ACCURACIES ACHIEVABLE BY GPS IN PRACTICAL ENGINEERING AND SURVEYING APPLICATIONS

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ABSTRACT

This paper is concerned with the accuracy of GPS when used in a dynamic mode for the most common surveying and engineering applications. It highlights three issues: modeling of multipath errors, correct assignment of stochastic models for basic GPS phase data and calibration of the performance of GPS systems. It is concluded that more work is required, especially in the detailed understanding of errors sources, before the full potential of GPS can be exploited by practising surveyors and engineers.

INTRODUCTION

GPS is rapidly becoming the default measurement tool for a very large number of standard civil engineering and land surveying operations. These include classical activities such as control surveys, topographical detail collection for large scale plans, setting out, and monitoring of deformation - as well as new developments such stakeless surveying (i.e. automatic guidance for civil engineering plant) and futuristic applications such as on-site robotics. For all of these applications knowledge of the accuracy being delivered by GPS is crucial. It is, however, only very rarely the case that the quality measures output by the GPS data processing component of the operation (either in real-time or in post-processing mode) properly describe the real quality of the results. This paper is concerned with quality of GPS - what determines it and how it is assessed.

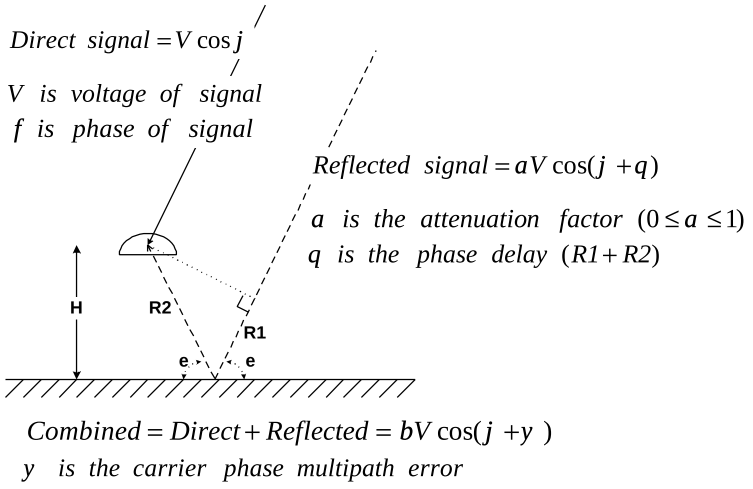
For many practical surveying and civil engineering applications the most significant error sources are those associated with multipath error estimation and analysis, as it is usually the single-most important problem in kinematic GPS applications. In this paper typical sizes and patterns of multipath errors are presented and methods for modelling it in real time are reviewed. Finally a method is discussed that can, for slow moving antennas, reduce such errors by about 50% of their normal size and some possible engineering applications of the method are highlighted. Throughout the analysis emphasis is placed on the height component of the position error. This is for two reasons: firstly it is the largest of the three components and so represents the ‘worst case’ scenario, and secondly to reflect the theme of this meeting (*importance of heights*). The Swedish National Land Survey has an international reputation for its excellence in the research and development of precise height measurement techniques and GPS is naturally playing an increasingly important role in its operations.

Evidence is presented for strong spatial correlation between phase measurements made to different satellites. It is shown that the fact that this correlation is ignored, which is normal practice in GPS data analysis, is a major factor in the poor performance of current quality assessment methods and real-time quality control measures.

Finally the issue of performance calibration of GPS systems is briefly discussed. This is a topic that has received little attention to date but is of increasing importance. It is easy to compare the performance of traditional surveying instruments such as EDM - where accuracy and range are usually simply related (and where the environment is of rather little importance). For GPS there are many other factors to consider, such as time to first fix (for RTK), range for guaranteed ambiguity determination, performance in partially masked environments (e.g. under light tree canopies), susceptibility to multipath and accuracy in different kinematic scenarios. Recommendations are made for some of the components of a standard testing facility to compare the performance of commercially available (and other) GPS systems.

MUTLIPATH MODELLING AND ESTIMATION

Multipath is caused by the mixing of GPS signals reflected from (usually nearby) objects with those directly received from the satellite. The basic set-up is shown below.



Detailed analysis of multipath shows that it is largely driven by the nature of the reflecting surface and that the maximum amplitude is one quarter of the wavelength of the signal being measured (i.e. 0.048m and 0.061m for L1 and L2 respectively). It is cyclic in nature (due to continuous change of distances R1 and R2), with the frequency depending of the distance of the reflecting object from the antenna (a nearby object leads to lower frequencies) and the satellite elevation angle.

