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THE MONITORING OF BRIDGE MOVEMENTS USING GPS AND PSEUDOLITES

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Abstract

For the monitoring of man-made structures, and specifically suspension bridges, it is desirable for the measurement system to deliver equal precision in all position components, all the time. When using GPS, the accuracy, availability, reliability and integrity of the position solutions is very dependent on the number and geometric distribution of the available satellites. Therefore the positioning precision is not the same in all three components, and large variations in positioning precision can be expected during a 24-hour period. This situation becomes worse when the line-of-sight to GPS satellites becomes obstructed, such as in urban environments.

Pseudolites can be used to augment GPS and improve a geometrically-weak satellite constellation, and in this paper the use of pseudolites to augment GPS signals for measuring the movements of suspension bridges is demonstrated. Experimental results and analyses are presented of a trial conducted at the Wilford suspension footbridge over the river Trent in Nottingham, UK.

It is shown that by using pseudolites to improve the existing satellite constellation that similar precision (sub-cm) can be achieved in both horizontal and vertical position components.

1. Introduction

One deformation monitoring application in structural engineering is measuring the movement of suspension bridges. Under unfavourable wind conditions or heavy traffic loads cable suspension bridges may move up to a few metres. Therefore, a positioning system used to monitor bridge movements can provide extremely valuable information. This information can be used to warn of dangerous conditions and estimate the long-term deterioration of the structure. Additionally, this information is of value to bridge designers and for traffic management.

The Global Positioning System (GPS) has been used for many years for the deformation monitoring of man-made structures such as bridges, dams and buildings, as well as geodetic applications, including the measurement of crustal motion, and the monitoring of ground subsidence and volcanic activity. The very precise carrier phase measurements can deliver cm-level positioning accuracy. However, when using GPS, the accuracy, availability, reliability and integrity of the position solutions is very dependent on the number and geometric distribution of the available satellites. In some situations, such as the monitoring of structures in built-up urban environments, the availability of GPS satellites may be insufficient for positioning requirements. Also, due to the geometric distribution of the GPS satellite constellation and the fact that GPS data below approximately 15 degrees are typically not used, the accuracy of the height component is generally 2 or 3 times worse than for the horizontal components. Additionally in mid and high latitude areas (>45 degrees) the accuracy in the North component is worse than the East component, due to the 55 degree inclination of GPS satellites (Meng et al., 2002).

One option to improving the satellite geometry is to use ground-based transmitters of GPS-like signals (called "pseudolites" or PLs). PLs can be optimally located to provide additional ranging information, and therefore improve the positioning precision. In addition, with enough PL devices (four or more) positioning without any GPS satellites is possible.

The Satellite Navigation and Positioning (SNAP) group at The University of New South Wales (UNSW) has been actively conducting research into high precision combined kinematic GPS-PL for the past three years. This has led to the development of innovative carrier phase single-epoch software that can process both GPS and PL data. Due to the comparatively small separation between PLs and user receivers, there are some challenging modelling issues, such as non-linearity, PL location errors, tropospheric delays, multipath and noise. These issues have been discussed in a series of papers by SNAP researchers (Barnes et al., 2002a; Wang et al., 2000, 2001; Dai et al., 2000). In addition, not all GPS receivers can track PL signals, and there are near-far signal strength issues. Because of these difficulties PLs are not yet a mainstream 'off-the-shelf' technology.

Deformation monitoring is one application where SNAP has explored the use of PLs (Barnes et al., 2002b; Dai et al., 2000). More recently the SNAP group, together with the IESSG at Nottingham University (UK), have been conducting research into the use of PLs for the monitoring of suspension bridges. The IESSG have been interested in the monitoring of suspension bridges using GPS and accelerometers for the past few years, and their research is documented in such papers as Meng (2002), Meng et al. (2002), Dodson et al. (2001). In this paper the results and analyses are presented of the augmentation of GPS with PLs for a trial conducted on a suspension footbridge.

