Leica VADASE
White Paper

PART OF HEXAGON

- when it has to be **right**

Leica Geosystems

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Abstract

This paper introduces the new Leica Velocity And Displacement Autonomous Solution Engine – VADASE. Available onboard the GR10 & GR25 reference station receivers and GM10 monitoring receiver, Leica VADASE solution provides fully autonomous precision high-rate velocity information of a GNSS station antenna. This allows scientists and engineers instant, reliable real time displacement and waveform analysis of fast movements.

Leica VADASE applies unique GNSS processing algorithms to work autonomously using standard broadcasted information and observations collected by one stand-alone receiver in real time. The solution does not depend on local, regional or global GNSS RTK correction services. We explain how this has been realized with Leica VADASE and illustrate its performance with selected tests. The given examples will assist to understand how to use and interpret the results, allowing the user to explore the potential of this method and to recognize its limits.
Leica VADASE provides new opportunities for applications where a continuous real time GNSS differential correction stream for absolute positioning cannot be reliably available, or where only post-processing solutions are applicable, but are too slow, to provide information for a first and fast potential risk analysis and disaster mitigation.

Leica VADASE is a solution for scientists and engineers who need actionable information about fast movements of man-made and natural structures as they occur. Running onboard the standard receiver, the autonomous solution is a powerful complement to any of the traditional methods.

Introduction

Since the early 1990s, GPS (Global Positioning System) proved capable of providing stations coordinates and velocities in a common global reference frame with centimetre and millimetre level accuracy, respectively [1]. At that time, the raw observations coming from the satellites were typically acquired every 30 seconds (or with a lower rate) and the data were combined together to achieve one position solution per day. These solutions were then stacked in time series of coordinates and they revealed as an invaluable tool to monitor long-period large scale geophysical and geodynamical events (e.g., crustal deformation, sea-level changes, post-glacial crustal rebound, co-seismic and post-seismic deformations). However, it was completely impossible to investigate or study the characteristics of any fast movement occurring in short time (e.g., waveform induced by an earthquake) as an event happens.

In the mid and late 1990s, the important advances achieved in GPS receiver technology, together with the increased data storage capability, gave the possibility to acquire and store satellite observations with much higher sampling rates. Since then, many researchers started to investigate the possibility to use the GPS receiver as a seismometer to represent the waveforms caused by large magnitude events [2]. In 2000, Ge demonstrated that a GPS receiver could retrieve the amplitudes and frequencies of oscillation generated by a shaker machine with an accuracy of few centimetres [3]. Those experiments can be considered as the first examples of a new field of utilization for the GPS sensors: the so called GPS Seismology. Larson defined the GPS Seismology as the application of conventional geodetic models in analysing GPS data at high sampling rates ($\geq$ 1Hz) and solving for the receiver position at every observation epoch [4].

At present, GNSS are commonly used for kinematic positioning, navigation and monitoring purposes in order to detect motions and displacements in (near) real time. For this two approaches are mainly used: Precise Point Positioning (PPP) and differential kinematic positioning.

PPP requires precise (or, at least, rapid) ancillary products (satellite orbits, clocks, and phase biases, Earth Orientation Parameters), which, at present, are not routinely available in real time with the due accuracy. This approach uses dual frequency observations acquired from a single Global Navigation Satellite Systems (GNSS) receiver and supplies a-posteriori high accurate displacements in a global reference frame [5]. Real time capabilities of this approach are limited by the accuracy and the availability of the ancillary required products, whose precision decreases together with time latency. Moreover, in order to reach the centimetre accuracy level, PPP needs a "convergence" time ranging from several minutes up to 1 hour. Each time the receiver loses the signal lock or experiences any tracking problems, the convergence time has to be re-applied and the user has to wait before a highly accurate position is available again.

Differential kinematic positioning requires a permanent GNSS network with a maximum average inter-station distance of up to tens of kilometres and common processing of the collected data in a centralised system. Although an accuracy level of few centimetres can be reached, the differential technique provides only relative positions with respect to a reference station. This is a serious limitation when strong earthquakes occur that may affect the entire area covered by the permanent network. For such events, the reference station is likely to be also affected by a displacement. Therefore, only relative co-seismic displacements (not in a global reference frame) may be recovered in real-time across the entire network area [6].

This paper describes the new solution introduced by Leica Geosystems to determine, in real time and in an absolute reference frame, the velocity and displacement of a single GNSS receiver and antenna with high accuracy. The solution is based on a "variometric" approach that only requires the observations collected by a single GNSS receiver and the standard GNSS broadcast products (orbits and clocks), which are ancillary information, routinely available in real time as a part of the broadcast satellites navigation message.

This innovative method has been initially described by the University of Rome "La Sapienza" and referred to as VADASE ("Variometric Approach for Displacements Analysis Stand-alone Engine"). It uses high-rate (1 Hz up to 20 Hz) GNSS data to obtain real time estimated velocities and displacements on the order of some cm/s and cm, respectively, without the need of any kind of additional correction stream or service.
The VADASE algorithm has been integrated into Leica Geosystems' GNSS reference stations Leica GR10 & GR25 and the Leica GM10 monitoring receivers as the unique "Velocity And Displacement Autonomous Solution Engine - VADASE". With this integration the novel approach becomes available to a wide range of GNSS users and applications such as wave-form analysis in seismology and tsunami early-warning systems, real time structural and geotechnical engineering monitoring or safety monitoring of infrastructures close to potential environmental hazards.

Leica VADASE represents the smart solution that enriches and complements the Leica Geosystems GNSS-based tools for monitoring. Using standard NMEA formatted messages, the information can be streamed in real time or logged onboard the receiver and published by FTP. Displacement events are recorded onboard the receiver, and the customer can be notified by email without any need for additional software. Users can also apply the latest versions of Leica SpiderQC, Leica GeoMoS or any other customised software for advanced data visualisation, analysis, threshold verification and notification.
With this instant information, professionals can obtain a deeper understanding of how movements occur, thus better evaluate support needs and take stronger fortification measures. Leica VADASE becomes a reliable partner in risk management.

Technical background of VADASE algorithm

VADASE Algorithm – Velocity

The computation of the velocity of a site location, or GNSS antenna position respectively, is enabled through the use of a highly accurate time-differenced phase observation. The time-differenced phase observation allows a very precise estimate of the position change on an epoch-to-epoch basis that is then transformed into a precise velocity estimate. By using time-differenced phase observations to estimate the velocity, the accuracy of the final velocity solution is independent of the update rate, with higher rate processing only required to capture also higher dynamic movements of a site location.

