Precise GPS Positioning: Prospects and Challenges

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BIOGRAPHY

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ABSTRACT

Carrier phase-based GPS positioning is now an indispensable tool for a wide range of precise applications in navigation, surveying and geodesy. To address such a variety of applications, many implementations of precise GPS techniques have been developed. Almost all techniques involve 'relative' positioning, in which one GPS receiver/antenna's coordinates are determined with the aid of measurements also made at a stationary base or reference receiver. In essence all of these techniques may be categorised according to a small number of attributes. Is the technique implemented in the post-processed or real-time mode? Does the scenario involve static or kinematic positioning? Is the inter-receiver distance comparatively short (say <10km) or very long (e.g. >1000km)? Is a single base station involved or a reference network of receivers? and so on. Each of these attributes also determines the data processing strategies that should be employed to ensure accurate and reliable positioning results. Over the last two decades 'precise GPS positioning' has played a role similar to F1 motor racing. That is, challenges to carrier phase-based GPS positioning spur research on new hardware, new data processing algorithms and new operational procedures, which are then incorporated into mainstream surveying and navigation 'products'. In this paper, the challenges, progress and outlook for high precision GPS positioning will be discussed, with particular emphasis on identifying the *constraints* and commenting on the prospects for addressing them in the near and medium term.

1. INTRODUCTION

The Global Positioning System (GPS) is an all-weather, global, satellite-based, round-the-clock positioning system developed by the U.S. Department of Defense, that became available to the civilian surveying and navigation community in the early 1980s. The standard mode of high accuracy *differential* positioning requires <u>one</u> reference GPS receiver to be located at a "base station" whose coordinates are known, while the <u>second</u> user GPS receiver simultaneously tracks the same satellite signals. When the carrier phase data from the two receivers is combined and processed, the user receiver's coordinates are determined relative to the reference receiver. However, the use of carrier phase data comes at a cost in terms of overall system complexity because the measurements are *ambiguous*, requiring the incorporation of an "ambiguity resolution" (AR) algorithm within the data processing software. Developments in GPS user receiver hardware have gone a significant way towards improving the performance of AR (Han & Rizos, 1997a).

The distance from the user receiver to the nearest reference receiver may range from a few kilometres to hundreds of kilometres. As the receiver separation increases, the problems of accounting for distance-dependent biases grows and, as a consequence, reliable ambiguity resolution becomes an even greater challenge. On the other hand, developments in "GPS Geodesy" have been so successful in the last 15 years, that relative accuracies of "a few parts per billion" are now possible even without AR. However, for so-called "high productivity" carrier phase-based GPS techniques, AR is crucial when small amounts of data are used (unlike the case for "GPS Geodesy" techniques).

Hence carrier phase-based positioning is the result of progressive R&D innovations. In addition to advances in AR techniques (Han & Rizos, 1997b), over the last decade or so several significant developments have resulted in this high accuracy performance also being available in 'real-time' – that is, in the field, immediately following the making of measurements, and after the data from the reference receiver has been transmitted to the (second) field receiver for processing. Precise real-time positioning is even possible when the GPS receiver is in motion. These systems are commonly referred to as RTK systems ("real-time-kinematic"), and make feasible the use of GPS-RTK for many time-critical applications such as machine control, GPS-guided earthworks/excavations, automated haul truck operations, and other autonomous robotic navigation applications. The crucial innovations therefore are:

- Real-time operation through the provision of communication links between reference and user receivers (Langley, 1993; Talbot, 1996), and mobile computing capabilities built into the user receiver equipment to carry out the necessary calculations.
- Efficient ambiguity resolution algorithms able to take advantage of improvements in GPS receiver hardware (that allow dual-frequency, high quality measurements to be made) (Han & Rizos, 1997a).
- AR being implemented even as the user receiver is in motion (so-called "on-the-fly" AR, or OTF-AR), and the post-AR positioning capability being equally applicable to static and kinematic positioning (Landau & Euler, 1992; Han & Rizos, 1997b).

Unfortunately, such advances are 'fragile' because there are still not yet as reliable and efficient as demanded by many applications. If the GPS signals were tracked and loss-of-lock never occurred, the integer ambiguities resolved at the beginning of a survey could be kept for the whole GPS kinematic positioning span. However, the GPS satellite signals are occasionally shaded (for example, due to buildings in "urban canyon" environments), or momentarily blocked (for example, when the receiver passes under a bridge or through a tunnel), and in most cases the integer ambiguity values are 'lost' and must be redetermined. This process can take from a few seconds up to several minutes with present commercial GPS systems for short-range applications. During this "re-initialisation" period the GPS carrier-range data cannot be obtained, and hence there is 'dead' time until sufficient data has been collected to resolve the ambiguities. If interruptions to the GPS signals occur repeatedly, ambiguity "re-initialisation" is, at the very least, an irritation, and at worse a significant weakness of commercial GPS-RTK positioning systems. The goal of all GPS manufacturers is to develop the *ideal* real-time precise GPS positioning system, able to deliver positioning results, on demand, in as easy a manner as is presently the case using pseudo-range-based differential GPS (DGPS) techniques, which typically deliver positioning accuracies of the order of 1-5 metres.

Another development that also results from innovations in "GPS Geodesy" is the concept of GPS users needing to only purchase and operate <u>one</u> carrier phase-tracking GPS receiver, but then rely on a network of reference receivers operated by a third party. (This can be attributed to the spectacular success of the continuously-operating global GPS network operated under the auspices of the International GPS Service, as well as the increasing number of local or regional permanent GPS networks established for a variety of purposes – Rizos et al., 1999.) Such networks could allow "service providers" to offer real-time services to users – through the necessary transmission of reference receiver data, or post-processing services via the Web.

