

Research article

Alexandru Lepadatu* and Christian Tiberius

GPS for structural health monitoring – case study on the Basarab overpass cable-stayed bridge

Abstract: The Basarab cable-stayed bridge is a newly built structure in Bucharest, Romania, which was inaugurated in June 2011. Before the official opening, in order to assure its qualification for traffic, it had to pass several loading tests with convoys of trucks and trams. For this, besides a priori evaluation using the Finite Element Method (FEM), levelling and acceleration measurements were made to identify vertical displacements, as well as vibration frequencies of the bridge. The three-day loading trial of the bridge represented a good opportunity for setting-up a GPS campaign for structural monitoring of the Basarab bridge. Taking advantage of the redundancy obtained via simultaneous multi-sensor measurements, it was possible to compare and validate the GPS estimated displacements with both FEM and levelling. Moreover, the dynamic behaviour of the bridge during a dynamic loading test was evaluated using a 20 Hz GPS observation rate and validated afterwards with vibration frequency estimates from acceleration time series. Along with simulations (FEM) and laboratory tests, the in situ monitoring of a structure has a particular importance in establishing the safety of a newly-built structure. Furthermore, in some cases permanent monitoring is needed for safety and economic reasons, especially for strategic structures such as dams and bridges. GPS technology can satisfy this request due to its real-time processing capability and thus it can be looked upon as a new and promising tool for dynamic evaluation of engineering structures. In this contribution we have also assessed the performance of GPS with regard to accuracy and false alarm probability demands for the continuous monitoring of the Basarab cable-stayed bridge.

Keywords: GPS, Cable-stayed bridge monitoring, Detection probability, Harmonic analysis

***Corresponding Author: Alexandru Lepadatu:** Faculty of Geodesy, Technical University of Civil Engineering Bucharest, now at Seaway Heavy Lifting Engineering Albert Einsteinlaan 50, 2719 ER Zoetermeer, The Netherlands, E-mail: alexandru_lepadatu@yahoo.com
Christian Tiberius: Delft University of Technology Faculty of Civil Engineering and Geosciences Department of Geoscience and Remote Sensing Stevinweg 1, 2628 CN Delft, The Netherlands

1 Introduction

Structural monitoring activities represent an important task of geodetic engineers, as it certifies the operational safety of the structure. Classical geodetic techniques are successfully used for this purpose, but in the last decade more and more studies focused on the use of GPS technology for structural monitoring of high-rise buildings [4] and suspended bridges [18, 13, 14]. The continuous development of construction techniques and materials offered civil and bridge engineers the possibility to come up with more sophisticated solutions and to design spectacular structures. The boost in complexity of recently built structures will require the development of new monitoring methods and techniques. Next to safety, there is also an economic reason for preventing potential loss of the structure, typically representing a big investment. The solution to all this is preventive behaviour. It is better to prevent than to act afterwards. By implementing a real-time monitoring system one can prevent dangerous scenarios - possibly affecting the construction, and at significantly reduced costs compared to the total investment [8]. In this sense, nowadays, important steps are being made for the development of permanent real-time monitoring systems with alarm triggering capabilities by integrating GPS receivers with other auxiliary sensors [5].

The latest developments in the GPS receiver industry, such as increasing acquisition rate and better positioning accuracy, recommend this type of satellite observations for monitoring purposes. The main advantage of GPS technology represents the possibility of directly measuring the displacements of a structure with respect to an absolute reference frame; thereby permanent displacements can be identified. In addition, high acquisition rate GPS receivers can be used for detecting natural frequencies of structures. The GPS performance for identifying the dynamic behaviour of a structure was confirmed by simulated vibration tests [8, 15, 17, 2], as well as by validation with other dedicated instruments for detecting structural vibrations (e.g. accelerometers). Moreover, with the development of the RTK (Real Time Kinematic) method, GPS technology has become an important tool also for real-

time structural monitoring thanks to radio and Internet communication techniques [16, 22].

As any measurement process, the reliability of GPS observations may be reduced in some cases due to uncontrolled error sources, such as multipath, (differential) tropospheric delay and cycle slips [9]. On the other hand, accelerometers may also be affected by long-term drifts. Therefore the integration of different, complementary sensors in a hybrid monitoring system is advisable to assure measurement redundancy and a higher reliability. See for instance previous studies related to the integration of GPS receivers with auxiliary sensors such as accelerometers [14, 8, 12], inclinometers and anemometers [23], robotic total stations [10, 6] and optical fiber [11] for monitoring the behaviour of structures.

In this contribution we present the GPS monitoring trial of the Basarab cable-stayed bridge in Bucharest, Romania. Using a monitoring network consisting of as many as 10 GPS receivers, the bridge deformation during complex loading tests was evaluated and then validated with FEM predictions and levelling measurements. Preprocessing techniques of the GPS observations were used in this study to identify and mitigate multipath and cycle slip errors in order to obtain better estimates. A harmonic analysis was conducted to identify and assess long-term periodic effects in the GPS time series (and which are likely to be attributed to multipath), exploiting the repeatability of the satellite configuration over successive days. Using a practical approach, the GPS capability of real-time monitoring and alarm triggering was assessed based on the achieved positioning accuracy as a function of the observation duration. An inventory on the capabilities and limitations of the GPS technology for structural monitoring was made based on a statistical approach using different assumptions regarding hazardous situations and false alarm probability. Furthermore we present a comparison between GPS and accelerometer-derived vibration frequencies of the bridge using simultaneous observations during a dynamic loading test of the structure. 20 Hz GPS data are used to assess the dynamic behaviour of the bridge, generated by loaded trucks passing over a discrete obstacle.

2 Bridge trial

2.1 Bridge description

The Basarab overpass (Figure 1) is one of the most important infrastructure projects made in Romania in the last 20



Fig. 1. Basarab cable-stayed bridge - aerial view (courtesy of Astaldi/FCC Construcción).

years. Designed to streamline the congested traffic in the city of Bucharest, the overpass is almost 2 km long and includes many viaducts, access ramps and two bridges. The cable-stayed bridge, built in order to overpass the railways near Bucharest central train station, is the most representative element of this structure. The deck of the bridge is supported by 60 (steel) cables anchored on an 84 m high H letter-form pylon. It consists of 5 bridge spans, the longest measuring 166 m. Furthermore, Basarab overpass represents a very important intermodal point, as it gathers together different means of transport like vehicles, trams, train and subway, and it includes a double tram station right on the cable-stayed bridge deck. The width of the bridge near the tram station is 43.3 m, this representing at that moment a record for any urban cable-stayed bridge in Europe.

2.2 Loading tests

Before the official opening for traffic, the overpass had to pass several qualification tests. The testing of the cable-stayed bridge was by far the most complex as the bridge was sequentially loaded during a three-day trial.

The loading test of the bridge consisted of several static loading cases, using both trams and trucks (about 43 tons each) with different deployment scenarios. For each loading case, a predefined number of trucks and trams were deployed according to a specific scheme (either on the left and/or right side of the bridge, and on different spans).

Besides static loading of the bridge, a dynamic loading test was also carried out during the third day of the trial, in order to perform a modal analysis of the structure. In this case, three trucks with equal weight crossed the bridge at

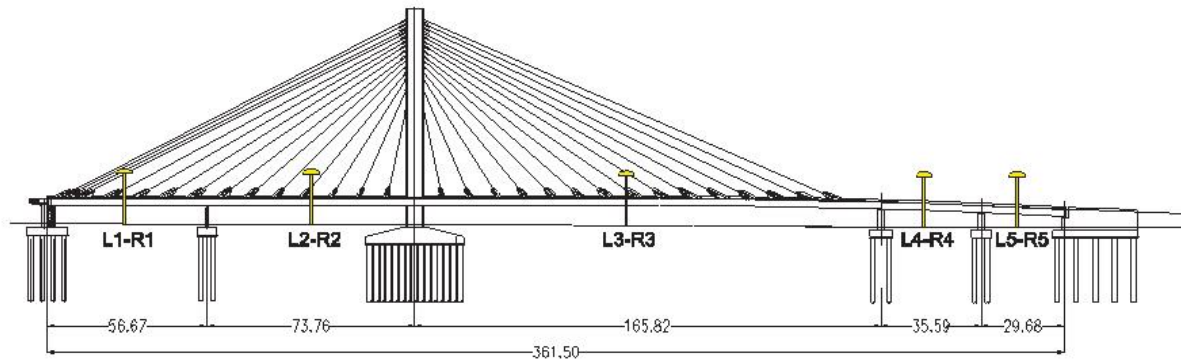


Fig. 2. Cross-section with GPS receiver locations on the bridge (R - right side; L - left side; 1 to 5 - span number; units in meters). Courtesy of Astaldi/FCC Construcción.

different speeds (30 km/h, 40 km/h and 60 km/h) while passing over a 5 cm thick fixed wooden plank. This obstacle was installed in the middle of the largest span (no. 3) - the location where the maximum amplitude of vibrations of the bridge was expected to appear. The idea behind this trial was that impulses generated by the impact of the truck axles with the wooden plank can be successfully identified in GPS time series. Along with GPS observations, simultaneous acceleration measurements using a tri-axial Brüel & Kjær accelerometer were made for validation purposes. The accelerometer was installed exactly on the iron nail in the bridge deck, representing the materialization of the GPS point (the GPS antenna was about 1.5 m above it, on a tripod). This was done to achieve maximum possible alignment between the two sensors, so that they capture the same phenomena.

2.3 GPS campaign

The GPS monitoring campaign has been conducted simultaneously with the loading tests. A GPS monitoring network was designed to cover observation points at the middle of each span on both sides of the bridge, and one reference station on the ground, located in the close proximity. A maximum number of 10 dual-frequency GPS+GLONASS receivers were used for this trial. The available equipment consisted of Topcon HiperPro and GR-3 integrated receivers/antennas. On the first day, Topcon HiperPro receivers were deployed on the bridge (Figure 3), while a Topcon GR-3 receiver was installed in a steady location nearby (on the parking lot of the Carrefour Orhideea Hipermarket) acting as a reference station.

The GPS stations were materialized approximately in the middle of each of the five spans, on both sides of the



Fig. 3. Loading test of the Basarab bridge with trucks and trams; GPS receivers (rovers) deployed on the bridge.

bridge, and their names are according to the span number and also with respect to the two sides of the bridge (Right-R and Left-L). Because a sufficient number of GPS receivers was not available at all moments to simultaneously cover all measurement points, the receivers were moved from one point to another (in the time interval between the loading cases) depending on where the impact on the bridge deck of the specific loading was predicted to be at maximum. On the first day, before starting the loading of the bridge, the GPS point positions were determined in a so-called T0 session. The resulting coordinates act as a reference for the other sessions in order to determine the bridge displacements.