Time-differencing the phase observations is required to remove the unknown ambiguity parameter. This allows the processing of the observations without the need to do any phase ambiguity resolution, and allows VADASE to produce a velocity estimate from any two epochs of phase observations. In order to estimate the velocity in VADASE, the following error sources need to be compensated:

- Ionosphere
- Troposphere
- Linearization errors
- Satellite orbit error

The ionosphere effects are mitigated by processing the IONOFREE linear combination, which mitigates the first order ionosphere drift in the velocity solution, while a precise tropospheric model is used to estimate and compensate for the troposphere drift. In the case of a single frequency solution, a precise a priori ionosphere model is used to compensate for the ionospheric effects. The linearization errors can also be minimised using two techniques. The first is to linearize the set of equations around an accurate known point, such as the site coordinates of the GNSS antenna. These should refer to the GNSS reference frame (WGS84) and be accurate to some decimetres or better. Secondly, the solution is iterated to further minimise any linearization biases. If the site coordinates are unavailable or of insufficient quality, a single point solution can also be used as the initial linearization point.

As Leica VADASE is realized onboard the receiver as a real time solution, the satellite orbit velocities required for the calculations have to be directly derived from the broadcast satellite ephemeris. In that the observations we are using are time-differenced phase observations, these are actually the position difference between subsequent epochs, which equates to the average velocity over the given time period. And since the velocities derived from the broadcast ephemeris are the instantaneous velocities at the epoch time, it is necessary to compensate these values to obtain the computed average velocity over the entire epoch. Thus VADASE also calculates the satellite acceleration and jerk to a high degree of precision in order to compute the correct expected average velocity term.

VADASE Algorithm - Displacement

The displacements in the VADASE algorithm are computed by integrating the estimated velocities according to the following formula:

$$Displacement_{Direction}(\mathrm{n}) = \sum_{t=1}^{n} Velocity_{Direction}(\mathrm{t})\,\mathrm{dt} \qquad (1)$$

where "*Direction*" is the East, North or Height velocity component, dt is the time difference between two epochs and "n" is the epoch.

Since even with a perfectly static antenna, due to processing noise, the estimated velocities will be different from zero and continually change by some small amount, the displacement integration need to differentiate between real movement and process noise.

Within Leica VADASE a straightforward velocity noise threshold is applied to detect movement of GNSS antenna and trigger the start and end of the displacement computation. Additionally a fundamental outlier detection based on the velocity component quality estimates (derived from the variances) detects and removes blunders from the raw velocity data. Depending on the desired application different displacement computation strategies may be desired.

Integration with Leica RefWorx and Leica SpiderQC

Leica RefWorx

Leica RefWorx is the firmware solution running onboard the Leica GR/GM-Series GNSS reference station and monitoring receivers. The Leica VADASE solution has been integrated into this firmware and is available in RefWorx V3.20 and onwards. The Velocity & Displacement Engine (V&DE), as Leica VADASE is also referred to within the RefWorx firmware, can be enabled and disabled using the embedded web interface. If enabled, the antenna's estimated velocities and displacements can be streamed or logged using two new Leica proprietary NMEA-type messages referred to as "Leica Geosystems Velocity Measurement – LVM" and "Leica Geosystems Displacement Measurement – LDM" message. In addition, while the V&DE is enabled, for each detected displacement, the start time, end time and total amount of displacement per component during this period will be reported in the onboard event log messages.

The V&DE configuration page is shown in Figure 1. The section "Current thresholds used for displacement detection" contains the current user-defined velocity thresholds for detecting displacements in North, East, and Height components, i.e. the V&DE will start integrating the velocities to obtain displacements only when one or more of these velocity thresholds are exceeded. Velocities below these thresholds are considered as process noise and will be disregarded. Or in other words the GNSS antenna position is considered static.

The section ''Computed thresholds'' contains the currently estimated velocity thresholds within or after the 24 hour threshold computation process. The threshold computation process is based on calculating the standard deviation of the antenna's velocity on each axis during a full day taking into account all observed satellite constellation geometries. The computed threshold value corresponds to a high confidence level of at least 99.9999%, i.e. in a static scenario this largely reduces the probability of false displacement detection. Once the computation process finishes, i.e. after 24 hours, the user can use these thresholds as guiding values to steer the displacement detection sensitivity as needed for his particular application.

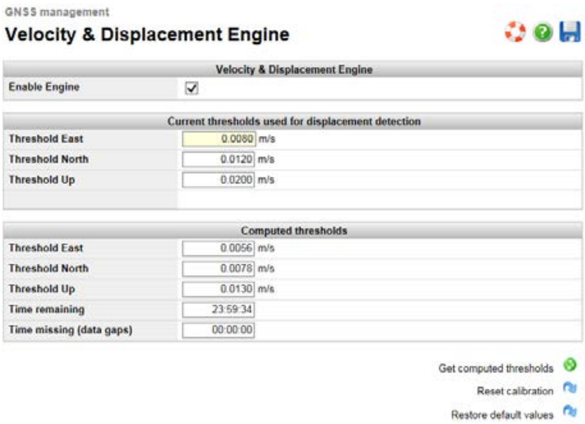


Figure 1: V&DE configuration page.

It is important to note that the idea behind the computed threshold computation process is to have a site location specific system "calibration". In fact, the tracking conditions and thus the velocity noise level can vary significantly from one site to another. Many factors can affect the velocity noise level, such as satellites geometry, multipath, obstructions and nearby sources of radio interference. Therefore, it is not recommended to have a unique default threshold for all sites. Consequently, velocity thresholds based on observations collected from a specific site should be taken over to replace the default thresholds if local conditions lead to a different noise level of the estimated velocities. If the computed velocity thresholds are higher than the default velocity thresholds, using the computed velocity thresholds will lead to a lower probability of false displacement detections compared to using the default velocity thresholds.

Leica SpiderQC

Leica SpiderQC is a multi-purpose GNSS data analysis software tool, which runs on a PC or server computer. It offers a comprehensive suite of features tailored to the inspection, alarming, display and distribution of quality information relating to the raw data products of a reference station or network. Furthermore, SpiderQC can be used to detect and visualise movements of your reference stations or other critical infrastructure (e.g., bridges, dams, landslides, etc.).

With the new release of Leica SpiderQC V5.3, the integration with Leica VADASE information for online and offline analysis has been added: LVM and LDM NMEA messages can be decoded and the time series of velocities and displacements can be displayed both in real time and in post processing.

In order to display the VADASE results computed on board a GR/GM receiver in real time, an LVM and/or LDM NMEA data stream needs to be configured in the GR/GM's web interface. Then, Leica SpiderQC can connect to the NMEA stream and the time series of velocities or displacements will be displayed in the "Real Time View" tab as shown in Figure 2.

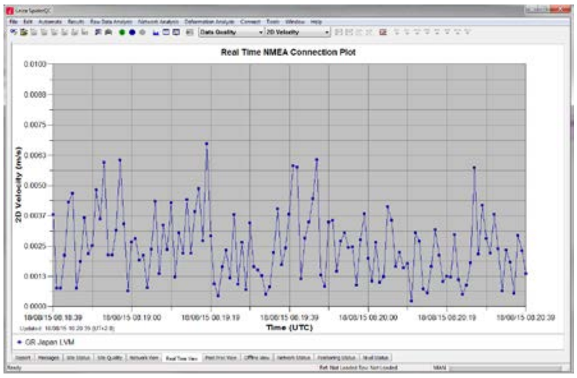


Figure 2: Real-time NMEA plot of 2D-Velocity

Both new NMEA message types can also be utilized for limit checks in Leica SpiderQC and can thereby be connected to messaging and events. Like this, an e-mail or other notifications can be triggered in case a certain velocity or displacement limit has been exceeded. This provides to the user the opportunity to instantly investigate and analyse the characteristics of the displacements.

