Software Defined Receivers in GNSS scientific applications: variometric approach to exploit GNSS-SDR phase observations

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Abstract

The use of GNSS for many high accuracy applications is continuously increasing. Most of the methodologies of GNSS data processing are based on the observations collected by conventional (geodetic and low cost) receivers. These devices are rather sophisticated, but appears as black boxes to the user: basically, the user does not have any access to the internal structure of the receiver. In this respect, a new class of devices has been recently proposed: the so-called Software Defined Receivers (SDRs). Up today, the use of SDR is still limited for experimental receivers, but their development, their very low cost and their flexibility have opened new possibilities including high precision applications. In this work, the variometric approach (implemented in the VADASE software) is applied to single frequency phase observation obtained from the open source multiconstellation GNSS-SDR software receiver.

The final aim of this work is twofold: one hand it evaluates the reliability of GNSS-SDR phase observations, on the other hand it asses VADASE reachable accuracy when applied to phase observation retrieved by a SDR. To these aims some tests were performed and an accuracy at the decimeter level was found.

The obtained results show that in the next future SDR will have an important role in GNSS scientific applications, going beyond the limits imposed from conventional GNSS receivers.

Keywords

GNSS-SDR, VADASE, real-time, multi-constellation, high-accuracy, phase observations

1 Introduction

In the last years the technological development (high performances GNSS receivers) and the progress in data processing, have been opening new opportunities for the use of GNSS in scientific applications where a positioning accuracy at the few centimeters level is required: precision farming, vehicle precise navigation, Earth monitoring and others. Unfortunately, existing solutions for these ambitious applications are typically very costly. In most cases dual frequency geodetic receiver are needed to reach a centimeter accuracy, but emerging investigation projects are moving toward the use of low cost single frequency receiver. Another important aspect to consider is that most of the proposed methodologies are based on the observations collected by conventional (geodetic and low cost) receivers. These devices are rather sophisticated, but appears as black boxes to the user. Basically, the user does not have any access to the internal structure of the receiver. In this respect, a new class of devices has been recently proposed: the so-called Software Defined Receivers (SDRs).

Differently from the classic ones, SDRs allow a complete interaction user-receiver and any kind of customization according to specific needs. SDRs are finding a great response in the current GNSS scenario particularly now that new signals (e.g. GPS L5 frequency) and new constellations (Galileo, GLONASS, Beidou) have been introduced and consequently receivers architecture must be continuously updated. When considering a SDR, the user can chose to extend the receiver functionalities to different constellations, allow phase observations in addiction to code observations, or integrate GNSS observations with other devices (such as accelerometers).

Up today, the use of SDRs is still limited for experimental receivers, but their development, their very low cost and their flexibility have opened new possibilities, including high precision applications.

This work aims to investigate the potentialities of the open source GNSS-SDR Software Defined Receiver. Its phase observations are exploited for the first time, in order to demonstrate the potentialities of SDRS in scientific applications. In particular, the reliability of GNSS-SDR phase observations is assessed exploiting the single frequency capabilities of the variometric approach implemented in the VADASE software, an innovative strategy for GNSS data processing.

In Section 2 GNSS-SDR is introduced and the state of art of its implementation is reported. The Sub-section 2.1 proposes a methodology to produce hybrid GPS-Galileo observables within the receiver. An overview of the variometric approach is given in Section 3. Finally, in Section 4, the first VADASE solution over GNSS-SDR code and phase observations are presented, considering simulated and real life signals.

2 GNSS-SDR

GNSS-SDR, available at *http://gnss-sdr.org* and mainly developed at CTTC (Centre Tecnologic de Telecomunicacions de Catalunya, Barcelona, Spain), is an open source GNSS software receiver (Fernández–Prades, Arribas, Closas, Avilés and Esteve, 2011).

The software, written in C++, is able to work either from raw signal samples stored in a file, or in real-time with a radio frequency front-end. It provides, under General Public License (GPL), the implementations of all the algorithms required by a GNSS receiver: raw sample reading and conditioning, execution of signal processing block performing acquisition, code and phase tracking, lock detectors, demodulation and decoding of the navigation message, observable computation and PVT (Position, Velocity, Time) solution. Moreover it makes availabale to the user observation and navigation files in the standard

RINEX format. The general diagram of the proposed software receiver is shown in Figure 1.