During arrival and departure of the trucks and trams, GPS observations were collected at a higher sampling rate (20 Hz). They have been post-processed in a Post Processing Kinematic mode (PPK) in order to analyze the dynamic behaviour of the bridge. As for the other cases (bridge with no loading, or statically loaded with trucks and trams), GPS measurements were acquired at a 1 Hz sampling rate,

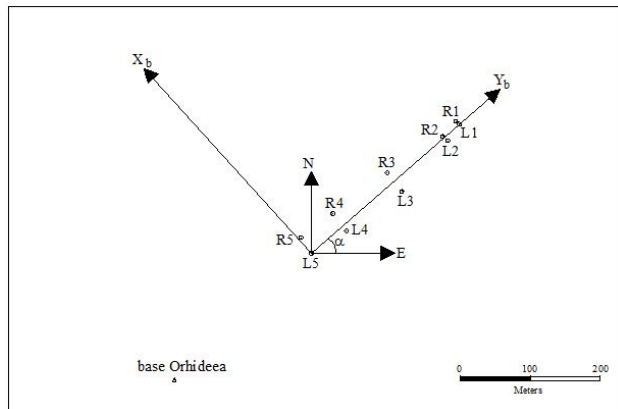


Fig. 4. Schematics of coordinate transformation in the local horizontal plane (NEU to $X_b Y_b Z_b$).

and processed afterwards in a static mode in order to determine the bridge displacements with respect to the initial T0 session.

2.4 GPS data processing

The GPS observations have been processed using the commercial software Topcon Tools v.8. The three-day measurement campaign resulted in a significant volume of GPS data. Because continuous GPS measurements were made also during loading and unloading of the bridge, the GPS data were first split accordingly to the loading cases. For example, the data were split in static and kinematic sessions with respect to the loading scenario of the bridge. In consequence, several jobs were obtained which were then processed either in static or in PPK mode.

Only independent baselines between the reference station and points on the bridge have been processed, using features for GPS data processing such as an elevation mask of 15° , GPS only, dual frequency GPS carrier-phase analysis.

For the sake of interpretation, and also to facilitate the comparison and validation of the GPS position estimates with the ones predicted by the Finite Element Method and also with levelling, we chose to represent the results in a local coordinate system of the bridge. First, a coordinate transformation from geocentric coordinates in WGS84 to the local topocentric coordinate system North-East-Up (NEU) was made, and then to a local coordinate system of the bridge ($X_b Y_b Z_b$) which axes should agree as good as possible with the longitudinal and transversal axes of the construction (Figure 4).

For each individual point, the NEU coordinate differences were computed using as a reference the coordinates from the static processing of the network for the first T0 session on day 1 - when there was no loading of the bridge. Then a rotation matrix R_α about the local vertical (Up-axis) was applied for each individual point in order to obtain the point coordinate differences in the bridge local coordinate system. The Y_b axis of the bridge local coordinate system was chosen to fit as much as possible the longitudinal axis of the bridge. However, because the bridge deck is not a straight line and it presents a small curve, the baseline between points L5 and L1 was chosen to act as the Y_b axis of the bridge local coordinate system. Thus, the origin of the new system will be in point L5 and α is the rotation angle between this axis and the E axis of the NEU coordinate system. The GPS results were analyzed in the bridge local coordinate system, which not only offers the possibility to assess the vertical displacements of the bridge, but also to evaluate its behaviour in a horizontal plane.

3 Long periodic effects in the GPS time series

3.1 Preprocessing

Even though many developments have been made to identify and mitigate errors in GPS positioning, some of them such as multipath and cycle slips can still have a substantial effect on the GPS observations. Commercial GPS data processing software does not always provide the proper means to identify these types of errors and that is why an a priori assessment of the quality of the GPS observations is advisable, especially for demanding high precision applications. For this purpose, a first quality check of the raw observations was made using linear combinations of the dual-frequency GPS measurements having as input the RINEX files [7]. The following formula gives the general expression for the linear combination, expressed in meters, of GPS frequencies f_1 and f_2 :

$$LC = \alpha \cdot L1 + \beta \cdot L2 \quad (1)$$

where $L1$, $L2$ are the carrier phase observables on f_1 and f_2 (for a certain satellite - receiver combination), and α , β are the corresponding coefficients.

By using different code/phase linear combinations and displaying graphically the results, a simplified and intuitive method to identify poor observations from a specific satellite is provided. After the identification of these possibly poor observations, the decision of excluding those ob-

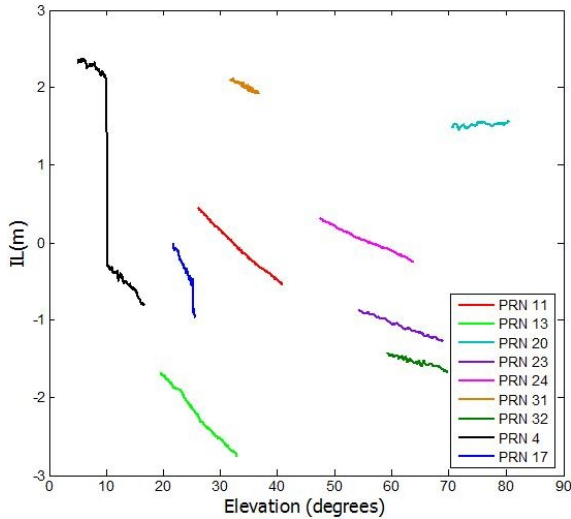


Fig. 5. Linear combination IL as a function of time for GPS point L2 for all satellites observed.

servations from future data processing can be made, and therefore better positioning solutions in terms of accuracy can be obtained.

$$IL = \frac{1}{\gamma - 1} \cdot L1 - \frac{1}{\gamma - 1} \cdot L2 \quad (2)$$

$$E(IL) = I + \frac{1}{\gamma - 1} \cdot N1 - \frac{1}{\gamma - 1} \cdot N2 \quad (3)$$

where $\gamma = \frac{f_1^2}{f_2^2}$, f_1, f_2 - GPS frequencies.

The IL linear combination operates with $L1$ and $L2$ carrier phase measurements and it removes effects from geometry, troposphere, satellite and receiver clocks. The only remaining effects are thus the ionosphere component I , and the real valued phase ambiguities $N1$ and $N2$, see (3). The ionospheric delay usually does not change rapidly over time, and thus any sudden alteration can be associated with cycle slips instead. Therefore, the IL linear combination proves to be extremely useful for cycle slip detection [20].

By looking at Figure 5 one can notice the appearance of cycle slips (sudden jumps). Thus, using the IL ionosphere linear combination of the $L1, L2$ phase observations converted to meters, two obvious examples of cycle slips due to a temporary loss-of-lock in the carrier tracking loop in the case of satellites (PRN) 4 and 17 (black and blue) can be observed.

In the case of satellite 4 this will not present an issue due to the fact that the satellite is below the chosen elevation mask of 15° , but for the other satellite (blue), even though the cycle slip is small, this effect is clearly visible in

the coordinate time series (it goes undetected in the baseline processing software). The coordinates present a jump of about 4 cm that can be associated with this cycle slip. By removing the 'bad' satellite, an important improvement of the time series is easily noticeable (Figure 6).

In order to make the best out of the GPS data and to satisfy the accuracy requirements for high precision applications, a priori treatment of the data is needed (manual preprocessing). There are also other linear combinations, such as the multipath combination (MC), which may prove efficient for multipath detection. By using single frequency code measurements (in this case on the f_1 frequency) and dual-frequency phase measurements, the combination removes effects from geometry, clocks, tropospheric delay and (first-order) ionospheric delay. By exploiting the MC combination, for example, one can identify whether the observations from a particular satellite are excessively affected by multipath [20].

$$MC_{1,2} = C1 + \frac{-(\gamma + 1)}{\gamma - 1} \cdot L1 + \frac{2}{\gamma - 1} \cdot L2 \quad (4)$$

If we neglect phase multipath and phase noise, the only remaining effects in this linear combination are code multipath, hardware delays and the ambiguities of the two phase measurements. By considering very little impact due to hardware delay and having in mind that phase ambiguities are constant in the absence of cycle slips, this combination proves to be dominated by the code multipath.

3.2 Multipath assessment using synchronized time windows over consecutive days

Multipath can represent an important source of error in GPS measurements. As we have also shown before, it is possible to identify the influence of this error using linear combinations of raw $L1$ and $L2$ observations. Multipath – for a static GPS receiver – typically induces temporary periodic effects in the position time series. The question that arises is whether indeed multipath is responsible for the (long-term) periodic effects that seem to contaminate the GPS position time series, as for instance shown in Figure 7.

In order to investigate on the potential impact of multipath, one can analyze the GPS positions acquired during the same time period over consecutive days [9, 19]. In this way, the repeatability of the GPS satellite constellation can be exploited as the GPS receivers will track the same satellites, with the same geometry during both days. Thus multipath effects should be very much the same in both cases.

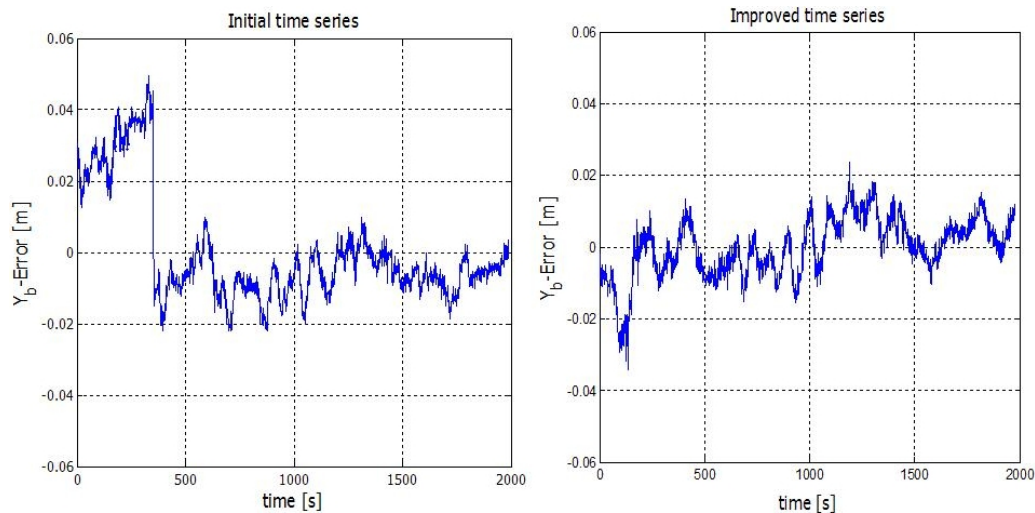


Fig. 6. Improvement of the GPS time series. Left – Initial time series; Right - Time series after removing the 'bad' satellite.

Taking advantage of the fact that the Basarab bridge GPS campaign has lasted for three days, we analyzed similar static (T0) GPS position time series acquired on day 1 and day 3 during the same time window. For this analysis, even though the T0 sessions of day 1 and 3 were static, they were converted to kinematic and then processed in PPK mode using Topcon Tools software. Hence the reference station Orhideea was fixed and the points on the bridge were treated as kinematic. The resulting time series include the kinematic solutions at every epoch (sampling frequency 1 Hz).

