Antenna Selection for Bridge Deformation Monitoring – Comparison of Multipath Mitigation Characteristics for Three Types of Antennas

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Key words: Antenna, Multipath, Bridge, Monitoring, Quality Control

SUMMARY

The area of bridge deformation monitoring using GNSS has been growing and developing over the last 10 – 15 years. The University of Nottingham is continuing research in this field with recent monitoring campaigns on the Avonmouth viaduct which is a steel-box girder structure, the Severn Crossing (suspension bridge) as well as the Soehae and Machang bridges in Korea which are cable-stayed bridges. In many of these tests large choke ring antennas have been used both at the reference and rover sites in order to mitigate the impact of multipath. The GNSS rover points are sometimes located using clamps on the handrail (Humber, Avonmouth) or poles affixed to the actual suspension cables, as was done in the Severn bridge tests. In these instances having a lightweight antenna would be desirable. For the Severn and Avonmouth tests lightweight choke-ring antennas were used. However the use of an even lighter antenna would be desirable. As a result a comparison test was conducted using three different types of Leica antennas in two different environments. The Leica AT504 choke ring antenna, the AT503 lightweight choke ring and the AX1202 (which is the lightest of the three antennas) were tested. The environments were a medium to high multipath environment close to a building and then a high multipath location which was simulated by placing a 2m wide reflective metal sheet close to the antenna.

The results showed that the AX1202 compared favourably with the other two choke ring antennas under medium to high multipath conditions. However under severe multipath the AT504 appeared more robust compared to the others. This suggests that where it is critical to have a lightweight antenna for bridge deformation monitoring, the AX1202 shows good multipath mitigation characteristic and can be used in conjunction with a standard choke ring antenna at the base station.

Antenna Selection for Bridge Deformation Monitoring – Comparison of Multipath Mitigation Characteristics for Three Types of Antennas

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1. INTRODUCTION

The use of GNSS for bridge deformation monitoring has become increasingly wide spread. A significant amount of research has been conducted in this field (Brown *et al*., 1999), (Roberts *et al*., 2006a, (Roberts *et al.*, 2006b), (Saeki *et al.*, 2008). Initial research focused on the use of GPS however, now there are multiple constellations in addition to GPS in the form of GLONASS, COMPASS and Galileo available currently or in the near future along with regional augmentation systems. This enables increased availability of a position solution and improved reliability. GNSS provides a stable three dimensional measurement of the dynamics of structures such as bridges. In addition high rate data output of up to 50Hz and 100Hz are now available in some survey grade receivers.

GNSS suffers from the limitation that it requires a clear line of sight between receivers and the GNSS satellites. In addition the GNSS signal may reflect off objects in the antenna environment leading to multipath errors. This causes errors in pseudorange and carrier phase observations and hence errors in positioning, and this effect is difficult to separate from actual short-term structural movement (Atkins, 2006). In a bridge environment there are many sources of multipath. From the bridge super-structure to vehicles, cyclist and pedestrians, as well as even the water surface. The simplest way to mitigate multipath is to locate the antenna in a 'clean' multipath free environment. However while that option may be implementable to a degree for the GNSS reference antenna, the rover antenna location is determined by the bridge dynamics that is required to be captured and so it would need to be on specified locations such as: at the mid-span or ¼ span or directly on the suspension cables, etc. These locations are also exposed to the elements and subject to the buffeting of the wind and other elements. In addition, it is required that local vibrations from the antenna attachment should be kept at a minimum as it is the bridge dynamics that is required to be captured, also ease of installation and long term stability of the installed hardware is required. Therefore an antenna which is small and light-weight but with good multipath mitigation characteristics is required.

2. ANTENNA DETAILS

Antenna Type	**Design**	**Dimensions** (dia x ht)	**Weight**
AX1202	SmartTrack+, Built-in ground-plane	170mm x 62mm	0.44kg
AT503 choke-ring	Dorne Margolin, JPL design	300mm x 75mm	2.45kg
AT504 choke-ring	Dorne Margolin, JPL design	380mm x 140mm	4.3kg

Table 1: Dimensions And Other Details Of The Three Antenna Types (Leica, 2005)

A typical choke-ring antenna consists of three to five concentric ring structures. The choke rings are generally a quarter wavelength deep, in order to create a high impedance surface that prevents propagation of surface waves near the antenna and excitation of undesired modes. The overall effect is a very smooth controlled pattern with low susceptibility to multipath (Kunysz, 2003).