2.1 A multi-constellation software receiver

The GNSS-SDR project started in 2010 with the implementation of all the steps to be operative with the GPS constellation (Arribas, 2012). The receiver was later extended to the Galileo constellation in a work developed within the Google Summer of Code program (Fernández–Prades, Arribas, Esteve, Pubill and Closas, 2012): in 2013, GNSS-SDR allowed to achieve for the first time a stand-alone Galileo-only position fix, in real-time, with an open source software defined GNSS receiver (GPS World staff, 2014).

At present it is a completely operative single-frequency GPS(L1)-Galileo(E1) receiver; for the next future its extension toward the GLONASS and Beidou constellations is already planned, as well as its extension to multiple bands.

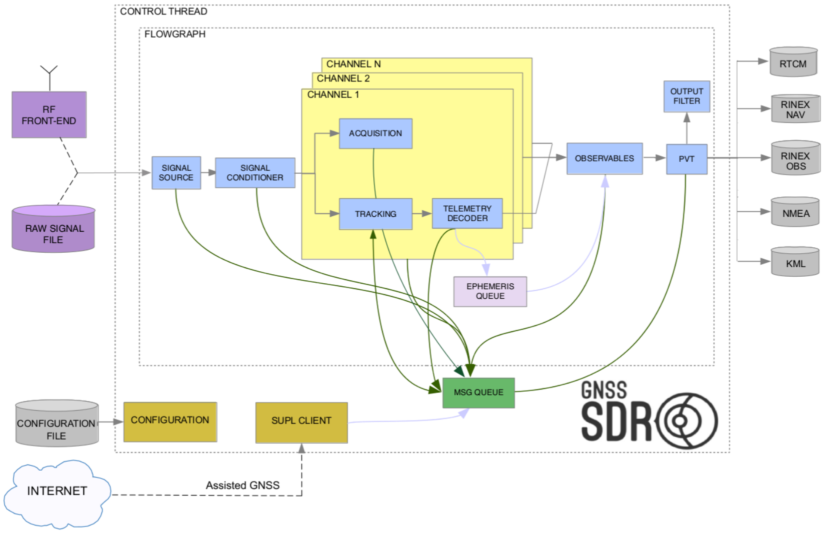

Figure 1: General diagram of the GNSS-SDR control plane and signal processing flow graph. Users can invoke a particular implementation and parameters for each processing block (blue boxes) via a single configuration file.

2.1.1 GPS-Galileo hybridization at observables level

In 2014 the receiver was further developed to work in a hybrid mode with respect to the GPS and Galileo constellations.

As a matter of fact, Galileo System Time (GST) and GPS Time (GPST) do not use the same time reference, and hence a time offset exists between both systems. From a PVT computation stand view, this means that the pseudoranges determined with Galileo are referenced to the GST, while the ones from GPS use the GPST. The difference between GPST and GST, if unknown, requires an extra equation and thus an extra in-view satellite in order to compute a PVT solution using both GPS and Galileo measurements in the same set of equations. Thus, five or more in-view GPS and Galileo satellites would be needed to obtain a hybrid PVT solution.

Those two internal times are derived independently on one another but, luckily enough, the GPS-Galileo Time Offset (GGTO) is distributed through Galileo's navigation message (European Union, 2010). This means that, if the GGTO is properly retrieved and included in the navigation solution, a total number of four in-view satellites (in any combination: 3 GPS and 1 Galileo satellites, 1 and 3, or 2 and 2) would be enough to compute a PVT fix, effectively allowing interoperability between both systems.

Exploiting the availability of the GGTO in the Galileo navigation message, an hybrid configuration of GNSS-SDR at the observables level was implemented (Arribas, Branzanti, Fernández–Prades and Closas, 2014). In the hybrid configuration, GNSS-SDR can combine GPS and Galileo data at the observable level, providing better capabilities than the ones that would be achieved by relying solely on one system. The final result is an expanded set of observations, that can be considered coming from a unique (expanded) constellation.

