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GPS/RTS data fusion to overcome signal deficiencies in certain bridge dynamic monitoring projects

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Abstract. Measurement of deflections of certain bridges is usually hampered by corruption of the GPS signal by multipath associated with passing vehicles, resulting to unrealistically large apparent displacements. Field data from the Gorgopotamos train bridge in Greece and systematic experiments revealed that such bias is due to superimposition of two major effects, (i) changes in the geometry of satellites because of partial masking of certain satellites by the passing vehicles (this effect can be faced with solutions excluding satellites that get temporarily blocked by passing vehicles) and (ii) dynamic multipath caused from reflection of satellite signals on the passing trains, a high frequency multipath effect, different from the static multipath. Dynamic multipath seems to have rather irregular amplitude, depending on the geometry of measured satellites, but a typical pattern, mainly consisting of a baseline offset, wide base peaks correlating with the sequence of main reflective surfaces of the vehicles passing next to the antenna. In cases of limited corruption of GPS signal by dynamic multipath, corresponding to scale distortion of the short-period component of the GPS waveforms, we propose an algorithm which permits to reconstruct the waveform of bridge deflections using a weak fusion of GPS and RTS data, based on the complementary characteristics of the two instruments. By application of the proposed algorithm we managed to extract semi-static and dynamic displacements and oscillation frequencies of a historical railway bridge under train loading by using noisy GPS and RTS recordings. The combination of GPS and RTS is possible because these two sensors can be fully collocated and have complementary characteristics, with RTS and GPS focusing on the long- and short-period characteristics of the displacement, respectively.

Keywords: GPS; RTS; data fusion; Gorgopotamos bridge; Greece; Structural Health Monitoring; dynamic multipath; noise; displacement; excitation; train

1. Introduction

GPS (Global Positioning System) and RTS (Robotic Total-Station or Robotic Theodolite) have different advantages and limitations for monitoring deflections of long-and even short-period bridges and of other structures when excited by wind and traffic load. The main characteristic of GPS is that it can record higher frequency oscillations but the signal-to-noise ratio in small-amplitude oscillations, below approximately 1 cm, is small (Kijewski-Correa and Kareem

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2003, Psimoulis and Stiros 2012). RTS on the other hand seems more suitable for small amplitude (a few mm), lower-frequency oscillations which are recorded with much higher signal-to noise ratio; still oscillations even above 3Hz have been recorded successfully (Psimoulis and Stiros 2007, Zarikas *et al*. 2010, Stiros and Psimoulis 2012). For this reason there have been efforts to combine these sensors, occasionally supported by recordings of accelerometers and other instruments (Roberts *et al*. 2004, Lekidis *et al*. 2005, Li *et al*. 2007, Meng *et al*. 2007, Yigit *et al*. 2010, Moschas and Stiros 2011, Psimoulis and Stiros 2012).

In particular, GPS recordings in the differential mode (i.e., leading to instantaneous coordinates of a rover (moving) receiver computed relatively to a nearby stable (base, reference) receiver), proved excellent in monitoring the response of bridges to dynamic loading, on the condition that the satellite signal is not permanently or temporarily interrupted or otherwise deformed by nearby objects, such as passing vehicles or members of the study structure (pylons, etc.). These last adverse conditions are met in the case of certain bridges in which the rover receiver installed on the deck, next to passing vehicles which temporarily block part of the sky view (Fig. 1). In the case of the Rosenbrücke bridge crossing the Danube river, Austria, Wieser and Brunner (2002) used both RTS and GSP to record the response of the bridge deck to passing vehicles, and their conclusion was that GPS data lead to unrealistically large reflection signals, forcing to limit their monitoring to RTS data; a point discussed in some detail below (section 3.1).

A somewhat similar situation was faced during the monitoring of the Gorgopotamos railway bridge in Greece. Measurements to a RTS reflector and a fully collocated GPS receiver on the handrail of this bridge revealed that GPS was again leading to unrealistic results. Still, the corrupted GPS signal correlated with the train passage and for this reason it was used as a precise time-stamp of the train passage (Stiros and Psimoulis 2012, Psimoulis and Stiros 2013)

In order to shed some light to causes and characteristics of this dynamic noise in GPS data, preventing its use in certain Structural Health Monitoring projects, Moschas and Stiros (in press a) simulated the bridge measurement conditions by measurements near a train track on solid ground, with the rover receiver in stable position. This permitted to study the effect of a passing train on the GPS recordings in systematic experiments under controlled conditions (only noise in measurements). The output of this study, summarized below, is that the train passage produces a dynamic multipath (Moschas and Stiros, in press a) with spectral characteristics very different from the common “static” multipath (Han and Rizos 1997, Ge *et al*. 2000, Kaplan and Hegarty 2006, Yi *et al*. 2012b) and which is reflected in noise of the rover coordinates; an effect broadly analogous to the effect of rotors and of the changing position of flying helicopters (Matayoshi and Okuno 2007). This noise correlates with specific features (reflective surfaces) of the train passing in front of the receiver, and its amplitude does not present a systematic value as it depends on the constellation of tracked satellites at the time of measurements.

Based on the results of these studies, and especially on the nearly systematic character of the noise deduced from our experiments, it was investigated whether and under which conditions it is possible to combine RTS and GPS data collected during the passage of a vehicle from a bridge, de-noise the GPS data and obtain additional, high frequency information for the response of the bridge to dynamic excitations. The results of this study are summarized below.

