Variometric approach for real-time GNSS navigation: First demonstration of Kin-VADASE capabilities

Mara Branzanti a,*, Gabriele Colosimo b, Augusto Mazzoni a

a Geodesy and Geomatics Division, Dept. of Civil, Building and Environmental Engineering, University of Rome “La Sapienza”, Rome, Italy
b Leica Geosystems AG, Heerbrugg, Switzerland

Received 29 October 2015; received in revised form 7 September 2016; accepted 23 September 2016
Available online 3 October 2016

Abstract

The use of Global Navigation Satellite Systems (GNSS) kinematic positioning for navigational applications dramatically increased over the last decade. Real-time high performance navigation (positioning accuracy from one to few centimeters) can be achieved with established techniques such as Real Time Kinematic (RTK), and Precise Point Positioning (PPP). Despite their potential, the application of these techniques is limited mainly by their high cost. This work proposes the Kinematic implementation of the Variometric Approach for Displacement Analysis Standalone Engine (Kin-VADASE) and gives a demonstration of its performances in the field of GNSS navigation. VADASE is a methodology for the real-time detection of a standalone GNSS receiver displacements. It was originally designed for seismology and monitoring applications, where the receiver is supposed to move for few minutes, in the range of few meters, around a predefined position. Kin-VADASE overcomes the aforementioned limitations and aims to be a complete methodology with fully kinematic capabilities. Here, for the first time, we present its application to two test cases in order to estimate high rate (i.e., 10 Hz) kinematic parameters of moving vehicles. In this demonstration, data are collected and processed in the office, but the same results can be obtained in real-time through the implementation of Kin-VADASE in the firmware of a GNSS receiver. All the Kin-VADASE processing were carried out using double and single frequency observations in order to investigate the potentialities of the software with geodetic class and low-cost single frequency receivers. Root Mean Square Errors in 3D with respect to differential positioning are at the level of 50 cm for dual frequency and better than 1 meter for single frequency data. This reveals how Kin-VADASE features the main advantage of the standalone approach and the single frequency capability and, although with slightly lower accuracy with respect to the established techniques, can be a valid alternative to estimate kinematic parameters of vehicles in motions.

© 2016 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: GNSS; Real-time navigation; High rate; Variometric approach; Kin-VADASE

1. Introduction

The use of Global Navigation Satellite Systems (GNSS) in kinematic positioning dramatically increased over the last decade for many navigational applications. The required accuracy depends on the specific application and ranges from few meters to few centimeters. Lower accuracy can be easily achieved with mass market receivers (e.g., by means of single point positioning with code observations), whereas better results can be achieved only through phase observations.

The most widely used technique in kinematic applications is the RTK (Real Time Kinematic) positioning, based on double frequency phase observations differential approach (double differences) between rover and reference receiver(s) (Kaplan and Hegarty, 2006). On one hand RTK is a high-performance technique (positioning accuracy at

* Corresponding author.
E-mail addresses: mara.branzanti@uniroma1.it (M. Branzanti), gabriele.colosimo@leica-geosystems.com (G. Colosimo), augusto.mazzoni@uniroma1.it (A. Mazzoni).
few centimeters level); on the other hand it requires the support of a GNSS Network infrastructure (Kim et al., 2013) and a continuous data link between the rover and the network caster.

Precise Point Positioning (PPP) utilizes the double frequency phase observations of a single GNSS receiver and the precise satellite products (mainly clocks and orbits). In order to operate in real-time, a data link between the rover and the precise product provider is needed (IGS real time Service, 2015; Ge et al., 2012; Geng et al., 2010).

Over the last years the use of GNSS-PPP has been continuously growing. Experiments demonstrated an accuracy at the level of millimeters to detect seismic motion (Xu et al., 2013); other studies (Jiang et al., 2014; Wang, et al., 2010). In order to operate in real-time, a data link between the precise satellite products (mainly clocks and orbits).

quency phase observations of a single GNSS receiver and the network caster.

2. The variometric approach

2.1. Functional model

The variometric approach is based on time single differences of carrier phase observations (Hofmann-Wellenhof et al., 2008) continuously collected using a standalone GPS receiver on standard GPS broadcast products (orbits and clocks) available in real-time.

Here we recall the functional model of the least square estimation of the variometric approach in order to better assess the developments discussed in the next subsections. For a complete description of the VADASE estimation model, please refer to the previous published papers (Colosimo et al., 2011; Colosimo, 2013).