3 VADASE

The Variometric Approach for Displacements Analysis Stand-alone Engine (VADASE) was originally proposed (Colosimo, Crespi and Mazzoni, 2011) as innovative solution to estimate in real-time rapid movements of GPS receivers. In this respect, it was thought to be applied in the seismology field.

The approach, based on time single differences of carrier phase observations (Hoffman-Wellenhof, Lichtenegger, and Wasle, 2008), only needs observations collected by a unique GNSS receiver and broadcast product available in real-time. Moreover, differently from other data processing approaches (i.e. differential positioning (DP) and precise point positioning (PPP)), VADASE does not require phase ambiguity solving (Teunissen and Keusberg, 1996), thus it is also able to work with single-frequency data only.

VADASE is implemented and continuously devoleped at Geodesy and Geomatics Divsion of “La Sapienza” University of Rome. It is subject of an international patent and was awarded the German Aerospace Agency (DLR) Special Topic Prize and the Audience Award at the European Satellite Navigation Competition 2010.

The effectiveness of VADASE was proved for seismology aims, through its application to the catastrophic Tohoku-Oki earthquake (Mw = 9, March 11, 2011, 02:03:51 UTC) (Branzanti, Colosimo, Crespi and Mazzoni, 2013) and to the Emilia earthquake (Mw = 6.1, May 20, 2012, 02:03:51 UTC) (Benedetti, Branzanti, Biagi, Colosimo, Mazzoni and Crespi, 2012). In the latter, the accuracy level of VADASE when processing L1 observations only was evaluated and an accuracy at few centimeters level was found.

Such high quality results, obtained from single-frequency observations of geodetic receivers, encouraged further experimentations considering observations collected by low-cost GPS and Galileo receivers. The results obtained exploiting the first four Galileo satellites in orbit were submitted to ESA (Branzanti, Benedetti, Colosimo, Mazzoni and Crespi, 2014) and the VADASE team received one of the 50 ESA Certificate for Galileo In-Orbit-Validation Fix 2014.

Finally, a kinematic implementation of the variometric approach was recently proposed, in the so-called Kin-VADASE (Branzanti, 2015), in order to extend its application to the navigation field and to retrieve kinematic parameters (accelerations, velocities and positions) of vehicles in motions (land, maritime or air vehicles)

4 GNSS-SDR and VADASE: software receiver to scientific applications exploiting the variometric approach

GNSS-SDR is one of the most advanced open-source Software Defined Receiver thanks to its multi-constellation approach, the continuous improvements in the implementation and for the availability of public bibliography.
Intense work was carried out to evaluate its functionality at the level of signal processing (Fernández–Prades et al. 2011) or PVT solutions based on code observations (Arribas et al. 2014). However, its intermediate products (RINEX observations and navigation files), mainly as regards the recent availability of phase observations, have never been exploited for scientific purposes.
At present, not all the standard low-cost hardware receivers allow the user to extract raw data (RINEX) for post processing purposes. Furthermore, Galileo-GPS low-cost receivers are hardly available in the current market, being the Galileo constellation still under development (its full operation capability is expected for the end of this decade). Thus, it is not so common to experiment and test scientific algorithms exploiting observations coming from both constellations.
As matter of fact, the possibility to extract GPS and Galileo RINEX files within GNSS-SDR is a precious opportunity for the GNSS scientific community.
This section wants to experiment and evaluate the potentialities of GNSS-SDR in scientific applications, exploiting the single frequency capabilities of the variometric approach. To this aims, some tests were performed on the bases of simulated and real life signal. The experimentations have a twofold purpose: on one hand they evaluate the reliability of GNSS-SDR phase observations, on the other hand they assess the accuracy that can be achieved in processing with a scientific software (VADASE) the observables produced by a software defined receiver.

4.1 Experiments with simulated signal

The first experiments were carried out considering synthetic data produced by the IFEN GmbH NavX-NCS Simulator. GPS and Galileo signals were generated simulating the whole Galileo constellation, in its final configuration. The geometry of the scenario is shown in Figure 2: six Galileo satellites and eight GPS satellites were visible in the sky.