2. Potential of GPS and RTS for the monitoring of dynamic movements

GPS and RTS with high (>1 Hz) sampling rate give an excellent potential for the monitoring of dynamic displacements in terms of instantaneous coordinates of a moving target or GPS antenna in a reference frame independent from the oscillating structure. Experimental studies on shake tables (Chan *et al*. 2006, Psimoulis *et al*. 2008) have proven the ability of GPS to record low frequency (<1Hz) and high frequency (frequency > 1 Hz) displacements although long-period noise affecting GPS measurements tends to mask displacement signals with millimeter amplitude (Kijewski-Correa and Kareem 2003, Moschas and Stiros 2011). On the other hand experimental studies have shown that RTS can accurately record low frequency oscillations (Gikas and Daskalakis 2006, Psimoulis and Stiros 2007) while for frequencies larger than approximately 2 Hz RTS tends to mis-record the oscillation amplitude. Over the last decades GPS has been successfully used for the monitoring of the dynamic displacements of engineering structures covering flexibe structures like high-rise buildings (Tamura *et al*. 2002) suspension and cable-stayed bridges (Ashkenazi and G. Roberts 1997, Nakamura 2000) and more stiff structures like pedestrian bridges etc (Meng *et al*. 2007, Casciati and Fuggini 2011, Moschas and Stiros 2011). On the other hand RTS has been successfully used in limited number of cases for the monitoring of structural displacements (Psimoulis and Stiros 2013, Gikas 2012). As GPS is affected by a wide variety of factors deforming satellite signal (multipath, tropospheric delays, diffraction etc) a large number of filtering algorithms have been developed in order to de-noise GPS measurements and push further the limits of its applications for structural monitoring. On many cases these methodologies include the combination of GPS with other sensors (for example accelerometers) (Meng *et al*. 2007, Kogan *et al*. 2008, Moschas and Stiros 2011). The present study presents an algorithm for counter-acting GPS signal deficiencies using RTS measurements in order to reconstruct the displacement time-history of a truss bridge under train loading.

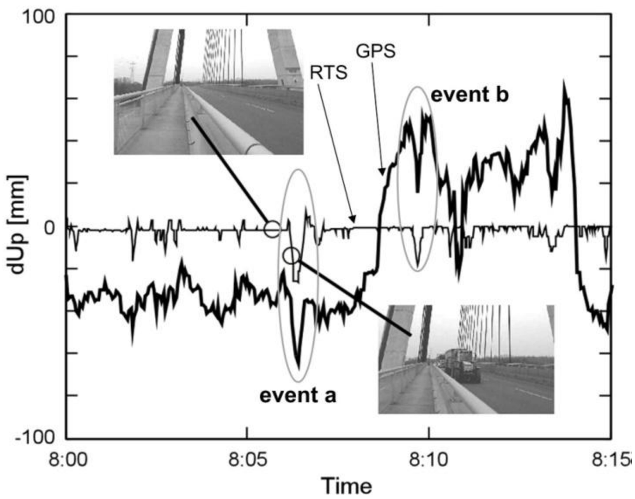

Fig. 1 GPS and RTS-derived vertical apparent deflections of the deck of the Rosenbrücke Bridge of Danube River in Austria during intervals of excitation by passing tracks and intervals of quiescence. GPS-derived deflections are very noisy (pseudo-displacements of several centimeters), attributed to high multipath noise, much larger than those derived by RTS. Modified after Wieser and Brunner (2002)

3. GPS signal deficiencies in structural monitoring - previous experience

3.1 Evidence from the Rosenbrücke Bridge, Austria

The performance of GPS for Structural Monitoring under unfavorable conditions has been investigated by a small number of published studies in the past. Wieser and Bruner (2002) used GPS and a Robotic Total Station to monitor the displacements due to traffic loads of the cable-stayed Rosenbrücke Bridge crossing the Danube river in Austria. A GPS antenna was installed on the handrail of the bridge deck in order to provide information on the deck oscillations, while the movements of a collocated reflector were recorded by the RTS. The computed (apparent) displacements by GPS were proved sensitive to dynamic bridge deck loads (passing vehicles), but several times larger than the displacements derived from the RTS (Fig. 1). Furthermore GPS measurements presented long-period fluctuations on both sides of the equilibrium point (large positive and negative displacements in Fig. 1) which are related with satellite signal diffraction and multipath effect by the bridge structural members. The conclusion was that RTS data were reliable, but due to multipath produced by cables and passing trucks close to the antenna, the GPS data were corrupted by noise not permitting any correction.

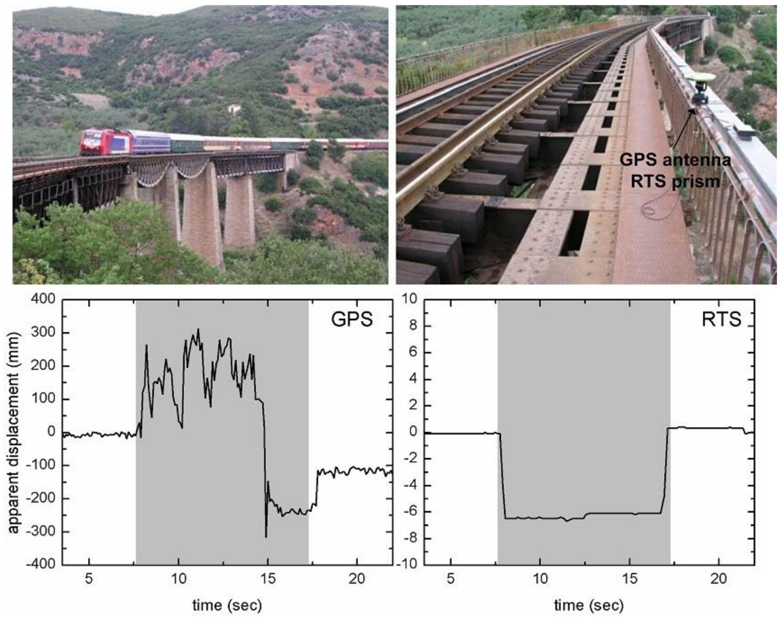

Fig. 2 Top: The historical Gorgopotamos bridge in central Greece crossed by a train (left) and collocated GPS/RTS sensors (right). Bottom: GPS and RTS measurements of the displacements of one of the bridge midspans during the passage of a 5-wagon train (train 52-see Table 1). The gray shaded area indicates the train passage interval, precisely marked by both sensors. GPS presents unrealistically large apparent displacements and a high-frequency signal, while in this case RTS recorded accurately only the semi-static displacement due to clipping (Stiros and Psimoulis 2012, Psimoulis and Stiros 2013)

3.2 Evidence from the Gorgopotamos railway bridge, Greece

Stiros and Psimoulis (2012) and Psimoulis and Stiros (2013) used a high quality RTS reflector fully collocated with a GPS antenna to measure the displacements of the deck of the historic Gorgopotamos Bridge in Central Greece during the passage of several trains (for details see Table 1). It was found that during the train passage RTS recorded displacements of the order of up to 6-7 mm, i.e., of the order of the amplitude of the noise in GPS, while GPS recorded apparent instantaneous deflections of 30 cm, and in several cases even more, with a direction opposite compared to the deflections recorded by the RTS (Fig. 2). Excessively large oscillation amplitude and erroneous direction of deflection derived by the GPS can be attributed to a combination of multipath and instantaneous masking of a number of satellites created by the train.Still, the GPS signal was found to correlate excellently with the train passage, and its recordings were used as a precise timer.

