Bridge Monitoring With Garmin Handheld Receivers

Emily COSSER, Chris J HILL, Gethin W ROBERTS, Xiaolin MENG, Terry MOORE and Alan H DODSON, United Kingdom

Key words: GPS, handheld GPS receivers, Gringo, Garmin, bridge deformation monitoring

SUMMARY

GRINGO (GPS RINEX Generator) is a program that has been developed at the IESSG to record the pseudorange and carrier phase output from 12-channel Garmin handheld GPS receivers in Rinex format. It means that data from Garmin receivers can be post-processed. Garmin receivers are considerably cheaper than survey-grade receivers and so could contribute to a more affordable monitoring system for bridges and other structures.

Experiments have been carried out to assess the accuracy of positioning with the output from the Garmin receivers in both static and kinematic modes. Results are compared directly to Leica system 500 receivers connected via a splitter to the Garmin receivers. The main challenge is cycle slip detection and repair, particularly as Garmin receivers can suffer from half cycle slips. This paper presents the results achieved and accuracies obtainable.

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1. INTRODUCTION

The University of Nottingham has been awarded a three year grant by the UK's Engineering and Physical Sciences Research Council to research the monitoring of structures, specifically bridges. One of the research aims was to use single frequency receivers instead of dual frequency, to develop a more affordable monitoring system. As an extension to the work conducted with single frequency receivers, experiments have been conducted with data from Garmin handheld GPS receivers.

Since the end of SA (Selective Availability) in 2000 the accuracies achievable by GPS receivers in standalone mode have greatly increased. This had led to great improvements in positioning quality achievable by handheld receivers and also reductions in price. This has been coupled with public awareness of GPS rising, so it is now possible to find handheld GPS receivers on sale in high street electronics shops used by motorists and outdoor enthusiasts.

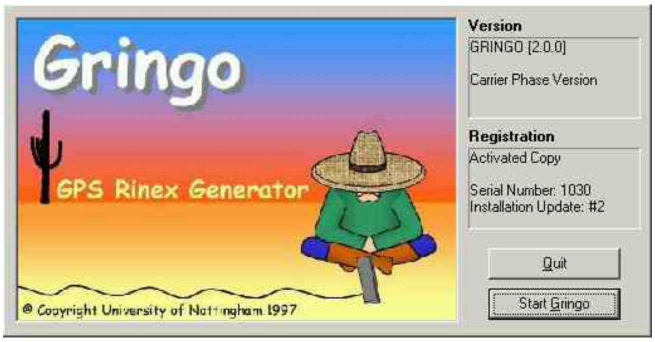
A Leica system 500 survey grade GPS dual frequency receiver costs £13,500 which is 20,535 Euros, while a Leica single frequency receiver reduces the price to £8,300 (12,625 Euros). While the data recorded by these receivers is very reliable, they can be too expensive for many monitoring applications. A Garmin receiver on the other hand can be purchased for between £100 and £400 (150 and 600 Euros). The Garmin receivers used for this experiment only cost £189 (283 Euros).

This paper outlines the software developed at the University of Nottingham, called Gringo, which extracts raw pseudorange and carrier phase data from Garmin GPS receivers. Kinpos is dual frequency kinematic GPS processing software which was modified by the authors to process single frequency data. This processing software which has been adapted to process Garmin data is also introduced, particularly focusing on the cycle slip detection method used for single frequency receivers in the context of bridge monitoring. Experiments carried out to compare the accuracies achieved with Garmin receivers and Leica survey grade receivers are discussed.

2. GRINGO

GRINGO (GPS RINEX Generator) is a program developed at the IESSG to record the pseudorange and carrier phase output from a Garmin handheld receiver and convert it into Rinex format. Owners of Garmin 12 channel GPS receivers can use the software to post-process the data from their receivers. Post-processing is usually only available with expensive survey grade receivers.