Additionally Leica SpiderQC allows the offline analysis of velocity and displacement data, that has been previously recorded onboard the receiver or within Leica SpiderQC from the real-time stream.

Performance Results

In this section Leica VADASE is analysed under various static and dynamic scenarios to provide a deep understanding about the performance of this solution. This understanding should allow engineers and scientists to identify how this solution could be applied within their specific application areas.

Static Performance

Velocity Noise Level

When the receiver's antenna is static, VADASE will still estimate a velocity. The velocity in this case will be randomly distributed with a standard deviation "σ". The value of σ is dependent upon various factors including the accuracy of the reference position of the antenna, number of satellites tracked, constellation geometry, observation time, ephemeris accuracy, ionospheric disturbance and multipath etc...

Under normal to favourable conditions, VADASE will output velocity noise in the horizontal and vertical components with a σ in the order of:

Noise level (mm/s)	East	North	Height
1σ	3	5	8

Table 1: VADASE velocity estimation noise level when the antenna is static

It is important to note that to obtain the minimum noise level possible, it is crucial to set up the GNSS antenna in a location with favourable tracking conditions. There must be ideally no obstructions blocking the satellite signals and there should be no multipath sources nearby the antenna. Besides, the reference position of the antenna must be accurate to few decimetres or better within the global reference frame.

The existence of noise in the VADASE velocity estimation also limits the useful integration time of the velocities to obtain displacements. As this noise is part of the solution and cannot be eliminated, it adds a bias to the displacement computation. The longer an actual movement lasts, the less accurate the total computed displacement will be. Therefore, the analysis of Leica VADASE displacement computation results for movements which last significantly longer than 5 minutes, must take this bias critically into consideration.

An example of 5 hours 1 Hz velocity estimation by VADASE from a static reference station antenna in Heerbrugg, Switzerland is shown in Figure 3, Figure 4 and Figure 5 for the East, North and Height components respectively. It can be seen that the noise level on the vertical component is the highest. On the horizontal component, the noise level on the North velocity is higher than on the East velocity component. This is due to the satellites geometry in the location of the reference station where more satellites are available in the east and west directions than in the north and south directions. For example, this will much less be the case in a geographical location close to the equator where the typical satellites geometry should be more equally distributed in all directions.

Finally, it can also be seen from these graphs that some velocity peaks randomly appear in all 3 components East, North and Height. There are many reasons for the existence of these peaks, such as the change of the satellites geometry, multipath, or cycle slips. Leica VADASE has been optimized to detect and filter these peaks in the displacement computation. Potentially undetected peaks would result in a displacement where actually the antenna was static.

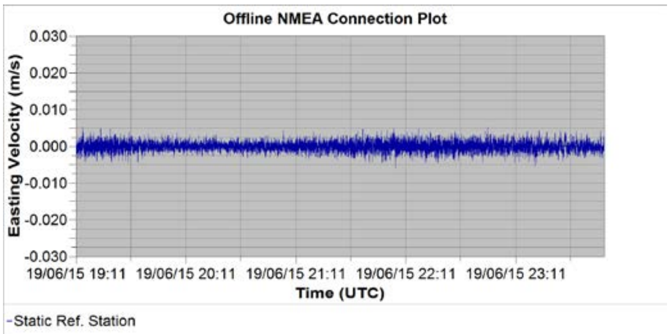


Figure 3: Easting velocity estimation by VADASE for a static reference station.

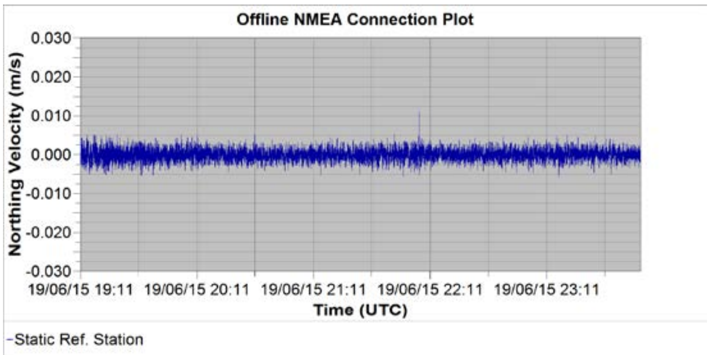


Figure 4: Northing velocity estimation by VADASE for a static reference station.

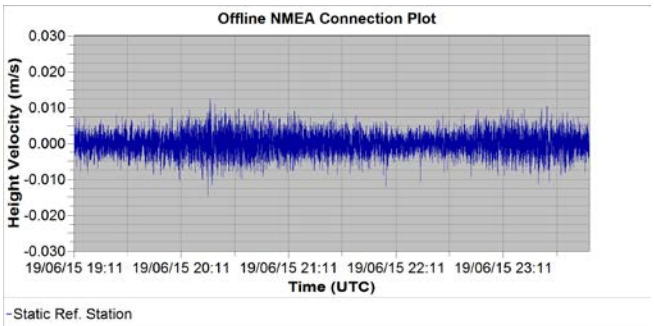


Figure 5: Height velocity estimation by VADASE for a static reference station.

Data Rates

Leica VADASE is capable of delivering velocities and displacements at the following rates: 20, 10, 5, 2 and 1 Hz. The higher data rates allow VADASE to detect faster movements. For instance, if VADASE works with 20 Hz sampling rate, movements with an oscillation frequency up to 10 Hz can be detected.

In terms of accuracy, all data rates obtain the same solution accuracy. In Figure 6 the East, North and Height velocities of a static GNSS reference station during a period of 5 minutes are shown for the different rates.

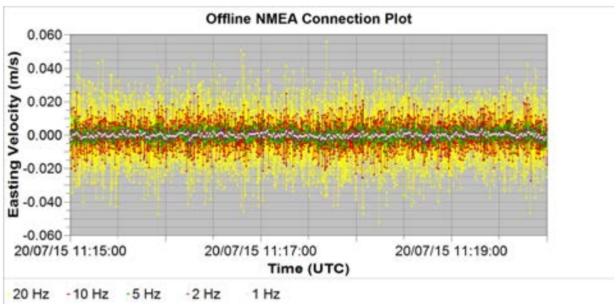


Figure 6: Comparison between different GNSS data rates solutions for East, North, and Height velocities of a static reference station in Heerbrugg.