Table 1 Details for the train passage events analyzed in the present study. P: passenger, F: freight, train. For all events shown RTS and GPS data are available

date	time (UTC)	train code	train type	No of wagons	measurement position
12.05 2006	10:59:38	NN	P	7	pylon
12.06.2006	6:29:17	23501	F	14	mid-span
12.06.2006	7:52:00	51	F	5	mid-span
12.06.2006	8:13:51	882	F	4	mid-span
12.06.2006	8:31:27	603	F	9	mid-span
12.06.2006	9:59:43	52	P	5	mid-span
12.06.2006	10:59:40	53	P	5	mid-span

3.3 Results from experimental studies

Heavy vehicles, especially trains passing from a bridge, are expected to produce both static and dynamic displacements in a bridge deck (Clough and Penzien 1993, Xia *et al*. 2000, Liu *et al.* 2009). In most cases, such deflections plus some noise can be recorded by geodetic sensors, GPS and RTS (Wieser and Brunner 2002, Watson *et al.* 2007, Li *et al*. 2007, Meng *et al.* 2007, Kogan *et al*. 2008, Park *et al*. 2008, Erdoğan and Gülal 2009, Yi *et al*. 2010a, Roberts *et al*. 2012, Yi *et al.* 2012a, Stiros and Psimoulis 2012).

In the case of conventional GPS measurements, noise is a result of various error sources like multipath, atmospheric delays and antenna/receiver noise and covers a wide band of low and high frequencies (Langley 1997, Han and Rizos 1997, Kaplan and Hegarty 2006, Moschas and Stiros

2012). In the case of vehicles passing in front of the GPS antennas an additional type of noise affects the GPS time series; this noise is due to the instantaneous reflections of GPS signals on the passing vehicles and to short-period changes in the satellite geometry due to satellite masking by the passing vehicles (Fig. 3)

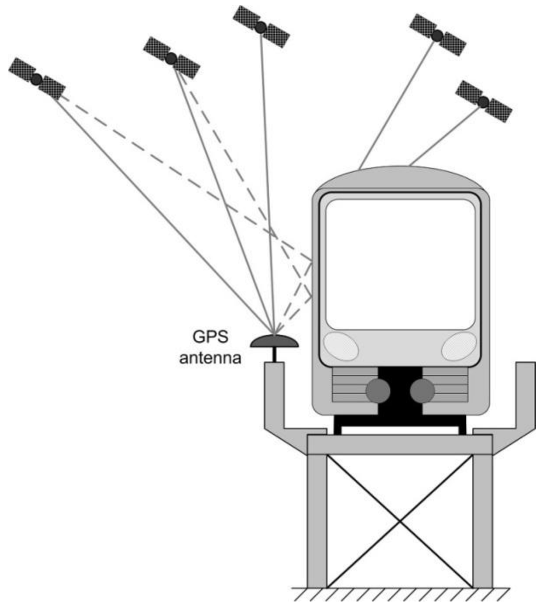

Fig. 3 Effects of a passing train on the satellite signals during the GPS monitoring of a bridge. Some of the satellites are temporarily masked by the passing train, while at the same time, signals from visible satellites are reflected on the train surface (dashed lines) producing multipath

In order to shed light to the characteristics of this noise, systematic experiments were made using several 100 Hz GNSS receivers (recently introduced in Structural Health Monitoring applications see Yi *et al*. (2013)) set on stable ground near a railway line. The aim of these experiments was to record the impact of trains travelling on non-deforming rails (i.e., with no semi-static and dynamic displacements) on receivers set on stable ground, in an environment with minimum ambient (static) multipath. In such conditions only dynamic multipath noise is recorded.

Various satellite signal processing strategies were adopted, including processing with different software, exclusion of the satellites temporarily masked by the passing trains, comparison between different collocated receivers and use of both GPS and GLONASS satellites. The results of this study, summarized by Moschas and Stiros (in press a) are that errors such as those appearing in Figs. 1 and 2 are mainly due to two factors, (i) changes in the satellite geometry induced by vehicles temporarily masking some satellites, and (ii) dynamic multipath created by the train and with a characteristic pattern, reflecting the succession of reflective surfaces of the train (Fig 3).

Their cumulative effect was a distorted displacement signal characterized by a baseline offset, wavelet-type events and higher frequency noise with peaks usually above 10-20 mm. The overall pattern of the signal distortion in ultra-high (100 Hz) sampling GNSS receivers was systematic (Fig. 4), but the amplitude of offsets and peaks was variable, rather chaotic, depending on the constellation of the tracked satellites. As will be shown in the following paragraphs similar characteristics of dynamic multipath due to moving trains (baseline offset and apparent displacements of several centimeters) were also observed in GPS measurements sampled at 10 Hz, which indicates that the observed effect is common in high-rate GPS measurements, regardless of the sampling rate.