Garmin communications protocols allow internal waypoints, tracks and other information to be exchanged with computers or other Garmin receivers. Some of these protocols are well documented but others are not documented by Garmin at all. GRINGO decodes one of the undocumented protocols which contains raw carrier phase and pseudorange data and logs this data in Rinex format. For more information about GRINGO see Hill, et al. (2000) and Hill and Moore (2002). The Garmin receiver must be connected to a laptop or data logger, by the serial port. The computer will then log the raw data in real time.



Version
GRINGO [2.0.0]
Carrier Phase Version

Registration
Activated Copy
Serial Number: 1030
Installation Update: #2

Figure 1: GRINGO start up screen

Moore, et al. (2002) conduct zero baseline trials with two Garmin receivers connected via a splitter to the same antenna. Zero baseline trials are useful as they remove a number of error sources associated with GPS such as atmospheric effects, satellite ephemeris errors and multipath, because the effects of these error sources are the same at both receivers. This test was carried out to analyse the ability of the decoding algorithms in GRINGO, as an independent decoding error on one receiver would not be found on the other receiver. The zero baseline trial was carried out over 10 minutes logging the data at a 1 Hz data rate. The data was processed using the ambiguity fixed carrier values in static mode and a distance of 0.0001m from the reference to the rover receiver was recorded. Analysing the raw carrier phase residuals the precision of the raw carrier phase measurement was calculated to be approximately 0.0014m.

It was not possible to carry out a zero baseline trial for the results shown this paper. The newer generation of Garmin receivers use only 2 AA cells, and so provide only 3 volts to power an external antenna. Older Garmin receivers used 4 AA cells and so provided more than 5 volts, which enabled them to power an external survey grade antenna. The Garmin 76 receivers used for the experiments in this project do not have enough power to run an external antenna and so the Leica receivers connected via a splitter ran the antennas. It would be possible to have an external power source running the antenna so that the Garmin could record data on its own. Connecting the Leica receivers to the ‘hot’ end of the splitter and the Garmin to the ‘cold’ end allowed the antenna to be powered. By using a three splitter configuration, a four receiver splitter test was attempted but, since the splitters were not amplified, the signal power was insufficient to enable tracking by the receivers on the cold end of the first splitter (the configuration can be seen in Figure 2.

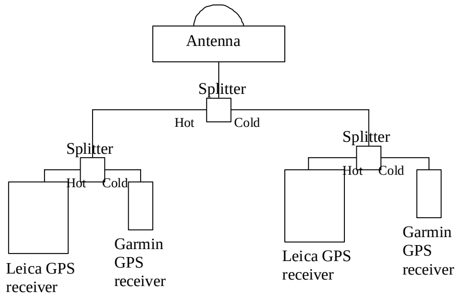


Figure 2: The zero baseline configuration

3. GARMIN DATA PROCESSING

The carrier phase from a Garmin receiver can slip by half cycle amounts, which also means that ambiguities have to be resolved to the nearest half cycle. It is not known why the receivers slip by half cycle amounts, but it is possible that they use a signal squaring approach to access the carrier. Conventional software packages will only detect full cycle slips and so do not cope well with Garmin data. P4 is static post-processing software that is provided with GRINGO, which will cope with the half cycle slips. However, so that kinematic data could be processed for the application of structural monitoring the in-house software Kinpos, developed at the University of Nottingham, was modified to cope with Garmin data.

Methods of accelerating the ambiguity search for single frequency receivers in the context of a bridge environment were introduced into Kinpos processing software. For a more detailed explanation of the software development, particularly the ambiguity resolution algorithms see Cosser, et al. (2004). The software was further modified to resolve integer ambiguities to the nearest half cycle and also detect cycle slips at the half cycle level.

