Potential of Detecting Dynamic Motion by Analysing SNR of GPS Satellite Signals

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Key words: SNR, GPS Records, Monitoring, Spectral Analysis

SUMMARY

High-accuracy GPS monitoring applications suffer from various biases, errors and signal attenuations which include multipath, obstructed satellites, etc. These factors significantly reduce the accuracy of the estimated position and/or displacement. Several methods and techniques have been developed by the authors to limit the noise of the GPS measurements and increase their accuracy and reliability, such as filtering the GPS time series for frequencies below 0.1 Hz to remove the noise due to the multipath effect. This study investigates the potential of using the signal-to-noise ratio (SNR) of the GPS records to detect motion and the corresponding frequency.

Several experiments of vertical excitations recorded by GPS receivers, have been carried out with the amplitude and frequency of the excitations varying from 8 mm to 4.5 cm and 0.01 to 1 Hz, respectively. The spectral analysis of the SNR of the GPS records successfully detected the frequency of the motion even for the excitations of small amplitude (< 1 cm) or low-frequency (i.e. < 0.1 Hz). This approach was also applied to the GPS records of a pedestrian bridge monitoring project, showing that the natural frequency of the bridge (i.e. 1.64 Hz) and the frequencies of the semi-static motion (i.e. ~ 0.02 Hz) could be detected from the spectral analysis of the SNR of the GPS satellite signals. The position of the satellites, with respect the antenna environment, was observed to determine the motion reflection on their SNR data.

This new approach can be beneficial in cases of unreliable or even no fixed GPS positioning solution available (e.g. in a heavy multipath environment or in a lack of adequate visible satellites), and to detect very low-frequency motions (i.e. < 0.1 Hz), which until now were ignored or filtered out during the GPS time series analysis.

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1. INTRODUCTION

In the last decade the potential for using Global Positioning System (GPS) in Structural Health Monitoring (SHM) has been revealed through experimental studies, which proved its ability in monitoring oscillations of sub-cm level displacement and high-rate frequencies (Çelebi and Sanli 2002; Häberling et al. 2015; Psimoulis et al. 2008), and applications to real monitoring of bridges (Larocca et al. 2016; Meng et al. 2007; Moschas and Stiros 2015) and tall buildings or towers (Breuer et al. 2008; Tamura et al. 2002), where the GPS monitoring was successfully used to estimate the main characteristics of the structures response.

However, the multipath effect has a significant impact on GPS monitoring, mainly in bridges, due to reflections of the satellite signals from structural elements (e.g. cables, tower, truss, etc.) before reaching the GPS antenna, introducing noise or bias into the GPS time series.

Although multipath interference is generally one of the greatest GPS error sources, it can be used favourably in GPS/GNSS monitoring applications. In recent years, GNSS-reflectometry introduced a new approach using the multipath effect for remote sensing (Bilich and Larson 2008; Chew et al. 2014; Larson et al. 2009; Roussel et al. 2016). These applications are based on the SNR sensitivity to carrier phase multipath. More specifically, while the direct signal reception remains constant, the characteristics of the multipath component of SNR (amplitude, phase, frequency) change according to the relative distance between the antenna and the reflecting object (e.g. the ground, the sea or the snow surface).

In the current study, the above principle of GPS-reflectometry is adapted to GPS structural monitoring applications through analysing the SNR variations in GPS satellite signals caused by multipath interference to detect frequencies of motion of structures.

2. SIGNAL-TO-NOISE RATIO AND CARRIER PHASE MULTIPATH

The multipath effect remains a dominant error source in GPS kinematic and structural monitoring applications. Multipath errors occur when the direct signals from the satellites interfere with those reflected from objects in the vicinity of the antenna. In the case of carrier phase multipath, the reflected signals introduce a phase shift to the received signal caused by the additional path they cover to reach the antenna. When the antenna oscillates vertically (Figure 1), the reflection point, also, oscillates with the same frequency across the reflecting surface, e.g. the ground. Assuming the satellite elevation angle fixed for a short period of time, the change in the path length of the reflected signal is only driven by the change of the antenna height (ΔH):

