

Then, in 1 Hz Single-Frequency Data VADASE Processing section we present VADASE L1 solutions and comparisons with VADASE L3 results previously obtained.

In 30 Second Data section we present results obtained by processing with VADASE original 1 Hz data decimated at 5, 15, and 30 s. From 1 Hz processing we detected that only one station underwent a significant permanent displacement: for such reason, for the sake of brevity, the low-frequency processing was applied just in this case. The comparison with accelerometers is presented and discussed in Comparison between VADASE and Accelerometer Solutions section.

Finally, in the Conclusions section we discuss conclusions and future research directions for GNSS seismology, in particular, toward the real-time application of the variometric approach, considering observations collected from geodetic (dual frequency and multiconstellation) and low-cost (single frequency) receivers. In the following, the discussion of the results is presented: to support it just the most significant figures and tables are shown in the paper. Supplementary material is quoted in the text and is available in Benedetti *et al.* (2014).



▲ **Figure 1.** Position of the Global Navigation Satellite Systems permanent positions station and their distances from the epicenter (reference stations are considered for differential positioning processing only).

GPS DATA PROCESSING

Here, we show the simulated real-time application of VADASE (in the sense that only standard GPS broadcast products available in real time were used) to observations collected during the earthquake at the ItalPoS GPS permanent stations. These include (in brackets their distances from the epicenter) BOLO (Bologna, 43 km), FERA (Ferrara, 21 km), MODE (Modena, 44 km), MOPS (Modena University, 44 km), MO05 (Finale Emilia, 9 km), SBPO (San Benedetto Po, 41 km), and SERM (Sermide, 16 km).

VADASE capabilities were fully exploited considering both dual-frequency data, applying the ionospheric-free combination (L3), and L1 single-frequency data applying the Klobuchar ionospheric model. VADASE solutions were obtained considering the data collected at 1 Hz sampling rate in the two minutes interval from 02:04:00 to 02:06:00 GPS time.

Four independent solutions were computed to assess the variometric results: two applying DP using Bernese GPS Software (Dach *et al.* [2007]) and TRACK software (http://www-gpsg.mit.edu/~simon/gtgk/; last accessed November 2012), a kinematic module of GAMIT, and two obtained through PPP by using Automatic Precise Positioning Server PPP (APP-PPP, http://apps.gdgps.net/; last accessed November 2012) and Canada Resource Reference System PPP (CSRS-PPP, http://www.geod.nrcan.gc.ca/; last accessed November 2012) online tools.

In case of DP, three additional permanent stations within ItalPoS network (VERO [Verona, 70 km], FAEZ [Faenza, 74 km], and PARM [Parma, 85 km]) were considered (Fig. 1); these stations were not significantly impacted by the earthquake, so they can be considered stable and used as reference.

According to our knowledge and software manuals, these four software were used in optimal conditions to obtain the best solutions. In particular, the manuals indications were followed as regards Bernese GPS Software and TRACK software, whereas the online tools were managed according to the default procedures.

Here, it has to be emphasized that it is necessary to consider a much longer data interval with respect to the two minutes used in VADASE processing to be able to solve the phase ambiguities. We acknowledge that, in principle, this is not a severe drawback, provided continuous data are collected. Therefore, an interval of three hours was processed with TRACK (from 00:00:00 to 03:00:00 GPS time) to improve ambiguity fixing, using IGS precise orbits; the Bernese preprocessing for ambiguity solving was made over an interval of 24 hours using observations subsampled at one minute. Conversely, the kinematic processing to estimate displacements was made over an interval of 45 min with 1 Hz observations. Even in this case, IGS precise orbits were exploited. A data span of one hour and 24 hours were considered for the APP-PPP and CSRS-PPP processing, respectively. We remark that the L1 single-frequency solutions were computed only with VADASE; in fact TRACK, APP-PPP, and CSRS-PPP strictly need dual-frequency data, and Bernese can compute a single-frequency solution applying a ionospheric model, but only with baselines shorter than 10 km (Dach *et al.* [2007]), whereas the considered baselines are always longer than 40 km. All the main processing features are summarized in Table 1. To perform the comparisons, the solutions for all the stations were aligned to the first epoch (02:04:00 GPS time) of VADASE solutions. Moreover, the above mentioned processing strategies for all the considered software were applied for MO05 station using 30 s sampling rate observations obtained decimating the original 1 Hz data.