We assume that subscript $r$ refers to a particular receiver and superscript $s$ refers to a satellite; $\Phi^r_s$ is the carrier phase observation of the receiver with respect to the satellite; $\lambda$ is the carrier phase wavelength; $\rho^s_r$ is the geometric range (i.e., the distance between the satellite and the receiver); $c$ is the speed of light; $\delta_t$ and $\delta_t'$ are the receiver and the satellite clock errors, respectively; $T_{\rho}$ is the tropospheric delay along the path from the satellite to the receiver; $p_t'$ is the sum of the other effects (relativistic effects, phase center variations, and phase windup); and $m_t$ and $c'_t$ represent the multipath and the noise, respectively. Eq. (1) is the difference in time $(\Delta)$ between two consecutive epochs $(t$ and $t + 1)$ of carrier phase observations in the ionospheric-free combination ($x$ and $\beta$ are the standard coefficients of L3 combination referred to the two phases L1 and L2)

\[ a[\lambda\Delta\Phi^r_s]_{L1} + b[\lambda\Delta\Phi^r_s]_{L2} = (e'_t \cdot \Delta \xi + c\Delta t_r) + \left(\Delta \rho^r_s\right)_{OR} + c\Delta t + \Delta T_{\rho} + \left(\Delta \rho^r_s\right)_{EOI} + \Delta m_t + \Delta c'_t \]  

where $e'_t$ is the unit vector from the satellite to the receiver, $\Delta \xi$ is the (mean) velocity of the receiver in the interval $t$ and $t + 1$, $\left|\Delta \rho^r_s\right|_{OR}$ is the change of the geometric range due to the satellite’s orbital motion and the Earth’s rotation, $\left|\Delta \rho^r_s\right|_{EOI}$ is the change of the geometric range due to the variation of the solid Earth tide and ocean loading. The term $(e'_t \cdot \Delta \xi + c\Delta t_r)$ contains the four unknown parameters (the 3-D velocity $\Delta \xi$ and the receiver clock error variation $\Delta \delta_t$) and $(\left|\Delta \rho^r_s\right|_{OR} - c\Delta t + \Delta T_{\rho} + \left|\Delta \rho^r_s\right|_{EOI} + \Delta m_t)$ is the known term that can be computed on the basis of known orbits and clocks and of proper well-known models (for a complete orbits, clocks and atmosphere error analysis, please refer to Colosimo (2013)). To account for higher disturbances on signals received by low elevations satellites, the observations are weighted by the squared cosine of the satellite zenith angle $(Z'_t)$ (Dach et al., 2007, p. 144), as follows

\[ w = \cos^2(Z'_t) \]  

Moreover, the different observations are treated as uncorrelated in the estimation process. The least squares
estimation of the 3-D velocities is based upon the entire set of variometric Eq. (1), 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. At least four satellites are necessary in order to estimate the four unknown parameters for each consecutive epoch couple. Differently from other data processing schemes (i.e. differential positioning (DP) and PPP), the variometric approach does not require phase ambiguity resolution (Teunissen and Keusberg, 1996) and it is also able to work with single-frequency data only.

Overall, one receiver works in standalone mode and the epoch-by-epoch displacements (which are equivalent to velocities) are estimated. Then, velocities are integrated (and derivative calculated) over the time interval of interest to retrieve the comprehensive receiver displacements (and accelerations). The integration process is affected by estimation biases due to possible mismodeling in Eq. (1) that accumulate over time and display their signature as a trend in the displacements (Colosimo et al., 2011). In static scenarios, the trend in the integrated velocities (i.e., displacements) is significant with respect to the displacements absence; on the other hand, when the receiver undergoes movements, the biases are concealed in the displacements, which are accurately and effectively retrieved by the variometric approach.