It can be seen that when the rate increases, the velocity and the 3D velocity quality are increased. This is due to the fact that VADASE estimates the change of the antenna position on an epoch-to-epoch basis. This is then transformed into a precise "meter per second" [m/s] velocity estimate. In other words, to obtain the velocity estimation, the change of the antenna position is up-scaled by dividing it with the time difference to obtain the velocity in [m/s]. Therefore, when the velocity is down-scaled by multiplying it by the time difference, the noise level will be similar for all the data rates as can be seen Figure 7. In this plot, the east epoch to epoch displacement is shown. It is obtained by multiplying the east velocity in Figure 6 by the corresponding time difference. In this case, it can be seen that all data rates have similar and comparable noise level.

Furthermore, if the total displacement is computed from the epoch to epoch displacements, it can be seen from Figure 8 that all the data rates have similar behaviour and same total displacement of around minus 2 cm.

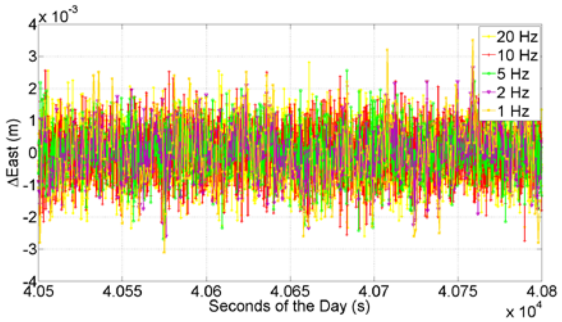


Figure 7: Comparison between different GNSS data rates solutions for east epoch to epoch displacement of a static GNSS reference station in Heerbrugg.

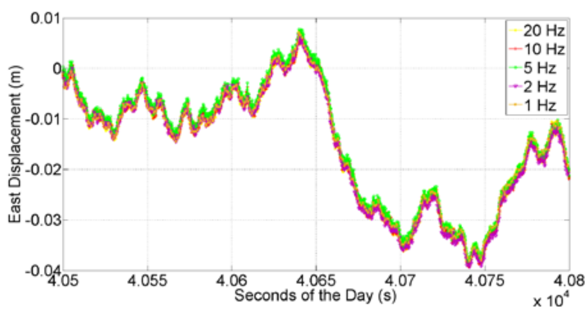


Figure 8: Comparison between different GNSS data rates solutions for east total displacement of a static GNSS reference station in Heerbrugg.

Supported GNSS

One of the main advantages of VADASE is its capability to work with multiple GNSS constellations and different frequencies without any compromise on the quality of the solution. The static performance of VADASE with different GNSS combinations can be seen in Figure 9, where the 1 Hz East, North and Height velocities from a static reference station in Tokyo are shown. For the same time period of 5 minutes, the velocities are computed using different GNSS enabled and also a GPS L1 only solution. It can be seen that the velocity noise level is very similar and almost comparable for GPS, GPS/GLO and GPS/GLO/BDS solution, however as expected, the velocity quality is better when more systems are enabled, i.e. more satellites are used for the solution computation.

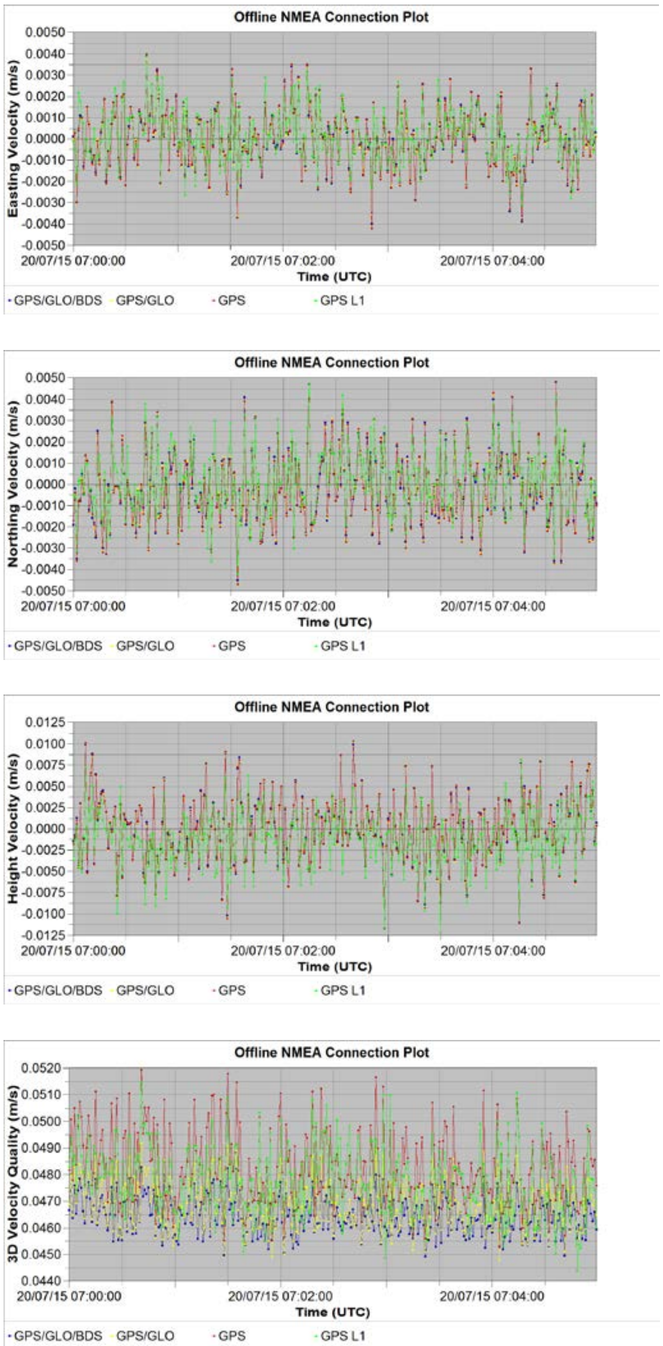


Figure 9: Comparison between different 1 Hz GNSS solutions for East, North, and Height velocities of a static GNSS reference station in Tokyo.

The solution with GPS L1 only is noisier and slightly more biased compared to the other solutions. This is mainly due to the ionospheric error. For a GPS L1 only solution the ionospheric error is modelled and

eliminated, whereas with a dual-frequency solution the ionospheric error can be largely eliminated in the estimation process. Due to the remaining ionospheric error in a single frequency velocity solution, when the antenna is subject to a dynamic movement, the computed displacement with a GPS L1 only solution will drift with time more than a GPS or GPS/GLO dual-frequency solution.
Figure **10** illustrates the drift caused by the ionosphere in a GPS L1 solution.