During the T0 sessions, the atmospheric conditions were normal on both days, and no disturbing factors (like strong wind) that could have influenced the bridge were noticed. There were some ongoing activities on the bridge deck at that moment but their influence should not have such a strong impact on the dynamic behaviour of the bridge. Hence, any variation we observe in these time series is most likely to be associated with GPS errors (e.g., multipath) and noise rather than actual motion of the bridge. This provides a first overview on the quality of the measurements.

Note that both T0 sessions on day 1 and day 3 were taken during almost the same period in time. The timing can be further exploited in order to assess the potential multipath influence by taking into account that for a fixed location on Earth the GPS satellites configuration repeats itself after 23h56min (basically same time, next day). Hence the same multipath pattern should repeat after this period under the premises that the objects causing the signal reflections have remained fixed.

In the sequel we will try to synchronize the corresponding position time series of day 3 with the ones of day 1 (using the time of day). By computing the cross-correlation between the two datasets, it is possible to evaluate the correlation and thus the time delay/advance with which this correlation appears. So, if present, multipath errors can be identified in the GPS time series as a long-term periodic effect with a repeat period of 23h56min. In other words, resuming to our case, by looking at the cross-correlation plot between time series of the position coordinates for day 3 and 1, a peak is expected to appear around a lag of 472 s. The same geometry of the satellites is obtained 3 min 56 s earlier with respect to the day before. A two-day difference translates into 7 min 52 s of difference in time, thus a correlation lag of 472 with a 1 Hz acquisition rate.

The outcome of such an analysis for the North component time series of point R3 can be seen in Figure 8. The dominant peak in the cross-correlation plot appears at lag 472, which is in agreement with the initial assumptions regarding the influence of multipath. The harmonics identified in the time series (see next subsection) are concluded to be mainly a consequence of multipath influence on the GPS observations. In this way, it was possible to evaluate the multipath influence for all overlapping points from day 1 and day 3. Better GPS time series in terms of accuracy were obtained by subtracting the harmonics associated with multipath.

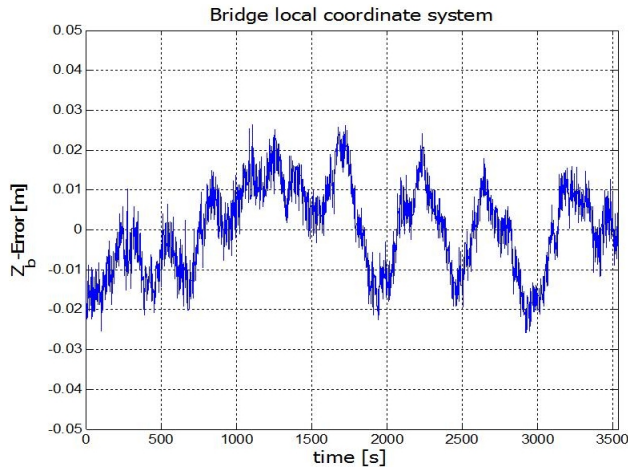


Fig. 7. Example of periodic (carrier phase) multipath effects in the GPS position time series, with a very clear oscillating behaviour from epoch 1500 onwards.

3.3 Harmonic analysis to identify oscillations in GPS time series

Knowing that the GPS time series are affected by periodic effects led to finding solutions for identifying and removing the harmonics from the dataset. These uncontrolled error sources can have negative and undesired effects on the positioning solution time series leading to the misinterpretation of the results. For structural monitoring applications, this aspect is particularly interesting because most of the time perturbations that appear have also a sinusoidal behaviour. Hence it is important to separate the actual oscillations of the structure from GPS multipath effects. In our case, several periodic effects in the behaviour of the bridge are likely to appear due to wind or passing vehicles and it is crucial to correctly separate these effects from the ones that are just noise or caused by different error sources. In the sequel we identify periodic behaviour in the position time series of the static session of day 1 and day 3, both sessions lasting for about half an hour.

There are several ways to identify the harmonics in a time series (frequency and amplitude). The most commonly used method is frequency domain analysis (e.g. Fourier analysis), but there are also time domain approaches. Because the nature of geodetic work is more related to the time domain analysis (e.g. monitoring the behaviour in time of a structure), in this contribution we present a time domain approach, namely the least squares harmonic estimation [1]. But regardless of the analysis method, one should be able to extract the same informa-

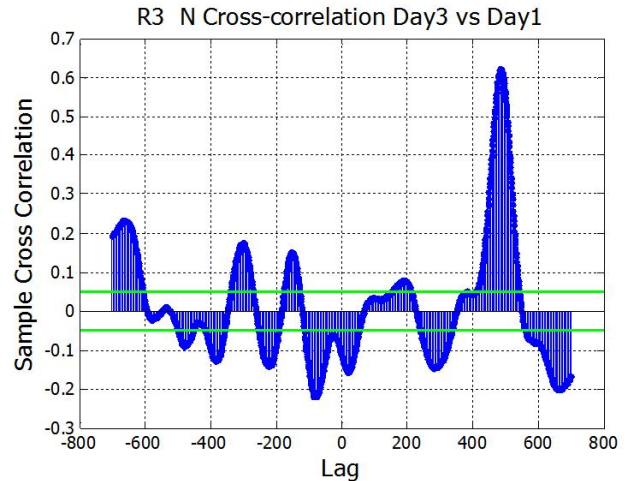


Fig. 8. Cross-correlation plot for synchronized GPS time series of day 1 and day 3 (for the N-coordinate component of point R3); data collection at a 1 Hz rate; green lines represent the approximate 95% confidence interval $(\pm 2/\sqrt{M})$, M -number of samples).

tion from a certain time series, the transformation from time to frequency domain being reversible.

The least squares harmonic estimation method introduces periodic components in the functional model [1]. One can assume that a time series can be expressed as a sum of trigonometric terms, like in the following:

$$y_i = \sum_{k=1}^n a_k \cos \omega_k t_i + b_k \sin \omega_k t_i \quad (5)$$

where: a_k, b_k – amplitudes; ω_k – angular frequency; n – number of trigonometric terms; $i = 1, 2, \dots, m$, m is the number of observations in vector y ;

$$\omega_k = 2\pi f = \frac{2\pi}{T} \quad (6)$$

where f - frequency (Hz) and T - period (s).

In matrix notation it can be written

$$E\{y\} = \sum_{k=1}^n A_k x_k \quad (7)$$

$$D\{y\} = Q_y \quad (8)$$

where

$$A_k = \begin{bmatrix} \cos \omega_k t_1 & \sin \omega_k t_1 \\ \vdots & \vdots \\ \cos \omega_k t_m & \sin \omega_k t_m \end{bmatrix}, \text{ and } x_k = \begin{bmatrix} a_k \\ b_k \end{bmatrix} \quad (9)$$

y is the vector of GPS time series and Q_y is the associated variance matrix, taken a scaled identity matrix.

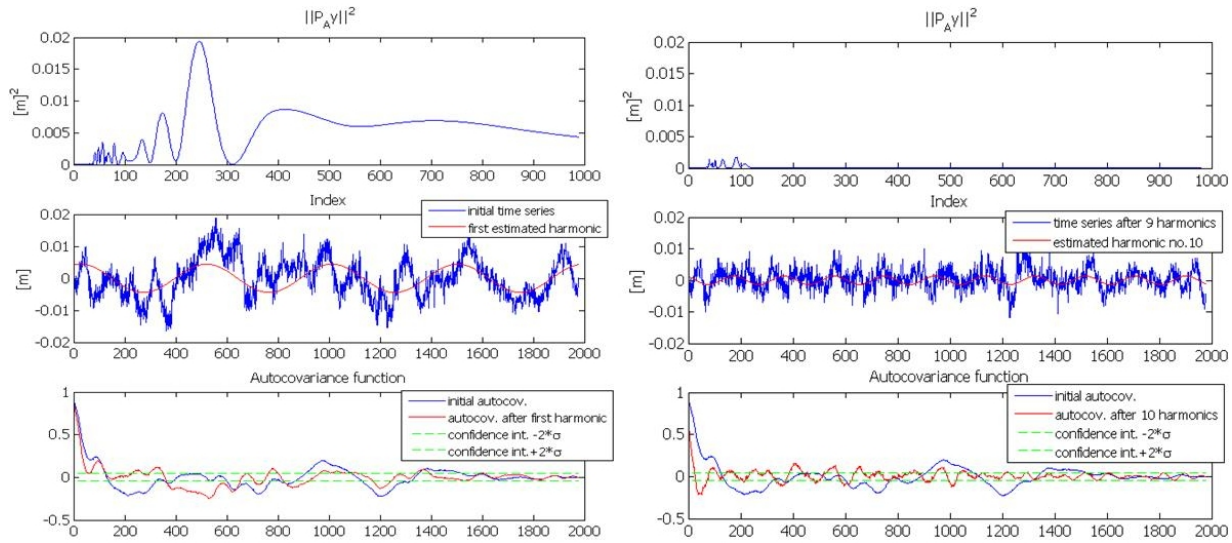


Fig. 9. Harmonic analysis procedure. Left: first harmonic estimation; Right: 10th harmonic estimation; Upper panels: $\|P_{A_k} y\|^2$ plot with highest peak values – the index on the horizontal axis is with respect to step size $T = 2$ s; Middle panels: GPS position time series – blue, estimated harmonics – red; Lower panels: normalized autocovariance of the GPS time series – blue, normalized autocovariance after removal of the newly identified harmonic – red. Both middle and lower panel show the time (in seconds) on the horizontal axis (matching the 1 s sampling interval).

In this way, the parameters (amplitudes) can be estimated by a simple least squares adjustment when the frequencies ω_k are known. In our case, if we want to identify the periodic effects in the GPS time series, so both the frequencies and amplitudes of the harmonics, things become more complicated. Therefore, in order to simplify the algorithm, the approach is to find a numerical solution for the system. Hence, a numerical search for a set of discrete frequencies ω_k is made, where $\omega_k = 2\pi/T_k$. The searching step for the frequencies can be determined using a Nyquist period T of 2 s, which is in agreement with the sampling theorem principle when we have an acquisition rate of 1 Hz for the GPS observations (Nyquist frequency is 0.5 Hz). In this way, the influence of each frequency ω_k in the original signal can be assessed, by constructing a graph for the values of $\|P_{A_k} y\|^2$, P_A being the orthogonal projector in the geometrical interpretation of least squares [21].

In this study the approach was to identify, using a script developed in Matlab, the frequency ω_k for which the value for $\|P_{A_k} y\|^2$ is at maximum. In other words, we searched for the frequency with the highest amplitude. Once this frequency is identified, the estimates for the amplitude components a_k and b_k are easy to determine using the model described by equation (9). This is an iterative approach, each of the identified harmonics being eliminated from the original signal before searching for another

frequency. In Figure 9 one can see the algorithm used in the harmonic analysis.