Figures 1 – 3 show AT503 light-weight choke-ring antennas and an AT504 standard choke ring antenna used in the monitoring of the Avonmouth Viaduct and Severn Suspension Bridge. Figure 4 shows the AX1202 light-weight antenna.

Figure 1 : GPS Antenna Set-up Showing AT503 Antenna, Clamp and Tribrach Attachment on the Avonmouth Viaduct

Figure 2: AT504 Choke Ring at One of the Reference Stations at the Avonmouth Harbour

Figure 3: AT503 Antenna Attached to Main Cable on Severn Crossing Suspension Bridge

Figure 4: An AX1202 Antenna (www.leica-geosystems.fr)

3. MULTIPATH SIGNATURE

For the antenna located on the bridge structure there are two types of multipath that will be experienced. One will be characterised as a low frequency fluctuation due to reflections from stationary objects in the antenna environment. As the satellites move, their elevation angle and thus satellite-reflector-antenna geometry changes leading to the fluctuations in the multipath characteristics. This is repeated with about a 4 minutes advance daily as the GPS satellites have an orbital period of about 11h 58min. The other type of multipath is a high frequency multipath with a period of sub-minute to 2 – 3 minutes. This is caused by mobile or dynamic reflecting surfaces in the antenna environment, resulting in randomization of the multipath effects (Ogaja and Satirapod, 2007).

The vertical deflection data collected at the midpoint of the Avonmouth viaduct was analysed in the frequency domain by computing its power and amplitude spectrum. The key frequencies identified for the bridge are shown the Table 2. The two frequencies of 0.526 Hz and 1.139 Hz were within the expected range for that type of structure. However the signal at a lower frequency with a longer period of about 16 seconds is not within the expected dynamics of the bridge and is very likely to be due to multipath. Such lower frequency ‘multipath’ component which is uncorrelated with temperature or other bridge dynamics have also been observed in other test data collected in bridge monitoring projects conducted by the University of Nottingham.

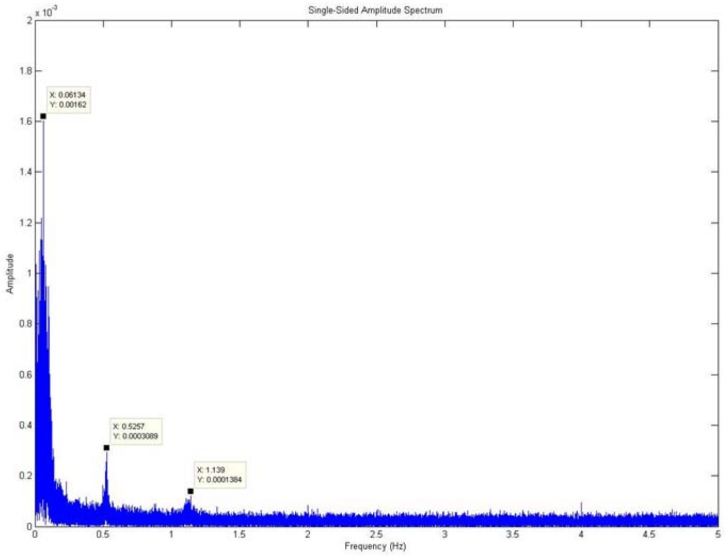

Figure 5 : Amplitude Spectrum for Avonmouth Midpoint Day 1 Vertical Deflection

Frequency (Hz)	Period (Seconds)
0.061	16.39
0.526	1.90
1.139	0.88

Table 2: Frequencies Detected for Vertical Deflections at Midpoint of Avonmouth Viaduct

4. ANTENNA TEST PROCEDURE

The aim was to test the three different types of antennas in two different environments. The first environment was in front of the old IESSG building. Here the building structure would serve as a source of multipath. In addition there was a footpath and road a few metres away. This would also provide a transient source of multipath in the people and vehicles passing by. The second test point was located in a grass field which was fairly open but had several trees around at about 15 – 20m away. A metal sheet approximately 2m wide and 1m high was installed at this location to provide a strong source of multipath from the highly reflective surface (Figure 14). The two test points (called IESSG and GRASS respectively) were coordinated by using a Leica TCR1201 total station to traverse from pre-established points with known coordinates to the points and back.