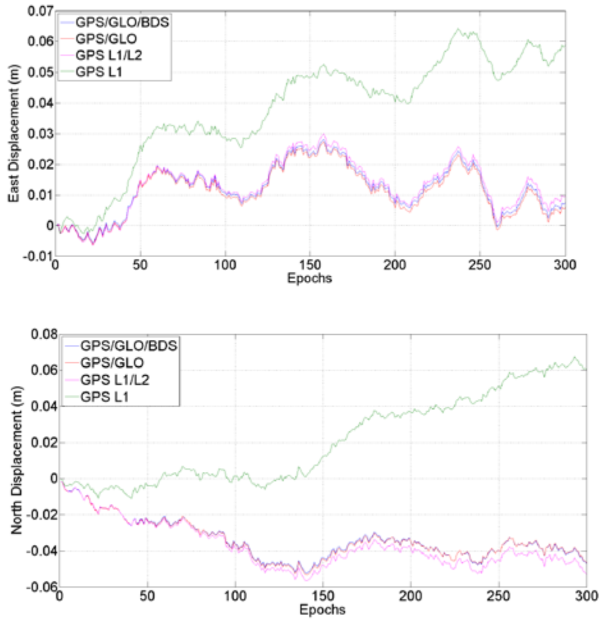


Figure 10: East and North displacements computed by integrating the velocities in Figure 9.

It can be seen that the GPS L1 solution in a static scenario is drifting more with time compared to the other solutions. As a result, single frequency displacements exhibit a drift that can be up to several cm higher, as compared to a dual-frequency solution. Nevertheless, similar short term motion patterns can still be obtained.

Dynamic Performance

Sensitivity

The velocity detection sensitivity of Leica VADASE is limited to the noise level of the estimation process. In fact, the noise level of the velocity estimation is an important factor to derive the sensitivity.
In order to derive a quantitative velocity sensitivity of Leica VADASE, we set up an AR10 antenna on a moving platform along two orthogonal 50 cm long axes in the East and North directions as seen in **Figure 11**. The platform is capable of moving computer controlled with speeds as slow as 1 mm/s. Taking into consideration that under normal and favourable condition the noise level of Leica VADASE velocities is 3 mm/s horizontally, the platform was programmed to move in the East and North direction with speeds from 3 mm/s to 9 mm/s along the length of an axis of 50 cm. We realised that with speeds up to 3 mm/s, we were not able to detect any considerable velocity as it was hidden in the process noise that was output. As soon as the velocity significantly exceeded 3 mm/s, Leica VADASE starts to detect the movement as can be seen in Figure 12. The lowest velocity that was identified was around 3.6 mm/s in the East and North directions. At this velocity, we are still very close to the noise level which dominates mainly the velocity estimation especially in the north direction. Therefore, despite the fact that Leica VADASE is capable of detecting velocities as low as 3.6 mm/s horizontally, with this estimation the displacement computation will be less accurate and biased due to the closeness to the noise level. Similarly, due to the generally higher noise in vertical direction, we estimate the vertical sensitivity to about 8 mm/s.

Figure 11: Dynamic platform on top of roof of building 03 in Heerbrugg Switzerland.

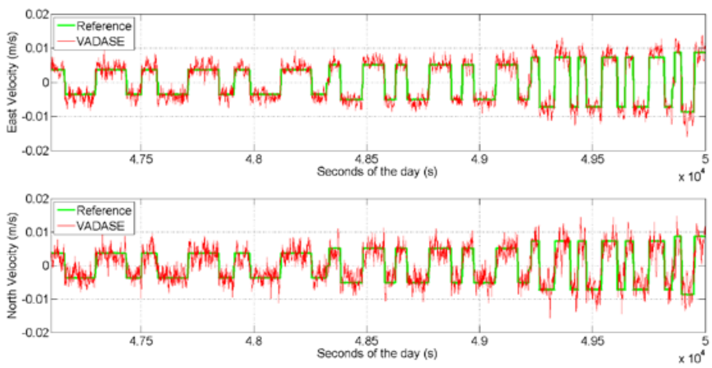


Figure 12: VADASE East and North estimated velocities compared to the reference solution during a sensitivity test.

Assuming that the VADASE velocities are normally distributed then 99.7% of the noise is within ±3σ. Therefore to start to obtain an accurate displacement computation, the minimum velocity should be at least higher than 3σ or about 10 mm/s horizontally and 20 mm/s vertically. Movement at lower velocities cannot be reliably detected. Based on this experience, the Leica VADASE default displacement thresholds have been defined with an increased confidence.

As a general case, the table below shows the minimum sensitivity for VADASE algorithm.

VADASE	East (mm/s)	North (mm/s)	Height (mm/s)
Minimum velocity detected	3.6	3.6	(8)
Recommended minimum velocity to be used for accurate displacement computation	8	12	20

Table 2: Velocities sensitivity of VADASE algorithm.

As previously explained above, within the RefWorx firmware, Leica VADASE velocity thresholds for displacement computation can be adjusted by the user to best match the specific application and account for local variations.

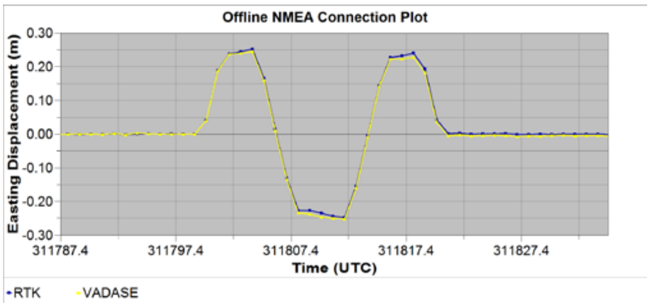
Comparison with RTK solution

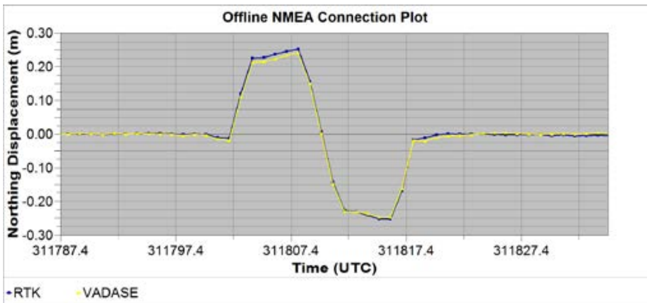
Using the same platform as in Figure **11**, we performed tests to compare the Leica VADASE solution with a RTK solution. For the RTK we used a reference station located in Bregenz (A) at a distance of 12.5 km from the location of the platform in Heerbrugg (CH). We programmed the platform to move horizontally according to two scenarios:

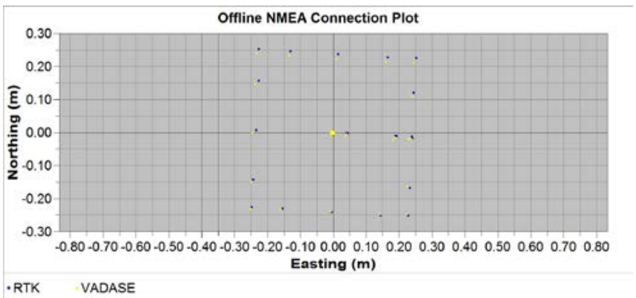
- Square movement starting from the centre of the platform, around the centre and back to the centre with a total duration of 25 seconds.
- Diagonal movement from North-East to South-West starting from centre of the platform and back to the centre with a total duration of 16 seconds.