Multipath causes an increase in ‘noise’ that leads to two related (but essentially different) problems. Firstly it is more difficult to solve for ambiguities – so the whole process fails more often that it would if multipath were not present, and secondly, even when the process succeeds, the results will be of a poorer quality. This paper is fundamentally concerned with the second of these problems.

In some applications it is possible to mitigate the amount and/or effect of multipath by adopting strategies such as:

- Siting antenna near surfaces with low reflectance
- Laying radio absorbent material around the antenna
- Using special antenna designs (with ground planes or choke rings)

But in practical engineering application these strategies are rarely applicable – the nearby surfaces are likely to be highly reflective (e.g. steel structures) and it might be essential to use lightweight antenna. Hence approaches based on modeling are often the only solution.

Multipath errors are clearly not random and are driven by basic physics. In principle they would be known if the exact geometry of the observing site was known and the reflectance properties of the reflecting surface were understood. Practical attempts to models multipath in this way have failed so most researchers in this area are trying more empirical approaches.

For instance the use of a technique based on signal to noise ration (SNR) developed by Comp & Axelrad (1996) has been investigated by Barnes, Ackroyd & Cross (1998) to assess its potential for RTK engineering surveying. What follows is a summary of the results - for more details of the mathematics and algorithm see *ibid*.

The data used for the test was collected on the roof of a building for a period of one hour with an elevation cut-off angle of zero degrees and a recording interval of 1Hz. Trimble 4000 SSE receivers were used and the baseline length was approximately 10m. Note that previous data collected on this roof had shown significant multipath. Full details of the data set and environment are given in (Barnes and Cross 1997) and a sample of the true double difference residuals (negated error) is given in Fig. 1.

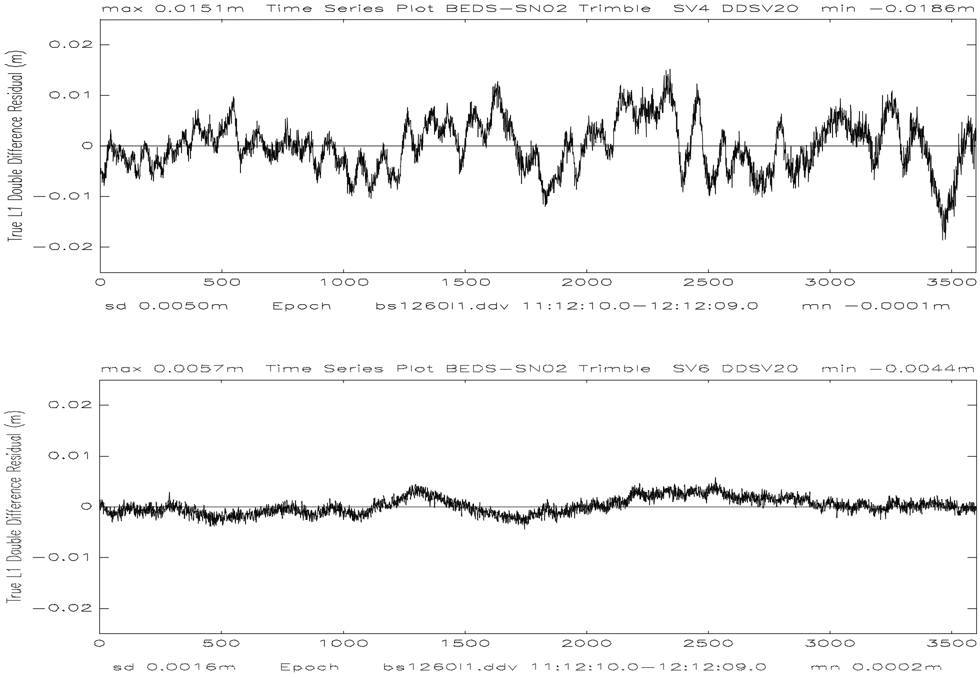


Fig. 1: True L1 double difference residuals for SV4 (20^o-3^o) and SV6 (50^o-80^o)

Several important (and well-known) trends can be seen in Fig. 1. The two most important, and most obvious, are the cyclic nature of multipath and its dependency on elevation angle. Fig. 2 shows a time series plot of the error in height following processing by the GASP software. The basic approach of GASP is described in Corbett & Cross (1995) but it is important to note that the results presented here will be ‘general’ and not dependent on GASP. This is because whilst different software might use completely different strategies for ambiguity determination (and so have different success/failure characteristics), when it comes to computing short vectors from a single epoch of double difference phase data (with already known ambiguities) they all use basically the same algorithm. Errors of up to 20mm can be found in Fig. 2 and a clear cyclic pattern - caused by the multipath is evident.