2. Wilford suspension footbridge trial

The Wilford suspension footbridge crosses the river Trent in Nottingham, UK, has previously been used in other trials by the IESSG (see Dodson et al., 2001, for details). To test the suitability of a PL-augmented GPS system for bridge monitoring, a test was conducted at the Wilford suspension footbridge on 16 October 2002. Three IntegriNautics IN200 PLs (PL12, PL16 and PL32) were used in the trial, and their configuration is illustrated in Fig. 1. The locations of the PLs were selected so that there was a clear line-of-sight to both the reference receiver antenna (base) and the bridge antenna (rover). Additionally, their location was selected so as to be easily surveyed by GPS (ie a relatively unobstructed view of the sky). Practical locations of the PLs was limited to the footpaths alongside the bridge, which were at negative elevation angles to the rover antenna. Also, the location of one PL (PL12) meant that the line-of-sight signal to the base antenna passed through one of the bridge arches, as indicated in Fig. 2. The elevation angles of the PLs from the base antenna were close to zero, and Table 1 lists the elevation and azimuth angles, and distance, of the PLs from both the base and rover antennas.

	Elevation (Deg.)		Azimuth (Deg.)		Distance (m)	
PRN	from base	from rover	from base	from rover	from base	from rover
PL12	0.2	-7.4	30.7	313.2	72.3	44.2
PL16	0.7	-4.1	68.1	72.1	135.7	29.8
PL32	0.5	-3.1	58.9	53.3	157.4	82.3

Table 1. Pseudolite geometry with respect to base and rover.

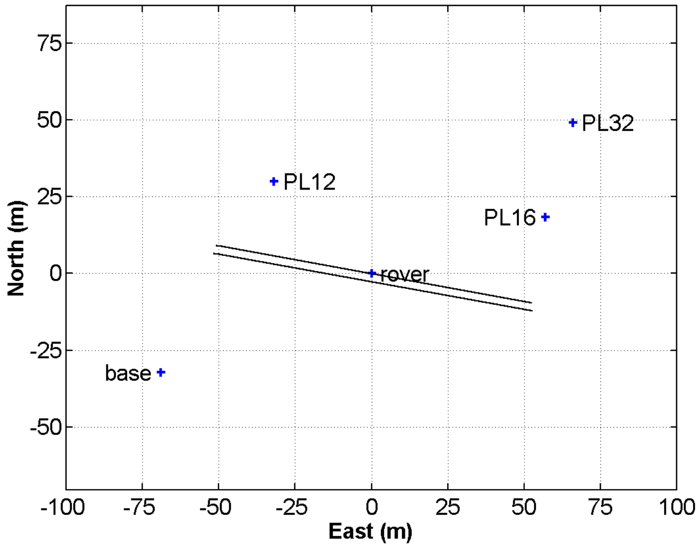


Figure 1. Location of GPS receivers and pseudolites.

Two types of GPS receivers were used in the trial, and connected to the same Leica AT502 antenna via a splitter. The low-cost (few hundred $US) single-frequency OEM Canadian Marconi Corp. (CMC) Allstar receivers were used to track the PL and GPS signals, while the Leica SR530 receivers tracked only the GPS satellite signals. The Allstar receiver allows the user to request particular PRN codes to be tracked, and this is a basic requirement for a PL-tracking GPS receiver. The Leica receivers were used to provide an independent check on the quality of the GPS data from the CMC receivers and their dual-frequency capability would enable ambiguities to be resolved kinematically On-The-Fly (OTF). Figs. 2 & 3 show the base, rover and PL locations for the trial.