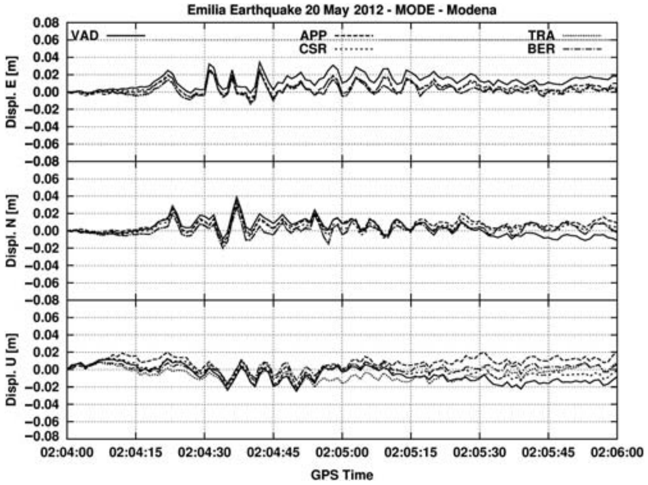
Table 1
Main Features of the Different Solutions

	Strategy	Orbits and Clocks	Observation Interval	L1/L2	L1 Only
VADASE	Variometric	Broadcast	2 min	Yes	Yes
BERNESE	Differential positioning (3 Reference Stations)	Precise (24 hours preprocessing)	45 min	Yes	No
TRACK	Differential positioning (3 Reference Stations)	Precise	3 h	Yes	No
APP	Precise point positioning	Precise	1 h	Yes	No
CSRS	Precise point positioning	Precise	24 h	Yes	No

Table 2
Solutions Accuracies (1 Hz Observations over the 120 s Interval 20 May 2012—02:02:00 to 02:04:00 GPS Time)

	Rmse (mm)		
	E	N	Up
VADASE L1	7	32	21
VADASE L3	9	31	17
APP	7	6	13
CSRS	4	5	11
BERNESE	4	5	10
TRACK	4	5	18

Last but not least, it is important to underline that also a preliminar analysis in a pre-event situation (no motion) was carried out, applying VADASE to 1 Hz data collected during the two minutes interval before the earthquake (from 02:02:00 to 02:04:00 GPS time). In this way it was possible to assess the noise level for all the software and the strategies applied, because this interval was already included within the four reference solutions due to the processing choices explained before. In this respect, the pre-event analysis (Table 2 and Ⓔ Table S1, available in the electronic supplement to this article) demonstrated the reliability of the processing strategies applied to the four software with a common noise level at about 0.5 cm for the horizontal components and better than 1.5 cm in height. The noise level of VADASE solution is around 1 cm in East, 3 cm in North and 2 cm in Up component, similar to what assessed in previous works (Branzanti *et al.* [2013]).



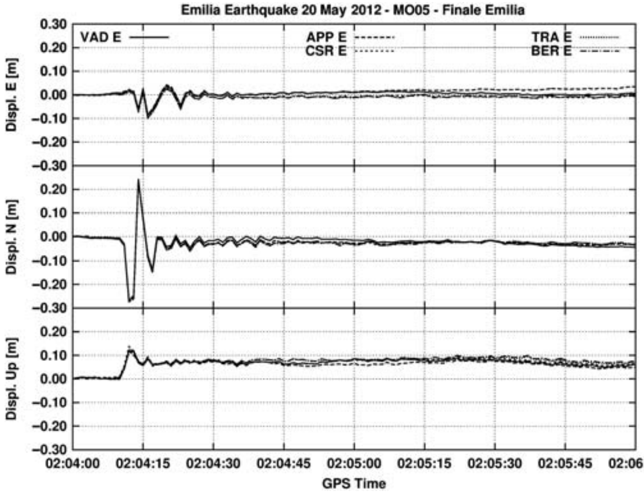
▲ **Figure 2.** Comparison among Variometric Approach for Displacements Analysis Standalone Engine (VADASE) and reference solutions at MODE station (1 Hz observations over 120 s interval 20 May 2012—02:04:00 to 02:06:00 GPS time, ionosphere-free processing).