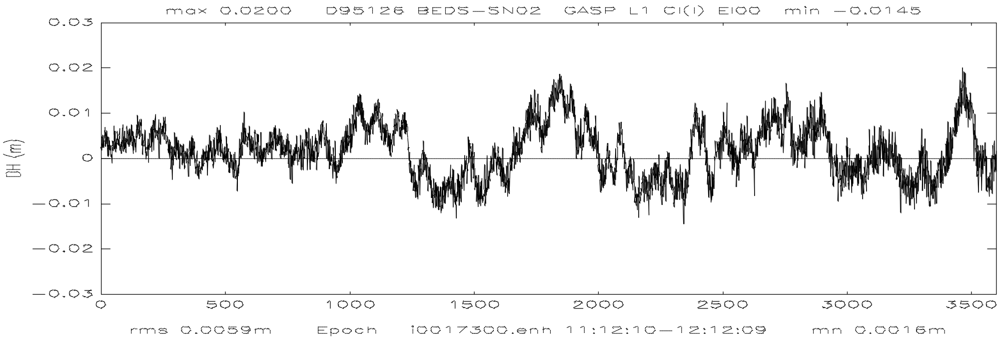


Fig. 2: GASP results for a scaled identity covariance matrix

The double difference SNR based multipath estimate was then computed for each L1 double difference phase observation and applied before again computing the positions with GASP. This time a simple elevation dependent stochastic model was used to reduce the effect of low elevation satellites. The new position error time series (height component) is shown in Fig. 3.

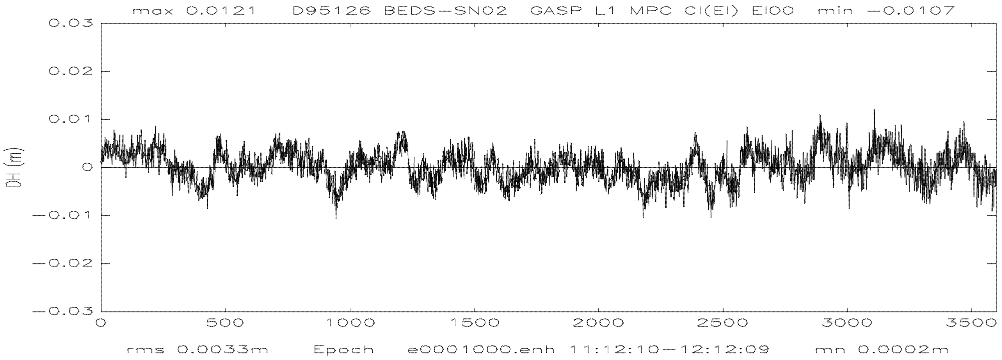


Fig. 3: GASP results following correction for multipath (SNR method) and use of an elevation dependent stochastic model

It can be seen that the RMS height error is 3.3 mm which is a 44% improvement over the standard current solution (Fig. 2, no multipath modelling and an identity matrix as a stochastic model). Medium to high frequency multipath fluctuations still remain in the series, but the low frequency multipath present in Fig. 2 are mostly removed in Fig. 3. It is important to note that the successful application of the SNR-based multipath technique relies heavily on an accurate knowledge of the antenna gain pattern in order to determine the direct SNR signal. It is possible that gain patterns might become distorted when the antenna is placed close to large conducting objects. Also routines which estimate the frequency and amplitude parameters are needed. The adaptive notch filter and adaptive least squares methods used here work sequentially and converge in typically 5 to 10 minutes, they are therefore suited to real time. However currently it is necessary to estimate manually the number of reflected multipath signals. Better spectral analysis routines would undoubtedly improve the final multipath estimates and the existing routines might work even better if the SNR had greater resolution. Hence, although the method clearly has enormous potential, considerable research and development would be needed before it could be implemented within a real-time kinematic GPS processing system.