2.2. The native VADASE: major applications and limits

The first implementation of the variometric approach was proposed in 2011 (Colosimo et al., 2011) in the VADASE software, as an innovative solution to estimate in real-time rapid movements of GPS receivers in a global reference frame (Crespi et al., 2015). To prove the effectiveness of the approach, the algorithm was implemented in a desktop application capable to process standard Receiver Independent EXchange format (RINEX) files containing observations and ephemeris acquired by a GNSS receiver. Its validity was proved in the GPS seismology field through the application to the catastrophic Tohoku-Oki earthquake (Branzanti et al., 2013; Colosimo et al., 2011) \((M_w = 9.0\), March 11, 2011), when VADASE was the first approach capable of computing accurate displacements caused on 2 International GNSS Service (IGS) Japanese stations (i.e., MIZU and USUD), immediately after the availability of data (Group on Earth Observations (GEO), 2011). VADASE was also applied to the Emilia earthquake (Benedetti et al., 2014) \((M_w = 6.1\), May 20, 2012) in case of small displacements. A comparison between VADASE solutions and credited software (GAMIT kinematic GPS processing module (TRACK, Herring et al., 2010), Automatic Precise Positioning Service (NASA Jet Propulsion Laboratory Automatic Precise Positioning Service, 2015)) was performed both using dual and single frequency observations. The agreement among the software resulted at the level of 1.1 cm and 1.5 cm for the horizontal and vertical components, respectively, for the dual frequency solutions and of 1.7 cm and 1.8 cm, for the horizontal and vertical components, respectively, for the single frequency solutions. Moreover VADASE results and velocity and acceleration solutions retrieved from accelerometers co-located with the GNSS receiver, were compared.

The variometric algorithm was conceived to detect, in real-time, fast and short duration displacements occurring to a single GNSS receiver. However, the original implementation in the VADASE software focused on seismology and monitoring applications, where the initial coordinates are known with high accuracy (i.e., better than 0.5 m, which is normally the case for reference stations receivers or monitoring markers) and the receiver is expected to undergo limited movements (up to few meters) around its starting position. Such choice reflected in the implementation of the software, as it is described in Fig. 1.

The initial receiver position \(P_0\) was simply retrieved from the RINEX header and used to compute, for all available \(N\) epochs, the known terms of the variometric Eq. (1) in order to derive the displacements between epoch \(t\) and \(t + 1\). Following the described processing design it appears evident how the performances of VADASE were significantly decreasing in kinematic applications, where the errors in the functional model (Eq. (1) computed using initial receiver position \(P_0\)) grew proportionally to the receiver movements. A more detailed analysis of the relation among accuracy error and receiver position is given in Colosimo (2013).

![Fig. 1. Main processing blocks of the VADASE implementation. The initial receiver position \(P_0\) is retrieved from the RINEX header. Then, for all epochs, \(P_0\) is used to compute the terms of variometric Eq. (1) and to estimate the receiver epoch-by-epoch displacement (i.e., velocity).](image-url)
3. Kin-VADASE: the kinematic implementation of the variometric approach

The goal of Kin-VADASE is to retrieve accurate kinematic parameters of moving receivers so that the variometric algorithm can be exploited also in GNSS navigation applications. In this section, the main differences between the original VADASE and the proposed Kin-VADASE are presented with specific focus on the implementation changes required.

3.1. Software architecture

The original implementation of the variometric approach for GNSS seismology and monitoring purposes was meant to detect velocities and displacements of permanent stations, which were modeled as receivers in pseudo-static conditions. As such, the initial coordinates were supposed to be known with high accuracy and they were constantly used in the variometric Eq. (1), as shown in Fig. 1 and explained in Section 2.2.

In Kin-VADASE initial coordinates, are continuously updated by the epoch-by-epoch variometric solutions, accounting for the estimated displacement with respect to the previous position. If the initial coordinates (i.e., starting position of the moving vehicle) are not known, they are estimated on the basis of code observations. Because of the nature of our approach (use of phase observations aimed to estimate velocities and not absolute position of the receiver), in this case the entire track of the moving vehicle will be biased by the starting point positioning error (e.g. few meters), but velocities and displacements will be retrieved with high accuracy.

In order to satisfy the kinematic requirements, the initial scheme used for implementing VADASE software was revised and updated as it is shown in Fig. 2. Initial coordinates $P_0$ are taken from the RINEX observation file header, or, if not available, are estimated for the first epoch on the basis of code observations. Then, at each epoch $i$ a new receiver position $P_i$, derived on the basis of the previous position and of the estimated velocity, is used to compute the variometric Eq. (1). Eq. (3) shows how the receiver position $P_{i+1}$ is updated based on the position $P_i$ and the computed velocity $V_{i+1}$ (expressed in terms of displacement):

$$ P_{i+1} = P_i + V_{i+1} $$

Additionally, in order to satisfy requirements related to navigation, Kin-VADASE allows direct visualization of the receiver’s trajectory on Google Earth platform by providing a suited Keyhole Markup Language (KML) output file.