RESULTS

1 Hz Dual-Frequency Data

A comparison between the VADASE and other software packages is shown in Figures 2 and 3 for stations MODE and MO05, respectively. The global root mean square error (rmse) between all software pairs for all stations is shown in Table 3.

Considering the illustrated pre-event noise level, good agreement exists among all the solutions. Overall, the rmse



▲ **Figure 3.** Comparison among VADASE and reference solutions at MO05 station (1 Hz observations over 120 s interval 20 May 2012—02:04:00 to 02:06:00 GPS time, ionosphere-free processing).

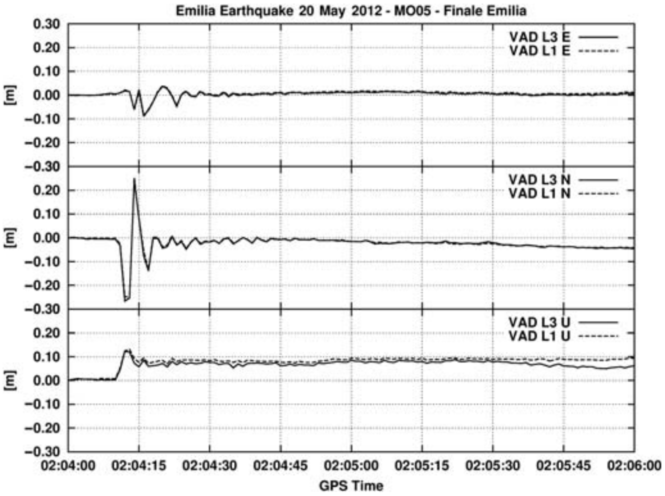
Table 3
Global Agreement among the Solutions (1 Hz Observations over the 120 s Interval 20 May 2012—02:04:00 to 02:06:00 GPS Time)

	Global Rmse (mm)														
	VADASE L1			APP			CSRS			BERNESE			TRACK		
	E	N	Up	E	N	Up	E	N	Up	E	N	Up	E	N	Up
VADASE L3	7	3	14	10	8	13	11	7	8	11	9	12	11	9	15
VADASE L1				14	9	16	16	8	10	17	10	7	17	10	18
APP							10	4	12	10	6	13	10	6	13
CSRS										4	5	7	4	5	15
BERNESE													1	1	16

for VADASE L3 solutions with respect to the reference ones are within 1.1 cm in the horizontal and within 1.5 cm in height. Quite similarly, the agreement among the reference solutions themselves are within 1 cm in horizontal and 1.5 cm in height, with a significantly better horizontal agreement at 1 mm level between TRACK and Bernese, both adopting the DP approach. For all sites the waveforms are clearly visible (for MO05 up to about 50 cm peak-to-peak), but only MO05 presents a significant coseismic vertical displacement of about 8 cm. The station by station results, in terms of rmse between each software pair, are shown in Ⓔ Table S2 (available in the electronic supplement); also, graphical results for the other stations are presented in Figures S1–S5, available in the electronic supplement.

1 Hz Single-Frequency Data VADASE Processing

After this first analysis of VADASE L3 solutions, additional solutions were computed with VADASE considering L1 frequency only, applying the Klobuchar ionospheric model (Klobuchar [1987]). VADASE L1 solutions were compared with VADASE L3 solutions and with all the already considered dual-frequency reference solutions. Graphical results as regards MO05 site are shown in Figure 4. Again, good agreement exists among all the solutions; overall the rmse for VADASE L1 solutions with respect to the VADASE L3 and the reference ones are within 1.7 cm in horizontal and within 1.8 cm in height. For all sites the waveforms are clearly visible similarly to VADASE L3 dual-frequency solutions.