$$\delta_{i+1} - \delta_i = 2\Delta H sin(\theta) \tag{1}$$

The signal-to-noise ratio (SNR) is a measure of the signal power relative to the noise power and it is given by the receivers for each frequency channel. Assuming one main signal reflection, the SNR is a function of the composite signal (direct + reflected signal) and can be expressed as follows:

$$A_c^2 = A_d^2 + A_m^2 + 2A_d A_m \cos(\psi) \tag{2}$$

Where A_c is the amplitude of the composite signal, A_d is the amplitude of the direct signal, A_m is the amplitude of the reflected signal and ψ is the phase of the multipath signal relative to the direct. The multipath relative phase is directly related to the path delay of the reflected signal as follows (Georgiadou and Kleusberg 1988):

$$\psi = \frac{2\pi}{\lambda}\delta \tag{3}$$

The dynamic multipath effect caused by the vertical oscillation of the antenna leads to variations on the path delay of the reflected signal (equation 2) and eventually, variations on the multipath relative phase (equation 3). At the same time, the phase of the direct signal changes as the antenna oscillates. The resulted amplitude variations of the composite signal are expected to introduce an oscillatory pattern in the SNR measurements.

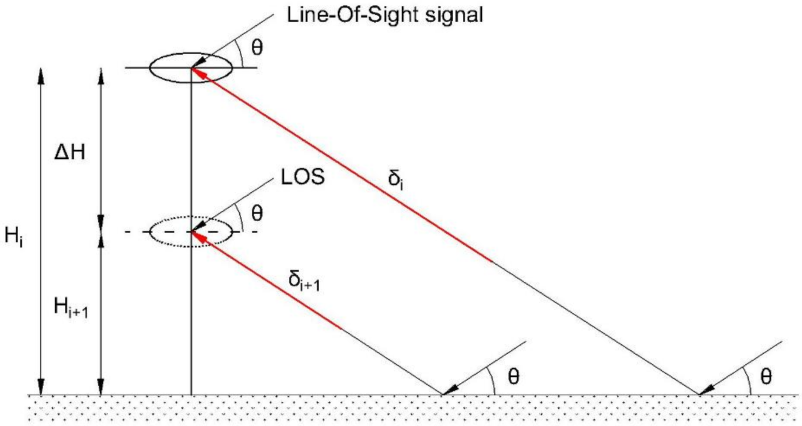

Figure 1. Geometry of ground reflections for a vertically moving antenna

3. EXPERIMENTS OF VERTICAL ANTENNA MOTION

3.1 Description of experiments and preliminary processing

The experiments were carried out on the roof of the Nottingham Geospatial Building located at the University of Nottingham (Figure 2). A GPS antenna was mounted on a heavy-duty tripod, where the height was adjustable using a manually rotating handle. A GPS station consisted of a Leica GS10 receiver recording at 10 Hz and an AR10 antenna installed on the tripod, while a GPS base station was set up on a concrete pillar 30 m away. Additionally, a Robotic Total Station (RTS) with a sampling rate capacity of 10 Hz was recording the motion, using a 360° prism mounted on the tripod below the GPS antenna.

A series of excitations were executed, simulating oscillation-pattern motions and semi-static pattern motions of bridges. The GPS antenna was subjected to various amplitudes and frequencies of vertical motion, ranging between 0.4 to 4.5 cm and 0.007 to 1 Hz, respectively, depending on the type of the excitation. The oscillation-type excitations reached up to 1 Hz, while the semi-static type excitations were of a very low frequency (< 0.1 Hz).

The GPS records were processed in the RTKLIB software using double differences and a cut-off angle of 10° to fix the ambiguities of both L1/L2 frequencies, resulting to the North, East and vertical component time series of the baseline vector. The SNR data of the GPS records used in the analysis derived from the S1 observable recorded in the RINEX file. The raw SNR data were converted from dB-Hz to a linear unit, i.e. voltage (V). After the unit conversion, the derived SNR time series have a dominant trend of parabolic pattern, expressing the change of the direct signal component of SNR due to the motion of the satellite along its orbit (Bilich and Larson 2008). The dominant trend was removed by subtracting a third degree polynomial from the SNR time series (Figure 3a) and the residual SNR time series express the variation due to multipath and antenna motion (Figure 3b).