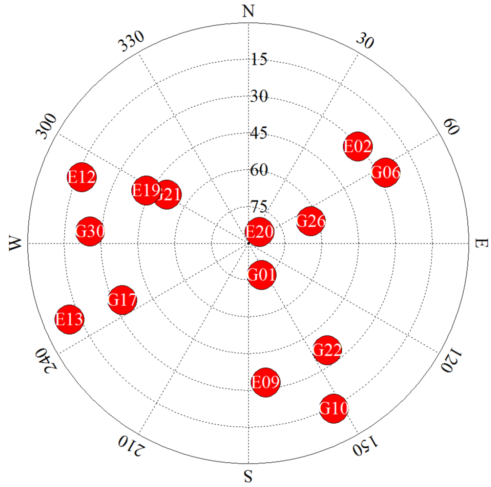

Figure 2: Visible GPS (G) and Galileo (E) satellites for the synthetically generated GNSS signals.

GNSS-SDR was set in its hybrid configuration to acquire, track, decode and produce observables of both constellations. Data were collected for a time interval of 3 minutes.

This experiment wanted to: *a)* evaluate the implementation of code and phase observables generation block in GNSS-SDR *b)* compare VADASE GPS solutions with VADASE Galileo solutions (using the same number of observations for each constellation), in order to make a comparison between constellations) *c)* exploit the hybrid configuration of GNSS-SDR to compute GPS-Galileo combined VADASE solutions *d)* compare the accuracy of the solutions obtained considering just one constellation at a time to the ones obtained from the hybrid approach.

To these aims, GNSS-SDR code and phase observations, collected in the standard RINEX format, were processed with the VADASE software in the following configuration: *1)* Galileo solution with six in view satellites *2)* GPS solutions with eight in view satellites *3)* GPS solutions with six satellites (satellites G22 and G26 were not used in the processing) in order to have GDOP values as similar as possible to the ones of the Galileo processing, and make a comparison between constellations under the same conditions *4)* GPS and Galileo combined solutions exploiting the fourteen satellites in view.

4.1.1 Code solutions

VADASE solutions over GNSS-SDR code observations are graphically represented in Figure 3, while statistics are reported in Table 1. GPS and Galileo solutions are at the same accuracy level when a similar geometry, with six satellites in view (GDOP values are 2.47 and 2.44 for GPS and Galileo respectively). The East and North accuracy is between one and two meters, while the RMSE value in the Up component is 6.2 m for GPS and 6.7 m for Galileo. In the hybrid solutions the number of satellites increases from six to fourteen, reducing the GDOP value to 1.55. In this satellite configuration the East and North accuracy in terms of RMSE of the solutions is 1.61 m and 1.97 m: it does not change significantly with respect to GPS-only and Galileo-only solutions, but with code observations higher performances can hardly be achieved. Differently, a significant improvement (of about 50%) occurs in the Up component, reaching a final accuracy of about 3 m.

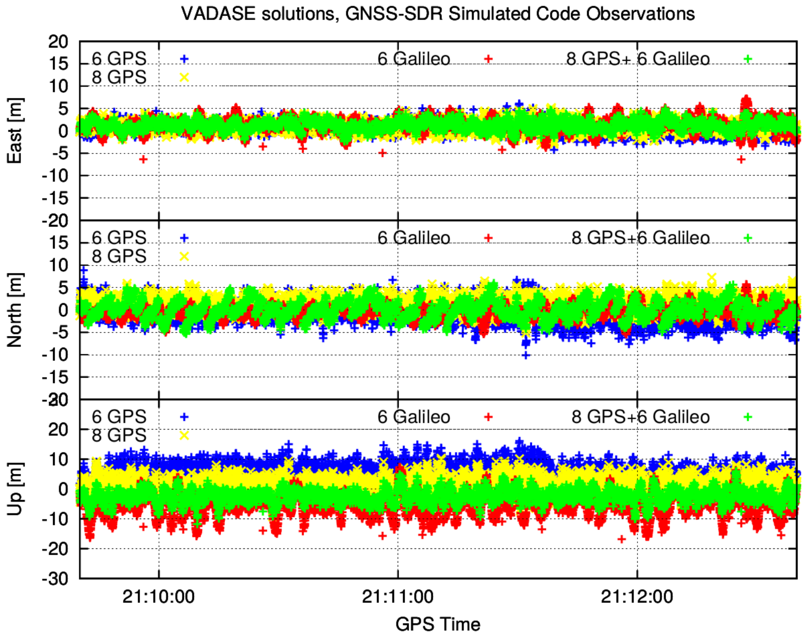

Figure 3: Experiment with simulated signal: VADASE solutions over GNSS-SDR code observations under different configurations (GPS, Galileo, GPS+Galileo).