▲ **Figure 4.** Comparison between VADASE L3 and L1 solutions at MO05 station (1 Hz observations over 120 s interval 20 May 2012—02:04:00 to 02:06:00 GPS time).

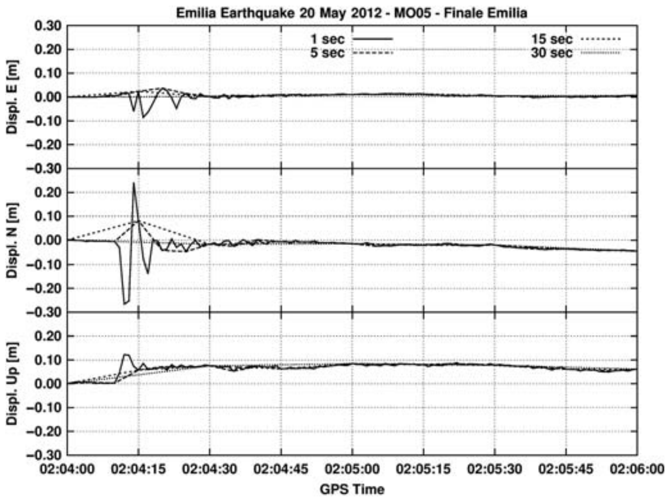
30 Second Data

In the previous paragraphs we largely confirmed the accuracy of VADASE L3 and L1 solutions within 3 cm or better, considering high-rate 1 Hz data only. Now we want to show the usefulness of VADASE in processing 30 s data (both single and dual frequency) to retrieve just permanent displacements and not waveforms, because in this case we cannot retrieve the full ground motion at its proper frequencies (periods of motion are around 5–10 s). Despite the quite promising results achieved by GNSS seismology in describing earthquake waveforms (e.g., Bock *et al.* [2011] and Avallone *et al.* [2012]), at present, only 30 s observations are publicly available worldwide, with few good exceptions of local/regional dense networks, for example the Plate Boundary Observatory and Japanese GeoNet (no public data) networks. In such direction we focus on MO05 station only, because it is the unique site displaying a significant coseismic displacement (about 8 cm in height). To this aim, we processed MO05 original 1 Hz data decimated at 5, 15, 30 s with VADASE. With the decrease of the acquisition frequency, poorer and poorer waveform reconstruction becomes evident, as obviously expected (Fig. 5).

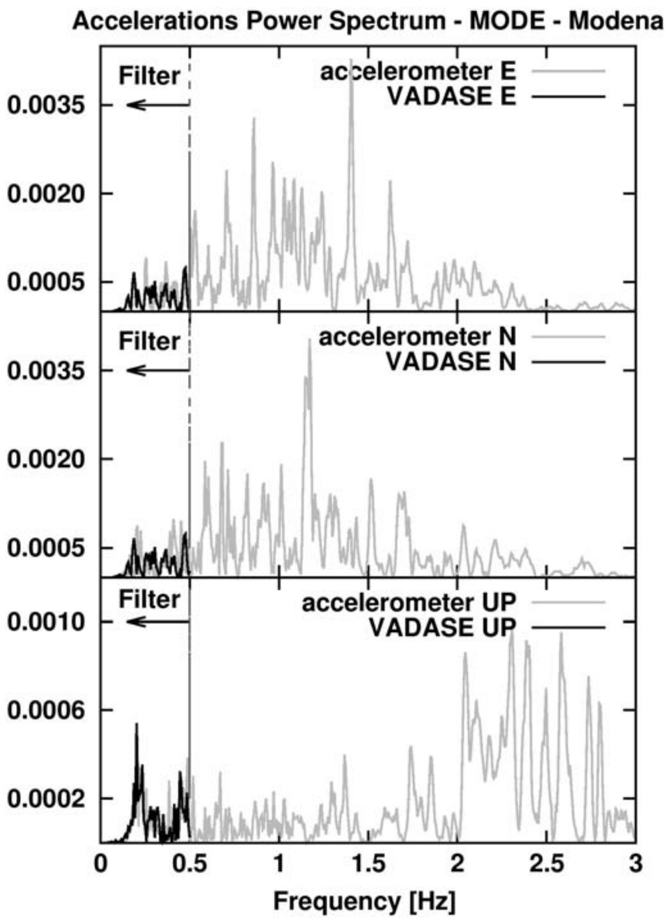
In addition, 30 s observations were processed with all the reference software and VADASE solutions were compared as before. The agreement of VADASE L3 with reference solutions is better than 1.5 cm in horizontal and 1 cm in height (Ⓔ Table S3 available in the electronic supplement). In addition, even in this case, a good agreement exists between VADASE L1 and L3 solutions (within few millimeter in horizontal and within 1.7 cm in height).