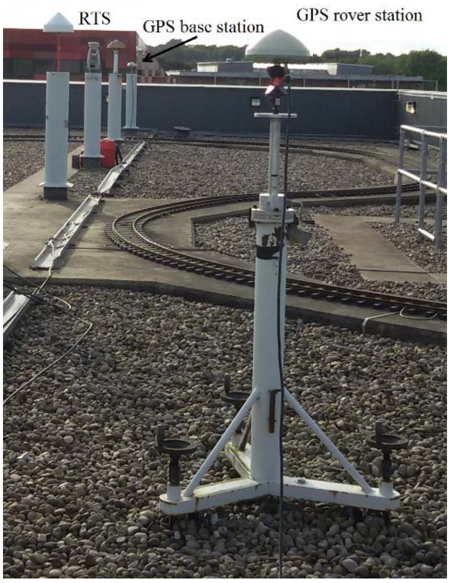

Figure 2. Experiment set-up consisting of the GPS antenna and the 360° prism mounted on a heavy-duty tripod, the GPS reference station and the RTS.

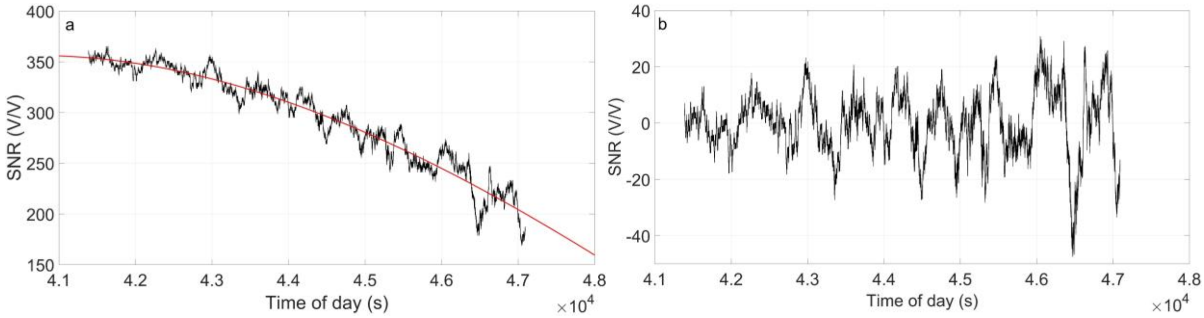

Figure 3. (a) SNR L1 time series for PRN 27 (black line) and the 3rd degree polynomial (red line) fit to the data to remove the direct signal effect, resulting to (b), the de-trended SNR residual time series.

3.2 Oscillation-type excitations

The SNR time series of several satellites recorded during the oscillation-type excitations (> 0.1 Hz) were observed to reflect oscillation patterns of similar frequency to the vertical oscillations imposed on the GPS antenna. Figure 4 presents the SNR de-trended time series for PRN 10 in an example of antenna motion, where the oscillation pattern of the excitation is visible also in the de-trended SNR time series.

3.3 Semi-static type oscillations

The semi-static excitations, which were expressed as low-frequency (< 0.1 Hz) step-pattern motions, are not easily distinguished in the raw SNR time series, since the SNR of the satellite signal is more susceptible to low-frequency noise, having a similar pattern to that caused by motion. However, in the executed experiments, there were identified cases where the vertical motion of the GPS antenna was reflected in the raw SNR time series. More specifically, Figure 5 presents the GPS and RTS displacement time series of four semi-static type excitations and the corresponding raw SNR time series of satellites PRN 27, PRN 22 and PRN 01. It is clear that the raw SNR time series of PRN 22 reflect the third and fourth excitation, while the raw SNR time series of PRN 01 and PRN 27 reflect the first and fourth excitation, respectively. The trend of the SNR time series, which for the cases of PRN 27 and PRN 01 is reversed to the trend of the antenna height variations, is due to the specific satellite-antenna-reflector geometry causing the multipath effect.