4.1.2 Phase solutions

The variometric approach was also applied to phase observations produced by GNSS-SDR. Even in this case, GPS only, Galileo only and combined GPS-Galileo solutions were carried out. Probably due to a problem in the tracking algorithm implemented in the receiver, GPS phase observations have a validity interval of only 35 seconds. Differently from GPS, Galileo solutions are stable for the entire time interval. This issue will be surely faced and solved in the future, but it is not the aim of this work opening a detailed discussion about the GPS tracking algorithm of the receiver. Thus, VADASE accuracy with GPS only and GPS-Galileo observations was assessed over the first 35 seconds (from 21:09:40 to 21:10:15, Figure 4, while Galileo accuracy was evaluated both over the first 35 seconds (to make a comparison between constellations) and over the entire interval.

Statistics over the reduced time interval (35 seconds) are presented in Table 2. Under the same satellite geometry (6 satellites used in the processing for both constellations), Galileo results are much more accurate than GPS. RMSE of GPS solutions is at the decimeter level in all the three components; RMSE of Galileo solutions is at the millimeters level in East and North and of few centimeters in the Up component. In the hybrid configuration, the final statistics improve with respect to the GPS only solutions. RMSE is 0.05 m, 0.03 m. 0.08 m in the East, North and Up components respectively. Galileo statistics over the entire three minutes interval are reported in Table 3: the accuracy is at the centimeter level in planimetry (0.007 m and 0.032 m in East and North) and of three decimeters in the Up component.

GPS				
	East [m]	North [m]	Up [m]	
Average	0.995	1.323	1.178	**8 Sat GDOP=2.27**
St. dev	1.055	1.471	2.568	
RMSE	**1.450**	**1.979**	**2.862**	
Average	0.683	-0.434	5.489	**6 Sa GDOP=2.47**
St. dev	1.240	2.238	3.003	
RMSE	**1.415**	**2.281**	**6.257**	
Galileo				
	East [m]	North [m]	Up [m]	
Average	1.252	-0.506	-5.547	**6 Sat GDOP=2.44**
St. dev	1.617	1.475	3.874	
RMSE	**2.045**	**1.567**	**6.707**	
GPS + Galileo				
	East [m]	North [m]	Up [m]	
Average	1.260	0.120	-2.462	**14 Sat GDOP=1.55**
St. dev	1.068	1.967	2.262	
RMSE	**1.651**	**1.971**	**3.344**	

Table 1: Experiments with simulated signal: statistic over a 3 minutes time interval of VADASE solutions with GNSS-SDR code observations under different satellite configurations (GPS, Galileo, GPS+Galileo).

GPS				
	East [m]	North [m]	Up [m]	
Average	0.062	-0.045	0.095	**8 Sat GDOP=2.27**
St. dev	0.038	0.043	0.06	
RMSE	**0.073**	**0.063**	**0.113**	
Average	0.058	-0.082	0.063	**6 Sat GDOP=2.47**
St. dev	0.035	0.103	0.096	
RMSE	**0.068**	**0.132**	**0.115**	
Galileo				
Average	0.001	-0.005	0.039	**6 Sat GDOP=2.44**
St. dev	0.002	0.003	0.024	
RMSE	**0.002**	**0.006**	**0.045**	
GPS + Galileo				
	East [m]	North [m]	Up [m]	
Average	0.042	-0.02	0.066	**14 Sat GDOP=1.55**
St. dev	0.026	0.022	0.040	
RMSE	**0.05**	**0.029**	**0.077**	

Table 2: Experiments with simulated signal: statistic over a reduced time interval (from 21:09:40 to 21:10:15) of VADASE solutions with GNSS-SDR phase observations under different satellite configurations (GPS, Galileo, GPS+Galileo).