Having a look at Figure 9, it can be noticed how the GPS time series is 'improving' after the identification and subsequent removal of the long-term periodic components (most probably associated with multipath). The top plot on the right shows that after identifying 10 harmonics, there is hardly any periodic signal power left.

By using this algorithm it was possible to identify the frequencies and amplitudes of the harmonics in the GPS time series. Furthermore, we checked whether these harmonics can be associated with multipath. Hence, the plot of amplitude versus frequency was made for the same points on day 1 and day 3 in order to verify whether or not the harmonic components match in both cases. If affirmative, we can state that these harmonics have long-term repeatability, most likely related to GPS multipath.

An example is given for point R3. The harmonics identified in the GPS Up component time series for day 1 (in blue) and for day 3 (in red) are plotted together in Figure 10. In each case 15 harmonics were computed, but it is obvious that only 3 of them have most significant amplitudes. Only these 3 pairs of harmonics (1, 2, and 3) were chosen for further analysis. On a first view, one can notice that the frequency range of the identified harmonics is the same in both cases. In addition, one can assume that pairs 1, 2 and 3 represent the same harmonic in the time series, thus the

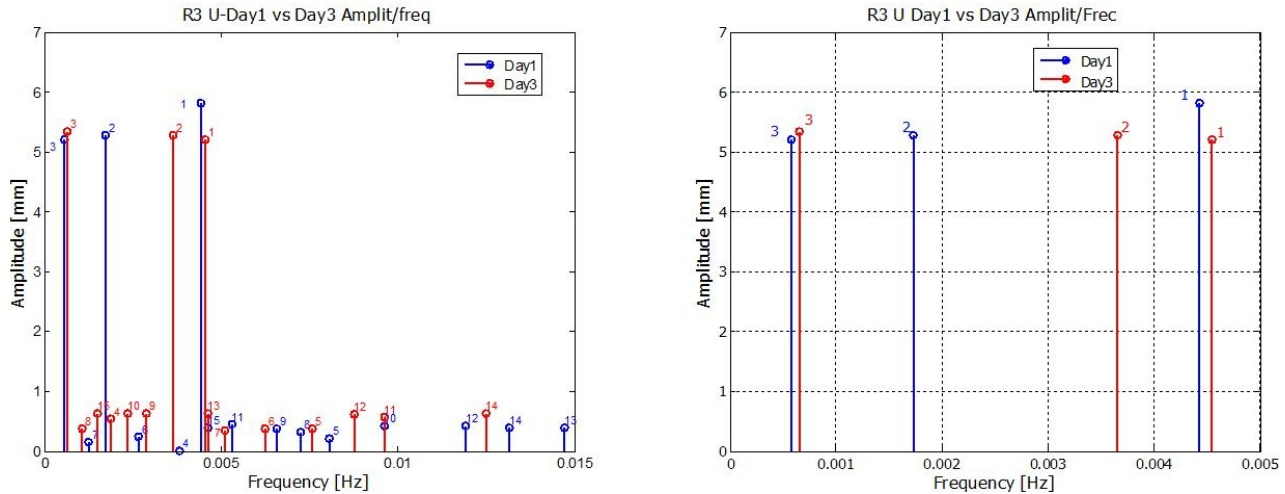


Fig. 10. Left – Estimated harmonics in Up coordinate time series of (kinematic) position of point R3; Right – Zoom in on the first 3 estimated harmonics.

same periodic effect appears in both day 1 and day 3. After our analysis, this assumption proves to be invalid for pair number 2. This particular case was deliberately chosen to prove the utility of the frequency/amplitude error bar estimates analysis in avoiding incorrect interpretation of the harmonics (Figure 10).

In order to statistically assess this assumption, we have tried to evaluate the precision of the estimated frequencies and amplitudes using harmonic analysis. The precision of the amplitude estimators can be derived directly from the functional-stochastic model (variance matrix of estimators a and b in (9)). The variance for the resultant amplitude ($c = \sqrt{a^2 + b^2}$), as shown in Figure 10, follows from the error propagation law. As for the frequency, this approach is not valid. Therefore, an empirical analysis on simulated data was made in order to determine the precision of the frequency estimators. By using the characteristics of the 3 identified harmonics from both cases, a sinusoidal signal containing those 3 harmonics from day 1 and day 3 was created. Over the sinusoidal signal, random noise was added starting from the derived standard deviation of the GPS position time series. Harmonic estimation was made for each of the 1000 simulations of the signal. Ideally, the same estimates should result every time, but this will not be the case due to signal corruption with noise. Hence, the precision of the frequency from the harmonic analysis can be assessed by analyzing the dispersion from the mean.

Using this approach for each of the two days, the 2σ confidence intervals were computed for both frequency and amplitude (horizontally and vertically respectively in

Figure 11). It can be seen that the two datasets are matching within this interval (Figure 11), meaning that the two pairs of harmonics represent, with 95% confidence, the periodic influence of the same error source on both days, most probably that of GPS multipath. These harmonics can later on be subtracted from the original GPS time series, this acting as a filter for the long-term periodic oscillations, which will lead eventually to more accurate GPS position solutions.

As shown above, GPS observations in structural monitoring are likely to be affected by multipath errors due to numerous obstacles present on site [3]. Mitigation of this error is of paramount importance, as its influence on the GPS position time series may pass as a sinusoidal trend that can be confused with the actual oscillations of the construction. In the case of a permanent GPS set-up for structure monitoring, we have to take all necessary means in order to remove (periodic) trends and biases caused by multipath. For example, harmonic analysis can be used as a tool for the identification of different sinusoidal effects in the time series and for filtering the data for unwanted error sources.

4 Assessment of bridge displacements via GNSS

Even though different techniques are used to theoretically evaluate the behaviour of a structure under certain conditions (e.g. FEM) and scale models are being tested in a laboratory (e.g. wind tunnels), in situ monitoring activities

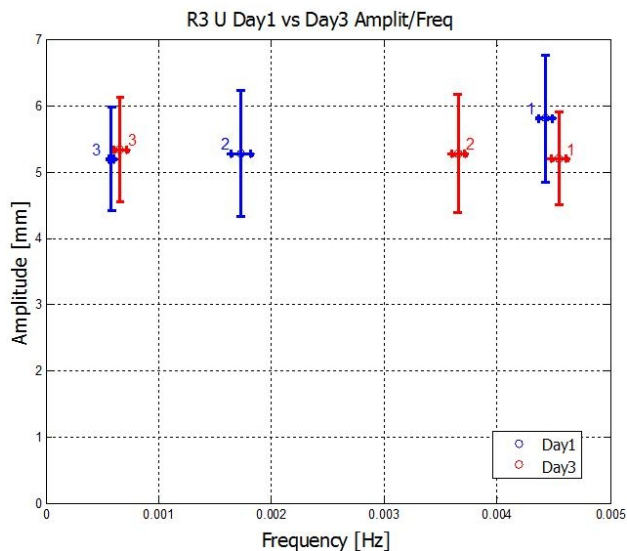


Fig. 11. Amplitude versus frequency with empirical 2σ error bars for day 1 and day 3 (simulated data set).

are very important and cannot yet be replaced. The actual behaviour of a construction in place and the natural conditions cannot be entirely anticipated and simulated, and the monitoring process can thus offer valuable information about anomalies likely to occur during the construction process. In addition, by a long-term observation period, extra knowledge can be acquired which can help improve future designing codes [4].

The sequential static loading of the cable-stayed bridge was made in order to certify the qualification of the structure to endure rush hour traffic in real life situations. Therefore, different scenarios were designed using convoys of trucks and trams deployed at different locations in order to assess the bridge behaviour under critical loading. To cover as many scenarios as possible, more than 10 static loading cases were performed – either with loads at different spans, on both sides or by loading the bridge on only one side. In this way, more comprehensive knowledge about the displacements is obtained, and one can check whether or not displacements are in accordance with predicted ones.

The behaviour of the different spans of the bridge was dependent on the loading case and we tried to cover with GPS receivers the spans where significant displacements were most likely to occur. GPS data were acquired after loading as well as unloading of the bridge to verify for eventually remaining (residual) displacements. Simultaneously, levelling measurements were also made for the purpose of comparing GPS and levelling derived ver-

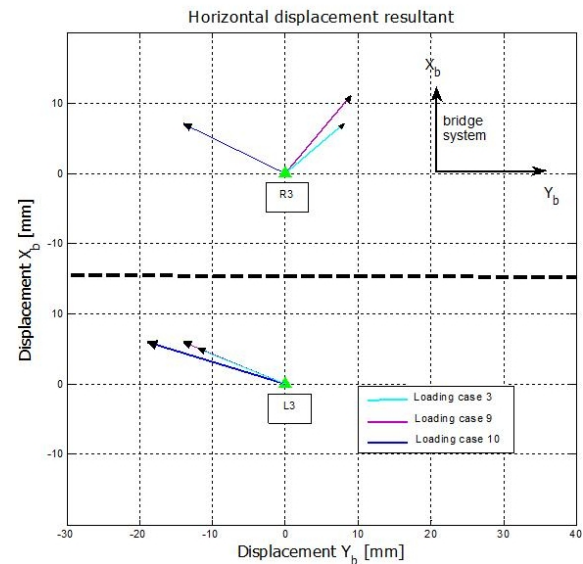


Fig. 12. GPS-derived horizontal displacements of the loaded bridge. Example for points R3 and L3 and loading cases 3, 9 and 10 (cf. Table 1).

tical displacements. In addition, results have been cross-validated also with FEM predictions.

The GPS displacements were computed in the local bridge coordinate system with respect to the T0 session of day 1 (before the loading of the bridge began). Therefore, negative values indicate downwards displacement of the bridge, and positive values upward movement.

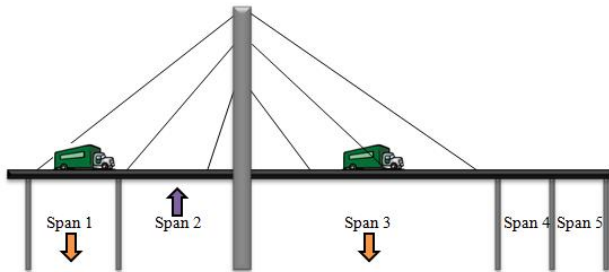
Even though the analysis of the GPS results aimed mainly at the detection of vertical bridge displacements, to benefit most of the 3D positioning solutions offered by GPS, we also analyzed horizontal displacements of the bridge.

Table 1 is an overview of the 3D displacements estimated by GPS during different loading cases. The GPS-derived vertical displacements of the bridge ranged from a couple of millimeters to centimeter level (the largest displacement being -115 mm), with an average standard deviation of 3 mm. The measured displacements in horizontal plane were much less significant, maximum 10-20 mm (1-3 mm standard deviation).