For each scenario, we computed two data rates solutions, at 1 Hz and 10 Hz. The 1 Hz Leica VADASE and RTK solutions for the square movement are shown in Figure 13and Figure 14, respectively. The 10 Hz VADASE and RTK solutions for the diagonal movement are shown in Figure 15 and Figure **16**, respectively. It can be seen from these figures that the VADASE solution is very close to the RTK solution and has a similar performance. The two solutions were accurate to a cm level compared to the precisely known reference movement. It is important to note that the component quality (CQ) for the VADASE solution increases exponentially with time as soon as a displacement is detected, as can be seen from Figure 13 and Figure 15. This is due to the fact that the VADASE solution is time correlated in contrast to the RTK solution which is not time dependent. Therefore, the longer the movement will last, the higher the uncertainty on the VADASE solution becomes. An additional impact is due to the measurement frequency. With higher sampling rate, the number of measurements accumulated over the same time period increases, which consequently leads to a higher CQ as can be seen in Figure 15.

Finally the mean and maximum error during the dynamic movement for VADASE and RTK compared to the reference movement are shown in Table **3**.







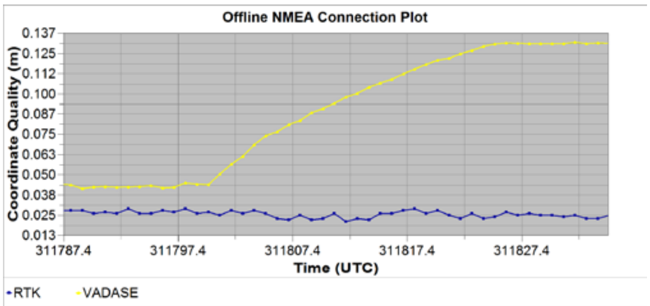


Figure 13: Above four graphs show 1 Hz VADASE vs RTK solution for the square movement scenario.

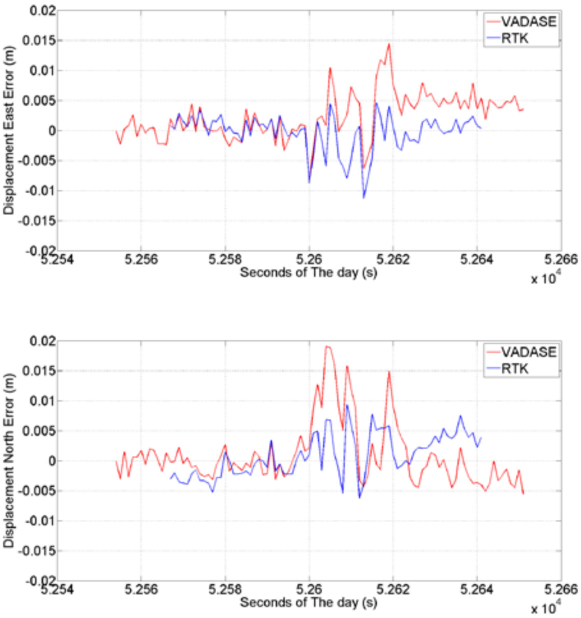
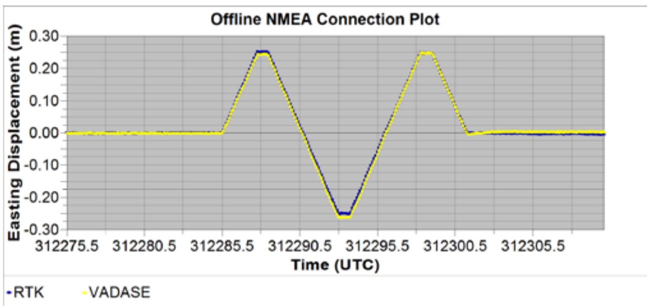
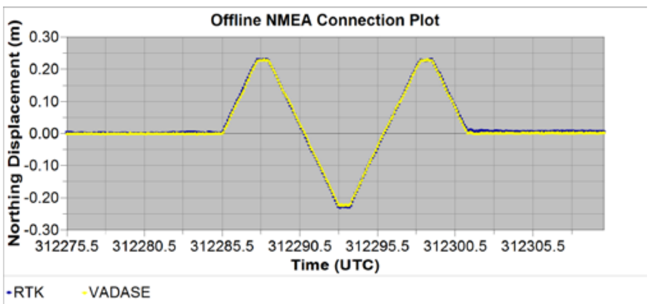
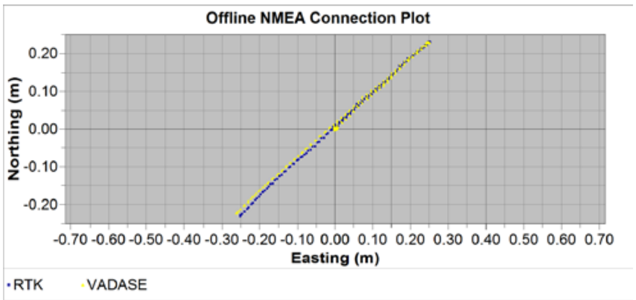


Figure 14: 1 Hz VADASE vs RTK solution East & North deviations in comparison to the reference movement for the 25 seconds square movement scenario.







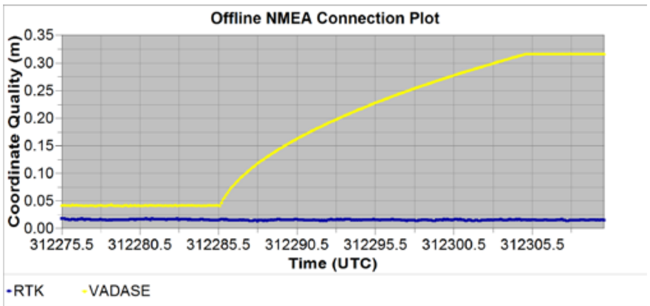


Figure 15: Above four graphs show 10 Hz VADASE vs RTK solution for the diagonal movement scenario.

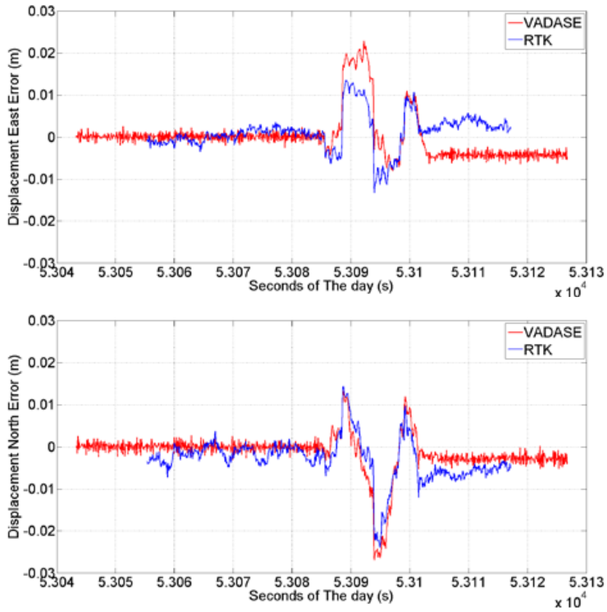


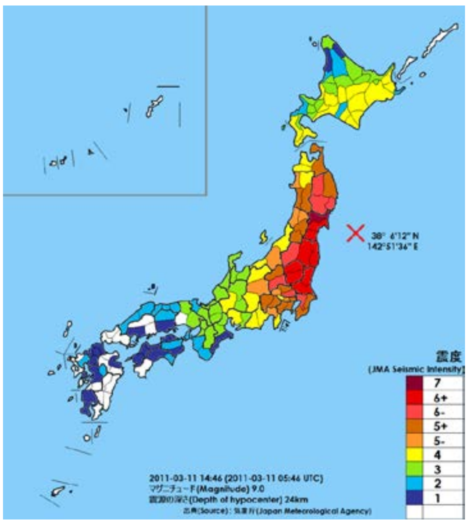
Figure 16: 10 Hz VADASE vs RTK solution deviation in comparison to the reference movement for the 16 seconds diagonal movement scenario.