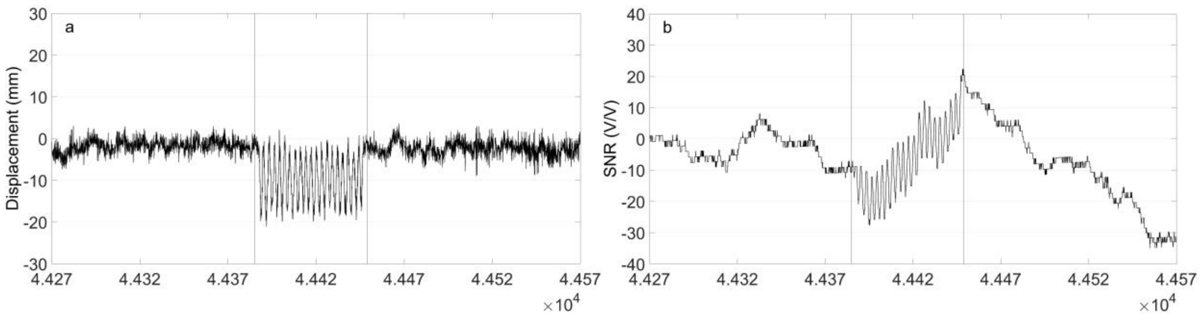

Figure 4. (a) GPS time series of vertical displacement and (b) SNR de-trended time series of satellite PRN 10 for antenna oscillations of 8 mm amplitude at 0.3 Hz.

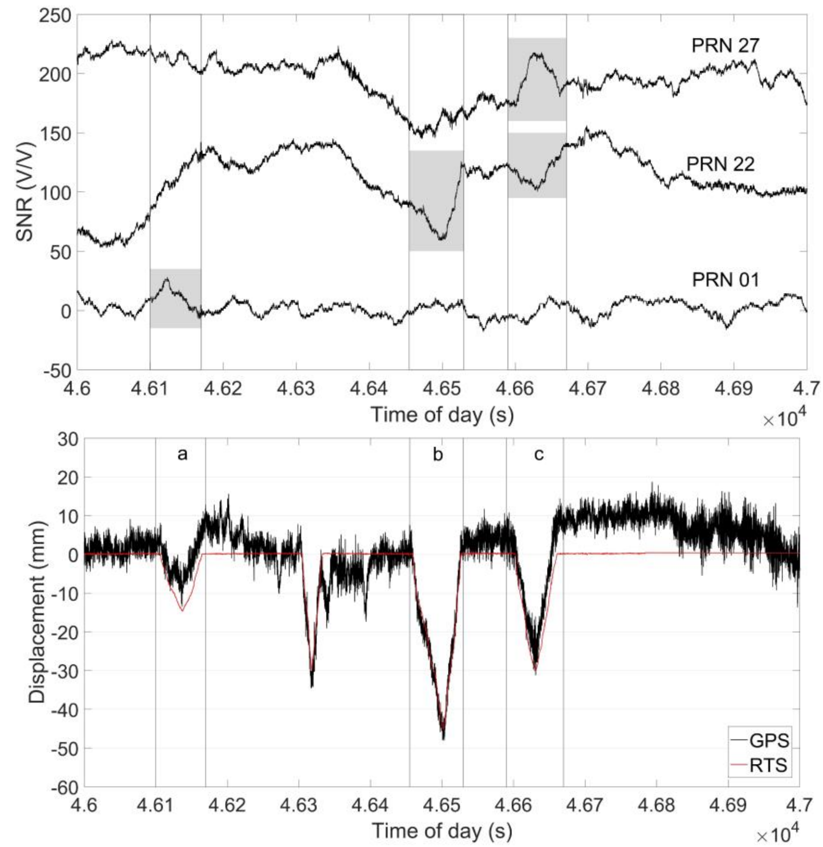

Figure 5. SNR de-trended time series for PRN 01, PRN 22 and PRN 27 offset on the y axis for clarity (top), corresponding GPS and RTS vertical displacement time series (bottom) and the highlighted intervals, denoted with coloured blocks, of semi-static type antenna motion of (a) 15 mm displacement and 130 s period, (b) 45 mm displacement and 145 s period and (c) 30 mm displacement and 125 s period.