4. Application to simulated data and model assessment

In order to validate the Kin-VADASE implementation, at first, several tests were performed on simulated data. A Spirent GNSS signal simulator (Spirent et al., 2007), able to reproduce in laboratory the framework of a navigation receiver installed on a dynamic platform, was used under different configurations. Radio Frequency (RF) signals were simulated as similar as possible to real conditions: the effects of high-dynamic host vehicle motion was exhibited, satellite motion was considered, ionospheric and tropospheric effects were reproduced through suitable models in order to consider the impact of the atmosphere in the signal propagation from the satellite to the receiver. A Septentrio PolarRx3eG dual frequency geodetic receiver was used to record and acquire the simulated data. Atmospheric delays were simulated considering Klobuchar and Saastamoinen models for ionosphere and troposphere, respectively. In addition to the signals, Spirent simulator provides trajectory reference coordinates for each epoch, which were used to assess Kin-VADASE accuracy. In this respect, the starting coordinates, needed only for the first epoch of Kin-VADASE processing, were supplied according to Spirent motion initial position. Here, two simulations are reported with the receiver placed on board land and aerial vehicle. In both experiments data were collected at 1 Hz sampling rate. In data processing, Saastamoinen model was used to take account of the tropospheric delay.
For each scenario, at first ionospheric free (L3) combination solutions were computed. Then, a second processing was carried out using only L1 observations and Klobuchar model (Klobuchar, 1987), in order to investigate Kin-VADASE capabilities for single frequency receivers.

4.1. Land vehicle

A receiver is simulated on board of a land vehicle moving on a horizontal rectangular trajectory of 2 × 1 km for several laps. Velocity is variable between 10 and 30 km/h (the motion could be compared with the one of an agricultural vehicle), decelerations and accelerations are performed 20 m before and after every 10 m radius curve (all the parameters can be set through the Spirent software interface). The total traveled distance was 21899.27 m over an interval of 2720 s. Statistics over the epoch-by-epoch differences between Kin-VADASE and Spirent reference coordinates are shown in Table 1. Both L1 and L3 solutions present an accuracy at the decimeter level (0.071 m, 0.177 m and 0.181 m for East, North and Up components, respectively, in L1 and 0.028 m, 0.012 m and 0.028 m for East, North and Up components, respectively, in L3). With respect to the reference total trajectory length, Kin-VADASE trajectory length relative error (computed as the absolute value of the difference between the length of the Kin-VADASE estimated trajectory and the reference one, divided by the reference one itself) is at the level of few mm/km (0.001 m/km and 0.002 m/km for L1 and L3, respectively). The comparison between Kin-VADASE and Spirent was also performed in terms of velocity (native output of Kin-VADASE) and acceleration (derived from velocities). The agreement is at the level of few mm/s and mm/s². Since Kin-VADASE coordinates are obtained by an integration process errors can increase over time. To evaluate the impact of this error, the 3D RMSE over time was computed and interpolated with a linear regression. It was found that 3D RMSE over time is 0.050 m/h for L1 and 0.043 m/h for L3 processing.

4.2. Aerial vehicle

The receiver is simulated to be on board of an air vehicle executing a full flight (take-off, cruise and landing). The aim of this experiment is to test Kin-VADASE potentialities when processing data acquired by a vehicle moving at high speed and subjected to a significant altitude variation. A maximum velocity of 460 km/h is reached in the flight phase, the total traveled distance is 68115.85 m over an interval of 733 s. Even if the characteristics of this simulation are completely different from the ones investigated in Section 4.1, Kin-VADASE confirmed its effectiveness. Statistics are reported in Table 2. Both L1 and L3 solutions present an accuracy at the decimeter level (0.071 m, 0.177 m and 0.181 m for East, North and Up components, respectively, in L1 and 0.051 m, 0.090 m and 0.116 m for East, North and Up components, respectively, in L3). With respect to the reference total trajectory length, Kin-VADASE trajectory length relative error is 0.002 m/km and 0.001 m/km for L1 and L3 respectively. 3D RMSE over time is 1.354 m/h for L1 and 0.752 m/h for L3. Velocity and acceleration differences are at the level of few mm/s and mm/s² for the horizontal components and at the level of one cm/s and cm/s² for the vertical component.