Solution	1 Hz Square Scenario			
	East Error [cm]		North Error [cm]	
	Mean	Max	Mean	Max
VADASE	0.34	1.45	0.72	1.91
RTK	0.22	1.13	0.24	0.93
Solution	10 Hz Diagonal Scenario			
	East Error [cm]		North Error [cm]	
	Mean	Max	Mean	Max
VADASE	0.58	2.3	0.35	2.7
RTK	0.12	1.4	0.27	2.4

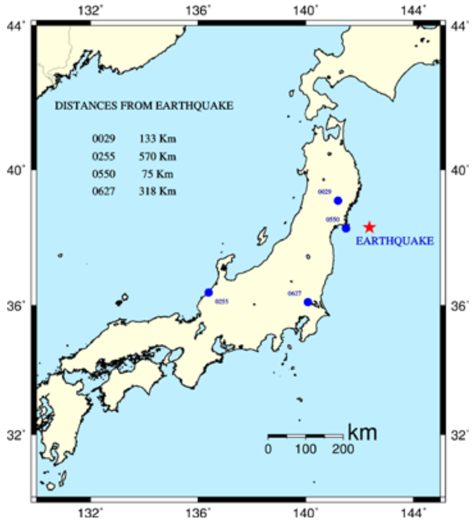
Table 3: Mean and maximum error during the dynamic movement for VADASE and RTK solutions in comparison to the reference movement.

Application Study - Japan 2011 Earthquake

The Leica VADASE performance has been evaluated using data of the Tohoku-Oki earthquake from March 11th 2011. The velocity and displacement of two stations, Oshika and Mizusawa1, were computed using the VADASE algorithm. The earthquake intensity and the stations distribution and distances with respect to the earthquake epicentre are shown in Figure 17.



(a)



(b)

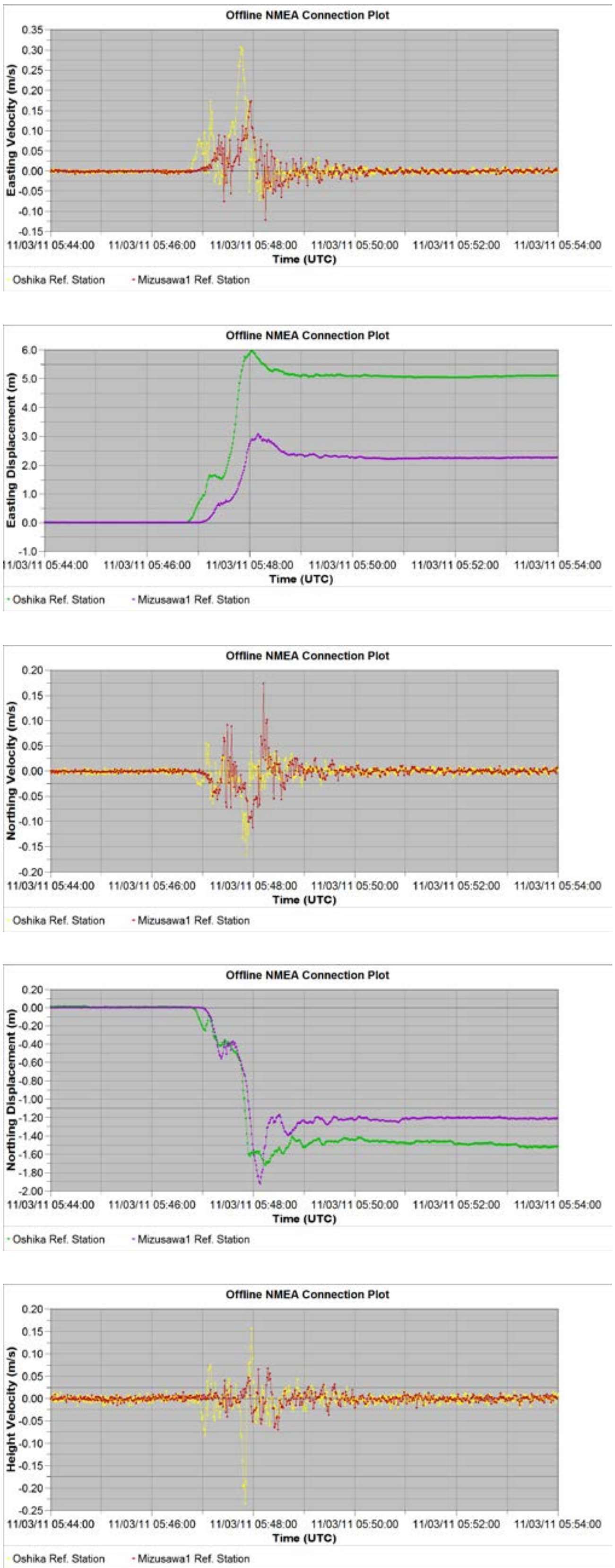
Figure 17: a) Map of seismic intensity observations resulting from mainshock of the 2011 earthquake off the Pacific coast of Tōhoku, b) Stations distribution and distances with respect to earthquake epicentre (0550: Oshika, 0029: Mizusawa1).

For the 3 hours interval (i.e., from 07:00:00 to 09:00:00 CET) of March 11th 2011, Geospatial Information Authority (GSI) of Japan provided hourly RINEX files in Hatanaka compression form with 1 second acquisition rate from Oshika and Mizusawa1 stations. These are part of the large GNSS Earth Observation Network System (GEONET). The stations coordinates as computed from the GEONET network solution of March 10th 2011 were separately provided and are listed in
Table **4**. The distance between Oshika and Mizusawa1 is 93.5 Km.

No	960550	940029
Name	- Oshika	Mizusawa1
X (m)	-3922366.964	-3862395.443
Y (m)	3119914.935	3105010.679
Z (m)	3931806.320	4001962.381

Table 4: ITRF05 coordinates coming from the GEONET F3 solution for March 10th 2011.