4.1 Pre-Test Planning

As part of the pre-test planning phase, it was important to determine the best orientation for the metal sheet that was likely to produce a significant multipath effect. The coordinates of both test points were put into the Leica GeOffice (LGO) Satellite Availability program. This generated a sky-plot for the points for the proposed day of the test. In addition an in-house software called the Urban Canyon GNSS Simulation Tool (UCGS) was also used to generate a sky-plot for the points. The advantage of the UCGS is that it utilises a 3D model of the environment to generate the sky-plots. The ground terrain and buildings are modelled in the UCGS tool, however trees are not modelled (Taha *et al*., 2008).

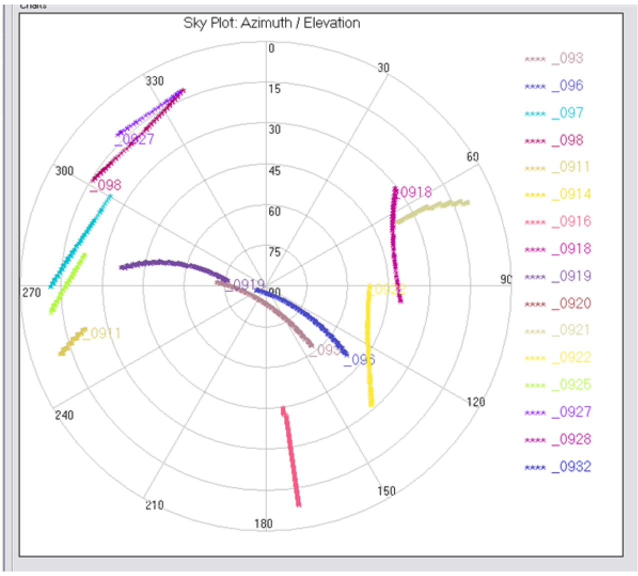

Figure 6: Pre-Test Planning Satellite Sky-Plot for Test Point GRASS

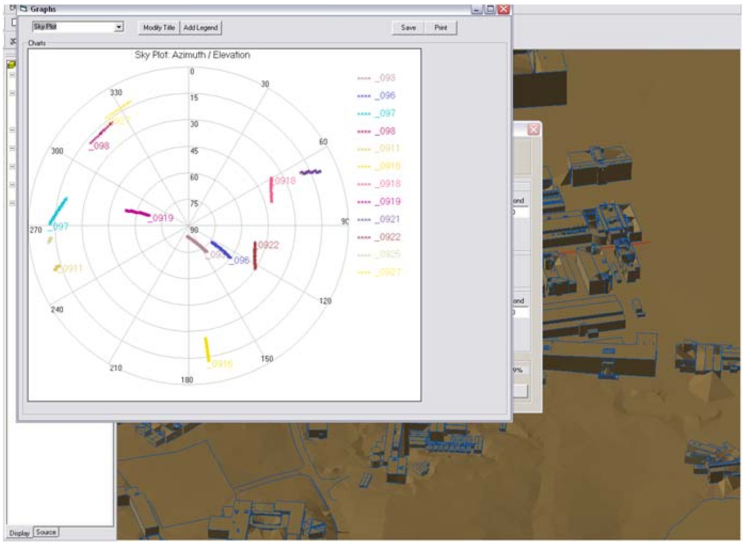

Figure 7: Pre-Test Planning Satellite Sky-Plot for Test Point IESSG. (The 3D Model Used with UCGS is in the Background).

Figures 6 and 7 show the respective sky-plots of satellites that should be visible at points GRASS and IESSG based on the location, terrain and surrounding buildings. Based on the pre-test sky-plots the metal sheet was orientated in a roughly North-South position at about 15-20º from North.

5. ANTENNA COMPARISON TEST RESULTS

The test was conducted over a 3-day period. Firstly the AX1202 was used at point IESSG with data collected for about 30 to 40minutes. The next day at roughly the same time period the point was occupied using the AT504 antenna and then the following day it is occupied using the AT503 antenna. A similar procedure was performed on point GRASS using the AT504 and then the AX1202 which is the lightweight antenna. The same antenna type pairs were used at the base station and the rover. A GX1230 receiver was used with all the antennas. The GPS data was collected at 1Hz. A Leica TCR1201 total station was used to establish the known (truth) value of the rover positions.

Figure 8 shows the test location for the point IESSG which is on the North West side of the building. The location where the antenna was set-up is circled in red.

5.1 Results of Test at Point IESSG

Figure 8: Location of Pt IESSG.

Figures 9 – 11 show the position error in the east, north and height components for the three data sets collected at IESSG using the different antenna types. It can be seen that the results from each antenna collected on consecutive days exhibit a similar pattern with about a 4 minute offset.