5. Application to real data

Here we present the first application of Kin-VADASE to real kinematic data with the twofold aim of: (i) assess the accuracy of the new kinematic implementation and, (ii) clearly show the limitations of the original VADASE approach. Moreover, the results presented in this section prove how Kin-VADASE does not significantly suffer the impact of the bias in the velocities estimation over kinematic data spanning a long period of time (e.g., several hours). In fact, as discussed in Section 2.1, when the receiver is moving, the displacements are dominant with respect to the bias. The same considerations do not hold for static cases: if several hours of static data are processed with the variometric approach, the drift over time is strongly impacting the final solution, which completely loses its reliability. For this reason the analysis of long period static data was not considered useful for the sake of the present work. Two test cases were studied using data collected from a dual frequency Leica Geosystems geodetic receiver. In the first test, presented in details in Section 5.1, observations at 2 Hz sampling rate were collected on board of a sail boat; in the second test, discussed in Section 5.2,
10 Hz observations were acquired from a receiver on board of a car. For the sake of the comparison, data were processed using both VADASE and Kin-VADASE. A reference solution was obtained by the post-processing relative positioning (Kaplan and Hegarty, 2006) algorithm implemented in the LGO (Leica Geosystems Office) software.

### 5.1. Navigation off-shore

Observations at 2 Hz sampling rate were collected from a receiver installed on board of a sail boat, during a navigation off-shore the Riva di Traiano (Civitavecchia, CTV, Central Italy) Harbor. The total traveled distance was 38006.69 meters over a time interval of 14399 s. The boat was moving with an average speed of 15 km/h with a maximum distance from the coast of about 18 km. Fig. 3, shows the boat trajectory in East-North obtained with VADASE (in green) and Kin-VADASE (in Blue). Both solutions start from Riva di Traiano Harbor, which is represented as a red square in the Figure; however, only Kin-VADASE solution ends again in the harbor, heading back fairly accurately nearby the starting point. Instead, when data are processed with the original implementation of the variometric approach, errors due to inappropriate model cumulate over time causing a wrong final position of the boat (green square in the plot), far from the Harbor about 2 km in the West component and 4 km South.

A deeper analysis was performed comparing VADASE and Kin-VADASE solutions with the one coming from LGO (Leica Geosystem Office) software. CTV station (1 Hz acquisition rate), located in Civitavecchia (Rome), less than 10 km away from the harbor, and belonging to Regione Lazio GNSS Network, was used as reference station. This favorable configuration ensures a maximum baseline length for the relative positioning processing of roughly 25 km. As stated before, the on board receiver was set at 2 Hz sampling rate. The variometric approach has no limitation regarding the sampling rate and high rate (>1 Hz) observations can be completely exploited to estimate high rate kinematic parameters. Differently, reference station data used for LGO solutions were available at 1 Hz sampling rate (this is the standard acquisition rate of GNSS permanent stations devoted to positioning services, like RTK), so it was possible to obtain a reference solution for the comparison at 1 Hz only. Thus the statistics over the comparisons LGO/VADASE and LGO/Kin-VADASE were computed exclusively over common epochs.

Figs. 4 and 5 show residuals of VADASE and Kin-VADASE, in the three components East, North and Up, respectively, in terms of final position displacements, with respect to LGO solution. Residuals are plotted in function of time (on X axis) and distance from the starting point of the navigation (colored bar). The plots can be interpreted as follows: the gradient of the curves represents the error in the epoch by epoch variometric solution (velocity), whereas the curve itself represents the error in the trajectory estimation. VADASE velocity error (Fig. 4) increases with the distance from the origin and reaches the maximum value (gradient of the residual over time) when the distance from the origin is maximum (i.e., red part of the plot). As a matter of fact, when the distance from the origin increases, using the initial position to compute the variometric solutions (as designed in the static implementation of the variometric approach) is proved to be not a valid approximation. After the first half of the plot, the distance from the origin decreases (the boat is returning to the harbor), causing also the velocity error in the VADASE solution to shrink. Nonetheless, the total cumulated error continuously increases over time for all the components (Fig. 4). Kin-VADASE residual with respect to LGO are in Fig. 5. In these solutions residuals seem to be completely independent to the distance from the initial position. Such statement is confirmed by Figs. 6 and 7 that show, VADASE and Kin-VADASE, respectively, 3D velocities residuals as function of the distance from the origin. In case of VADASE, the correlation coefficient between the residuals and the distance reaches 0.98, whereas the Kin-VADASE residuals correlate with the distance only with a coefficient of 0.22.