4. MONITORING OF WILFORD BRIDGE

The Wilford suspension Bridge is a pedestrian bridge, with a 68.5 m long span consisting of a steel deck covered with wooden slabs and supported by two main cables and two masonry riverside anchorages. There have been many studies on GPS monitoring of Wilford Bridge estimating the main modal frequency to be about 1.68 - 1.74 Hz (Meng et al. 2007; Meo et al. 2006; Yu et al. 2014). Even though in some studies the amplitude of the dynamic displacement was estimated to be of cm-level, it was not possible to estimate potential semi-static displacement, due to the dominant long-period noise. For the monitoring of the Wilford bridge, three GPS receivers and two RTS were used. The two GPS antennae were mounted with two 360° reflectors on top of the handrails at the two sides of the mid-span and a third GPS antenna was set about 100 m away from the bridge, used as the reference GPS station for the double-difference solution.

The bridge was excited by a group of 15 people producing 13 excitations, of four different types (walking, jumping, swaying, marching). Figure 6 presents the GPS and RTS vertical displacement time series for the duration of the measurements, where it is clear that the GPS time series is contaminated by significant low- and high-frequency noise, due to signal obstructions (e.g. by the cables) and multipath, masking the response of the bridge during the excitations, while the RTS displacement time series were more precise containing of low-noise level and providing a clearer view of the deck deflection for the different excitations.

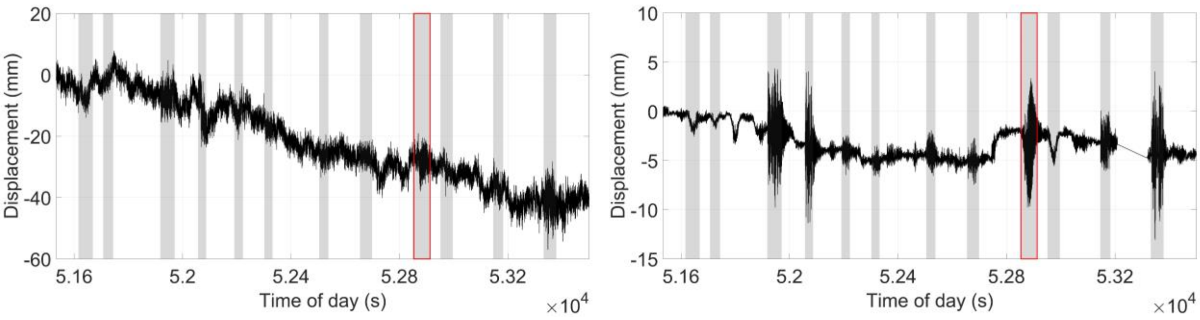

Figure 6. GPS (left) and RTS (right) initial vertical displacement time series during the experiment. The coloured zones indicate the intervals of the excitations and the red framed block indicate the marching excitation analysed in this study.

4.1 Marching excitation

The GPS and RTS displacement time series were filtered using a high-pass and a low-pass Type I Chebyshev filter at 0.1 Hz and decomposed to short-period and long-period components, expressing potentially the dynamic and semi-static displacement of the bridge (Figure 7), respectively. The spectral analysis of the initial GPS and RTS displacement time series corresponding to the marching excitation interval revealed a dominant peak at 1.64 Hz, which is the natural frequency of the bridge (Figure 8a). The spectral analysis of the SNR time series of PRN 18, PRN 24 and PRN 28 satellites, corresponding to the time interval of the excitation, also clearly revealed the peak of 1.64 Hz (Figure 8b).

Regarding the semi-static displacement, the RTS spectrum of the initial displacement time series revealed a peak at 0.018 Hz (Figure 9a), which is the frequency of the semi-static displacement time series shown in Figure 10d. The GPS spectrum of the initial displacement time series did not appear to have this frequency, but the SNR spectra of PRN 15, PRN 17, PRN 18 and PRN 24 showed a peak at 0.018 Hz (Figure 9b). The fact that the frequency of the semi-static displacement appeared in the spectra of the SNR time series, means that the corresponding displacement is contained in the GPS time series, masked though by long-period noise. Thus, based on the frequency detected in the SNR time series spectra, the initial GPS time series can be filtered accordingly to reveal the semi-static displacement. In the current case, a low-pass filter was applied to the GPS initial displacement time series with a cut-off frequency of 0.03 Hz, and the GPS semi-static displacement of a 2 mm amplitude was extracted, similar to the amplitude derived from the filtered semi-static displacement of the RTS time series (Figure 7b and d). As expected, the spectrum of the GPS low-pass filtered displacement time series exhibited a significant peak at 0.018 Hz (Figure 9a), which corresponds to the frequency of semi-static displacement (Figure 9b).