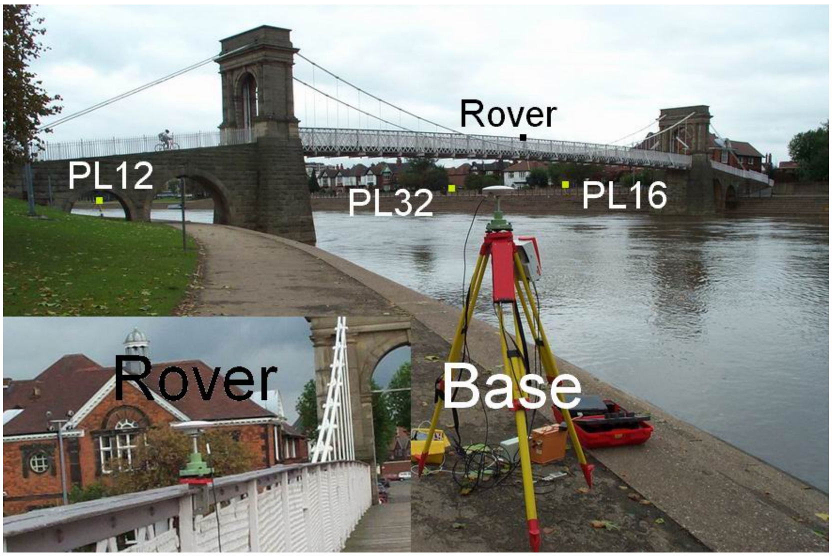


Figure 2. Pseudolite locations in relation to base and rover GPS receivers.

Figure 3. Locations of three pseudolites on the river bank footpaths.

The PLs were assigned GPS PRN codes 12, 16 and 32, and operated in a pulsed mode with a 10% duty cycle. Their power was adjusted to give good signal-to-noise ratios (above 45-dBHz) at both the base and rover, and not too strong so as to jam the GPS signals. All PLs used passive patch antennas, manufactured by Micropulse. During the test both the Allstar and Leica receivers collected approximately 50 minutes of data at a 1Hz sampling rate. The Leica receivers were also used to survey the locations of the PLs.

2.1 Geometry analysis of GPS and pseudolite augmented GPS

There were between 4 and 5 satellites available above 15 degrees during the trial, and Fig. 4 shows the elevation and skyplot of the satellite and PLs, with respect to the rover. It is useful to investigate the geometry of the GPS satellites during the trial, and the improvement due to the PL augmentation at the rover antenna. Figs. 5a & b show the Dilution of Precision in East, North and Vertical directions, together with the number of SVs/PLs available. (The information related to the DOP values is also summarised in Table 2.) From Fig. 5a it is clear that the drop in the number of GPS satellites from 5 to 4 has a major impact on all the DOP values. The mean DOP values indicate that the worst geometry is in the Vertical component (3.7), then North (2.1), and best in East (1.1). With the addition of the three PLs, the drop in number of satellites from 5 to 4 has less of an impact on the DOP values, as indicated in Fig. 5b, and the mean DOP values are all less than 2 (Table 2). The best geometry improvements are in the Vertical (58%) and East (46%), and the least improvement is in North (20%). Moreover, the average DOP in the Vertical (1.5) is slightly better than in the North (1.7), when GPS is augmented with PLs.