To assess the accuracy of Kin-VADASE, statistics over the residual with respect to LGO were computed. Results are reported in Table 3 for Kin-VADASE L3 and L1 processing. When both frequency are used to process data, an overall horizontal accuracy of few decimeters was achieved (RMSE value is 0.43 m and 0.32 m in East and North
respectively), while the RMSE value increases up to 0.60 m in 3D.

As expected, since the real ionospheric delay is only partially removed by the Klobuchar model broadcasted parameters, the accuracy decreases (RMSE is 0.89 m and 1.17 m in East and North, 1.74 m in 3D) when solutions are obtained with L1 only. The achievable accuracy in trajectory length estimations is 0.050 m/km for L3 processing and 0.075 m/km in single frequency processing. Velocity and acceleration differences are at the level of few mm/s and few mm/s² for the horizontal and vertical components.

RMSE variation over time is shown in Fig. 8 for single and double frequency processing. With a linear regression (displayed as dashed line in the figure), we found an accuracy of 1 dm/h and 4 dm/h for L3 and L1 processing.

The above considerations and statistics refer to the Kin-VADASE solution retrieved using accurate starting position of the receiver: at the first epoch, Kin-VADASE and LGO coordinates are the same. Some further tests were performed to evaluate how errors on initial position could
propagate into the variometric solution (i.e., velocities and displacements of the receiver). To this aim, an error over each component of the starting position of 0.3 m, 1 m, 2 m, 5 m (that is an initial 3D error of 0.52 m, 1.73 m, 3.46 m and 8.66 m respectively) was imposed and the related Kin-VADASE solution (in L3 configuration) were estimated. Fig. 9 shows that each solution suffers, as expected, an initial bias and that the impact over the epoch by epoch velocities estimation increases after roughly 2 h of processing. The 3D RMSE was 1.08 m, 2.72 m, 5.20 m, 12.66 m respectively.

5.2. High rate capability

The experiment was performed in a small airport near Arezzo (Tuscany, Italy). With the aim of testing high rate capabilities of Kin-VADASE, 10 Hz observations were collected for a short interval (about 7 min) with a Leica Geosystems double frequency geodetic class receiver, installed on board of a car. In this experiment a 10 Hz reference solution could not be computed with the standard differential approach, due to the fact that 10 Hz observations from a permanent station were not available.
Fig. 7. Kin-VADASE 3D velocities residuals with respect to LGO in function of distance from the origin (test 1: navigation off-shore, receiver installed on board of a sail boat).

Table 3
Sail boat: comparison of Kin-VADASE solutions (L3 and L1) with LGO L3 solutions.

<table>
<thead>
<tr>
<th></th>
<th>L1</th>
<th>L3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position [m]</td>
<td>E</td>
<td>N</td>
</tr>
<tr>
<td>St. dev.</td>
<td>0.469</td>
<td>0.615</td>
</tr>
<tr>
<td>Average</td>
<td>–0.757</td>
<td>1.000</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.891</td>
<td>1.174</td>
</tr>
<tr>
<td>Rel. error in Traj. [m/km]</td>
<td>0.075</td>
<td>0.050</td>
</tr>
<tr>
<td>3D RMSE [m]</td>
<td>1.742</td>
<td>0.595</td>
</tr>
<tr>
<td>3D RMSE over time [m/h]</td>
<td>0.408</td>
<td>0.122</td>
</tr>
</tbody>
</table>

Fig. 8. Kin-VADASE 3D RMSE over time. The dashed line represents a simple linear regression model over the curves (test 1: navigation off-shore, receiver installed on board of a sail boat).
Therefore, the original observations were decimated to 1 Hz sampling rate and a standard L3 differential solution (using the LGO software) was obtained using as reference CAMU permanent station, placed in Cortona (about 20 km far from the test area) and belonging to ItalPos GNSS network. The comparison among 10 Hz Kin-VADASE solution and 1 Hz LGO solution was performed with respect to pairs of corresponding epochs. Fig. 10 shows the 10 Hz car trajectory estimated with Kin-VADASE on Google Earth platform.