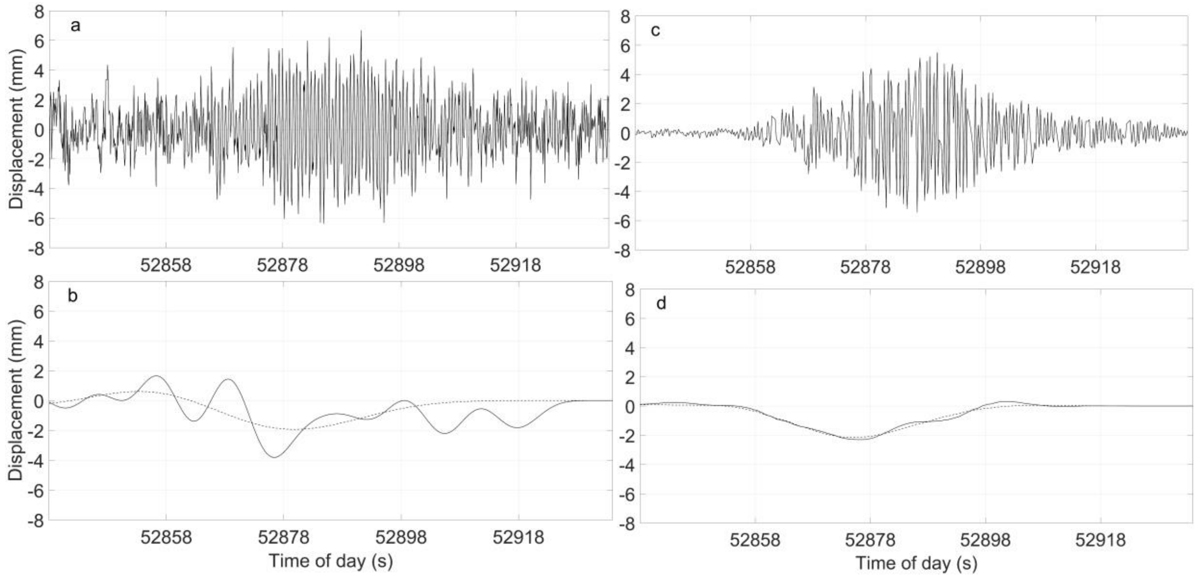

Figure 7. GPS (a) short-period and (b) long-period component and RTS (c) short-period and (d) long-period component for the marching excitation. The high- and low-pass filtered time series with cut-off frequency at 0.1 Hz are indicated with solid lines and the low-pass filtered GPS and RTS time series with cut-off frequency at 0.03 Hz are indicated with dashed lines.

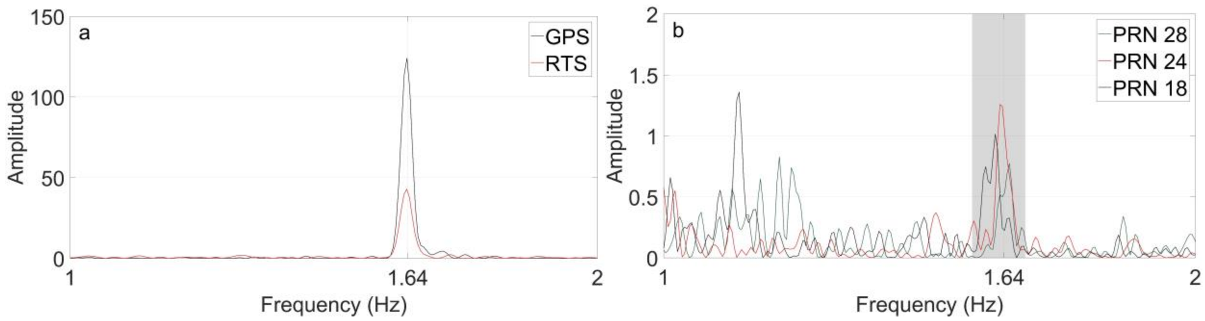

Figure 8. (a) GPS and RTS spectra and (b) SNR spectra for PRN 18, PRN 24 and PRN 28 in the interval of the marching excitation.