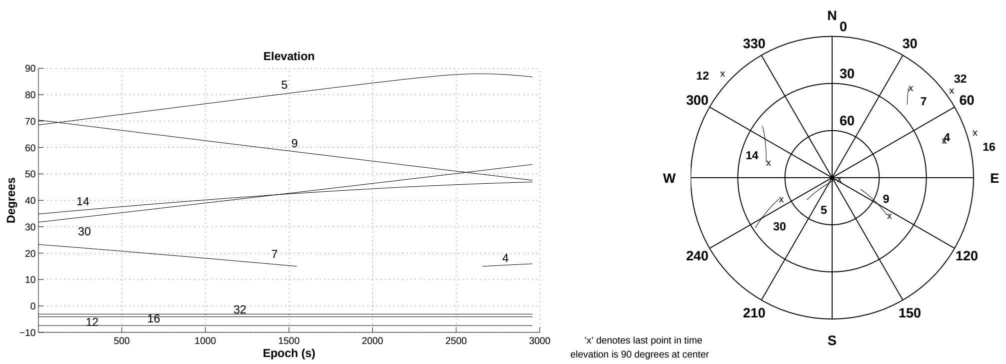
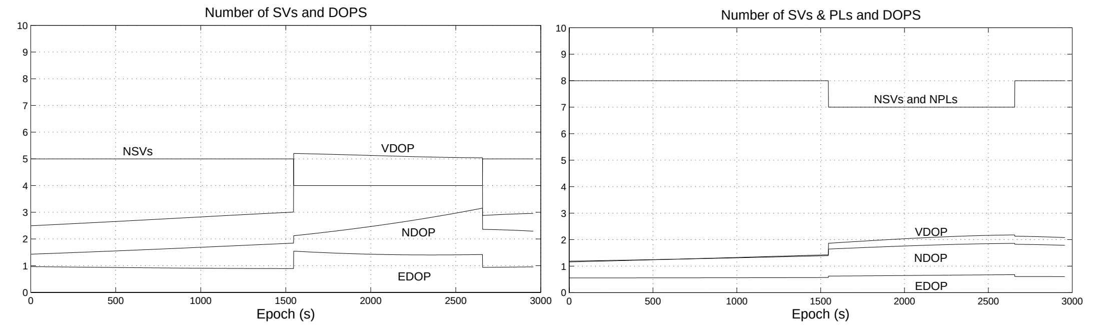


Figure 4. Elevation and skyplot of GPS satellites and pseudolites with respect to rover.



(a) GPS-only. (b) GPS augmented with pseudolites.

Figure 5. Dilution of precision with respect to rover.

		Solution			
		GPS-only	GPS-PL	% Diff.	GPS-PL no SV30
No. SVs, PLs		4-5 SVs	4-5 SVs, 3 PLs		3-4 SVs, 3 PLs
	Max	1.5	0.7		1.0
EDOP	Min	0.9	0.6		0.6
	Mean	1.1	0.6	46	0.7
	Max	3.2	2.2		3.6
NDOP	Min	1.4	1.2		1.8
	Mean	2.1	1.7	20	2.4
	Max	5.2	1.9		2.6
VDOP	Min	2.5	1.2		1.5
	Mean	3.7	1.5	58	1.9

Table 2. Summary of DOP values for GPS-only and GPS augmented with pseudolites.

2.2 Data Processing and pseudolite multipath error

The PL and GPS data was processed using the baseline software developed by SNAP at the UNSW. For all the data processing a satellite elevation mask of 15 degrees was used, and the final solution type was L1 double-difference ambiguity-fixed. For PLs used in a static environment, over short distances, multipath is the dominant error and theoretically is a constant. Therefore, it is necessary to determine any multipath biases associated with the PL data before using them in position computations. In order to compute the multipath biases it was assumed that any small bridge movements would not significantly affect the PL multipath bias. Using only the GPS data from the Allstar receiver, the static coordinates of the rover were determined. Then, using the computed rover coordinates, carrier phase double-differenced residuals were computed for the GPS and PL data using SV5 as a reference satellite (assumed to have no long term biases). Plots of double-differenced residuals for the PLs and satellites are given in Figs. 6 & 7 respectively. The double-differenced residuals for the satellites are as expected, with small mean values (less than 8.3 mm) indicating no significant biases. There are visually some small time series fluctuations, which are possibly due to bridge movement and/or multipath. It is clear from Fig. 6 that the PL double-difference residuals have significant constant biases, caused by the multipath. The mean values of the time series, in millimetres, are 47.2 (PL12), 29.8 (PL16) and –13.8 (PL32). The largest bias is for PL12, and could be due to the fact that the line-of-sight passes through one of the bridge arches (Fig. 2), as noted previously. Using the mean values, the PL data was corrected for the constant bias (due to multipath). Finally in the data processing, three different types of single-epoch kinematic solutions were computed for the rover: GPS-only Leica, GPS-only Allstar, GPS-PL

Allstar. The initial L1 ambiguities of the single-frequency data were resolved using the previously computed static coordinate of the rover.