Figs. 11 and 12 show position residuals of VADASE and Kin-VADASE with respect to LGO in function of time and distance from the origin; Figs. 13 and 14 show 3D velocities residuals in function of distance from the origin. As it was already described for the test in Section 5.1, the increase of the residuals suffered by VADASE grows proportionally to the distance from the origin (correlation coefficient is 0.92, Fig. 13). On the contrary, the residuals of Kin-VADASE do not correlate with the distance (correlation coefficient is 0.03, Fig. 14) and seem to follow a non deterministic pattern (Fig. 12).

Statistic over the 1 Hz epoch-by-epoch comparison are reported in Table 4. An accuracy of few centimeters in planimetry and one decimeter in the Up component was achieved with L3 solution; L1 solution accuracy is at the decimeter level in planimetry and slightly better than one meter (0.93 m) in the Up component.

Velocity and acceleration differences with respect to the reference trajectory are at the level of few mm/s and few mm/s² for the horizontal and vertical components. With respect to the reference total trajectory length, Kin-VADASE trajectory error is 0.241 m/km and 0.157 m/km for L1 and L3 respectively. 3D RMSE over time is 8.892 m/h for L1 and 0.702 m/h for L3, while the total 3D RMSE is 0.932 m and 0.123 m for L1 and L3 respectively. The lower global accuracy obtained for L1 solutions is mainly due to a major bias and dispersion in the Up component (average and standard deviation values

Fig. 9. 3D difference between LGO and Kin-VADASE solution computed when each component of the starting position is affected by an error of 0.3 m, 1 m, 2 m, 5 m (test 1: navigation off-shore, receiver installed on board of a sail boat).

Fig. 10. 10 Hz car trajectory estimated with Kin-VADASE on Google Earth platform.
of L1 Up position are $-0.823$ m and $0.426$ m as reported in Table 4). Actually, if only the horizontal components are considered, the 2D RMSE over time improves up to $1.105$ m/h and the total 2D RMSE is $0.106$ m (values not reported in Table 4). The root cause of the notable difference in the L1 and L3 solutions’ accuracy, which is dramatically lower with respect to the previous experiment, is being currently investigated in more details.

Finally, Kin-VADASE solution when each component of the starting position was affected by an error of $0.3$ m, $1$ m, $2$ m, $5$ m was computed. Epoch by epoch velocities and the trajectory of the vehicle is still retrieved with high accuracy and the solution is mainly affected by the initial bias. The global 3D RMSE of the epoch by epoch difference with LGO is $0.55$ m, $1.72$ m, $3.42$ m, $8.46$ m when the initial 3D error is respectively $0.52$ m, $1.73$ m, $3.46$ m, $8.66$ m (3D difference over time are represented in Fig. 15).

This experiment showed that the variometric approach high rate capability is an added value with respect to standard real-time positioning approaches, since it allows to overcome the problem of the availability of high rate observations from permanent stations. From an application point of view, it could be realized an integration between standard RTK positioning and Kin-VADASE: RTK could provide 1 Hz positioning and VADASE could increase the position density at a higher desired rate (at present,
Table 4
Application to high rate real data. Comparison between Kin-VADASE 10 Hz solutions and 1 Hz differential approach solutions (comparison performed with respect to pairs of corresponding epochs). Statistics over East, North, Up and 3D differences of L3 and L1 solutions.

<table>
<thead>
<tr>
<th>High rate solutions</th>
<th>L1</th>
<th>L3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traj. length = 1653 m, Duration = 389 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Position [m]</strong></td>
<td>E</td>
<td>N</td>
</tr>
<tr>
<td>St. dev.</td>
<td>0.023</td>
<td>0.059</td>
</tr>
<tr>
<td>Average</td>
<td>0.031</td>
<td>0.080</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.039</td>
<td>0.099</td>
</tr>
</tbody>
</table>

| Rel. error in Traj. [m/km] | 0.241 | 0.157 |
| 3D RMSE [m]                | 0.932 | 0.123 |
| 3D RMSE over time [m/h]    | 8.892 | 0.702 |
receivers able to acquire at 100 Hz are commercially available. Moreover, Kin-VADASE could supply a bridging solution in case of failure of RTK positioning.