STOCHASTIC MODELLING AND ACCURACY ASSESSMENT

Although not discussed in detail here the standard precision measures associated with the foregoing solutions do not, in general, reflect the real quality of the data. In other words the variation in the true position errors (e.g. those in Figs. 1 and 2) are not matched by similar fluctuations in the time series of the standard deviations. The formal standard deviations, as expected, simply show gradual, almost linear, changes due to changes in geometry plus occasional jumps due to new satellites entering or leaving the observable part of the constellation. Also, although the average unit variance oscillates wildly, it does not correspond to the true errors. The mean unit variance is, however, close to unity, reflecting the fact that the average values for the variances of the double difference phase measurements have been correctly estimated.

It is a fundamental goal of those working directly with GPS data and developing algorithms and software for position estimation that any formal precision measures computed from the least squares process should really reflect the quality of the solution. The currently available GPS processing software does not do this. The fundamental reason is that multipath errors vary rapidly with time – so causing the quality of the data to vary rapidly. All current solutions use very simple stochastic models, either an identity matrix (multiplied by a constant) or some sort of simple elevation based function (to force the final solution to better fit the date from higher elevation satellites).

Better understanding the multipath can lead to improvement in both the quality of the final solution and in the fidelity of the quality measures. The first part of this assertion has already been proved (by the differences between Figs. 2 and 3). That the second part is, in principle, true is shown by an experiment based on the following procedure.

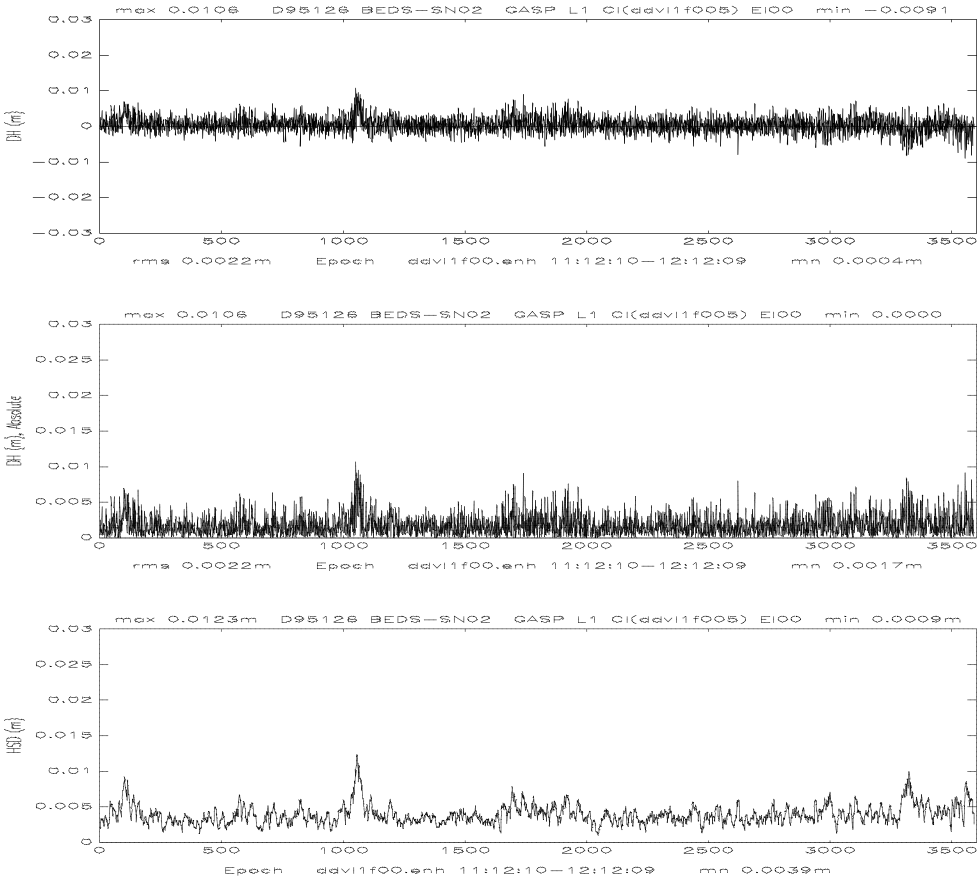
- For each double difference, at each epoch, the true errors have been computed using the known station coordinates. Time series such as those in Fig. 1 have been obtained.

- Each double difference true error has been squared and also cross-multiplied by every other error at that epoch, time series of squared values and cross-products have hence been produced.

- Using a simple moving average (based on a one minute window) average values of these squares and cross products have been computed. These are estimates of the variances and covariances of the true double difference errors - so enabling a covariance matrix of double differences to be constructed at every epoch.