COMPARISON BETWEEN VADASE AND ACCELEROMETER SOLUTIONS

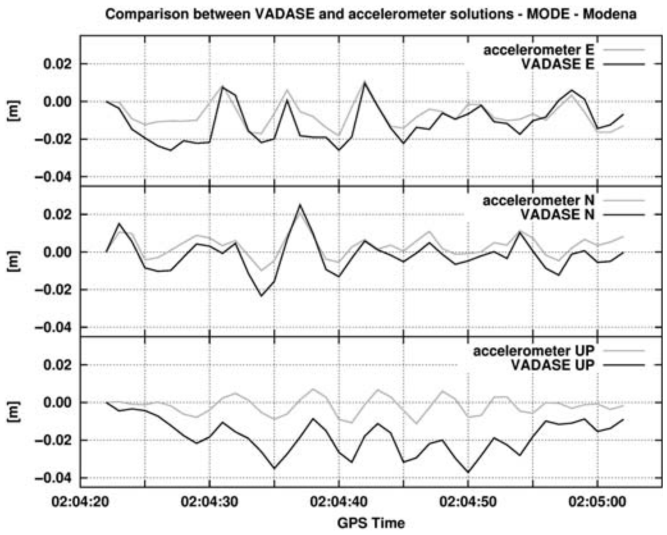
In addition to the comparison between GNSS results, the availability of triaxial accelerometer in Modena, located near the



▲ **Figure 5.** Comparison among MO05 VADASE L3 solutions at MO05 station (data processed at different rates over the 120 s interval 20 May 2012—02:04:00 to 02:06:00 GPS time).



▲ **Figure 6.** Comparison between VADASE and accelerometer acceleration-frequency spectra from 0 to 3 Hz at MODE station.



▲ **Figure 7.** Comparison between VADASE and accelerometer solutions (displacements) at MODE station (40 s interval 20 May 2012—02:04:22 to 02:05:02 GPS time).

ItalPoS MODE station, allowed the comparison between VADASE and accelerometer solutions. The accelerometer data, provided by Istituto Nazionele di Geofisica e Vulcanologia, Rome, Italy, are characterized by an acquisition frequency of 100 Hz and are supplied after a preliminary passband filtering from 0.1 Hz to 40 Hz.