6. Conclusion and perspectives

This work shows the results of the Kinematic implementation (Kin) of the Variometric Approach for Displacement Analysis Standalone Engine (VADASE) to simulated and real data. Kin-VADASE builds on VADASE, already implemented within seismological and monitoring applications, to fully extend its use in the navigation field. This new methodology allows real-time estimation of kinematic parameters from a single receiver placed on a moving vehicle using single (or double) frequency observations. After describing the Kin-VADASE algorithm, this work validates its theoretical model performing preliminary tests based on synthetic data. The paper also shows how Kin-VADASE overcomes the limitation of the original implementation of the variometric approach (static VADASE).

A thorough analysis on Kin-VADASE results was performed over data acquired under two completely different conditions. In the first test, 2 Hz data were acquired with a double frequency geodetic class receiver, installed on board of a sailboat, during a long (about 4 h) navigation off-shore. In the second experiment, 10 Hz observations were collected for a short interval (about 10 min) from a geodetic class receiver, installed on the roof of a car. Data were processed both with VADASE and Kin-VADASE. The final accuracy of Kin-VADASE was assessed comparing its solution with the one obtained by a standard post-processing relative positioning (LGO, Leica Geosystems Office software).

In both experiments Kin-VADASE outperformed its predecessor. VADASE error in velocities estimation is highly correlated with the epoch-wise distance of the receiver from the starting point of the movement: the correlation coefficient between VADASE residuals (with respect to LGO) and distance from the origin is higher than 0.9 in both experiments. Consequently, the final trajectory obtained through velocities integration might not be accurate. Differently, Kin-VADASE results were independent from the distance from the origin, allowing a reliable reconstruction of the entire motion. In the first experiment an overall 3D RMSE of 0.6 m for L3 and 1.74 m for L1 was achieved with respect to LGO solutions. In the second experiment the total 3D RMSE is 0.123 m and 0.932 m for L3 and L1 respectively. The lower global accuracy obtained for L1 solutions is mainly due to a major bias and dispersion in the Up component. In fact, if only the horizontal components are considered, 2D RMSE improves up to 0.106 m.

Moreover, both experiments showed that the accuracy of retrieved velocities and displacements is dependent on the quality of the initial receiver position. In more details, when applied to long period navigation (more than 1 h data), Kin-VADASE has a lower accuracy with respect to the one of the established techniques. Despite this, it presents significant and very promising advantages, i.e. the use of a unique GNSS receiver and the possibility to exploit high rate (>1 Hz) observations to retrieve high rate kinematic parameters. Also, since Kin-VADASE algorithm requires only broadcast products and needs no ambiguity resolution, it can, in principle, run in real-time directly on board the GNSS receiver, as it was already shown for the original VADASE (Tawk et al., 2016).
In order to figure out the best applications simulating KinVADASE, further experiments should be performed under different acquisition condition, such as obstructed environment, or with real data collected by aerial vehicles. Further, in order to confirm its single frequency capabilities, future experiments are planned using observations collected by low-cost single frequency receivers.

The efficiency of the proposed technology, in terms of costs and computational complexity, pushes towards the use of the variometric approach not only for scientific purposes, but also for industrial aims to reach many activities of our everyday life.

Acknowledgements

The authors are indebted with the Centro Avanzado de Tecnologas Aeroespaciales (CATEC) research center in Sevilla, for the great opportunity to collect synthetic data using Spirent GNSS signal simulator, for the precious scientific support in simulating GNSS data, and for the warm hospitality during the research period spent in the center. Also, the authors would like to thank the Regione Lazio GNSS Service for providing observations collected at CTVT (Civitavecchia) permanent station and ItalPos for the observations collected at CAMU (Cortona) permanent station. Variometric approach, implemented in the VADASE software in its “static” version, is subject of an international pending patent, generously supported by the University of Rome “La Sapienza”. VADASE was awarded the German Aerospace Agency (DLR) Special Topic Prize and the Audience Award at the European Satellite Navigation Competition 2010 and was partially developed thanks to one-year cooperation with DLR Institute for Communications and Navigation at Oberpfaffenhofen (Germany).

References


IGS real time Service. //igs.org/rts/monitor (last accessed January 2015).


NABA Jet Propulsion Laboratory Automatic Precise Positioning Service. //apps.gdps.net/ (last accessed January 2015).