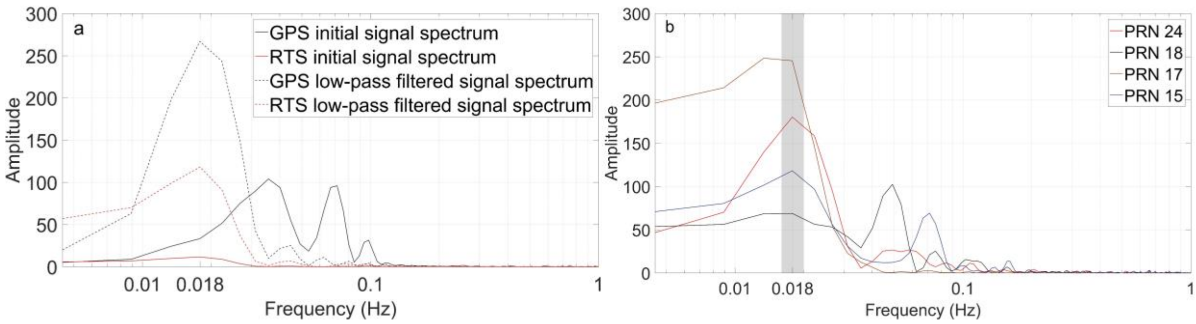

Figure 9. (a) GPS and RTS spectra of the initial displacement time series and spectra of the low-pass filtered GPS and RTS displacement time series at 0.03 Hz for the marching excitation, (b) SNR spectra for PRN 15, PRN 17, PRN 18 and PRN 24 in the interval of the marching excitation.

5. CONCLUSIONS

In this study, a new approach on the utility of the signal-to-noise ratio of GPS signals was proposed for GPS structural monitoring applications, focusing on the retrieval of frequencies of motion. Based on experiments of vertical antenna vibrations it was shown that SNR measurements can be sensitive to antenna motion of a few millimetre level at a wide range of frequencies. Additionally, the real bridge monitoring application showed the potential of the SNR of the GPS signal to reflect high- and low-frequencies of motion in the more complex situation of a real structural response.

6. ACKNOWLEDGEMENTS

The authors would like to thank Mr. Sean Ince, Dr. Lukasz Bonenberg and the MSc and MEng students, who participated on the monitoring of the Wilford Bridge.

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BIOGRAPHICAL NOTES

Ioulia Peppa is a Ph.D. student at the Nottingham Geospatial Institute, the University of Nottingham. Her research interests are in GPS/GNSS multipath detection and mitigation techniques on structural monitoring.

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Dr Xiaolin Meng is Fellow of the Royal Institute of Navigation and Chair of R&D Special Interest Group. He is Leader on Positioning and Navigation Technologies, and Autonomy at the University of Nottingham in the UK. He is the founding director of the Sino-UK Geospatial Engineering Centre, a dedicated international centre for technology exchanges with four branches in the UK and China. He has been Special Professor of the Chinese Academy of Surveying and Mapping, Wuhan University and Tongji University in China since 2004, 2006 and 2010, respectively. He holds a PhD in Highway, Urban Road and Airport Engineering from Tongji University in Shanghai in 1998, and a PhD in Space Geodesy from the University of Nottingham in 2002. He is the author of more than 250 journal and international conference papers and currently leading R&D projects of multi-million pounds. His research focuses include precision agriculture/Agri-Tech, structural health monitoring of long bridges, connected and autonomous vehicles, precise GNSS and Earth Observation for wide engineering and environmental applications, integrated location and sensing sensor systems for intelligent transport systems and services, location-based services, advanced geodetic data processing, etc. He has been chair for special study groups of the key international associations and sits on a number of editorial boards for international journals.

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