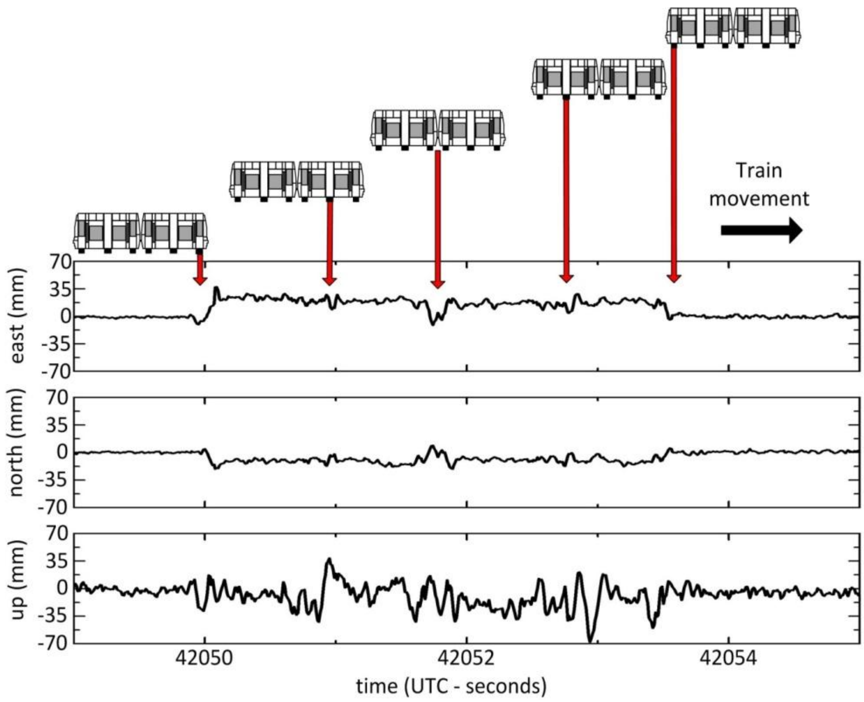

Fig. 4 Dynamic multipath noise in a 100 Hz GNSS receiver recording near a passing train. This noise has a typical pattern and is characterized by a baseline offset during the passage of the train, wavelet-type peaks correlating with the sequence of passing reflective surfaces (marked by red arrows) and short-period noise larger than in normal circumstances (from Moschas and Stiros, in press a)

4. Combined analysis of GPS and RTS data from the Gorgopotamos Bridge

The Gorgopotamos Bridge crosses a rather narrow valley in central Greece. It was constructed in 1905 and reconstructed twice during or just after World War II. At present, and after the reconstructions, the bridge is supported by two steel truss pylons, up to 16 m high, and four masonry pylons up to 32 m high. Pylons are mostly founded on marls. From the structural point of view, the bridge deck represents a system of seven metal trusses, approximately 30 m long each, on which the railroad line is lying (Fig. 2 top). This historical bridge is to be abandoned after the completion of a new railroad line.

We collected GPS and RTS data during the passage of trains of different types crossing this bridge with low velocities, of the order of 20-35 km/h. Measurements were made in different environmental conditions, in spring and in summer, under different satellite constellations, and in different points on the deck (in a mid-span, above a pylon, etc.; Table 1; for details see Stiros and Psimoulis (2012) and Psimoulis and Stiros (2013)).

A GPS antenna-receiver (JPS Legacy-E antenna with a JPS Legacy-H receiver) with a sampling frequency of 10 Hz collocated with an RTS AGA reflector was clamped on the handrail of the bridge. This installation position was chosen because the bridge handrail was stiffly connected on the bridge deck and was following particularly the vertical oscillations of the bridge. A similar, base receiver was operating in a nearby position free of the effects of the passing train.

A Leica 1201 RTS with a nominal sampling frequency of 10 Hz was used, but the sampling rate is unstable (jitter effect) with a mean rate of 5-6 Hz (Psimoulis and Stiros 2007, 2012).

An analysis of RTS data supported by GPS recordings revealed semi-static and dynamic deflections with an amplitude of 5-7 mm at the specific midspan of the bridge, and dominant frequencies of the order of 3.2 Hz during the passage of trains (Stiros and Psimoulis 2012, Psimoulis and Stiros 2013).

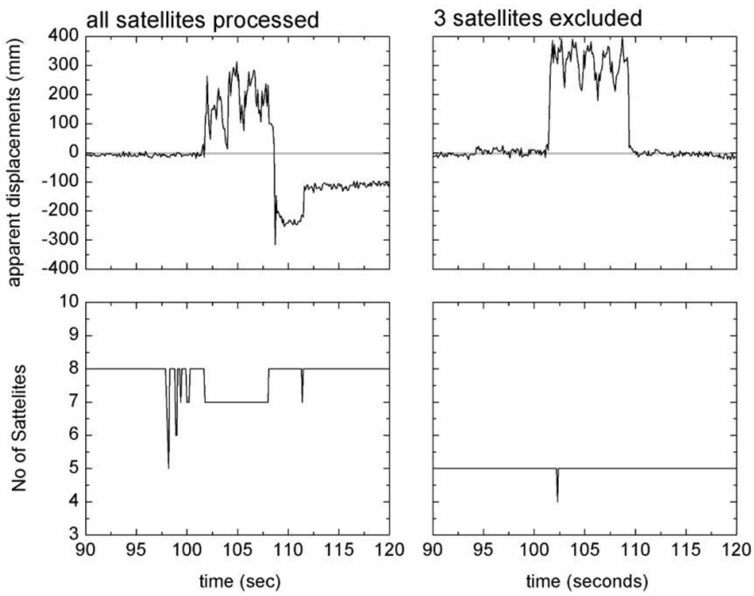

Fig. 5 Upper line: Vertical apparent displacements at a Gorgopotamos bridge midspan during the passage of a 5-wagon train (train 52). Results obtained after processing GPS measurements with all visible satellites (left column) and excluding satellites temporarily masked by the passing train (right column). Lower line: Number of tracked satellites. In both cases apparent deflections are highly exaggerated because of the multipath

GPS measurements were processed in kinematic mode using the Leica Geo Office (LGO) software and a 15^o cut-off angle. Because the bridge is located in a valley, low-elevation satellites, were not visible, and in total 7-8 GPS satellites were tracked, but 2-3 of them were temporarily masked by the passing trains (see Figs. 3, 5 and 6). Following the results of Moschas and Stiros (in press a) processing was carried out in two ways: a) using all instantaneously available satellites and b) excluding satellites temporarily masked by the passing trains, so that the set of tracked satellites before, during and after the train passage remains constant (see Figs. 3 and 5). Care was taken so that all solutions are characterized by fully fixed ambiguities. GPS and RTS-derived coordinates were transformed into apparent displacements around the equilibrium position using a simple linear transformation (Roberts *et al*. 2004, Psimoulis and Stiros 2008, Stiros and Psimoulis 2012). Finally, isolated point peaks were considered as outliers on the basis of the 3-sigma criterion and were excluded from further processing. Vertical apparent displacements from selected trains are presented in Fig. 6.