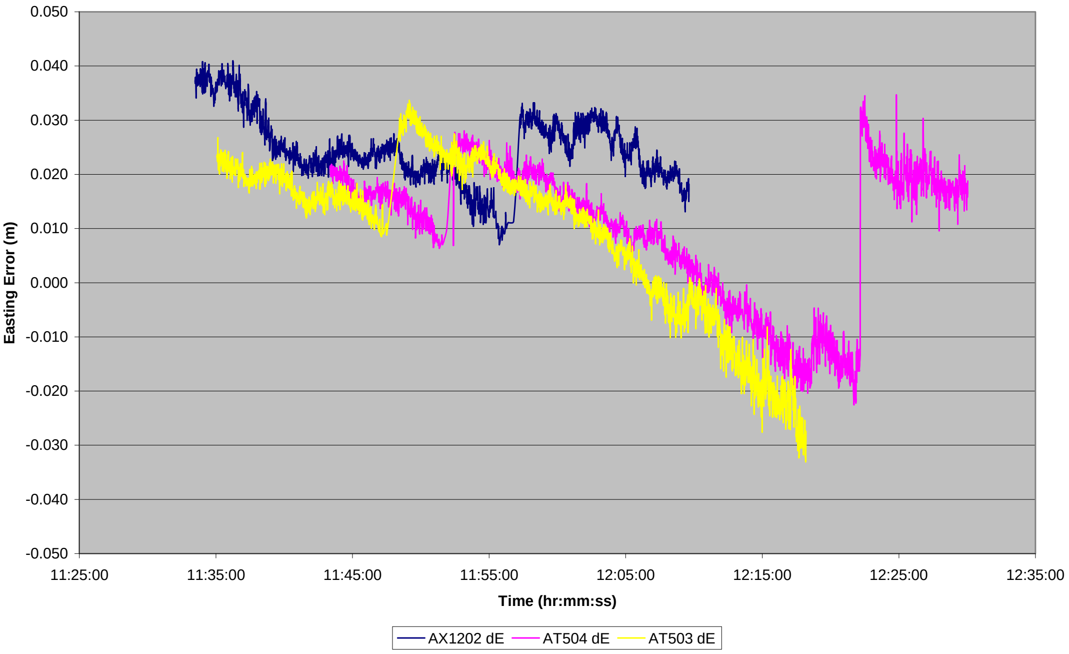

Figure 9: The Difference Between the Eastings and the Truth Value for pt IESSG

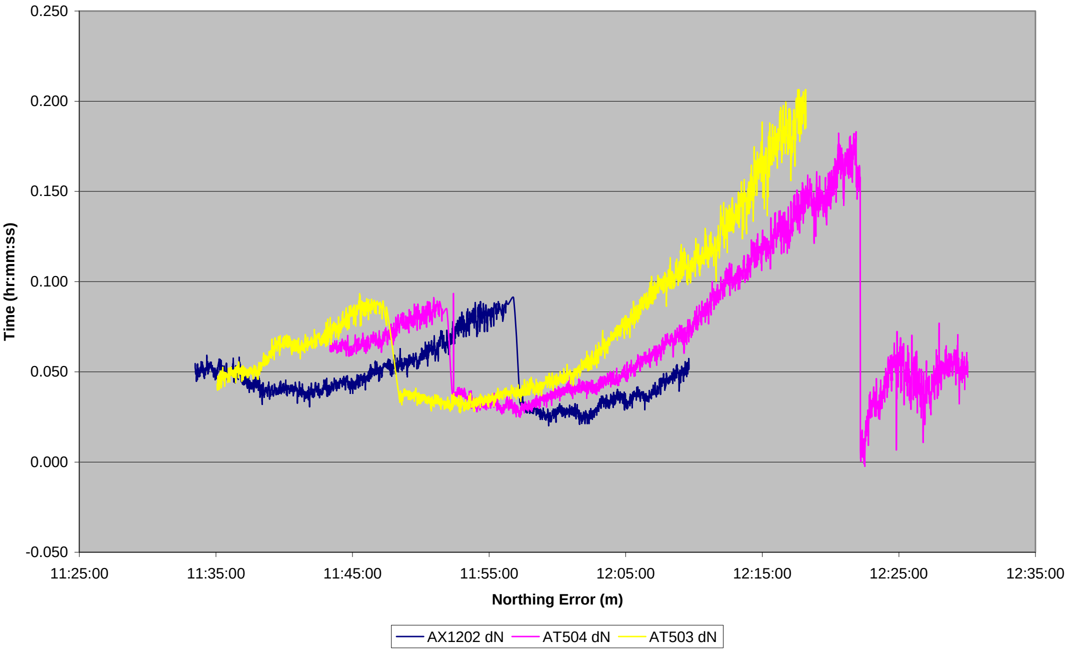

Figure 10: The Difference Between the Northings and the Truth Value for pt IESSG

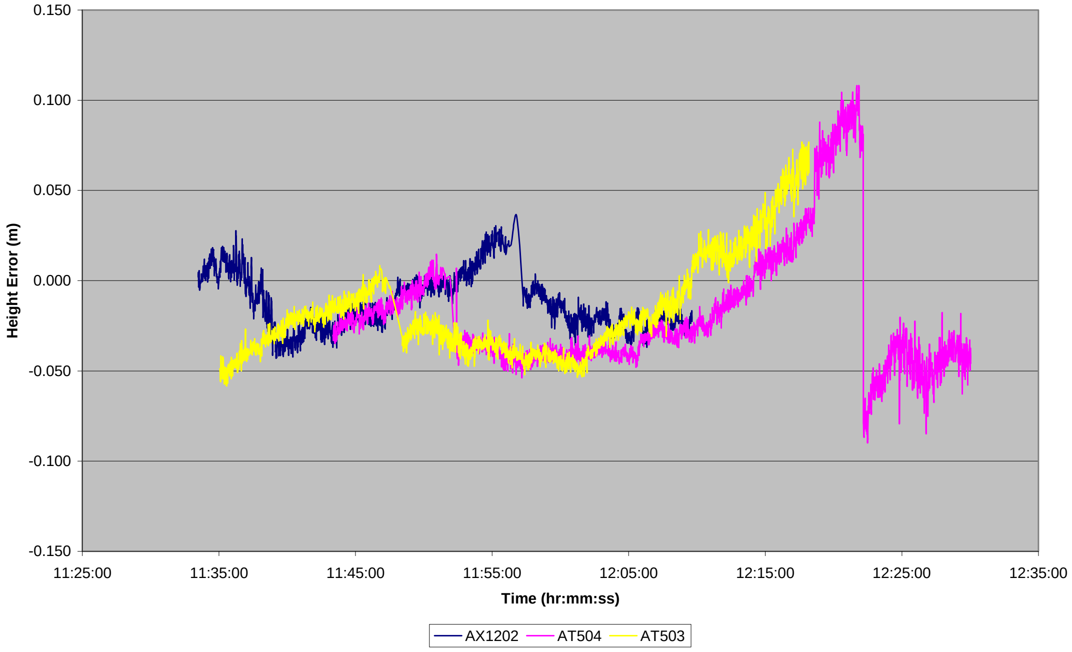

Figure 11: The Difference Between the Heights and the Truth Value for pt IESSG

The eastings error is within +/- 4cm while the Northings error increases up to 20cm with the height errors at +/- 10cm. The large deviations in position especially towards the latter part of the dataset was due to the combined effect of multipath and poor Position Dilution of Precision (PDOP). Figure 12 and 13 show the PDOP graph and the sky-plot with MP1 multipath estimates respectively. It can be seen that PRN 28 is at a low elevation angle, rising above the 10º elevation mask. However the signal from this satellite is occasionally interrupted. This is likely due to intermittent obstructions in the satellite-antenna path. This is also a significant source of multipath. In addition PRN 6 and 3 are high elevation satellites however they appear to be obstructed and no longer visible at about half way and two thirds way into the observation session.

Due to the difficult conditions the AT503 dataset was only able to generate code solutions after 12:18 pm. There are no phase solutions after 12:09 pm for the AX1202 data set. This is likely due to the fact that at about 12:09 pm the battery needed to be changed in the rover. After the battery was replaced even though there were at least 5 satellites in view because of poor PDOP and high multipath the integer ambiguity could not be resolved.