- Positions, precision measures and test statistics have been computed in the normal way.

This procedure is called here the *reverse engineered* solution – because it would not of course be possible without prior knowledge of the positions (something that would never be known in practice). The results from the application of this procedure to the data set already introduced are shown in Fig. 4



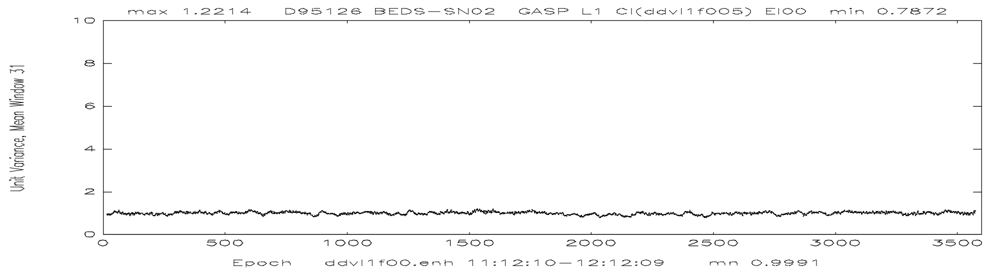


Fig. 4: GASP results for a correct (reverse engineered) stochastic model

The overall height RMS from the reverse engineered solution is 2.2 mm, a 63% improvement over the identity matrix model, and the maximum height error is reduced to 1.1 cm. Clearly the use of a more correct stochastic model has significantly improved the results. Perhaps more important is the fact that the series exhibits a much more random (white noise) behaviour with only occasional small increases and no low frequency multipath fluctuations. This shows that the use of the correct correlation in the stochastic model has had the same affect as modeling the multipath error as part of the functional model. This will not surprise geodesists with knowledge of estimation theory. It is well known that, in principle, systematic measurement errors can either be treated functionally or stochastically. The reason for including the experiment here is simply to emphasise the power of proper stochastic modeling and to encourage research into the derivation of transferable models for typical GPS operations and environments.

Perhaps the most valuable conclusion, however, relates to the quality measures. It can been seen clearly from Fig. 4 that the height standard deviations follow almost exactly the trends in the absolute height error and give a very high fidelity indication of position quality. The more correct models, not surprisingly, not only produce better quality results, but also produce better estimates of that quality – something that is most definitely missing from current solutions.

GPS CALIBRATION ISSUES

As has been mentioned, during the past two or three years the RTK technique has become the preferred surveying method for a wide variety of applications (especially in engineering). This trend does, however, raise a number of performance related issues worthy of serious consideration. One obvious question is how accurate is a particular RTK system? It is relatively simple to assess the precision of such systems but to examine accuracy in a truly kinematic environment is non trivial (the earlier descriptions in this paper are based on static tests), especially in environments that exhibit variable (in time and space) multipath conditions. Other questions include: how fast can the system recover initial ambiguities, how is this speed affected by dynamic environments such as multipath and foliage, how do differing satellite geometries and DOP (Dilution of Precision) values affect system performance, and how does one know that the resolved ambiguities are correct? In short, how would one go about benchmarking a RTK GPS system?

This section presents a number of tests, described in more details in Edwards et al (1999) which together might form the basis of a methodology for the assessment of the performance of such systems, together with some typical results that might be obtained. Detailed analysis of such test results may go a long way to answering some of the questions raised. It should be noted that the main purpose of raising this issue in this paper is to stimulate debate on the topic, not to discuss the performance of particular systems in detail.

Kinematic tests

One of the fundamental problems in the development of benchmark tests for RTK GPS is how to assess accuracy as well as precision. In order to achieve this in a truly kinematic environment the 'true position' of the roving GPS antenna must be recorded at the same instance that a GPS position is recorded. One place at which a facility capable of doing this has been constructed is at the Central Laboratory of Roads and Bridges, Nantes, France, Peyret (1995). The facility known as SESSYL, is essentially a mobile petrol-powered train that can carry a GPS receiver and antenna and which travels on an oval track (about 180m in length) with a known trajectory. GPS positions can be compared with ‘true positions’ in order to measure their accuracy (rather than just the precision). Although the track is located in a basically clean multipath environment, multipath can be induced by attaching a metal plate to the train and by parking large vehicles near to the track. Complete losses of lock can also be caused by temporarily erecting a wire mesh tunnel over part of the track. In February 1997 a number of tests were carried out using SESSYL and are reported in detail in *ibid*. The objective was to:

- assess the accuracy of an RTK system using different antenna combinations in both clean and multipath environments, and

- measure the speed of recovery of ambiguities (On-The-Fly) after complete loss of lock on all satellites.