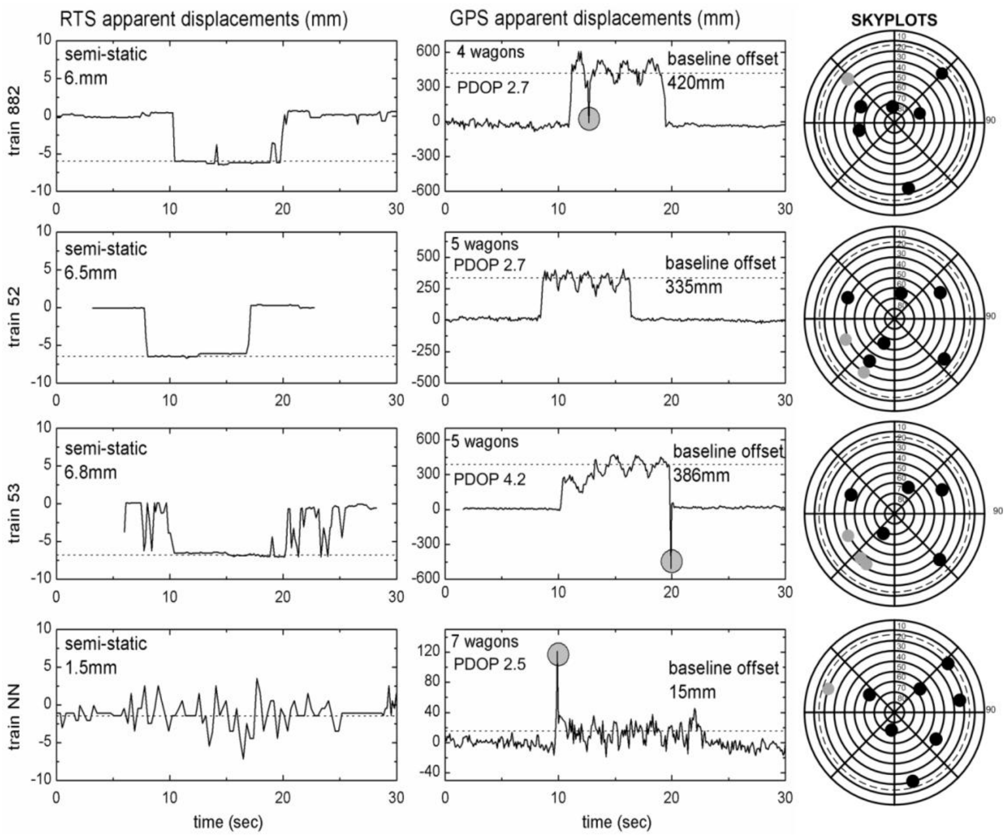

Fig. 6 Vertical apparent displacements in the Gorgopotamos Bridge for typical train passage events from RTS (left column) and GPS excluding temporarily masked satellites (middle column). The corresponding skyplots are shown to the right.Grey circles in the GPS apparent displacements mark isolated measurements which were removed as outliers. Satellites temporarily masked by trains and excluded from processing are in gray. A dashed circle marks the elevation cut-off angle. PDOP is also marked. RTS records mostly semi static displacements (see paragraph 4.). GPS shows very large apparent displacements with a characteristic pattern as a result of multipath. Measurements for trains 53 and 882 were for a midspan of the bridge, and for train NN above a pylon with foundations permitting slight elastic movements

Using a low-pass filter (see Appendix 1), the long- and short-period components of apparent GPS and RTS displacements were computed. Then, from the long-period components of the apparent displacements, a mean elevation (baseline) for the intervals before, during and after the train passage was also computed. Results for the vertical axis for a representative case (train NN) are shown in Fig. 7.

In comparison with previous evidence summarized above, it was found that GPS shows apparent displacements several orders of magnitude higher than RTS (Fig. 6) and unrealistic baseline offsets (15 mm for train NN; Fig. 7), but the corresponding waveforms have a characteristic pattern with peaks equal to the number of wagons in each train. RTS on the other hand, poorly recorded overall waveform due to clipping (mis-recording of peak displacements during movement of the reflector with high velocities, see Psimoulis and Stiros 2012), but it recorded accurately the semi-static displacements. In some cases the amplitude of dynamic deflections was clearly recorded and it was possible even to compute spectra of oscillations.

These spectra are dominated by the excitation frequencies due to successive wagons passing from a certain opening (Stiros and Psimoulis 2012, Psimoulis and Stiros 2013).

Hence, selected results from each of the two sensors are reasonable, because semi static displacements with values close to the ones recorded by the RTS have been reported in experimental and analytical studies of steel bridges with a similar opening (see Lee *et al*. 2006), while the displacement waveform obtained by GPS is typical for various types of railroad bridge decks excited by passing trains (see Fig. 7 in Xia and Zhang 2005 and Fig. 18 in Zhang *et al*. 2008).

From the results of Figs. 5 and 6 showing representative results from a number of trains analyzed, we can identify two end-cases.

(a) *substantial corruption of the GPS signal by dynamic multipath.*

This is the case of trains 53, 882 in Fig. 6: apparent displacements are dominated by a high baseline offset, >300 mm, essentially larger than the semi-static deflections derived from RTS (6-7 mm) and a series of nearly identical “wide-base” peaks with amplitude of the order of 200 mm, equal in number with the number of wagons. This series of peaks can be explained as apparent coordinate changes induced by the movement of the main reflective surfaces of the train and their frequency correlates with the bridge excitation frequencies which dominate the deflection spectra derived from RTS observations (see Fig. 6 in Stiros and Psimoulis 2012). Spectral analysis of GPS-derived apparent displacements (for example trains 53 and 882 in Fig. 6), revealed that these excitation frequencies are in the range 0.18-0.60 to 1.0 Hz and, when removed using a bandpass Chebyshev filter (for the design properties of the filter see Moschas and Stiros (2011)), they led to time series reflecting only noise clearly not representative of the real movement constraint from RTS (Stiros and Psimoulis 2012). It can therefore be concluded that such cases correspond to a substantial, beyond repair corruption of the GPS signal, and they are not further discussed in the present paper.

Our analysis of data from Gorgopotamos and several experiments revealed that criteria determining the presence of substantial corruption due to dynamic multipath are the high level of baseline offset (more than 20 times the deflection amplitude derived from RTS), the relatively small number of tracked satellites (4-5) and the relatively large value of PDOP (see Fig. 6).