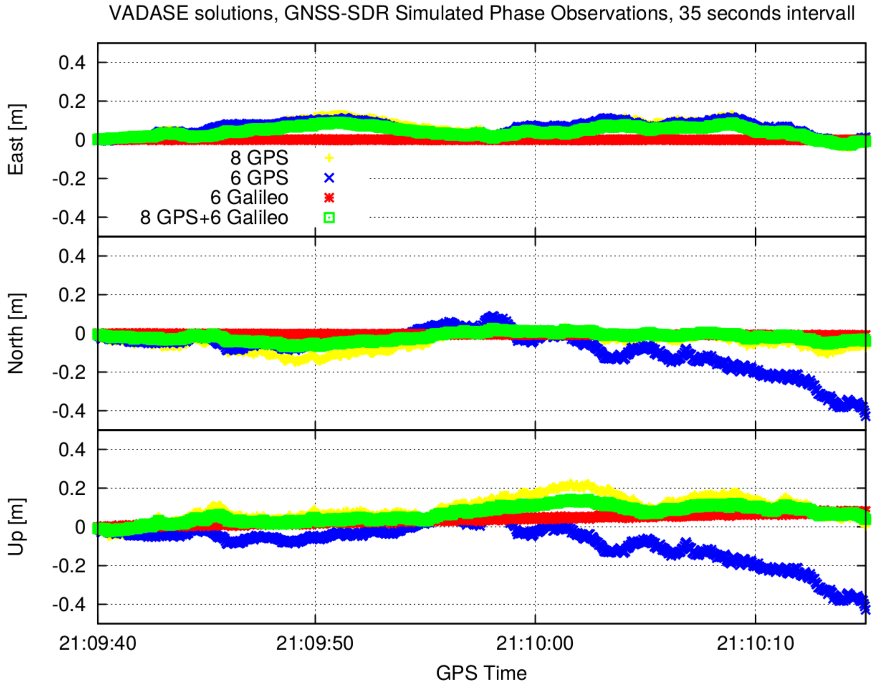

Figure 4: Experiments with simulated signal: zoom over the first 35 seconds of VADASE solutions with GNSS-SDR phase observations.

Galileo				
	East [m]	North [m]	Up [m]	
Average	-0.005	-0.028	0.27	**6 Sat GDOP=2.44**
St. dev	0.004	0.015	0.159	
RMSE	**0.007**	**0.032**	**0.313**	

Table 3: Experiments with simulated signal: statistic over a 3 minutes time interval of VADASE solutions with GNSS-SDR Galileo phase observations.

4.2 Experiments with real life signal

Here the capability of GNSS-SDR for high precision applications is effectively investigated, through the application of the variometric approach to phase observations retrieved from real life signal. In the experiment only GPS observations were collected, thus the GPS-Galileo interoperability with real data is not investigated, but it is addressed to future studies.
The satellite geometry during the data collection is reported in Figure 5. As the case of simulated signal, GPS solutions phase observations have a reduced period of reliability. Hence, accuracy was assessed over the time interval from 10:17:15 to 10:17:50. Statistics are reported in Table 4 and solution are graphically represented in Figure 6.
The RMSEs of the solutions are 0.15 m, 0.20 m, 0.12 m in the East, North and Up components respectively. As expected, the performances with real life signals are slightly worse that the ones obtained with simulated data, due to the presence of unmodelled sources of error both from GNSS-SDR and VADASE. Moreover, the satellite geometry is not in favour of a good final accuracy

(GDOP values are variable between 9.1 and 11.5). However the obtained results are really encouraging and represent the first step towards the use of SDRs to high accuracy scientific applications.

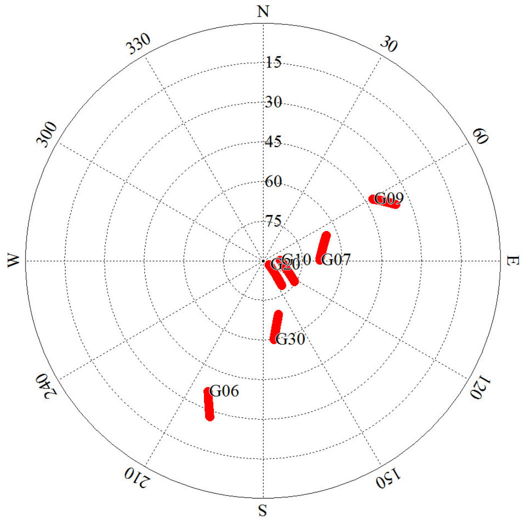

Figure 5: Visible GPS satellites in the experiment with real signal.