3.1 Cycle Slip Detection

One of the challenges associated with processing single frequency data is the method of cycle slip detection. In the dual frequency version of Kinpos a number of methods were employed to detect cycle slips which included coarse detection with the range residual method, and more accurate checks with the ionospheric residual and four observables equations (Pattinson 2000). Both the ionospheric residual and four observables methods need data from two frequencies to be able to detect slips. The range residual method could be used for single frequency data, but it can only be used to detect and correct slips of greater than ±4 cycles. A new method of cycle slip detection needed to be implemented.

In the context of bridge monitoring the receivers are not completely kinematic. They are moving all the time, but never by a very large amount. Due to this fact it can be assumed that any large jumps in the carrier phase from epoch to epoch are likely to be caused by cycle slips and not receiver movement. So, a method based on the triple order time difference of the carrier phase, $\delta\varphi_f^{\,i}(t_k)$, is used to detect cycle slips based on equation (1) below:

$$\begin{aligned}\delta\varphi_f{}^i(t_k) = {} & [\varphi_f{}^i(t_k)+\Delta\varphi_f{}^i(t_{k-1})] - 3[\varphi_f{}^i(t_{k-1})+\Delta\varphi_f{}^i(t_{k-1})] + 3[\varphi_f{}^i(t_{k-2})+\Delta\varphi_f{}^i(t_{k-2})] \\ & -[\varphi_f{}^i(t_{k-3})+\Delta\varphi_f{}^i(t_{k-3})]\end{aligned} \tag{1}$$

where:

$\varphi_f{}^i(t_k)$	is the carrier phase measurement for satellite *i* on frequency *f* at time t_k.
$\Delta\varphi_f{}^i(t_k)$	is the carrier phase correction for satellite *i* on frequency *f* at time t_k. This carrier correction is the accumulation of all the slips on frequency *f* that have occurred since the start of the observation session.

If the triple difference, $\delta\varphi_f{}^i(t_k)$, is larger than a specified threshold then a cycle slip is detected. For Garmin receivers this threshold is set to be 0.5 cycles and for other receivers it is set to 1 cycle. Through cycle slip simulations it was shown that this method could detect all cycle slips at the 1 cycle level, however when it was set to 0.5 cycles a large number of false cycle slips were introduced into the data. So, the software will now only detect cycle slips of 1 cycle or greater, but for Garmin receivers will detect them to the nearest half cycle.

If no cycle slip is detected at time t_k then the current cycle slip correction is set to the previous one, i.e. $\Delta\varphi_f{}^i(t_k) = \Delta\varphi_f{}^i(t_{k-1})$ and no further calculations are made for this satellite at frequency *f*. If a cycle slip is detected then the algorithm will try and repair the cycle slip by using equation equation (2) below:

$$\Delta\varphi_f{}^i(t_k) = \Delta\varphi_f{}^i(t_{k-1}) + \lfloor \delta\varphi_f{}^i(t_k) \rfloor \tag{2}$$

where $\lfloor \; \rfloor$ denotes rounding the value to the nearest integer. A repair is formed only if the variance of the slip value is greater than the sample variance computed from the third order difference.

This method requires that four epochs of data for each satellite have accumulated before cycle slip detection can occur (three epochs for the triple-order time difference equation to be formed and one further epoch to compute the variance test). For the first three epochs coarse cycle slip detection occurs with the range residual method. The range residual RR_f for frequency *f* is calculated using equation equation (3) below (Roberts 1997):

$$RR_f = \frac{(\rho_f{}^i(t_k) - \rho_f{}^i(t_{k-1}))}{\lambda_f} - (\varphi_f{}^i(t_k) - \varphi_f{}^i(t_{k-1})) \tag{3}$$

where:

$\rho_f{}^i(t_k)$	is the pseudorange measurement for satellite *i* on frequency *f* at time t_k.
λ_f	is the wavelength for frequency *f*

For data from geodetic receivers the range residual method can detect cycle slips of ±4 cycles or larger due to the noise on the pseudorange. The pseudorange is actually noisier for a Garmin receiver and so the range residual method can only be used to detect cycle slips of ±10 cycles or greater. Although the range residual method can detect cycle slips it is not accurate enough to be able to effectively correct them. So, during the first three epochs a cycle slip is simply flagged and no attempt at correction is made. At the fourth epoch a cycle slip can be detected by equation (1), the triple-order time difference method, but this slip will simply be flagged and not corrected as there is no variance measure to test it against. At the fifth epoch and higher flagged cycle slips that pass the variance test are corrected.