(b) *limited corruption of the GPS signal by dynamic multipath*.

This is exemplified in the graphs for train NN, with apparent displacements up to one order of magnitude higher than those derived from RTS (see Fig. 6). These specific measurements were made on top of a pylon, and in normal circumstances no vertical deflection is expected. However, because of compressibility of saturated argillaceous rocks, representing the foundations background during the specific measurements, a slight vertical movement (a few mm) is expected for long/heavy trains (see Stiros and Psimoulis (2012), especially Figs. 2(i), 2(l) and 3(c)).

In this last case GPS apparent displacements were very different from those of the previous cases, and very similar in pattern to what is expected in absence of dynamic multipath, but with much higher amplitude. Hence, at first view multipath was much smaller leading to scale distortion of apparent displacements. Results were further analyzed in combination with RTS data.

As is shown in Fig. 7, showing details of this train, clipping in RTS is limited and the full waveform of displacements is relatively well recorded. The corresponding displacement diagram shows a semi-static deflection of -1.5 mm (minus indicating a downward direction), and a dynamic deflection of the order of ±5.0 mm. Both these estimates are reliable (see above and Stiros and Psimoulis (Stiros and Psimoulis 2012)). GPS on the other hand shows a very similar pattern, but with an upward baseline offset of 15 mm and short-period oscillations of the order of ±30 mm.

From these GPS and RTS time-series, their long and short-period components were obtained using a moving average filter with a window of 4 seconds and a step of 0.1 second. The filter characteristics were chosen on the basis of supervised learning experiments in order to filter the long period noise of the GPS and RTS signals and retain the useful, structural vibration sugnal.The long and short period components of the RTS-derived apparent displacements correspond to the semi-static and dynamic components of the real motion, of course contaminated by some noise (Psimoulis and Stiros 2007, 2008, Stiros and Psimoulis 2012). The waveforms of the short period components of RTS and GPS are confined to the same time interval, stamping the train passage and are similar in pattern, but their amplitude is different, up to 30mm for GPS, up to 5 mm for RTS (Fig. 7). This difference is likely to indicate an overall scale effect for GPS, imposed by the increased distance covered by the satellite signals because of the combination of direct and reflected rays (Fig. 3).

Spectral analysis of the short-period components of the GPS and RTS are shown in Fig. 8. This analysis was based on the NormPeriod code and least squares permitting the analysis of unevenly sampled RTS data (jitter effect, see (Psimoulis and Stiros 2007, 2012 Stiros *et al*. 2008)) without introducing additional noise and the determination of the statistical level of significance of spectral peaks (Pytharouli and Stiros 2008). The two diagrams indicate a similar spectral context for both GPS and RTS, and contain similar peaks around 0.56 (0.59) Hz, 1 Hz 2.0 and 3.8 Hz.

Frequencies around 0.56 Hz can be attributed to the excitation due to the passing wagons: the train passage lasted 12.5 seconds, so each of the 7 wagons passing from measurement point every 1.8 second, i.e., with a frequency of approximately 0.56 Hz. The frequency at around 1 Hz was observed in all trains examined, so it may be attributed to secondary oscillations of the bridge. Finally spectral peaks at around 3.8 Hz and between 2.0-2.5 Hz are likely to reflect dominant frequencies of the bridge deck, not precisely recorded because of spectral leakage (cf. Fig. 5 in Stiros and Psimoulis (2012)).

The strong similarity of the waveforms of apparent deflections and of the spectra of GPS and RTS (Figs. 7 and 8) and the difference of their amplitude are likely to indicate that GPS-derived apparent displacements reflect scale distortion due to a somewhat uniform multipath for all satellite signals used in the solution. This means that the short-period component of the GPS apparent displacements corrected for the scale effect can be used to derive the dynamic component of the displacement. Hence, it is possible to reconstruct the GPS signal as a superimposition of the semi-static displacement derived from RTS, and from the short-period component of GPS, corrected for the scale effect from the amplitude of displacement derived from RTS using the equations of Appendix 1 as is shown in Fig. 7 for train NN. This correction can also be based on the mean amplitude of dynamic displacements (short-period-components) which can be derived from the k-filter, derived from supervised learning experiments (Psimoulis and Stiros 2012).

Filtering is constrained by the dominant frequency of the signal, derived from independent evidence (accelerometer measurements, for instance), and permits band-stop filtering in the time domain, of different amplitude for the two sensors, to account for their different types of noise. The mean oscillation amplitude is then calculated as the average of the high and low peaks separately

This weak fusion of GPS and RTS data is possible when dynamic multipath causes a *limited corruption* of the satellite signals. This is under the conditions that at least 6 satellites are tracked, the PDOP is relatively low (up to the order of 2.5) and the ratio of the mean distorted to the mean real signal is of an order up to 10.

While the possibility of a remnant multipath noise cannot be ruled out, the overall results are consistent with predictions of waveforms and of the amplitude of oscillation derived from studies in somewhat similar bridges (see Lee *et al*. 2006), Fig. 7 in Xia and Zhang 2005 and Fig. 18 in Zhang *et al*. 2008).