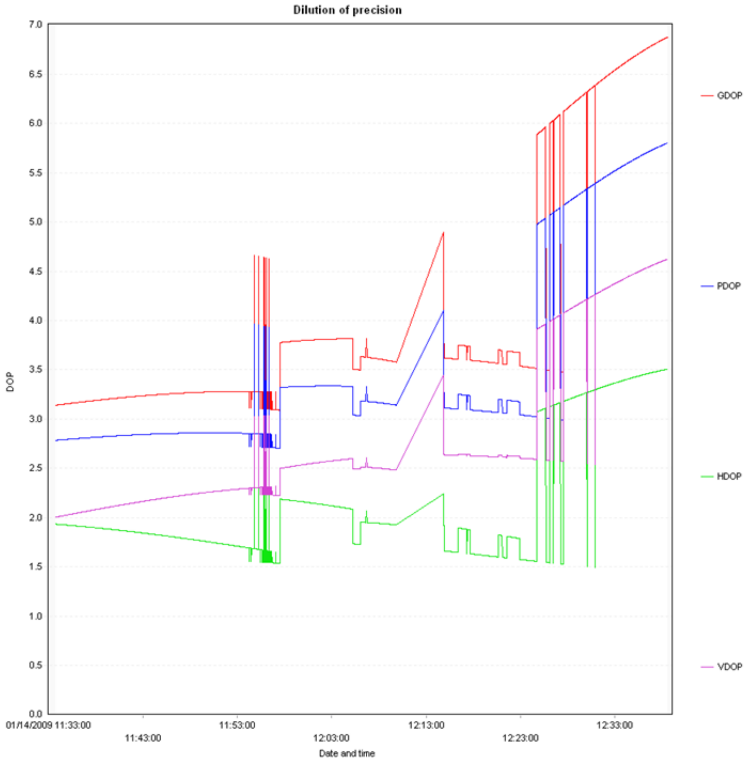

Figure 12: DOP Values for Point IESSG

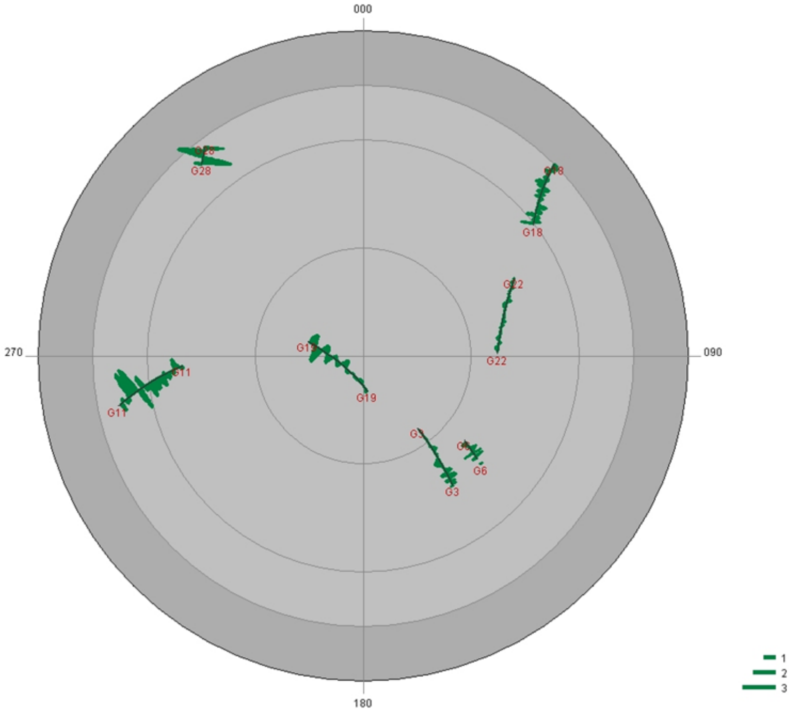

Figure 13: MP1 Multipath Sky-Plot for Satellites Visible at Point IESSG

	AX1202		
	dE	dN	dH
Mean Error	0.023	0.047	-0.011
2 SD	0.011	0.038	0.029
RMS Error	0.024	0.051	0.018
RMS Vector	0.059		
	AT504		
	dE	dN	dH
Mean	0.017	0.050	-0.030
2 SD	0.010	0.036	0.030
RMS	0.017	0.053	0.033
RMS Vector	0.065		
	AT503		
	dE	dN	dH
Mean	0.019	0.050	-0.029
2 SD	0.005	0.018	0.013
RMS	0.020	0.054	0.032
RMS Vector	0.065		

Table 3: Summary of Results at Point IESSG

The RMS vector is computed as $[(\text{RMS dE})^2 + (\text{RMS dN})^2 + (\text{RMS dH})^2]^{1/2}$

The result summary in Table 3 was computed using the same amount of data for about a 22 minute period with a 4 minute shift for each data set collected on consecutive days. That is:
AX1202 (on day1) – 11:48:00 to 12:09:38
AT504 (on day 2) – 11:44:00 to 12:05:38
AT503 (on day 3) – 11:40 :00 to 12:01:38

The results show that the three antennas have similar deviation from the true value, as well as similar spread about their mean. However the RMS error vector for the data collected with the AX1202 which is the light-weight antenna at 0.059m is less than that for the AT504 and AT503 choke-ring antennas which is 0.065m. However because the summary statistic in Table 3 was computed only for the period when a phase solution was possible. It does not reflect the robustness of the AT504 which can be seen in Figures 9 – 11. It can be seen that several minutes after the other two data sets are only able to provide a metre level code solution, the AT504 data was still able to provide a cm level phase solution.