4. STATIC TRIALS

Two static trials were conducted on the University of Nottingham campus in January 2004. For the first trial a Leica 510 single frequency GPS receiver and a Garmin handheld GPS receiver were connected via a splitter to an AT501 navigation antenna for a zero baseline trial. For the second trial the same receiver configuration of Leica and Garmin receivers was used at two difference set ups, one for the reference and one for the rover. The data from the first day was processed as a zero baseline trial and also, to investigate the raw data quality, the range residual variable was examined. On the second day the short baseline was processed from Leica reference to Leica rover and from the Garmin reference to Garmin rover. Both trials were carried out with a data rate of 1 Hz (which is the maximum possible with the Garmin receivers).

4.1 Range Residual

The range residual variable was calculated for the Leica and Garmin data by equation (3). This variable is a good indicator of the quality of the pseudorange and carrier phase data from each receiver. The individual pseudorange and carrier phase values were split into different files for the different satellites and the range residual values for each individual satellite were calculated. The range residual for the Leica data only can be seen in Figure 3, while the comparison of the range residuals for the Leica and Garmin receivers can be seen in Figure 4, both for satellite 16. It can be established that the quality of the raw data for each receiver is very different.

Figure 3and

TableTable 1 show that the range residual for the Leica data is about ±10cm at maximum, but it is usually around the 3cm mark. The standard deviation for the range residuals is 2.3cm. This value is typical of other results from the Leica receiver. Figure 4 and Table 1 show that the range residual for the Garmin data is much worse, reaching 8 metres at maximum and usually being around 2-4 metres. The standard deviation in this case is 1.978m.

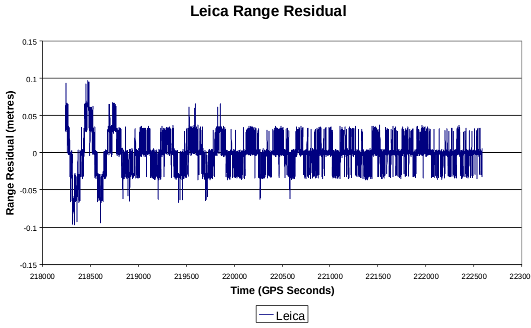


Figure 3: The range residual for the Leica data for satellite 16

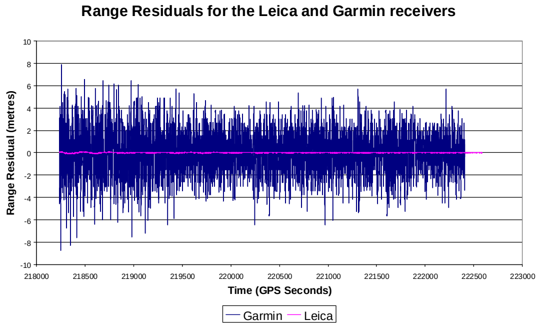


Figure 4: The range residuals for the Garmin and Leica data for satellite 16

Range Residual	Maximum (m)	Minimum (m)	Standard Deviation (m)
Leica	0.096	-0.096	0.023
Kinpos	7.895	-8.651	1.978

Table 1: Summary of results for the range residuals for Leica and Garmin receivers

The reason for the huge differences in range residual values is due to the accuracy and quality of the pseudorange data. For the Garmin receivers the pseudorange is not very accurate at all. The quality of the Leica pseudorange data is improved by pseudorange smoothing which occurs in the receiver itself. Pseudorange smoothing involves using the more precise carrier phase data to improve the pseudorange observable. This large pseudorange error should not affect the processing of the Garmin data too much as it is the carrier phase that is used mainly for positioning solutions.