GPS				
	East [m]	North [m]	Up [m]	
Average	0.131	-0.154	0.054	**5 Sat 9.1<GDOP<11.5**
St. dev	0.067	0.123	0.109	
RMSE	**0.147**	**0.197**	**0.121**	

Table 4: Experiments with real signal: statistics over 35 seconds time interval of VADASE solutions with GNSS-SDR phase observations (GPS constellation).

5 Conclusion

In this work the reliability of GPS L1 and Galileo E1 code and phase observations produced by the open source GNSS-SDR is investigated. The receiver was used in its hybrid configuration, in order to produce GPS and Galileo observations referred to a unique system time, allowing to work with a unique "expanded" constellation. Observations were processed with an innovative methodology of GNSS data processing (implemented in the VADASE software), which is capable to work also with single-frequency phase observations. In particular, GPS only, Galileo only and GPS-Galileo solutions were computed.

In a first stage the implementation of GPS and Galileo observable generation was validated over simulated signal. The results demonstrated that observations are correctly retrieved (for the considered time interval) and that the opportunity to set the receiver in a hybrid configuration is a considerable added value: the user can effectively work with an expanded constellation, improving the satellite geometry and consequently the final accuracy.

The effective accuracy was assessed over real life GPS phase observations. An accuracy at the decimeter level in the three component was found with five

satellite in view.
The performed experimentations showed the potentiality of the integration between GNSS-SDR and VADASE and the achieved results suggest that SDRs will have an important role in the future scientific (or industrial) high accuracy applications.

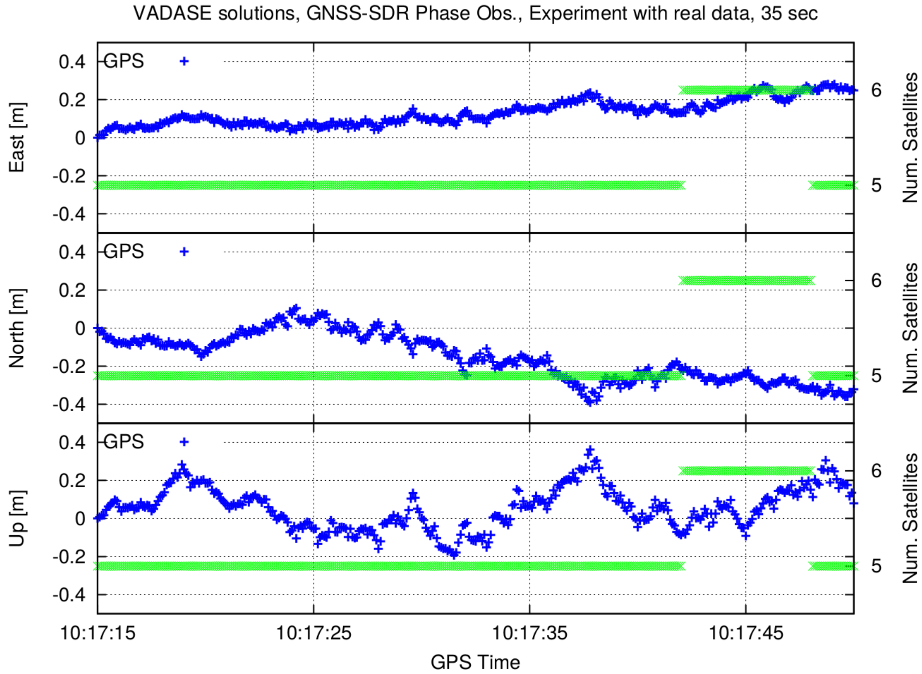

Figure 6: Experiments with real signal: VADASE solutions with GNSS-SDR phase observations over the entire acquisition interval (GPS constellation).

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