Larger displacements were found along the Y axis of the local bridge coordinate system (more or less along the longitudinal axes of the bridge) rather than for the cross-cut direction. This phenomenon was according to expectations having in mind the deformation pattern of this type of bridge. Observing Figure 12, one can see the resulting horizontal displacements of the bridge for three loading

Table 1. GPS-derived 3D displacements of the bridge for different loading cases. Standard deviation values propagated from Topcon Tools output.

Loading case	Pt.	Displacements/ Standard deviation [mm]					
		X_b	σ_{X_b}	Y_b	σ_{Y_b}	Z_b	σ_{Z_b}
Loading case 8	L4	1	1	0	1	-3	2
Day1_C1	L5	6	2	8	1	-4	3
	R4	3	1	2	1	-4	3
	R5	9	1	1	1	-7	3
Loading case 3	R2	4	2	-9	1	-1	4
Day2_C2	R3	7	1	-8	1	-115	3
	L2	5	2	-13	2	52	2
	L3	5	1	-12	1	-99	10
	L4	-1	2	-12	1	-5	4
Loading case 7	R2	7	2	-9	2	4	3
Day2_C4	L2	10	2	-14	1	43	2
	L4	-4	3	-14	3	10	5
Loading case 10	R1	17	1	-12	1	-8	3
Day3_C1	R3	7	2	-14	1	-111	3
	R4	7	1	-22	1	0	3
	L3	6	1	-19	1	24	4
Loading case 9	L1	14	1	-19	1	12	3
Day3_C2	L3	6	1	-14	1	-114	3
	L4	-24	6	-16	4	-22	9
	R3	11	2	9	1	-17	3

**Fig. 13.** Schematic of load distribution and bridge behaviour during loading case 3.

cases. As stated before, it is obvious that the displacements are more prominent along the Y_b axis.

As an example, for loading case 3, convoys of trucks and trams deployed on spans no. 1 and 3 are causing downward displacements of the two bridge spans, as illustrated in Figure 13. Consequently, due to the load distribution and the structural characteristics of the bridge, span no. 2 presented a small uplift. Small movements of the bridge could be identified in the horizontal plane for this particular loading.

Table 2 presents the vertical displacements estimated by different techniques during several loading cases.

We have chosen for our analysis three significant loading cases (3, 9 and 10) that provide a good overview on how different loading distributions are affecting the behaviour of the bridge. Table 3 presents a diagram with the loading positions on the bridge deck for each case.

The bridge displacements (in vertical direction) for two loading cases (3 and 10) determined by three different techniques are plotted together in Figure 14. The direction of the displacement, downward or upward with respect to the reference, is also visible in this figure.

By analyzing the results, we can conclude that the performance of the GPS technique to measure the bridge displacements is satisfying, especially in view of a validation in the 3σ confidence interval of the GPS results with the other two techniques. Due to a smaller order of magnitude of the levelling accuracy compared to GPS, we choose to graphically represent only the error interval for the GPS measurements.

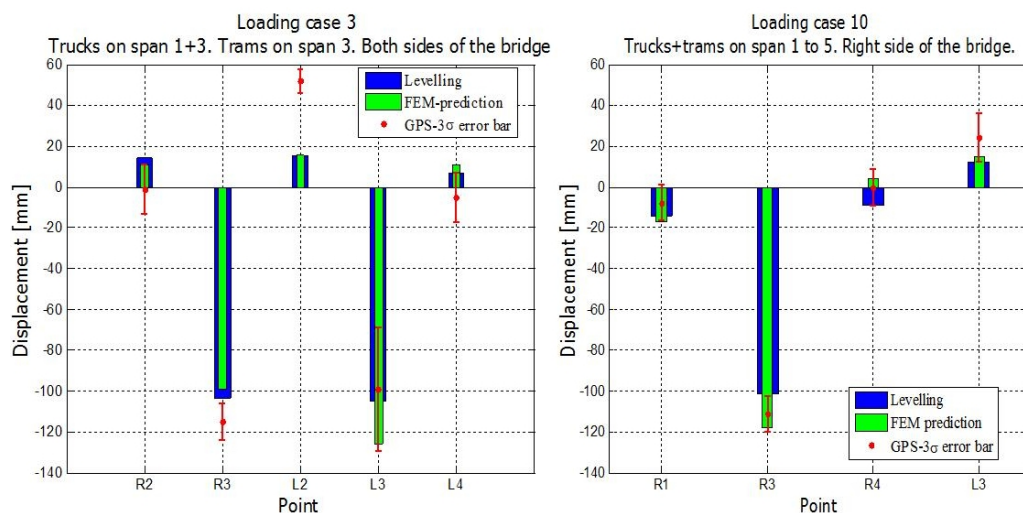
The level of disagreement between the solutions can be also associated with the fact that the GPS observation points not always matched entirely with the levelling marks. In some situations, the trucks' deployment on the bridge could have obstructed the satellite visibility and that is why we had to choose the GPS observation point a couple of meters away.

Table 2. Vertical displacements of the bridge as observed by GPS and levelling, and predicted by Finite Element Method (FEM).

Loading case	Pt.	Displacements [mm]			Std. Dev. [mm]
		GPS	Levelling	FEM	GPS
Loading case 8	L4	-3	1.0	-2.3	2
Day1_C1	L5	-4	-0.4	-1.5	3
	R4	-4	1.0	-2.7	3
	R5	-7	-0.3	-3.4	3
Loading case 3	R2	-1	14.0	10.9	4
Day2_C2	R3	-115	-103.0	-99.0	3
	L2	52	15.0	15.4	2
	L3	-99	-104.6	-126.0	10
	L4	-5	7.1	10.8	4
Loading case 7	R2	4	11.5	9.2	3
Day2_C4	L2	43	18.8	13.1	2
	L4	10	7.6	11.3	5
Loading case 10	R1	-8	-14.3	-16.8	3
Day3_C1	R3	-111	-101.5	-117.9	3
	R4	0	-8.7	4.1	3
	L3	24	12.4	14.7	4
Loading case 9	L1	12	-14.3	4.6	3
Day3_C2	L3	-114	-124.4	-126.7	3
	L4	-22	-6.0	10.8	9
	R3	-17	-20.4	-99.6	3
Loading case 9	L3	-9	-	-	2
Day3_C2_D	R3	-8	-	-	3

Table 3. Bridge loading diagram.

Loading case	Bridge side	Span 1		Span 2		Span 3		Span 4		Span 5	
		Trucks	Trams	Trucks	Trams	Trucks	Trams	Trucks	Trams	Trucks	Trams
3	Left										
	Right										
9	Left										
	Right										
10	Left										
	Right										

**Fig. 14.** Vertical displacements of the bridge under loading estimated by GPS (red dot, and with error bar), levelling (blue) and FEM (green).

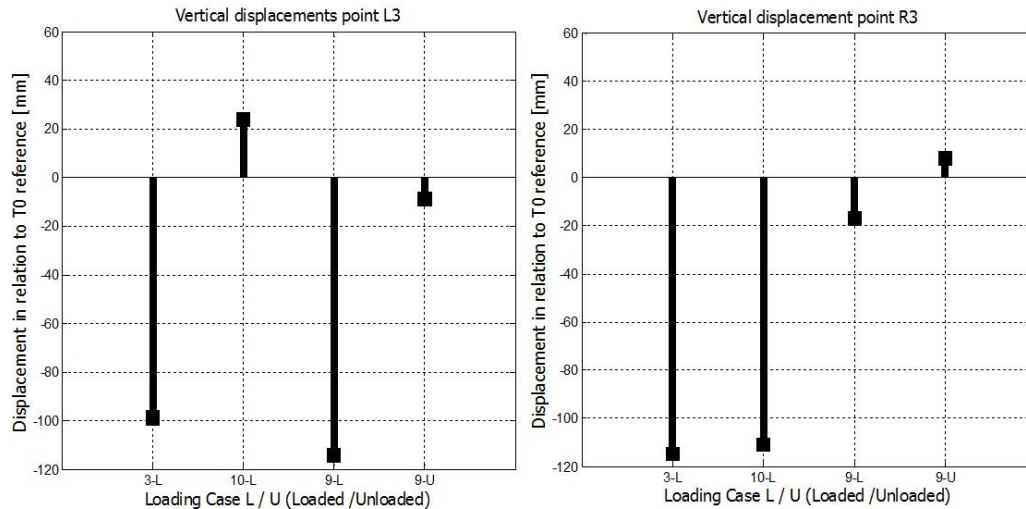


Fig. 15. Vertical bridge displacements over time during a sequence of different loading cases, point L3 at left, and point R3 at right.

Having a look at Figure 15, one can observe the time behaviour of points L3 and R3. By comparing the displacements in the two parallel figures for the same loading cases, we can derive information about the deformation pattern on both sides of the bridge. Depending on the load location, such a flexible structure can exhibit both downward and upward vertical displacements. For instance, when the load was distributed at both sides (e.g. loading case 3) the displacements for points R3 and L3 had the same direction. But in case of loading only one side of the bridge (loading case 10), the displacements in the two points were in opposite direction, though in agreement with what we expected. For loading case 9, which in principle represents a mirrored scenario upon the longitudinal axis of the bridge with respect to loading case 10, points R3 and L3 had the same displacement direction. This different behaviour of the measured points can be caused by the fact that the bridge is not exactly symmetric about the longitudinal axis, as it is slightly curved. The same pattern of displacement was confirmed by FEM analysis and by levelling measurements.

Analyzing the results in the above figure, and having in mind that better displacement estimates obtained via levelling come through a labour-intensive process at high costs and the fact that the expected displacements for this bridge are at centimeter level, we can conclude that GPS is a viable tool for successfully monitoring cable-stayed bridges by meeting the accuracy requirements for this type of applications.

5 Real-time and alarm triggering capability of a GPS permanent monitoring system

5.1 Statistical assessment of GPS displacement estimates

Commercial GPS data processing software (e.g. Topcon Tools) tends to produce too optimistic positioning solutions in terms of precision measures as they do not take into account time correlation in the observations. A more realistic assessment of the GPS positioning precision can be made by considering the empirical precision (in case of repeated measurements).