In order to process that data on a GR10 receiver with Leica VADASE enabled, the Rinex Hatanaka files have been transformed into Leica Binary2 (LB2) format. During the onboard processing, the computed velocities and displacement were logged into a NMEA log files containing the LVM and LDM messages. Then these result files have been processed and analysed using Leica SpiderQC. The velocities and displacements, plotted with SpiderQC around 10 minutes of the main earthquake shock, are shown in Figure 18.



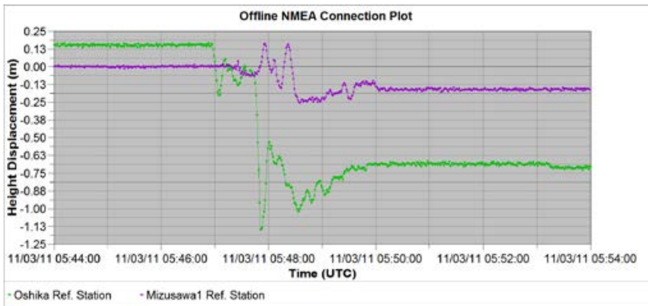


Figure 18: East, North, and Height velocities and displacements of Oshika and Mizusawa1 reference stations during the 2011 earthquake off the Pacific coast of Tōhoku, Japan computed by Leica VADASE.

From these figures it is possible to see that the earthquake arrival is clearly detectable from the sudden velocity change in the three components East, North and Height. Also, it is possible to see the displacements experienced by the antenna with respect to the initial position (which is referenced to as zero for all components). As can be seen, as soon as significant velocities are detected by the algorithm, the antenna movements and co-seismic displacements can be retrieved with an accuracy of few centimetres within intervals of several minutes.

At the end of the earthquake shock, Mizusawa1 East, North and Height co-seismic total displacements were at 2.25 m, -1.20 m, and -0.17 m respectively. Oshika East, North and Height co-seismic total displacements were at 5.2 m, -1.60 m, and -0.8 m respectively.

It is important to note that for this data set, the velocity thresholds were set to 0.8 cm/s, 1.2 cm/s and 2 cm/s for the East, North and Height components respectively. Hence, whenever the estimated velocities were lower than the sensitivity thresholds, the antenna was considered as static and no velocity integration was performed.

For a comparison, a global PPP solution from the GSI Rinex files during the earthquake was also computed. Figure 19 and Figure 20 show the comparison between VADASE and PPP displacement solutions for Mizusawa1 and Oshika reference stations. It can be seen that the Leica VADASE solution is very similar to the PPP solution. The average difference between both solutions is shown in Table **5**.

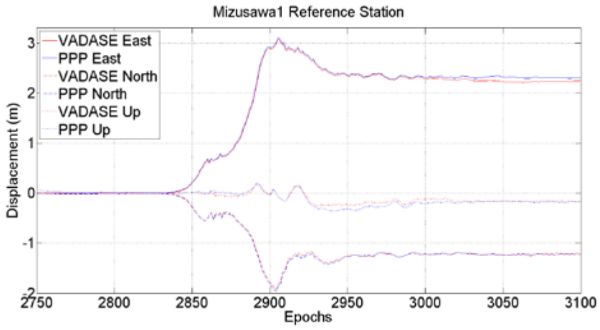


Figure 19: Comparison between VADASE and PPP displacement solution for Mizusawa1 reference station.

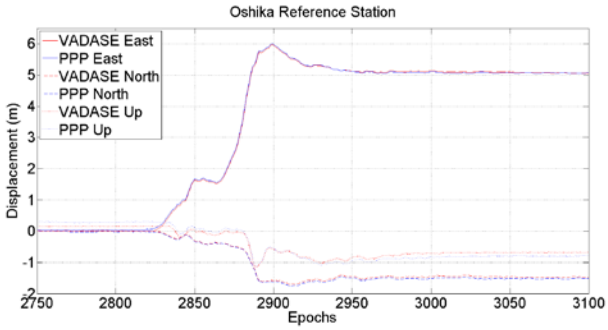


Figure 20: Comparison between VADASE and PPP displacement solution for Oshika reference station.

Average difference between VADASE and PPP after earthquake main shock	East (m)	North (m)	Height (m)
Mizusawa1	0.0677	0.0137	0.0240
Oshika	0.0106	0.0202	0.0875

Table 5: Average difference between PPP and VADASE displacements after earthquake's main shock.

Conclusion

Leica VADASE (Velocity And Displacement Autonomous Solution Engine) has been newly introduced as part of the RefWorx firmware to run onboard the Leica GR10 & GR25 reference station and Leica GM10 monitoring receivers. This new solution provides fully autonomous velocity and displacement information of a GNSS antenna in real time and at high data rates (1 Hz up to 20 Hz).

We have explained how these velocities are determined, just based on the GNSS broadcast products (orbits & clocks), and how displacements can be derived. Furthermore insight was given into the RefWorx firmware operation and user interface for Leica VADASE and the Leica SpiderQC application software for online and offline data analysis.
The typical performance of this solution has been demonstrated. The estimated velocities exhibit a noise level for the East, North and Height components of 3 mm, 5 mm and 8 mm respectively. Based on this and the sensitivity tests, we have learned that Leica VADASE can detect antenna motion with velocities higher than 3.6 mm/s. For practical purposes and to obtain reliable movement detection and displacement computation at a high confidence level, we concluded the sensitivity thresholds in the East, North and Height components should be at least 8 mm/s, 12 mm/s and 20 mm/s respectively. To allow the user to adjust the sensitivity to his application needs, these thresholds can be configured within the firmware. Static tests also showed that with the impact of the standard velocity noise a bias is introduced to the accumulated displacement. The useful integration time is 5-10 minutes, if the accuracy of the total displacement is of importance, which allows the detection and analysis of a variety of sudden shock events to the monitored infrastructure. The user should be aware of this when integrating velocities over longer periods or even continuously. A comparison with a traditional differential RTK solution also supports this conclusion. For short movements, both solutions deliver similar cm-level accuracy. With this in mind, Leica VADASE can be an excellent complement within an RTK monitoring solution, as it can still deliver fast movement detection, when an RTK solution has lost its differential correction input.

Furthermore, it has been demonstrated, that the solution works equally well with using one or more satellites constellations. Also it can be used with the single frequency variant of the GM10 receiver, if the slightly higher bias due to the ionosphere impact is acceptable for the intended application.

Finally the solution was successfully proven based on a data set from the 2011 Tohoku-Oki Japan earthquake, where it compared well with a post-processed PPP solution. Operating a Leica reference station and monitoring GNSS receiver with VADASE running in real time, provides instant information about the impact of such an event as it is occurring.

With Leica VADASE critical data is relayed in real time for immediate and efficient decision making based on unique processing algorithms, all non-dependent on GNSS RTK correction services. This allows scientists and engineers instant, reliable real time displacement and waveform analysis of fast movements. Obtaining a deeper understanding of how structural movements occur, you can better evaluate support needs and take stronger fortification measures. With the ability to integrate into early-warning systems, Leica VADASE helps alert you to potential disasters and protect life.

With peace of mind that no surprises are lurking, Leica VADASE can be your reliable partner in risk management.

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