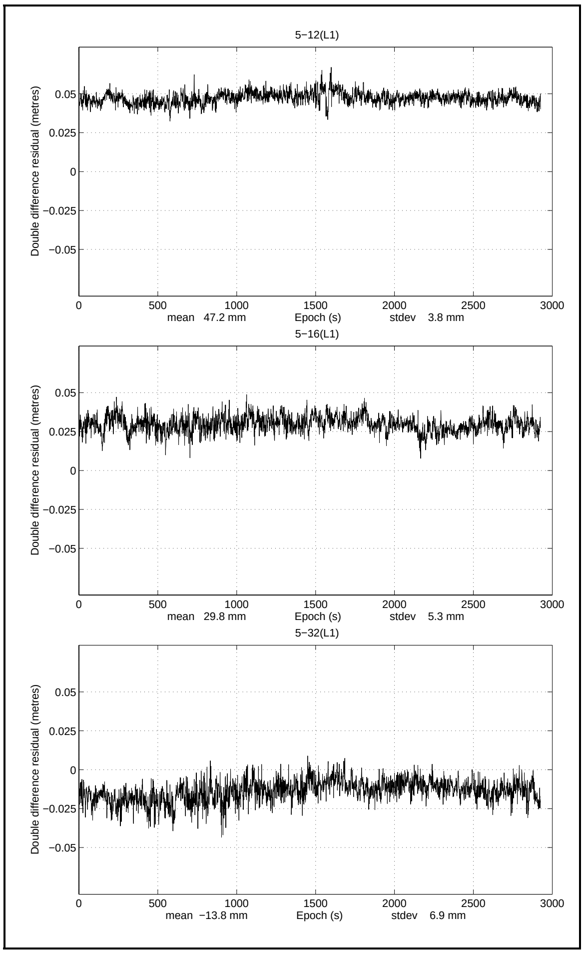


Figure 6. PL DD residuals.