First of all a spectral analysis of accelerometer and VADASE derived accelerations (always referring to the interval from 02:04:00 to 02:06:00 GPS time) was carried out to select the common spectral interval to be considered for the comparison (Fig. 6). Because the highest rate of VADASE solutions for MO05 is 1 Hz (hence Nyquist frequency is 0.5 Hz), accelerometric data were low-pass filtered at 0.5 Hz. The filtered accelerations were then double integrated and synchronized over two minutes interval to compare the VADASE and accelerometer results in terms of displacements (Fig. 7). The MODE station experienced a limited shaking, with maximum peak-to-peak amplitudes of about 5 cm in the horizontal components and 2 cm in height (in this case quite close to the already estimated accuracy level), for a short interval of about 40 s from 02:04:22 to 02:05:02 GPS time. Therefore, to evaluate VADASE and accelerometer solutions agreement, which is how both sensors are able to retrieve the same shaking phenomenon, we focused in this interval and the comparison (after having aligned the two solutions at the first epoch) was not only based on the rmse, but mainly on the correlation coefficient. Overall, rmse were 0.8, 0.6, and 1.8 cm for East, North, and Up components, and correlation coefficients were 0.77, 0.93, and 0.57, respectively, with a good agreement in the horizontal components and, as expected, a more doubtful result in the height due to quite small displacements.

CONCLUSIONS

The variometric approach VADASE, for which the reliability was already proven immediately after the disastrous 2011 Tohoku-Oki earthquake, was applied to the 2012 Emilia (Italy) weaker earthquake. Moreover, we take the occasion to develop a thorough comparison among VADASE and four other renowned scientific software (TRACK module of GAMIT, Bernese, APP-PPP, and CSRS-PPP postprocessing service), implementing the two most adopted processing approaches, the DP and the PPP.

A preliminary noise level assessment in a pre-event situation without shaking was carried out, which highlighted a common behavior of the reference software, with a noise of about 0.5 cm for the horizontal components and better than 1.5 in height, and worse behavior for VADASE, around 1 cm East, 3 cm North, and 2 cm Up, in agreement with previous works.

Then the dual-frequency 1 Hz data collected at several ItalPoS stations during a 120 s interval when the earthquake occurred were processed both with VADASE and with the four reference software. Each of these four software was used in the most favorable way (mainly with respect the phase-ambiguity-fixing problem), to get their respective optimal solutions, which were used as reference. Overall the rmse for VADASE L3 solutions with respect to the reference ones are within 1.1 cm in horizontal and within 1.5 cm in height, quite similar to the agreement among the reference solutions themselves. Second, because VADASE is also able to work with single-frequency data, differently from all the reference software, also VADASE L1 solutions were computed. A similar agreement, only slightly worse with respect to the previous case, was achieved, being the rmse for VADASE L1 solutions with respect to the VADASE L3 and the four reference ones within 1.7 cm horizontally and within 1.8 cm in height.

Finally, for MO05 site, the unique displaying a significant coseismic displacement (about 8 cm in height), we processed data decimated at 5, 15, 30 s to investigate on the capability of VADASE to retrieve overall coseismic displacements, apart from waveforms.

The agreement between VADASE and reference solutions with 30 s rate observations, which is the standard for the GNSS permanent stations worldwide, is better than 1.5 cm in horizontal and than 1 cm in height, and similarly for VADASE L1.

Finally, an independent comparison was carried out with the displacements retrieved from a triaxial accelerometer, approximately collocated with MODE station. Good results were obtained, not only in terms of rmse (lower than 1 cm in planimetry and lower than 2 cm in height). However, what is more important in case of displacements for which the magnitudes are of the same order of the noise level, in terms of correlation coefficients (especially in the horizontal components), highlighting that two sensors are capable to retrieve the same shaking phenomenon in their overlapping spectral interval.

These results lead to the following conclusions: the variometric approach, just by using standalone GPS receiver and standard GPS broadcast products (orbits and clocks) commonly available in real time, confirmed its effectiveness in retrieving real-time waveforms (with high-rate observations only) and coseismic displacements with an accuracy (with respect to the reference solutions) ranging between 1 and 2 cm on average, whichever solution is considered (dual- or single-frequency, high- or low-rate observations); this accuracy is quite similar to the overall agreement among the reference solutions.

These results are clearly quite promising: on one hand they push toward the enlargement of the IGS high-rate network and also the GNSS stations that broadcast their observations in real time (for example RTCM, Radio Technical Commission for Maritime Services, format via NTRIP, Networked Transport of RTCM via Internet Protocol). On the other, they pave the way to the application of low-cost single-frequency receivers to real-time GNSS seismology. It is evident that the use of low-cost receivers can allow a remarkable increase of the number of GPS permanent stations, ensuring a much more detailed coverage of seismic-hazard areas.