The analyzed data consisted of one GPS static session (of approximately 30 min duration), which was split afterwards into smaller time windows (with durations of 1, 2 ... 15 min). This session was considered to be representative for the GPS measurement campaign in terms of average number of visible satellites and satellite geometry. For each new window, a set of position estimates with corresponding standard deviations was derived (from the processing software). Thus we now obtain 30 solutions of 1 min each, 15 solutions of 2 min each and so on. Of particular interest for this monitoring application are the vertical displacements of the bridge and that is why we have focused our attention hereinafter on the Up component of the GPS position estimates. Our conclusions rely on the premises that the geometry of the satellites is not changing very much during the full GPS observation session. This

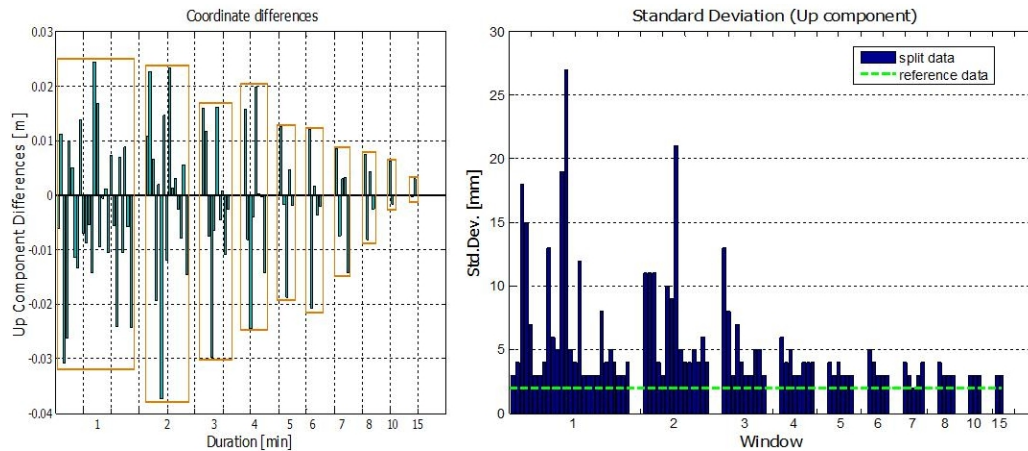


Fig. 16. Left – Up component differences for different GPS observation window durations; Right – Formal precision of GPS Up component estimator versus observation window duration.

was considered to be reasonable enough given only 30 min window duration and the high altitude of the GPS satellites.

The left side of Figure 16 shows the variation of the estimates computed for each of the new windows with respect to the reference value (the position obtained by processing the full 30-minute window). A decreasing trend in magnitude of the position differences can be easily observed along with the increase of the window duration. The same behaviour can be also noticed for the formal precision, as it becomes better for longer observation windows. This can be seen in the right plot of Figure 16, where the formal precision of the Up-component estimator is presented, as it resulted from the GPS data processing with Topcon Tools. The values outputted by the software are believed to represent the a posteriori formal precision, $\hat{\sigma}$. This software output tends to be too optimistic and that is why a better, more realistic assessment of the precision can be made by computing the empirical precision (see Figure 17).

In this case, by exploiting the availability of repeated data, other aspects such as time correlation in the observations are taken into account in the assessment of precision.

Furthermore, the influence of the precision of the reference coordinate on the empirical precision of GPS estimated differences was also taken into account. However, the results showed only a very small influence (sub-millimeter level).

5.2 Operational requirements and performance

After obtaining a first overview of the quality of the GPS position estimators, we have performed an assessment of the GPS performance as a possible real-time monitoring system. Hence, taking into account several reasonable assumptions regarding the number of false alarms per year and the missed detection probability level, we assessed the capability of GPS positioning to successfully identify bridge displacements with high reliability. By using the concept of statistical hypothesis testing (under a normal distribution assumption), we have evaluated the GPS performance for the detection and validation of bridge displacements. It can happen that in reality the bridge has not moved at all, but that based on the GPS measurements – due to noise – we nevertheless conclude it has, because the obtained position estimate exceeds a certain threshold value (leading to a false alarm), and the other way around, that the bridge has moved in reality (possibly even by a critical displacement), but that the GPS measurements do not show that, again due to measurement noise (missed detection).

Assuming four critical values (decision thresholds) for the vertical displacement of the bridge, we have computed a graph for the level of significance (false alarm probability, given in Figure 18) of the GPS position estimates with respect to the observation window duration (we are concerned here with false alarm, hence in reality there is no displacement of the bridge). In this figure the green dashed line represents the threshold for the level of significance of 0.01% (equivalent to 99.99% confidence level) chosen here in order to meet the most demanding safety require-

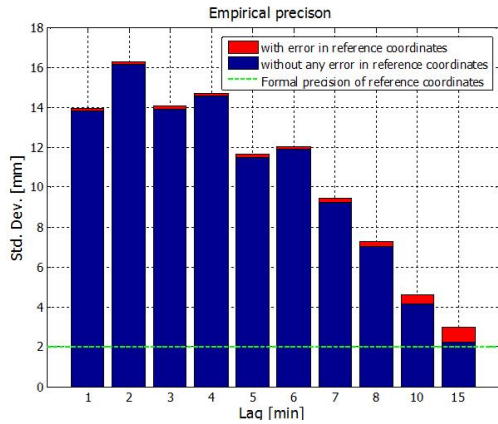


Fig. 17. Empirical precision of GPS position differences for each observation window duration. Green line gives the formal precision of the coordinate estimate from the full 30-minute window.

ments. The values of the actual precision of the GPS position estimator correspond to the ones presented in Figure 17. Due to the fact that bridge spans can present both downward and uplift behaviour, we chose to perform two-sided testing. From this graph one can observe the GPS window duration needed for the identification of a certain critical value in order to benefit of high confidence levels. For example, for being able to work with a critical value of just 30 mm with more than 99.99% confidence, one would need at minimum an 8 min GPS observation window (Figure 18).

Figure 19 shows the missed detection probability ($1 - \gamma$) in a logarithmic scale as a function of the GPS observation window duration, for a fixed value of the false alarm probability $\alpha = 0.0001$ in case of different critical displacements of the bridge (from an operational point of view, the values of 15, 30 and 50 mm have been chosen). From this plot, one can observe where the imposed threshold for $1 - \gamma$, 10^{-3} (which is a value frequently used in practice for hazardous situations), is exceeded for each of the four critical displacements of the bridge. Hence, with a larger value for the critical displacement, the curve of $1 - \gamma$ versus window length becomes more favorable; a larger displacement is 'easier' (quicker) to detect with GPS position measurements.

This means that in case of a critical displacement of the bridge of 80 mm (light blue line), a GPS observation window of just over 6 min is sufficient, to detect such a displacement in case it really is there (and only miss it in 1 out of every 1000 cases), and at the same time issuing an alarm in only 1 out of every 10000 normal cases. In this

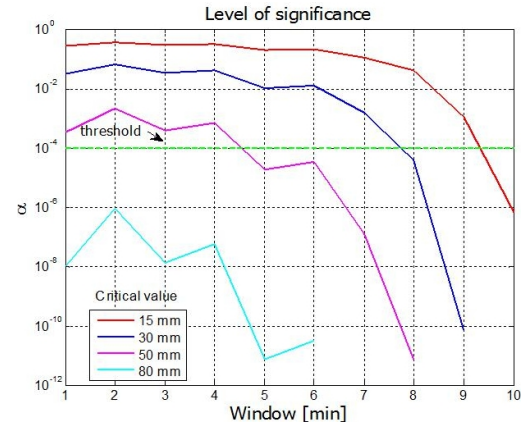


Fig. 18. Level of significance of displacement detection based on GPS position estimate versus observation window duration, for four different decision thresholds.

case, the detection delay would be 6 min (equal to the minimum required GPS measurement window duration).

Having in mind that any measurement process is inevitably accompanied by errors, in our analysis we have assumed some reasonable numbers for the false alarms that could be acceptable in one year (from an operational point of view). Starting from this supposition, we calculate the false alarm probability α for several assumed numbers of the false alarm per year (FA/year) and with respect to the observation window duration.

If we assume the $\frac{\text{FA}}{\text{year}}$ number to be 1, 6 and 12 respectively, and then by considering the number of days in one year to be 365, we obtain the false alarm interval to be:

$$\frac{\text{FA}}{\text{year}} \text{ interval [days]} = \left(365; \frac{365}{6}; \frac{365}{12} \right) \quad (10)$$

Then the probability of false alarm α can be derived for each GPS observation window as follows:

$$\alpha = \frac{\text{GPS observation duration [min]}}{\frac{\text{FA}}{\text{year}} \text{ interval [days]} \cdot 1440 \left[\frac{\text{min}}{\text{days}} \right]} \quad (11)$$

where 1440 is the number of minutes in one day. For example, for 12 FA/year and a 4-minute observation window, we arrive at $\alpha = 0.0001$ (the value used in our previous computations). We have noticed that whatever the imposed false alarm rate per year is, the acceptable false alarm probability is proportional to the observation duration. In addition, the acceptable false alarm probability is becoming larger with an increasing number of the acceptable false alarms per year (shorter interval). In other words, we have a larger false alarm probability for a larger number of fixed false alarms per year.

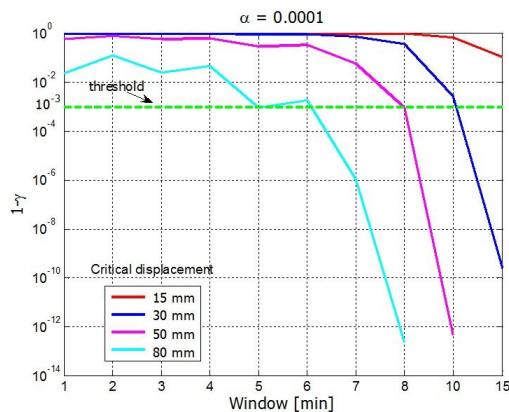


Fig. 19. Probability of missed detection ($\beta = 1 - \gamma$) versus GPS observation window duration for a fixed level of significance $\alpha = 0.0001$.

When the false alarm is kept at a fixed rate per year, then, with the increase of the GPS observation duration, we have fewer decisions to make per year and thus α per decision can be larger. This is translated into a smaller value for ($\beta = 1 - \gamma$) and furthermore into a larger value for the probability of correct decision (γ), in a particular decision. Hence, a longer GPS observation window is better in terms of probability of correct detection. Also the maximum acceptable α is larger per decision. Besides this, as it can also be seen in Figure 17, a larger observation window corresponds to a better precision of the position estimators, which has also a positive impact on γ .

The two aspects mentioned above converge to the same conclusion that for longer GPS observation windows we can benefit from a larger detection probability but, of course, all at the cost of a longer delay in action.

Having in mind the number of FA/year and also the critical displacements we considered earlier, we have analyzed the missed detection probability with respect to the observation duration. Hence, in Figure 20, the variability of the missed detection probability for different scenarios is given against the GPS observation duration.

The observed trend in this graph is that the missed detection probability (per decision) is smaller for larger critical displacements of the bridge, but also for higher numbers of acceptable false alarms per year.