5.2 Results of Test at Point GRASS Using Metal Reflector Sheet

The AX1202 and the AT504 were further tested using a metal reflector sheet. The AT504 data was collected first then on the following day the AX1202 was used. The data collection for the AX1202 started about 10 mins after the start time of the AT504. However the common multipath signature can be observed.

Figure 14: Antenna Set-up with Metal Reflector Sheet at pt GRASS

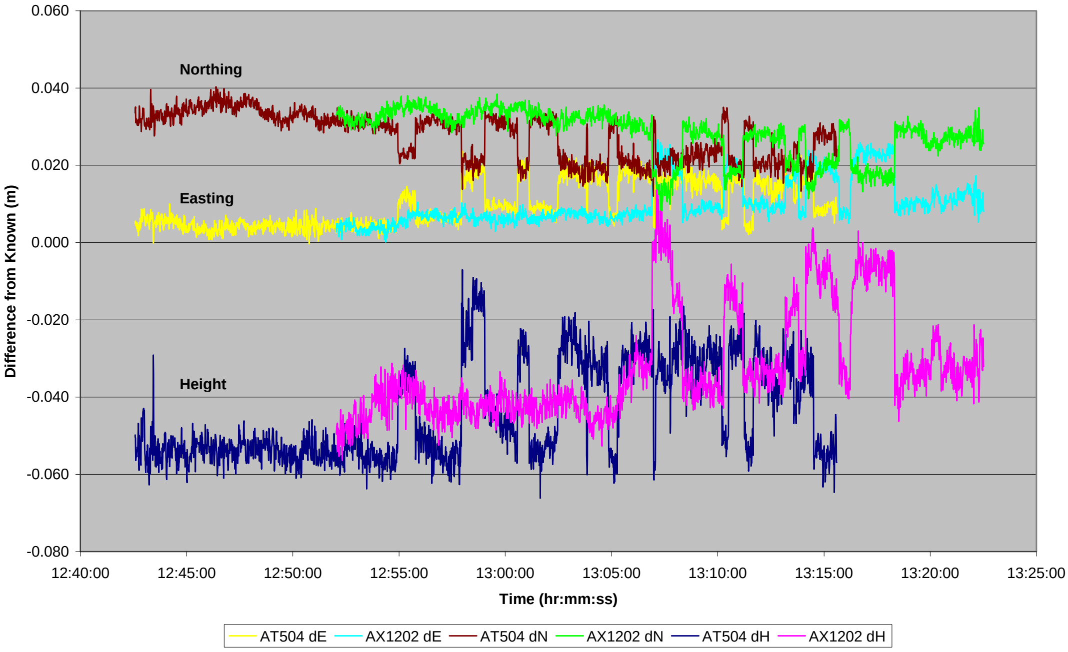

Figure 15: Difference in Coordinates from Truth (using all the satellites in view)

The jumps in the graph above are likely to be due to cycle slips in the PRN28 data.