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APPENDIX A

VADASE FUNCTIONAL MODEL AND CURRENT REFINEMENTS

Here we recall the functional model of the least-square estimation of the variometric approach and highlight some current refinements. For a complete description of the Variometric Approach for Displacements Analysis Standalone Engine (VADASE) estimation model, please refer to Colosimo *et al.* (2011a), Branzanti *et al.* (2013), and Colosimo (2013).

We assume that subscript r refers to a particular receiver and superscript s refers to a satellite. Φ_r^s is the carrier phase observation of the receiver with respect to the satellite. λ is the carrier phase wavelength, ρ_r^s is the geometric range (i.e., the distance between the satellite and the receiver), c is the speed of light; δt_r and δt^s are the receiver and the satellite clock offsets, respectively. T_r^s is the tropospheric delay along the path from the satellite to the receiver, p_r^s is the sum of the other effects (relativistic effects, phase center variations, and phase windup); and m_r^s and ε_r^s represent the multipath and the noise, respectively. Equation (A1)is the difference in time (Δ) between two consecutive epochs (t and $t+1$) of carrier phase observations in the ionospheric-free combination (α and β are the standard coefficients of L3 combination referred to the two phases L1 and L2)

$$\begin{aligned}\alpha[\lambda\Delta\Phi_r^s]_{L1} + \beta[\lambda\Delta\Phi_r^s]_{L2} = {} & (\mathbf{e}_r^s \cdot \Delta\xi_r + c\Delta\delta t_r) \\ & + ([\Delta\rho_r^s]_{OR} - c\Delta\delta t^s + \Delta T_r^s \\ & + [\Delta\rho_r^s]_{EtOl} + \Delta p_r^s) \\ & + \Delta m_r^s + \Delta\varepsilon_r^s, \qquad \text{(A1)}\end{aligned}$$

in which $\mathbf{e}_r^s \cdot \Delta\xi_r$is the dot product between the unit vector from the satellite to the receiver and the (mean) velocity vector of the receiver in the interval t and $t+1$. $[\Delta\rho_r^s]_{OR}$ is the change of the geometric range due to the satellite's orbital motion and the Earth's rotation. $[\Delta\rho_r^s]_{EtOl}$ is the change of the geometric range due to the variation of the solid Earth tide and ocean loading.

The term $(e_r^s \cdot \Delta\xi_r + c\Delta\delta t_r)$ contains the four unknown parameters (the 3D velocity $\Delta\xi_r$ and the receiver clock error variation $\Delta\delta t_r$) and $([\Delta\rho_r^s]_{OR} - c\Delta\delta t^s + \Delta T_r^s + [\Delta\rho_r^s]_{EtOl} + \Delta p_r^s)$ is the known term that can be computed on the basis of known orbits and clocks and of proper well-known models. The least-squares estimation of the 3D velocities is based upon the entire set of variometric equations (A1), which can be written for two generic consecutive epochs (t and $t+1$). The number of variometric equations depends on the number of satellites common to the two epochs, and at least four satellites are necessary to estimate the four unknown parameters for each consecutive epochs couple.

In Colosimo *et al.* (2011a), it was shown that the velocities estimated with VADASE can be affected by bias that displayed their signature as a trend in the displacement waveforms computation obtained by simple velocities integration over time. Moreover, it was shown that this trend can be considered linear and removed if the integration interval is limited to few minutes. Since the first implementation of VADASE, the software has been continuously developed and some refinements have been carried out in the model and code.

In particular, the accuracy of the time used in the orbits computation was significantly improved, what lead to a remarkably reduction of the amplitude of trend cumulating in the displacements waveforms.

Thanks to this refinements, all the VADASE waveforms presented in this work are obtained from estimated velocities by simple integration without applying any detrending strategy.

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