Taking into account a predefined acceptable threshold of 0.001 for the missed detection probability, this graph can be used to set the duration of the GPS observation window that satisfies the condition dictated by the inputs (critical displacement of the bridge and fixed number of FA/year). For example, if the critical bridge displacement is 50 mm, and if the accepted number of FA/year is 6 (green

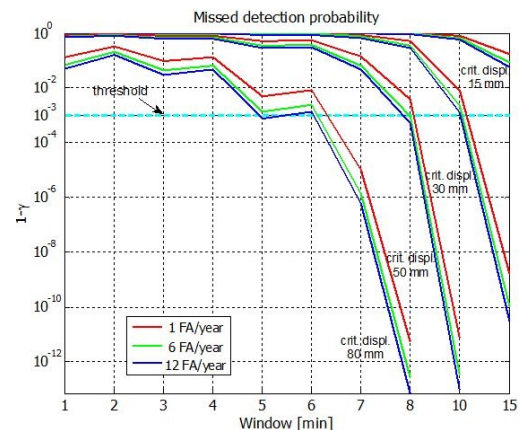


Fig. 20. Probability of missed detection ($\beta = 1 - \gamma$) versus GPS observation duration with respect to fixed numbers of FA/year and for different critical displacements of the bridge.

line), then we need a minimum duration for the GPS observation window of 8 min, in order to satisfy the missed detection probability demand at this critical displacement.

In the next plot (Figure 21), it can be observed that for a fixed critical displacement of the bridge, the probability of missed detection is becoming smaller with an increasing GPS observation window duration. At the same time, for a fixed GPS observation window duration the probability of missed detection decreases as the critical displacement of the bridge becomes larger. In other words, the larger the bridge critical displacement and window duration, the more favorable the curve of missed detection β versus FA/year shows.

One can notice that for an 8 min window, the β probability in the case of a 50 mm displacement is below the threshold only starting at 6 FA/year (Figure 21 - left). This trend can also be clearly observed from the right-hand side plot (for 50 mm critical displacements), in which the red line represents the 8 min GPS observation window.

This analysis and the resulting plots are proven to be very handy for choosing the proper GPS observation window duration needed for the monitoring program of the bridge to satisfy certain imposed standards (e.g. 0.001 missed detection probability, and maximum 6 FA/year).

This type of assessment of the GPS performance can give a first impression about the possibilities and limitations of this technology to be part of a real-time monitoring system for a cable-stayed bridge. The obtained results indicate that for the Basarab bridge and other similar constructions, GPS can be a viable monitoring tool which can be exploited in order to avoid dangerous scenarios by taking into account both safety and economic aspects.

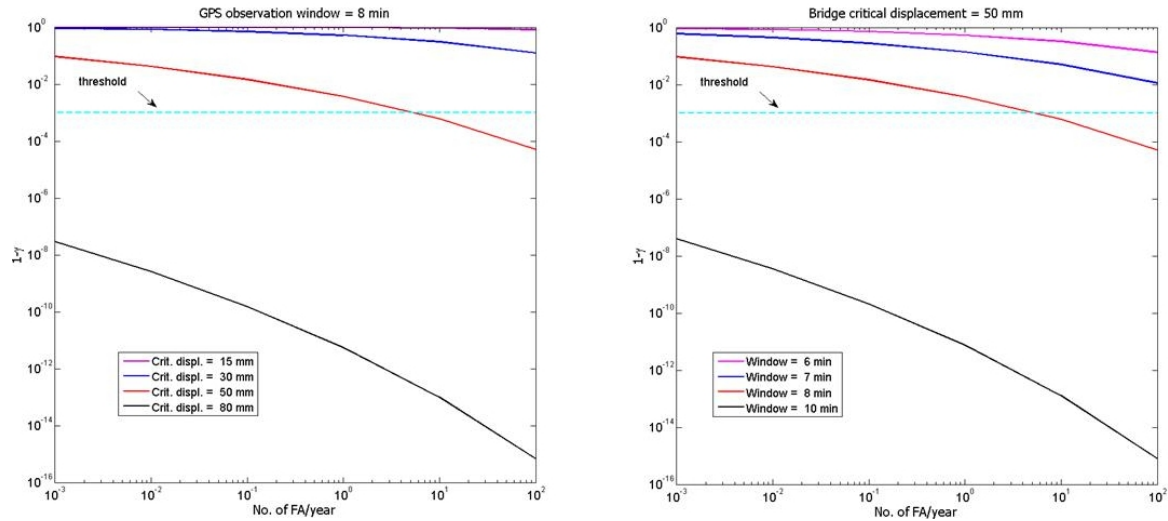


Fig. 21. Probability of missed detection ($\beta = 1 - \gamma$) versus fixed number of false alarms per year for a GPS observation window of 8 min (left) and for a bridge critical displacement of 50 mm (right).

6 First steps in assessing the Basarab bridge dynamic behaviour with GPS

Monitoring the vibration frequencies of a structure can offer valuable information regarding the behaviour and health of the structure. Any shifts in the natural frequency could indicate a possible structural damage (a change in the stiffness) that will be very hard to detect otherwise. Hence, modal analysis represents an important tool for structural health monitoring. The feasibility of using 20 Hz GPS observations for successfully identifying the Basarab bridge vibration frequencies was investigated during a dynamic test when several trucks passed over a fixed obstacle (a wooden plank) at different speeds. The frequency interval we searched for was below 10 Hz (according to the Nyquist sampling theorem). For validation purposes, accelerometer measurements were used. Hence simultaneous observations with GPS and accelerometer have been made in order to assess the dynamic behaviour of the Basarab bridge (Figure 22).

The wooden plank of 5 cm thickness was installed in the middle of span 3 on the left side of the bridge, nearby the GPS observation point. The three-axial Brüel & Kjaer accelerometer was fixed on the iron nail used for materializing the GPS point in order to facilitate the comparison between the two sensors. Three trucks of the same weight passed over the wooden plank at different speeds: 30 km/h, 40 km/h and 60 km/h. The mass distribution on

each of the truck axles can be seen in Figure 23. By using a GPS-accelerometer comparison and validation, the assessment of the oscillations caused by the impact of the trucks with the above mentioned obstacle was performed.

The 20 Hz GPS observations have been processed in the PPK mode, a position solution resulting each 0.05 s. Significant bridge oscillations have been obtained only in the vertical direction, so along the Z axis of the accelerometer and the corresponding Z_b axis of the local bridge coordinate system used for GPS.

From simultaneous GPS and accelerometer measurements in point L3, two time series resulted: the GPS time series representing the position of point L3 every 0.05 s and the acceleration time series with a higher rate of 4167 Hz. The two datasets were acquired during the same event, and even though they represent different quantities, using a frequency analysis it should be possible to identify the same bridge oscillations.

A first obstacle consisted of the GPS and accelerometer time series synchronization. Continuous measurements were made during the pass of the three trucks with both GPS and accelerometer, but we had to cut the time series in order to capture the exact moment of the truck passing over the obstacle. Although these events were clearly visible in the acceleration time series (Figure 24 - Left), this is not the case for GPS.

The GPS time series from the right plot of Figure 24 represents the output of around 40 min of continuous observations during which the trucks used for the static loading have left the bridge and the thus the dynamic testing began.

Table 4. Identified frequencies in GPS and accelerometer (ACC) time series (in Hz). HA - harmonic analysis. PS - frequency domain analysis, power spectrum.

Event 1				Event 2		Event 3	
GPS		ACC		GPS	ACC	GPS	ACC
HA	PS	HA	PS	PS	PS	PS	PS
9.67	9.60	9.67	9.60	9.92	9.67	9.38	9.61
8.44	8.70	8.40	8.40	8.75	8.40	-	8.36
7.11	7.10	7.12	7.05	7.73	7.12	7.81	7.73
6.09	6.10	6.36	6.40	6.17	6.36	6.41	-
5.47	5.50	5.34	5.25	5.23	5.34	5.63	5.31
4.06	4.10	4.32	4.30	-	4.32	4.61	4.45
3.28	3.35	3.05	-	-	-	3.91	3.75
2.19	2.20	2.29	2.15	2.27	2.29	-	2.27
1.48	-	1.53	-	-	1.53	1.41	1.33
						-	0.32

**Fig. 22.** GPS + accelerometer monitoring system.

Even though we knew the approximate moment when the trucks passed over the wooden plank, it was very hard to identify this exact moment in the GPS displacement time series. The passing trucks might have led to movements of the tripods (on which the GPS antenna is set-up) with respect to the bridge-deck. Thus, small 'jumps' of the tripods may have hampered the vibration analysis. On the other hand, in the acceleration time series, the impact of each of the five truck axles was visible due to a higher sensitivity of the accelerometer (Figure 25).

In order to exactly identify the passing moment of the truck, we had to cut the acceleration time series in smaller parts (of only 3-4 s) for each of the three events. We did so having in mind the speed of the truck which gives the time interval when the effect caused by its pass will be sensed. Then we calculated the power spectrum for each of the three events and the dominant frequency has been identified. An algorithm was developed to automatically search for this dominant frequency in the GPS time series spectrum. The size of the search window in the GPS time series was also set to correspond to the same interval of 3-4 s, in

order to retrieve the passing moment of the trucks. In this way we could also successfully identify in the GPS time series the moments corresponding to the dynamic trial. Therefore a comparison of the power spectrum of the two synchronized datasets was now possible.

By analyzing the frequency values from GPS and accelerometer data given in Table 4, one can get a first impression of the 20 Hz rate GPS capability to identify the vibration frequencies of the Basarab cable-stayed bridge. After the comparison and validation with the accelerometer, we can say that the maximum obtained discrepancy between the two sensors is 7%. Moreover, in the same table, for the first event we have presented the frequencies derived by two methods (harmonic analysis and Fast Fourier Transform - FFT), the results being similar. Probably, a better match between the two sensors could have been obtained with a better in situ synchronization of the sensors, using different filtering procedures or perhaps a GPS receiver with an even higher acquisition rate. All these ideas can be materialized in a future work. From accelerometer data resulted that the dominant frequency of the bridge vibrations was between 11 Hz and 12 Hz. Unfortunately due to GPS sampling rate limitation at 20 Hz we could only investigate the frequencies below 10 Hz. This range of frequencies had smaller amplitudes, being more difficult to detect and therefore some gaps occur in the table above.

7 Conclusions

This contribution presents the use of GPS technology for monitoring of cable-stayed bridges. By using GPS satellite observations, we have determined 3D displacements of the Basarab bridge during loading with convoys of trucks and trams, and thus we could assess the structure's behaviour

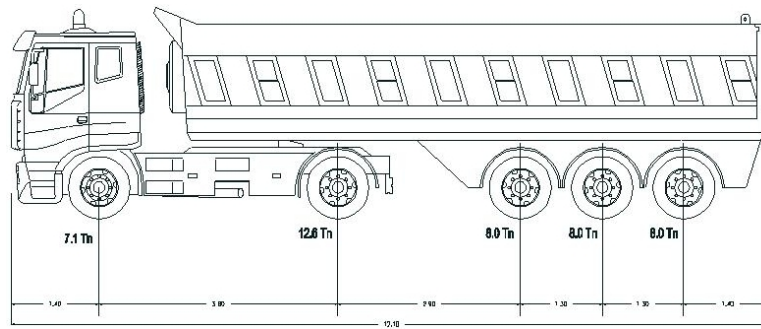


Fig. 23. Side view of a truck used for the dynamic testing (courtesy of Astaldi/FCC Construcción).