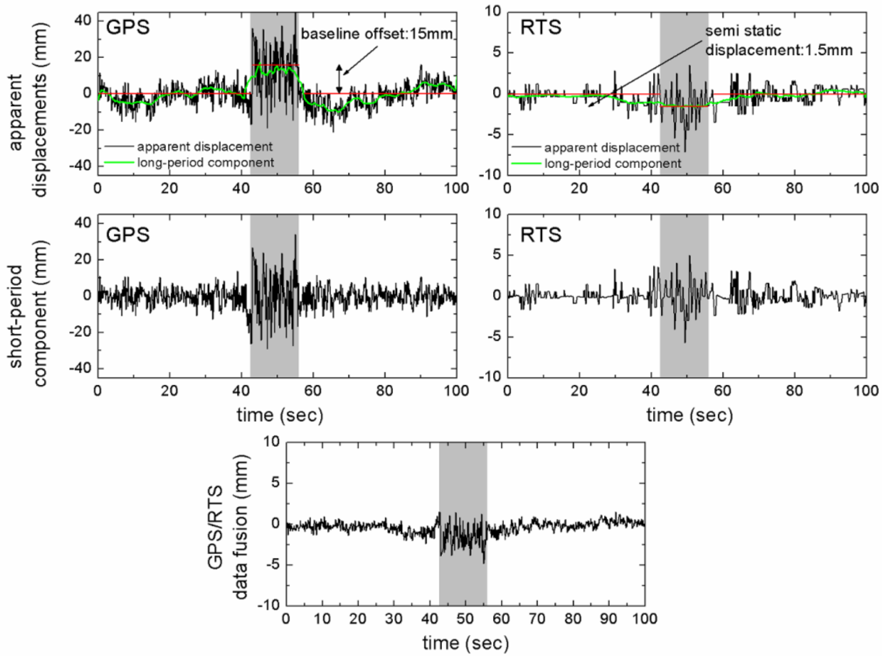

Fig. 7 Upper row: GPS (left) and RTS (right) apparent vertical displacements for train NN. A green line indicates their long-period component, while two red lines mean elevations before, during and after the passage of the train. The mean elevation offset for GPS indicates a systematic error, but for RTS the real semi-static deflection. Middle row: GPS and RTS short period components resulting from subtraction of the long-period component from the apparent displacements. Lower row: Deflection time-series reconstructed after fusion of GPS and RTS measurements

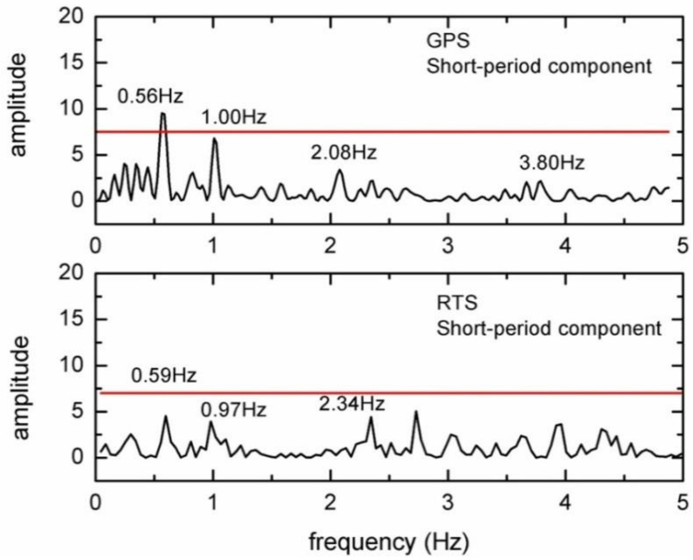

Fig. 8 Spectra of the GPS and RTS short-period components for train NN (see Fig. 7) calculated using the NormPeriod Code. Both spectra present similar frequency peaks which can be attributed to the excitation frequency due to the passing wagons and possibly the free vibration of the bridge deck. A red line marks the 95% statistical significance level of the peaks

5. Discussion

In the past it was believed that passing of a vehicle/train in front of a GPS antenna/receiver produces signal corruption beyond repair, except for the cases of large deflections in rather flexible bridges and controlled multipath (Watson *et al*. 2007, Kogan *et al*. 2008, Yi *et al*. 2010b, Roberts *et al*. 2012). Previous discussion revealed that the passing of a train in front of a GPS antenna/receiver produces two distinct effects. *First*, a temporary change of the geometry of observed satellites which introduces a bias in calculated coordinates and deflections. This bias is removed excluding satellites temporarily blocked (Fig. 3) and using solutions with fully fixed ambiguities. *Second*, a dynamic multipath producing an overall distortion of the satellite signal. In the diagram of apparent displacements, this distortion is expressed as a baseline offset correlating with the interval of the passage of the vehicle/train in front of the receiver on which are superimposed wide-base pulses correlating with the reflective surfaces and increased high-frequency noise (Fig. 4). The question is how to de-noise this corrupted signal, and under which conditions.

Previous studies have shown that various filtering techniques permit to de-noise time series of GPS-derived apparent displacements and obtain estimates of dynamic deflections at mm scale, in both long-period and rather stiff structures (Roberts *et al*. 2004, Zheng *et al*. 2005, Chan *et al*. 2006, Kijewski-Correa *et al*. 2006, Meng *et al*. 2007, Kogan *et al*. 2008, Psimoulis *et al*. 2008, Casciati and Fuggini 2011, Moschas and Stiros 2011, Psimoulis and Stiros 2012). Techniques to remove static multipath have also be proposed (Roberts *et al*. 2002, Choi *et al*. 2004, Zheng *et al*. 2005, Kijewski-Correa *et al*. 2006, Kogan *et al*. 2008, Yi *et al*. 2011), but are not suitable for dynamic multipath reduction/removal, because this multipath is highly correlated with the passing vehicles.

Our strategy for removing dynamic multipath noise is based on the fact that GPS and RTS are sensors with complementary characteristics, GPS suitable for measurement of relatively high-frequency oscillations, and RTS for low frequency displacements (Psimoulis and Stiros 2008, Psimoulis and Stiros 2012), In addition, the two sensors are affected by different types of noise, and in particular RTS is free from multipath which is a major threat for GPS. For these reasons we propose a weak fusion of these sensors in order to reconstruct GPS waveforms for bridge monitoring.

At first, time series of coordinates based on fully fixed GPS solutions excluding temporarily masked satellites and then time series of apparent displacements are computed. Then if the GPS deflection signals correlate with those deriving from RTS, a further investigation is made.

At a second step the RTS and GPS-derived times series of apparent displacements are analyzed into short- and long-period components using a simple technique (a moving average with step 0.1 second and a 4 seconds window) derived from experiments of supervised learning (Psimoulis and Stiros 2012). For RTS, the long-period component describes the semi-static displacement, while the short-period component is not always possible to be computed due to clipping. For GPS, the long-period component permits to compute the baseline offset, while the short-period component may be used for the reconstruction of the deflection waveforms, if the signal corruption is limited.

This condition is satisfied when the solution is of good quality (at least 6 satellites are continuously tracked and the PDOP is relatively low, up to the order of 2.5), and that the overall coordinate bias is relatively small, an absolute value of the ratio of an order up to 10 for apparent displacements of GPS and RTS (see Fig. 6). This corresponds to limited signal corruption which practically tends to produce a rather uniform multipath and a scale effect in the signal. In such cases, the overall distortion of the signal consists of a base offset correlating with the interval of the passage of the vehicle/train in front of the receiver, superimposed wide-base pulses with scale distortion and increased high-frequency noise. The scale distortion can be assessed from the spectral content of the GPS in comparison to that of RTS (Fig. 8) or eventually an accelerometer.