4.2 Zero Baseline

The data from the Leica and Garmin receivers connected via a splitter to the same antenna was processed on a zero baseline. The Leica receiver was used as the reference while the Garmin receiver was used as the rover. As mentioned previously a zero baseline trial eliminates many of the error sources associated with GPS such as the atmosphere and multipath. This test would give an idea of the accuracy achievable with the Garmin receivers.

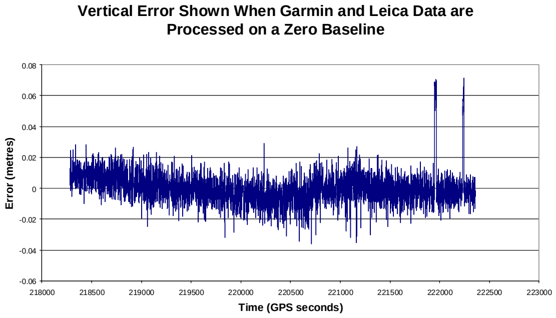


Figure 5: The vertical coordinate error shown when the Leica and Garmin data is processed on a zero baseline

The results from the Garmin and Leica receivers on a zero baseline can be seen Figure 5 above. In zero baseline trials where two Leica receivers had been used the spread of vertical coordinates had been around the 2cm level, which is initially similar for this trial. The unusual thing about Figure 5 is that there appears to be a slow drift within the data. Zero baseline trials from Leica only receivers do not display this movement; all the coordinates are evenly spread about the mean value.

This movement could be attributed to the receiver clock errors in the Garmin receivers which are not removed fully by the processing software. To investigate this, the clock offsets at each epoch were calculated for the Leica and Garmin baseline using the P4 software. The first derivative of the clock offset was calculated and can be seen in Figure 6 overlaying the positioning solution. The first half of the positioning data has a downward trend which can also be seen in the clock offset. When the clock offset derivative starts to flatten out the positioning solution rises. The large jumps in the clock offset derivative are due to missing epochs in the Garmin data. It does seem from the graph that there is a relationship between the clock offset derivative and the positioning solution.

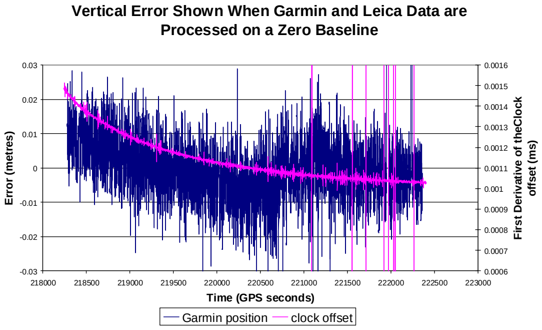


Figure 6: The vertical coordinate error shown when the Leica and Garmin data is processed on a zero baseline overlaid with the first derivative of the clock offset

4.3 Short Baseline

In this trial two different short baselines were processed, one between the reference Leica receiver and rover Leica receiver and one between the reference Garmin receiver and the Garmin rover. These two baselines were identical, as the Leica and Garmin receivers were connected via splitters to the same antenna at both ends of the baseline. So, these circumstances provide a means of directly comparing the results achieved by the Garmin and Leica receivers.

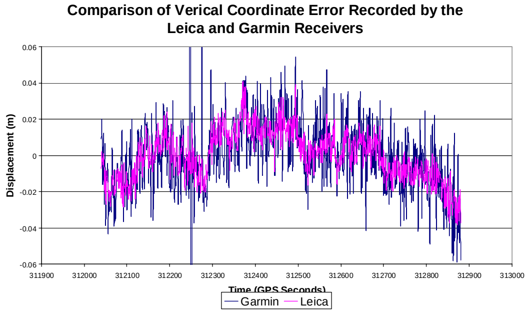


Figure 7: The comparison of the vertical coordinate error recorded by Leica and Garmin receivers over a short baseline