Ambiguity resolution tests

A crucial factor in the operational use of RTK GPS is the speed with which it can initialise (i.e. solve for integer ambiguities), prior to the commencement of a survey or at some point during it following 'loss of lock' due to the masking of some or all of the satellites (for instance after passing under a bridge). In an optimum environment, free from multipath and obstructions one might reasonably expect any RTK system to resolve for integer ambiguities in around 2 minutes (120 sec) or less. Of greater interest, however, is the effect that varied dynamic environments with medium/high multipath, or partial tree cover might have on initialisation times.

Following the somewhat inconclusive results obtained from the SESSYL ambiguity resolution tests, the following experiments were designed to examine further RTK ambiguity resolution performance. Of particular interest was ambiguity resolution under harsh conditions, namely in the presence of high multipath and under partial tree cover. The overall objective was to:

- assess the speed and accuracy of an RTK system for the computation of initial integer ambiguities with different satellite geometries.

The method adopted for these experiments was to undertake a series of controlled re-initialisations of the RTK system over a period of time. This was achieved by using successive antenna pulls (removal of antenna leads) at the rover receiver forcing total loss of lock to all satellites, as though driving under a bridge. Two environments were chosen, a concrete rooftop (known to induce high levels of multipath) and an area of medium to dense tree cover. Average baseline lengths were 10m and 50m respectively for the rooftop and tree cover environments.

Signal tracking sensitivity test

The experiments outlined in the preceding section provide a method of testing the ability of an RTK system to recover ambiguities in two differing dynamic environments. However during a typical survey the rover antenna is often moving within such environments, e.g. an urban area or along a hedgerow containing mature trees. Of particular interest is the ability of an RTK system to deliver fixed ambiguity solutions whilst moving through such an environment which will cause temporary degradation/obscuring of the GPS signals. A method of quantifying system performance in just such an environment now outlined below.

The methods used for this test could range from the very complex to the very simple. One simple test would be to mount the roving RTK antenna on to the roof of a vehicle, and then drive the vehicle along an avenue of trees. The tree canopies would interfere with the incoming GPS signals to varying degrees as the vehicle moved along. The result would be degradation in signal quality and an increase in the noise within the system, which might well affect the ability of the system to deliver fixed ambiguity solutions. Clearly standard conditions need to be described so that the experiments could be (almost) replicated in different parts of the world.

General remarks

We live in a world in which it is expected that the quality and performance of almost everything we buy and/or use can be described by a set of standard parameters (albeit often empirical). Indeed such parameters (when fully understood and properly interpreted) can be extremely helpful when selecting between choices. For instance when buying a car it would be natural to compare an enormous number of them: fuel consumption, top speed, boot (trunk) capacity, length and width, safety and comfort features, etc.

In the geodetic sciences we have been used to dealing with fewer parameters, perhaps just accuracy, range and weight, but with RTK GPS the situation is far more complicated, as this paper has shown. It is important to consider, *inter alia,* accuracy, time to resolve ambiguities and ability to maintain lock, as well as others (not addressed here) such as operating distance. Unfortunately, and unlike traditional systems, all (or at least most) of these things depend very heavily of the prevailing conditions (multipath, level of masking, nature of dynamics, etc) and on a number of system features (type of antennas, satellite geometry, number of satellites, etc), so assigning suitable parameters is not a simple task.

CONCLUSIONS

Multipath is the dominant technical problem in the (even more) widespread use of GPS in kinematic operations for general surveying and engineering applications. It affects the accuracy that can be delivered, the fidelity with which that accuracy can be described and the ability to derive integer ambiguities in order to start the positioning process.

It has been shown that there are two modelling approaches that can, in principle, alleviate the problem – but much more research is needed (a) to turn them into practical real-time solutions, and (b) to understand them better in order even to begin this process.

Also this paper has indicated a number of tests that could perhaps be used to develop standard parameters to describe the performance of RTK GPS. What is now needed is for professional and scientific bodies to take the initiative in designing standard tests in standard conditions. It will then be possible for all potential users to make informed judgements between competing equipment. At the moment it is extremely difficult for anyone, even someone with a deep knowledge of GPS, to select hardware in an objective manner.

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