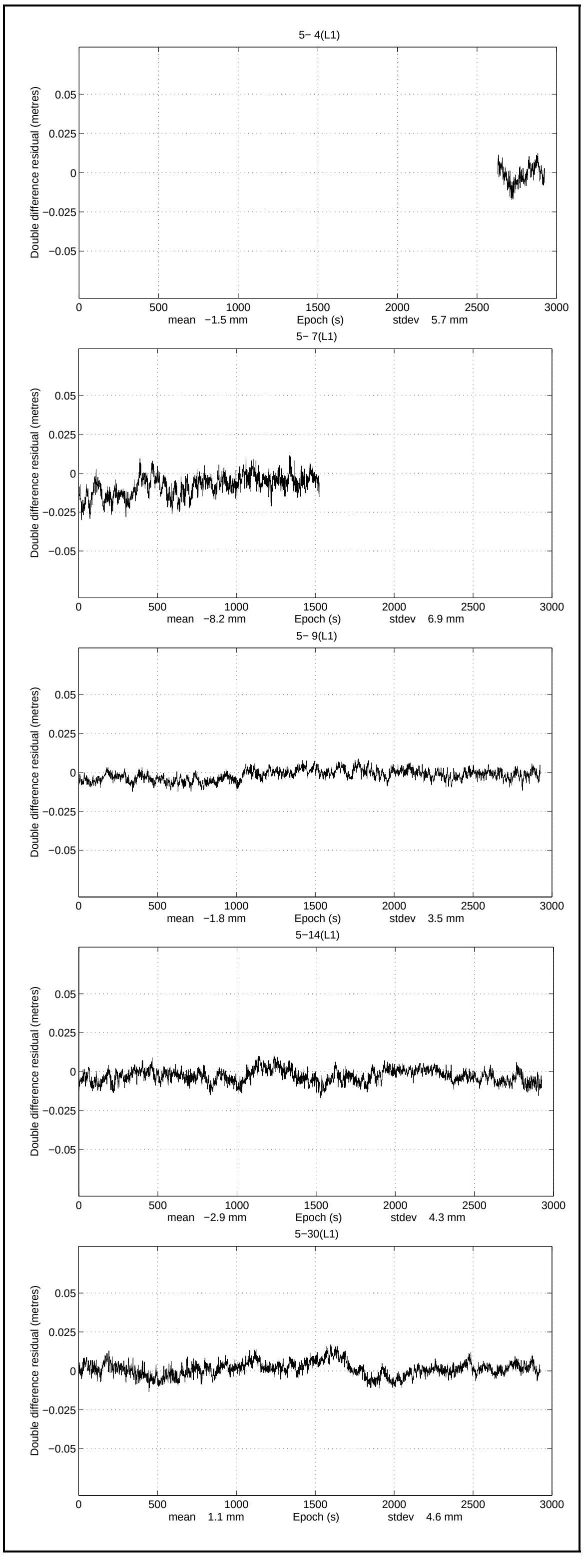


Figure 7. GPS DD residuals.

2.3 Results of GPS-only positioning

Figs. 8 & 9 show the GPS-only positioning results in East, North and Vertical (mean centred) for the Leica and Allstar receivers respectively. Visually comparing the position time series for both receivers it is clear that the fluctuations in both are very similar, but there is less noise in the Allstar solution. The standard deviations of the Allstar solution are between 7 and 12% smaller than those of the Leica (Table 3). This shows that the low-cost Allstar receiver can provide good quality L1 carrier phase data. From the position time series it is also clear that the precision in the Vertical and North are worse than the East, with standard deviations approximately two times larger. From the geometric analysis in section 2.1 this result is as expected, with best to worst precision in the position components of East, North, Vertical.

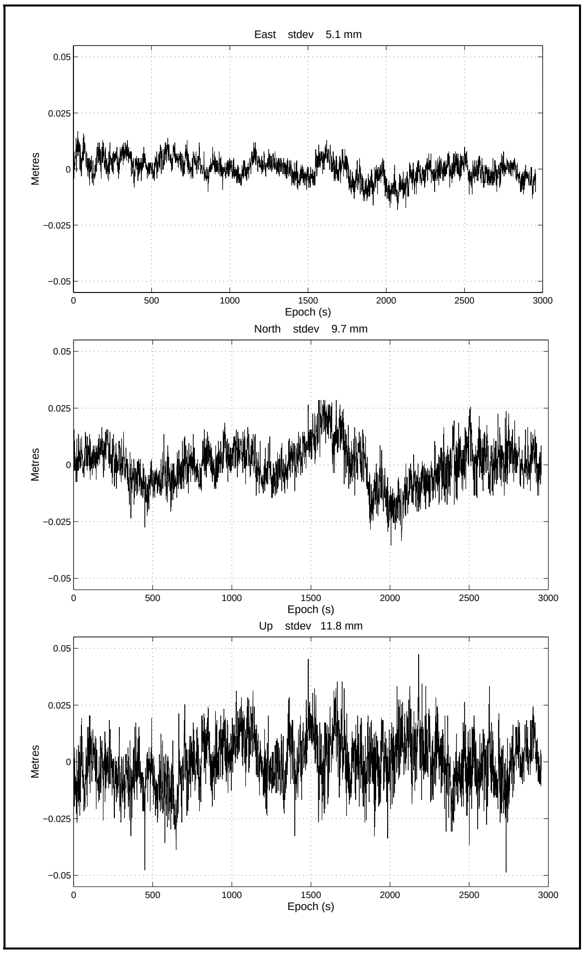


Figure 8. Leica SR530 GPS-only positioning result in East, North and Vertical.