	Standard Deviations (m)		
	East	North	Vertical
Garmin	0.0048	0.0139	0.0282
Leica	0.0025	0.0056	0.0135
Ratio- Garmin/Leica	1.9472	2.4847	2.0793

Table 2: Summary of the standard deviations for the Leica and Garmin receivers over a short baseline while the receivers were static

The vertical coordinates for the Leica and Garmin receivers can be seen in Figure 7. It can be seen in this Figure that the general pattern of the coordinates is the same for both types of receiver, probably due to the multipath characteristics at the reference and rover sites. It is obvious however, that the Leica solutions are less noisy than those provided by the Garmin receivers and this is further confirmed by the standard deviations that are shown in Table 2. For the short baseline trial the standard deviations of the Leica coordinates are half that of the Garmin coordinates for the east and vertical components, with a bigger difference in favour of the Leica receivers in the north component. This is a good result considering the difference in quality of the Leica and Garmin raw data.

5. KINEMATIC TRIALS

A Leica single frequency GPS receiver and Garmin handheld GPS receiver were connected via a splitter to an AT503 choke ring antenna at both the reference and rover locations. The reference location was on a known point on the tower of the IESSG building, while the rover was located on a monument outside the IESSG building, far enough away so that it had a clear view of the sky. The rover antenna was located on top of the monument which had a movable plate. The plate was made to move up and down in the following ways:

- GPS time 121352 the plate was made to move downwards approximately 15cm.
- GPS time 121459 the plate was made to move upwards approximately 15cm.
- GPS time 121578 the plate was made to move down and up approximately 15cm three times in succession.
- GPS time 121817 the plate was made to move downwards approximately 15cm.
- GPS time 121890 the plate was repeatedly made to move up and down approximately 2cm for approximately 100s.
- GPS time 122430 the plate was repeatedly made to move up and down approximately 2cm for approximately 100s.
- At all other times the plate was stationary.

The results can be seen in Figure 8, which compares the results recorded by the Garmin reference and rover, the Leica reference processed with the Garmin rover and the Leica reference and rover. It can be seen from the graphs the movement of the monument is recorded well by all of the receiver combinations. The movements of 15cm at the beginning of the observation session are clearly visible as well as the small displacements of 2cm nearer the end of the observation session.

The absolute coordinates for the different receivers, however, are not the same. Both for the Garmin reference and rover data and also for the Leica reference and Garmin rover, there is an offset in the absolute coordinates. This is caused by errors in the initial ambiguity values, probably because the ambiguities have to be solved to the nearest half cycle whenever there is Garmin data present. The interest of the authors is using Garmin receivers for bridge dynamic deformation monitoring and so the relative movement of the receivers is of most importance. If the situation were truly dynamic this offset in coordinates would pose more of a problem.

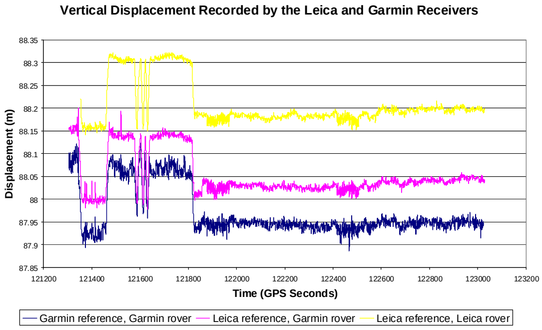


Figure 8: The vertical displacement recorded by the Leica and Garmin receivers for the kinematic trial

When the receivers are static the noise in the Garmin data is about twice as bad as the Leica data for this situation also. What is most interesting is that even with this high noise value the Garmin receivers still seem to pick out all the movement of the monument.