This algorithm can be easily modified to adapt measurements from other sensors, for instance an accelerometer (Meng *et al*. 2007, Kogan *et al*. 2008) or microwave/radar interferometers (Gentile and Bernardini 2008, Gikas 2012) etc, At a third step the displacement signal can be reconstructed from the RTS semi-static displacement and the short-period GPS displacement during the interval of the train passage corrected for a scale effect. The scale can be computed from the mean value of the GPS and RTS-derived peaks, using any peak-picking algorithm or more preferably the k-filter (Psimoulis and Stiros 2012). Despite clipping, this is possible because in the majority of cases RTS can record certain peaks (Stiros and Psimoulis 2012). The resulting time series is composed by the reliable semi-static component of displacement derived from RTS, its spectral content is assessed by independent data (RTS or accelerometer) and its amplitude is constrained by RTS. The details of calculations are presented in Appendix 1.

The above approach is suitable for the dynamic multipath produced by a series of reflective surfaces, several wagons of a train for instance passing in front of a nearby GPS antenna or a convoy of trucks, but for signals with mild corruption (see Fig. 6). There are cases, however, of isolated vehicles producing a short signal of the type of a travelling pulse. In such cases, apart for an obvious base offset correction, the GPS signal may be directly corrected for the scale effect from the amplitude of the RTS and GPS peaks (see Fig. 1, event a).

In the present study the proposed methodology for correction of GPS measurements was applied for a railroad bridge where a very low train velocity is permitted (20-35 km/h, see paragraph 4), compared with modern standards (velocities above 100-200km/h (Xia and Zhang 2005, Zhang *et al.* 2008)). Higher train velocities will result in a higher appearance frequency of displacement peaks (more than 2-3 peaks per second see Fig. 10 in Xia *et al*. (2003) and Fig. 19 in Zhang *et al.* (2008)). As displacement peaks of several millimeters appearing with a frequency of 2-3 Hz have been recorded in the past by GPS (Psimoulis *et al*. 2008), even for higher train speeds the waveform of the bridge displacement is expected to be well described by GPS measurements, permitting the application of the methodology presented in the present study.

The technique is discussed for vertical displacements, but it can be applied also to horizontal displacements of bridges, which are more common than previously thought (Brownjohn *et al*. 1992, Xia and Zhang 2005, Lee *et al*. 2006, Macdonald 2009, Moschas and Stiros, in press b), and the corresponding GPS estimates are less noisy (c.f. Fig. 3).

6. Algorithm

The technique proposed above can be summarized in the following algorithm. The threshold values in steps 1, 4 and 5 have been derived on the basis of the analyzed data but seem not confined on the examined case study as the measurement conditions were very typical of similar structural monitoring applications.

Step 0: GPS and RTS apparent displacements are available

Step 1: It is examined whether there exist significant differences in the GPS and RTS, (difference by a afactor of 10 between GPS and RTS). If not, the algorithm terminates.

Step 2: If a significant difference exists GPS data are reprocessed excluding satellites that are temporarily masked by passing vehicles.

Step 3: The new solution is then tested again as in Step 1.

Step 4: In the case of long (>1-2 sec) signals, the long-period component of the new solution is computed. If the absolute value of the ratio of the mean offset to the corresponding long-period component of the RTS is larger than 10 and the solution is not good (less than 5-6 satellites tracked and PDOP >2.5-3.0) the algorithm terminates. In the case of short signals (isolated vehicles) instead of the long-period component, the peak values form the GPS and RTS are compared.

Step 5: The spectral content of the short-period component of the GPS is compared with that of RTS or of an accelerometer, if available. If the two spectra are very different (different dominant spectral peak in GPS and RTS spectra) the algorithm terminates.

Step 6: Corrected waveform from GPS and RTS data fusion is computed using the equations shown in Appendix 1 for long waveforms, and peak to peak ratio for pulse-type peaks (isolated vehicles).

Step 7: End of the algorithm

7. Conclusions

Signal corruption mainly because of multipath is a serious problem for the measurement of displacements of bridges using GPS in the case of relatively stiff constructions. Based on field data and systematic experiments we have been able to show that signal corruption is due to two major effects, (i) changes in the geometry of satellites which can be faced by entirely excluding satellites which get temporarily blocked by passing vehicles thus preventing instantaneous change of satellite constellation during the vehicle passage, and (ii) dynamic multipath, different from the static multipath, which seems to have a typical pattern, but amplitude of its components depending on the geometry of observed satellites.

In cases of limited corruption of the GPS signal by dynamic multipath, an algorithm which permits to reconstruct the displacement time-series using a weak fusion of GPS and RTS data is proposed.

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Appendix 1

Data fusion equations:

We assume two time series of apparent displacements u(t) for GPS and x(t) for RTS for a certain axis.

Using a high-pass filter (a moving average with a window length of 4seconds and step of 0.1 second , see (Moschas and Stiros (2011) and Psimoulis and Stiros (2012)) we decompose these two time series into long period-components, $u_l(t)$ for GPS and $x_l(t)$ for RTS, and into short period components ($u_s(t)$ for GPS and $x_s(t)$ for RTS).

For the interval of multipath bias (coinciding with the trains or other vehicles passing in front of the GPS/RTS), the semi static displacement is defined as an average of the RTS long-period component during the whole interval ($x_{l,0}$). The equivalent value for the GPS ($u_{l,0}$) represents a base offset due to errors in GPS measurements.

The scale correction factor α is computed from from Eq. (1) and scaling of the GPS short-period component is based on Eq. (2). Finally the time-history of the bridge deflections is reconstructed by superimposition of the RTS semi static displacement and the corrected (scaled) short-period component of the GPS apparent displacements (Eq. (3)).

$$a = \frac{x_{l,o}}{u_{l,o}} \tag{1}$$

$$u_{dyn}(t) = a u_s(t) \tag{2}$$

$$y(t) = x_l(t) + u_{dyn}(t) \tag{3}$$