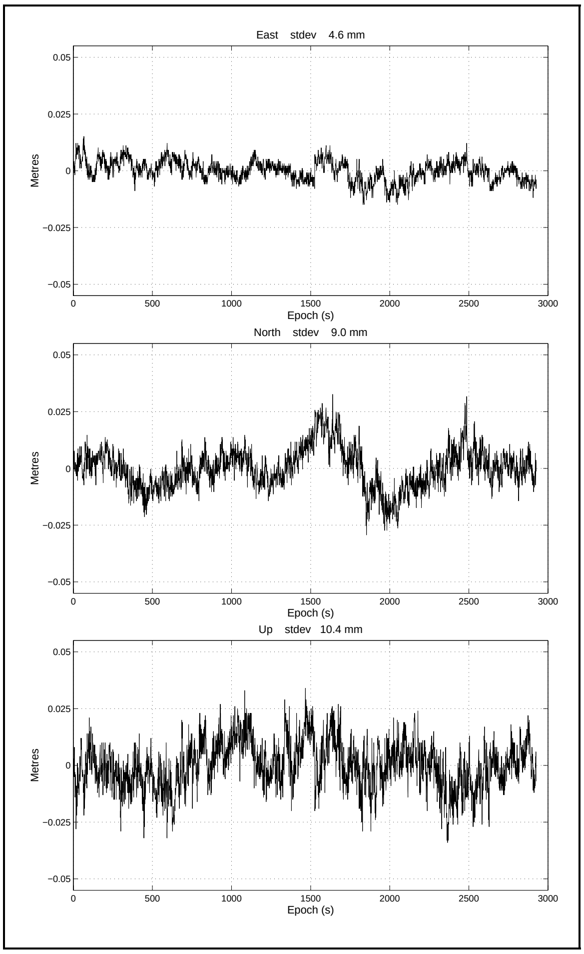


Figure 9. CMC Allstar GPS-only positioning result in East, North and Vertical.

L1 single epoch solution type	Standard deviation (mm)			% Diff. of upper two solns.		
	East	North	Vertical	East	North	Vertical
Leica GPS-only (4-5 SV)	5.1	9.7	11.8			
Allstar GPS-only (4-5 SV)	4.6	9.0	10.4	10	7	12
Allstar GPS-PL (4-5 SV, 3 PL)	2.7	8.5	7.2	41	6	31

Table 4. Standard deviations of East, North and Verical time series for GPS-only and GPS-PL.

2.3 Results of GPS-PL positioning

Fig. 10 shows the PL-augmented GPS solution (GPS-PL) positioning results for East, North and Vertical from the Allstar receiver, and Table 4 gives the standard deviations of the position time series. The standard deviations in the East component are less than 3mm and smaller by 41% in comparison to the GPS-only solution. Also, many of the fluctuations present (probably due to multipath) in the GPS-only time series have been reduced. In the Vertical component time series the standard deviation is now 7.2mm (sub-cm) and smaller than the GPS-only solution by 31%. Visually the fluctuations in the Vertical component time series have changed significantly and are similar to the North time series. The standard deviation in the North component is smaller using the PL data, but only by 6%. Moreover, the standard deviation in the Vertical component is better than the North. From the geometric analysis in section 2.1 this result is as expected, with best to worst precision in the position components of East, Vertical, North. However, the percentage improvements in the East, North and Vertical standard deviations when using PLs are less than those expected from the geometric analysis (see Tables 2 & 4). This is also expected, because the PL and satellite measurements do not have exactly the same precision and are not completely uncorrelated. It is worth noting that the standard deviations of the double-differenced residuals for PLs 16 and 32 were significantly greater than PL12, and the reason for this is not known (all PLs had similar SNR values).

2.4 Analysis of GPS-PL result

Does the GPS-PL solution time series correctly depict the actual movements of the bridge? For this it is useful to consider the orientation of the bridge with respect to the position components. From Fig. 1 it can be seen that the length of the bridge runs approximately in an East-West direction. Therefore movements in the East-West direction are expected to be small, and this clearly is the case in the East time series plot (Fig. 11). On the other hand Vertical and North movements of the bridge *are* expected. However, some of the fluctuations in the North and Vertical time series are very similar and of very low frequencies (approximately 1000 seconds). Because of these two factors the very low frequency fluctuations in the North and Vertical time series are *unlikely* to be actual bridge movement. Instead, it is believed that the fluctuations are due to multipath present in satellite 30. Visually comparing the double-differenced residuals for satellite 30 in Fig. 7 with the North and Vertical time series in Fig. 8, the fluctuations present are extremely well correlated. The data was also processed with satellite 30 removed, giving measurement data from 3-4 GPS satellites and 3 PLs. However the standard deviations of the position solutions became worse, especially in the North. Through geometric analysis this is expected (see Table 2), because the North DOP with this processing configuration is worse than when satellite 30 is included in both the GPS-PL and GPS-only solutions. In this trial GPS satellite 30 was critical to the North geometry and its multipath error propagated into the positioning solution.