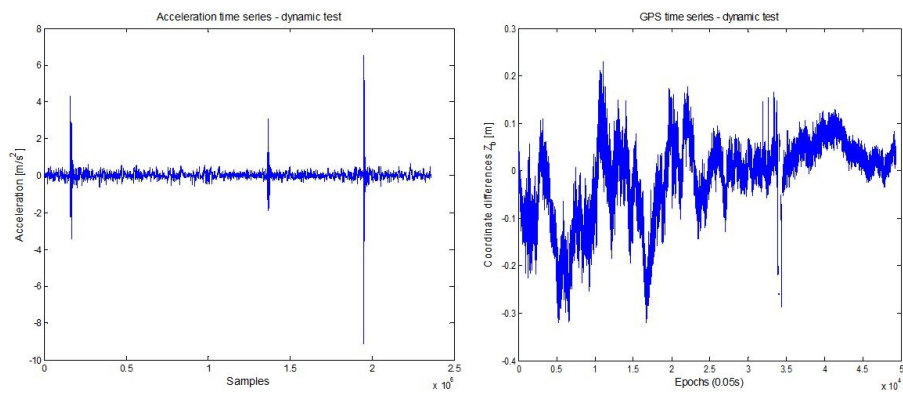


Fig. 24. Left – Acceleration time series during the pass of the three trucks. Horizontal axis corresponds to a time interval of approximate 9 min; Right – GPS time series with the dynamic test between epoch 20000 and 30000. Horizontal axis corresponds to a time interval of approximate 40 min.

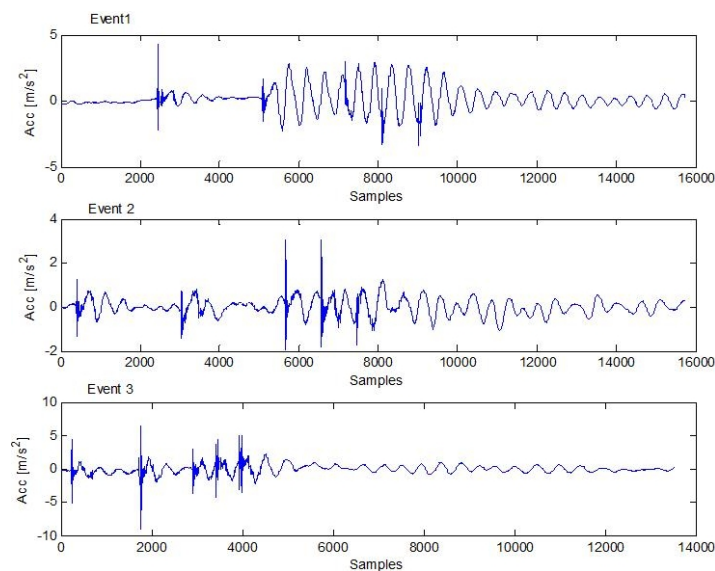


Fig. 25. Zoom in on the acceleration time series for each event, with each event lasting just 3-4 s. The impact of all 5 axels of the truck can be identified.

during different loading scenarios. Moreover, the GPS results have been compared and validated with Finite Element Method (FEM) predictions and levelling data, concluding that all three are in relatively good agreement.

The centimeter-scale vertical displacements expected to occur for this type of structures qualify GPS as a viable tool for deformation monitoring of such objectives. GPS technology presents many advantages compared to classical surveying techniques (e.g., levelling). We refer here to characteristics such as the no-visibility requirement between observation points, reduced time for measurements and fast, near real-time processing. Moreover, with GPS one could set-up an autonomously working monitoring system without the need of manpower on site. All these represent the added value of GPS technology for efficient monitoring applications.

In order to address the more and more complex demands of today's society for early warning in case of hazardous situations, we have assessed the GPS reliability to detect critical displacements of bridges and to avoid false alarm triggering as much as possible. A statistical approach was used to evaluate the performance of GPS for continuous monitoring of bridges, tackling aspects such as observation window duration, critical expected displacement and tolerated number of false alarms per year. This way, a first overview on the level of GPS accuracy is provided.

The ability of high rate GPS observations (e.g., 20 Hz) for identifying the bridge vibration frequencies was also tested. The bridge vibrations caused by a truck passing over an obstacle were successfully identified using GPS. GPS results were validated with results obtained from simultaneous acceleration measurements.

Consequently, GPS proves to be a viable and reliable tool for monitoring not only the displacements of a structure but also its dynamic behaviour. A priori treatment and harmonic analysis of the time series can prove to be extremely useful for improving data quality and obtaining better position solutions. Additionally, current developments of this technology and its continuous evolution (e.g. higher acquisition rates) recommend GPS for real-time monitoring applications that can cover monitoring of much higher vibration frequency ranges as well.

Acknowledgements

This research was developed in a first stage at the Faculty of Geodesy, Technical University of Civil Engineering Bucharest (grant POSDRU/88/1.5/S/57351) as part of a

PhD program. A large part of the work was carried on afterwards within the Geoscience and Remote Sensing Department of Delft University of Technology, during an internship of the first author. The authors would like to express their gratitude to Astaldi/FCC Construcción association for facilitating the GPS/accelerometer measurement campaign during the bridge testing and for sharing part of their data for this study.

References

- [1] Amiri-Simkooei A. R., Tiberius C. C. J. M., Assessing receiver noise using GPS short baseline time series, *GPS Solutions*, Springer-Verlag **11** (2006), 21–35.
- [2] Breuer P., Chmielewski T., Górsm P., Konopka E., Tarczynski L., The Stuttgart TV Tower — displacement of the top caused by the effects of sun and wind, *Engineering Structures*, Elsevier Ltd. **30** (2008), 2771–2781.
- [3] Brunner F. K., Bridge Monitoring: external and internal sensing issues, *Structural Health Monitoring and Intelligent Infrastructure* Balkema (2006) 693–698.
- [4] Çelebi M., Sanli A., GPS in pioneering dynamic monitoring of long-period structures, *Earthquake Spectra* **18** (2002), 47–61.
- [5] Chrzanowski A., Szostak-Chrzanowski A., Bond J., Increasing public and environmental safety through integrated monitoring and analysis of structural and ground deformations, published in *Geomatics Solutions for Disaster Management* (eds: J. Li, S. Zlatanova, A. Fabbri) Springer, (2007), 407–426.
- [6] Gikas V., Daskalakis S., Comparative testing and analysis of RTS versus GPS for structural monitoring using calibration measurements upon sinusoidal excitation, 13th FIG Symposium on Deformation Measurement and Analysis, 4th IAG Symposium on Geodesy for Geotechnical and Structural Engineering (2008) Lisbon, Portugal.
- [7] Gurtner W., Estey L., The Receiver Independent Exchange Format - version 3.01, (2009), <http://igscb.jpl.nasa.gov/igscb/data/format/rinex301.pdf>.
- [8] Kijewski-Correa T., Kareem A., Kochly M., Experimental Verification and Full-Scale Deployment of Global Positioning Systems to Monitor the Dynamic Response of Tall Buildings, *Journal of Structural Engineering* **132** (2006), ASCE, 1242–1253.
- [9] Kijewski-Correa T., Kochly M., Monitoring the wind-induced response of tall buildings: GPS performance and the issue of multipath effects, *Journal of Wind Engineering and Industrial Aerodynamics*, Elsevier Ltd. **95** (2007), 1176–1198.
- [10] Lekidis V., Tsakiri M., Makra K., Karakostas C., Klimis N., Sous I., Evaluation of dynamic response and local soil effects of the Evripos cable-stayed bridge using multi-sensor monitoring systems, *Engineering Geology*, Elsevier Ltd. **79** (2005), 43–59.
- [11] Li X., Peng G. D., Rizos C., Ge L., Tamura Y., Yoshida A., Integration of GPS, Accelerometer and Optical Fiber Sensors for Structural Deformation Monitoring, *Proceedings of the 17th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2004)*, Long Beach, CA. (2004), 211–224.

- [12] Meng X., Roberts G. W., Cosser E., Dodson A. H., Real-time bridge deflection and vibration monitoring using an integrated GPS/accelerometer/pseudolite system, *Proceedings of the 11th FIG Symposium on Deformation Measurements* (2003), Santorini, Greece.
- [13] Meng X., Dodson A., Roberts G., Cosser E., Hybrid sensor system for bridge deformation monitoring: Interfacing with structural engineers, *Proceedings of IAG Symposium, A Window on the Future of Geodesy* **128** (2005), 83–88.
- [14] Meng X., Dodson A. H., Roberts G. W., Detecting bridge dynamics with GPS and triaxial accelerometers, *Engineering Structures*, Elsevier Ltd. **29** (2007), 3178–3184.
- [15] Nickitopoulou A., Protopsalti K., Stiros S., Monitoring dynamic and quasi-static deformations of large flexible engineering structures with GPS: Accuracy, limitations and promises, *Engineering Structures*, Elsevier Ltd. **28** (2006), 1471–1482.
- [16] Ogaja C., Rizos C., Wang J., and Brownjohn J., High precision dynamic GPS system for on-line structural monitoring, *5th Int. Symp. on Satellite Navigation Technology & Applications*, 24-27 July (2001) paper 35, CDROM, Canberra, Australia.
- [17] Psimoulis P., Pythaorouli S., Karambalis D., Stiros S., Potential of Global Positioning System (GPS) to measure frequencies of oscillations of engineering structures, *Journal of Sound and Vibration*, Elsevier Ltd. **318** (2008), 606–623.
- [18] Roberts G. W., Cosser E., Meng X., Dodson A., High frequency deflection monitoring of bridges by GPS, *Journal of Global Positioning Systems* **3** (2004), 226–231.
- [19] Roberts G. W., Meng X., Dodson A. H., Cosser E., Multipath mitigation for bridge deformation monitoring, *Journal of Global Positioning Systems* **1** (2002), 25–33.
- [20] Teunissen P. J. G. and Kleusberg A., *GPS for Geodesy*, 2nd edition, Springer (1998).
- [21] Teunissen P. J. G., Simons D. G., Tiberius C. C. J. M., *Probability and observation theory – lectures notes AE2E01*, TU Delft (2009).
- [22] Wan Aziz W. A., Zulkarnaini M. A., Shu K. K., The Deformation Study of High Building Using RTK-GPS, *From Pharaohs to Geoinformatics*, FIG Working Week and GSDI-8 Cairo, (2005) Egypt.
- [23] Yigit C. O., Analysis Of Wind-Induced Response Of Tall Reinforced Concrete Building Based On Data Collected By GPS And Precise Inclination Sensor, *PFIG Congress 2010, Facing the Challenges – Building the Capacity* 11-16 April (2010) Sydney, Australia.

Received October 10, 2013; accepted February 10, 2014.