6. CONCLUSIONS

The Garmin receivers have been tested and compared to Leica geodetic receivers in a number of environments. The raw range residuals showed a very noisy Garmin pseudorange compared to the phase smoothed Leica pseudorange. A zero baseline trial with the Leica and Garmin receivers showed a small noise value, but also a drift in the coordinates that is most probably due to uncorrected receiver clock errors for the Garmin receivers.

On a short baseline the Leica receivers showed results that were twice as good as the Garmin receivers, which is a good outcome considering the price difference for each receiver. In a kinematic trial the Garmin and Leica receivers showed the same movement, but the absolute coordinates of the Garmin receivers were wrong probably due to initial ambiguity problems caused by the half cycle values.

These initial trials have been conducted to evaluate the effectiveness of using Garmin receivers to measure deformations of structures, specifically bridges. It is known that the data rate of 1 Hz is probably too slow to measure all the movement of some structures, for example the Wilford Bridge where a number of trials conducted by the University of Nottingham have taken place (Dodson, et al. 2001). For this bridge it should be possible to use the Garmin GPS data in conjunction with accelerometers to provide a higher data rate for measuring the dynamic deformations. For structures or environmental processes that move slowly, it may be possible to use Garmin receivers to monitor their long term movements.

ACKNOWLEDGEMENTS

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BIOGRAPHICAL NOTES

Ms Emily Cosser is a research student at the Institute of Engineering Surveying and Space Geodesy, University of Nottingham. She graduated in 2001 with a BSc in Mathematics from the University of Nottingham. Since 2001 she has been working towards her PhD on bridge monitoring with GPS and other sensors.

Dr Chris Hill is a Senior Research Officer at the IESSG. He holds a BSc in Civil Engineering from the University of Nottingham and gained a PhD in Satellite Geodesy, for research on the use of satellite laser ranging for the determination of geophysical parameters. He is a member of the Royal Institute of Navigation.

Dr Gethin Roberts is a senior lecturer at the University of Nottingham. He is also the chairman of the FIG's Working Group 6.4 "Engineering Surveys for construction works and structural engineering", as well as chair of Task force 6.1.1 "Measurements and Analysis of Cyclic Deformations and Structural Vibrations". He is also the UK's commission 6 delegate.

Dr Xiaolin Meng is a senior research fellow at the Institute of Engineering Surveying and Space Geodesy, the University of Nottingham. He holds a PhD in Highway, Urban Road and Airport Engineering from Tongji University in Shanghai, China and a PhD in Satellite Geodesy from the University of Nottingham. His research interests are in engineering surveying, satellite geodesy, spatial database development and quality control, GIS for

Transportation (GIS-T), Intelligent Transportation System (ITS), GIS and GPS integration, and GPS, pseudolites and INS for structural integrity monitoring.

Professor Terry Moore is Professor of Satellite Navigation and Director of the IESSG at the University of Nottingham. He holds a BSc degree in Civil Engineering and a PhD in Space Geodesy, both from the University of Nottingham. He is a Fellow, and a Member of Council, of the Royal Institute of Navigation and a Member of the (US) Institute of Navigation.

Professor Alan Dodson is Professor of Geodesy at the University of Nottingham, and Head of the School of Civil Engineering. He has a BSc in Civil Engineering, a PhD in Engineering Surveying and a DSc in Engineering Geodesy. He is a member, and recent Director, of the IESSG at Nottingham. He is a Fellow of the Institution of Civil Engineers, and the Royal Institute of Navigation, a member of the Royal Institution of Chartered Surveyors, and an editor of the Journal of Geodesy. Professor Dodson was, until recently, President of Section 1 (positioning) of the International Association of Geodesy (IAG) and is a past Dean of the Faculty of Engineering at the University of Nottingham.

CONTACTS

Emily Cosser
IESSG
University of Nottingham
University Park
Nottingham, NG7 2RD
UNITED KINGDOM
Tel. + 44 115 951 3933
Fax + 44 115 961 3881
Email: isxec@nottingham.ac.uk
Web site: http://www.nottingham.ac.uk/~isxec