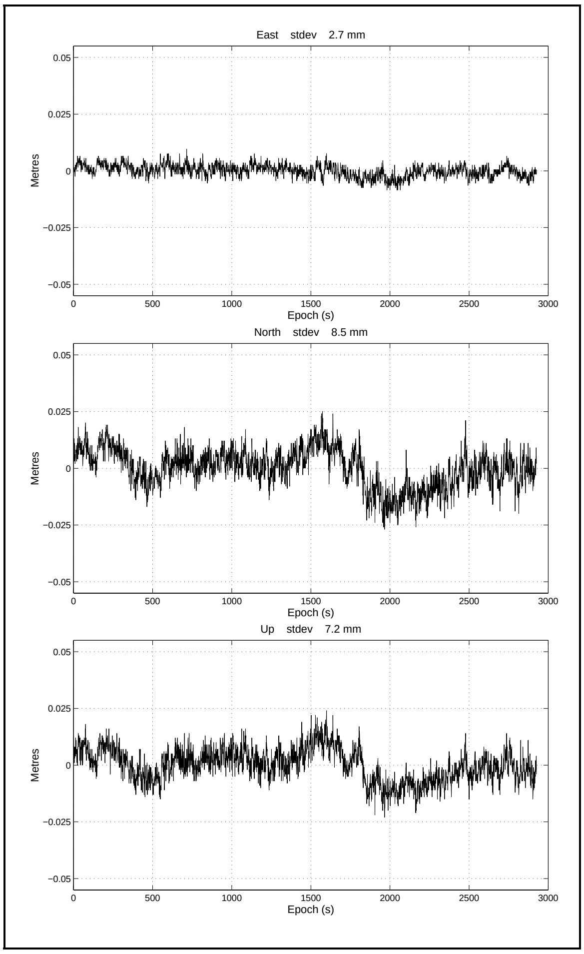


Figure 11. GPS-PL CMC Allstar positioning result in East, North and Vertical.

3. Concluding remarks

In this paper it has been demonstrated that when GPS is augmented with PLs similar positioning precision (sub-cm) can be obtained for both the horizontal and vertical components. Due to location of the pseudolites in this trial, the best improvements in precision were in the East and Vertical components by 41% and 31% respectively, and least in the North component (6%).

Furthermore, if positioning precision in the North direction at the Wilford suspension footbridge is to be improved then (geometrically) better pseudolite locations must be found.

The pseudolite measurements had constant biases due to multipath error, of which the largest was nearly 5cm. However the almost static nature of the trial allowed the multipath bias to be calibrated and removed from the pseudolite measurements.

The low-cost single-frequency CMC Allstar receiver provided good quality GPS measurement data and tracked the pseudolite signals for the entire trial without difficulty. These GPS receivers therefore have the potential to be used in a low-cost system for deformation monitoring. The SNAP group has developed a single-frequency RTK software that requires static initialisation to resolve carrier phase ambiguities, and is currently working on an On-The-Fly (OTF) ambiguity resolution version.

In the trial, multipath error from one of the satellites propagated into the North and Vertical positioning time series and contaminated any detectable bridge movements. This satellite was critical to the North-South geometry and so could not be removed from the solution. There are several possible options by which satellite multipath could be reduced, and these include the use of choke-ring antennas, developing a multipath 'signature' of the bridge, or removing the low frequency trends from the position time series using wavelets.

Acknowledgments

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