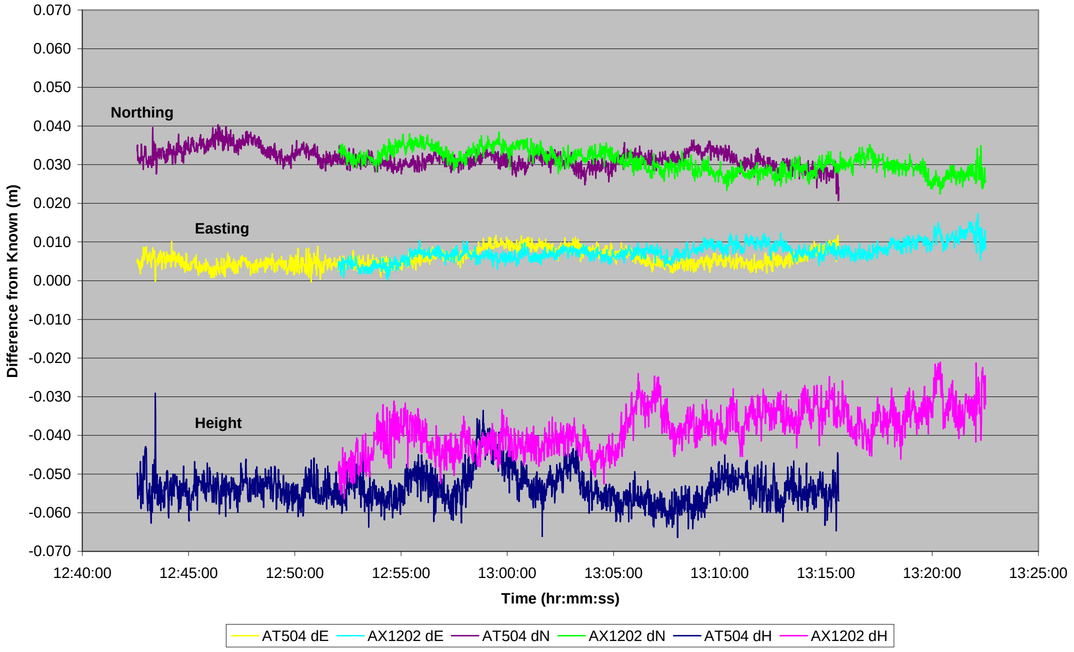

Figure 16: Difference in Coordinates from Truth (removing PRN28 from the processing)

A summary of the results is provided in Tables 4 and 5:

	AT504			AX1202		
	dE	dN	dH	dE	dN	dH
Mean	0.010	0.028	-0.044	0.010	0.028	-0.032
2*SD	0.012	0.012	0.025	0.012	0.013	0.028

Table 4: Summary of Results at GRASS – using all satellites available

Removing the bad satellite data from PRN 28 from the processing:

	AT504 w/o PRN28			AX1202 w/o PRN28		
	dE	dN	dH	dE	dN	dH
Mean	0.006	0.032	-0.054	0.008	0.031	-0.038
2*SD	0.004	0.005	0.009	0.005	0.006	0.011

Table 5: Summary of Results at GRASS – removing SV28 data from the processing

The results from Tables 4 – 5 show that the accuracy and precision of the data collected using the AX1202 are comparable to that collected using the AT504 antenna.

6. CONCLUSION

The AT504 antenna is able to maintain lock to the GPS signals in difficult high multipath environment enabling a phase GPS solution to be computed. The AX1202 however shows good performance in medium to high multipath environments. The AT503 shows similar performance to the AT504 although in severe multipath condition during the latter part of the test at point IESSG, it was unable to maintain lock on the carrier phase. The Phase Lock Loop (PLL) correlates the recieved phase to that of the receiver's local oscillator. This allows phase lock to be maintained. Noise, multipath and other factors can affect the PLL's ability to track the carrier phase .

The results showed that the AX1202 compared favourably with the other two choke ring antennas under medium to high multipath conditions. However under severe multipath the AT504 appeared more robust compared to the others. This suggests that where it is critical to have a lightweight antenna for bridge deformation monitoring, the AX1202 shows good multipath mitigation characteristic and can be used in conjunction with a standard choke ring antenna at the base station.

The tests show that irrespectie of the antenna type, there is still a requirement for a robust multipath mitigation algorithm when processing GNSS data from difficult high multipath environments. As shown in the tests even where the data collected using the AT504 choke-ring antenna was able to produce centimetre level positions, these positions still deviated from the truth by up to 8 or 9cm. Which exceeds the desired noise threshold for precise applications such as bridge deformation monitoring.

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BIOGRAPHICAL NOTES

Oluropo Ogundipe is a Research Fellow at the IESSG, University of Nottingham. She has a Bachelor's degree in Surveying and Land Information from the University of the West Indies and a PhD in Engineering Surveying from the University of Nottingham. Her current research focus includes Indoor Positioning and Object Recognition for the Blind and the use of GNSS for bridge monitoring, Her research interests include RFID positioning, Network RTK GPS, sensor integration and multipath mitigation.

Gethin Roberts is a Professor of Geospatial Engineering and the Dean of Science and Engineering at the Ningbo (China) campus of the University of Nottingham. He is heavily involved with the Chartered Institution of Civil Engineering Surveyors, being a Fellow, a past regional chairman, a Vice President and a member of various committees. He is also significantly involved with the International Federation of Surveyors (FIG).

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