Issues such as the cost of top-of-the-line GPS receivers, time-to-AR, distance from reference receiver(s), number of visible satellites, minimisiation of multipath disturbance, operation of reference receivers, etc., can be considered *constraints* to high precise GPS positioning (Han & Rizos, 1996c). Over the last few years several important developments have occurred that address some of the main constraints, and offer hope for significantly improved commercial GPS products and services:

(a) Under certain conditions decimetre-level positioning accuracy has been possible even when the baseline lengths have been up to hundreds of kilometres in length via, e.g., the implementation of network GPS carrier phase-based positioning techniques.
(b) Reliable OTF-AR in the shortest period of time possible, even with just one measurement epoch, is possible. Given very short 'time-to-AR' the notion of cycle slips, or having to "re-initialise" the ambiguities, has no meaning because so-called 'instantaneous' OTF (IOTF) is then the normal mode of kinematic positioning for all epochs (Rizos & Han, 1998).
(c) Third generation dual-frequency GPS receivers capable of making carrier phase and pseudo-range measurements on the two L-band frequencies is a necessary prerequisite for very fast OTF-AR or IOTF-AR.
(d) Improved multipath mitigation within the GPS receivers/antennas themselves.
(e) Continuously-operating reference receiver networks that support real-time or Web-based precise GPS navigation and surveying. These are being established in many countries/cities, and offer the opportunity to develop innovative services to a wide range of users. In addition, the global tracking network of the IGS functions as the 'backbone' for precise static and kinematic GPS positioning.
(f) The use of integrated GPS-GLONASS receivers – do they contribute anything over and above GPS-only receivers?

It must be emphasised that crucial contributions to the development of new innovative GPS kinematic positioning techniques have been made by the universities. In almost all cases, university-based researchers have developed the necessary algorithms and demonstrated the feasibility of new techniques. Commercial products and operational implementations have followed.

In this paper the focus is on the status, prospects and challenges of carrier phase-based kinematic GPS positioning. Even though tremendous advances have been made in the development of *ultra-precise* static GPS positioning techniques ("GPS Geodesy" techniques address mainly geodynamic, geodetic and geoscientific applications), overcoming the challenge of cm-level accuracy positioning of a moving user receiver will ultimately benefit a far wider user community. In addition, this is where much of the R&D by university-based researchers, and by instrument manufacturers, is being undertaken. *In fact, from the point of view of precise navigation and surveying the static mode of positioning can be considered a special case of the kinematic mode of positioning.*

2. CARRIER PHASE-BASED GPS KINEMATIC POSITIONING

Current precise GPS positioning techniques are the result of university research carried out during the 1990s, that has been subsequently implemented by GPS manufacturers in their carrier phase-based "GPS Surveying" products. In particular, over the past decade or so, several developments have occurred which deliver high accuracy performance in 'real-time' –- that is, in the field, immediately following the making of measurements, and after the data from the reference receiver has been transmitted to the user receiver's computer for processing. Real-time positioning is even possible when the GPS receiver is in motion (with AR being carried out using an OTF algorithm). These systems are commonly referred to as RTK systems ("real-time-kinematic"), and make feasible the use of GPS for time-critical applications such as machine control, GPS-guided excavations, container port operations, etc.

2.1 Instrumentation Developments

In the last decade the instrumental developments that have made reliable RTK systems possible, with very short 'time-to-AR', using OTF-AR algorithms, can be identified:

- So-called 'third generation' dual-frequency GPS receivers, measuring carrier phase and pseudo-range on both the L1 and L2 frequencies, which is a prerequisite for very fast OTF-AR (Han & Rizos, 1996b).
- Advances in receiver electronics, antennas and data processing algorithms that mitigate the disturbing influence of multipath, ensuring that AR is reliable (the correct integers are resolved) even with very fast OTF-AR.
- Advances in chip-level electronics and DSP algorithms that make possible comparatively low-power hardware (of the order of a few Watts), making user equipment lighter, more compact and easier to integrate with other equipment.
- Development of GPS receiver products that have tightly integrated GPS+com links (single-frequency UHF or spread spectrum), making the user's task of operating an RTK system a lot easier than it was in the past.
- Receivers capable of 10-20Hz (RTK-generated coordinate) output, able to address critical machine-control applications.
- Receivers with >24 correlator channels, making them feasible to track signals other than GPS, such as GLONASS, WAAS ("Wide Area Augmentation System"), CDMA coms channels, and ultimately Galileo satellite signals.

It must be emphasised that the above list is not exhaustive. GPS, unlike any satellite-based positioning system before it, benefits from continuous and vigorous innovation, not all of which is attributable to the demands of the comparatively small high precision positioning 'market'. It is estimated that more than 90% of positioning applications do NOT require carrier phase-based techniques, but advances in electronics that are occurring in the 'mass GPS market' are contributing to the niche 'high precision market' as well. With respect to the GPS system itself, two additional civilian frequencies will be transmitted by the Block IIF and Block IIR satellites from about 2003 onwards. The L2 signal will be modulated by the C/A code (or possibly another, improved PRN code), making it possible to design dual-frequency GPS receivers at a significantly lower cost than is currently the case. The additional civilian signal on L5 will also significantly improve the reliability of AR (Han & Rizos, 1999).

There is pressure on GPS manufacturers to produce general-purpose carrier phase-based products on the one hand, and application-specific products on the other hand. In general, the "form-factors" for carrier phase-based GPS products are: (a) OEM boardsets ("original equipment manufacture") suitable for system developers, (b) products intended for embedded applications such as machine control, and (c) "man portable" systems for surveying. Two examples of the latter are shown in Figure 1. They are designed as modules that permit reconfiguration in different ways: backpack, on-the-pole, tripod-mounted.

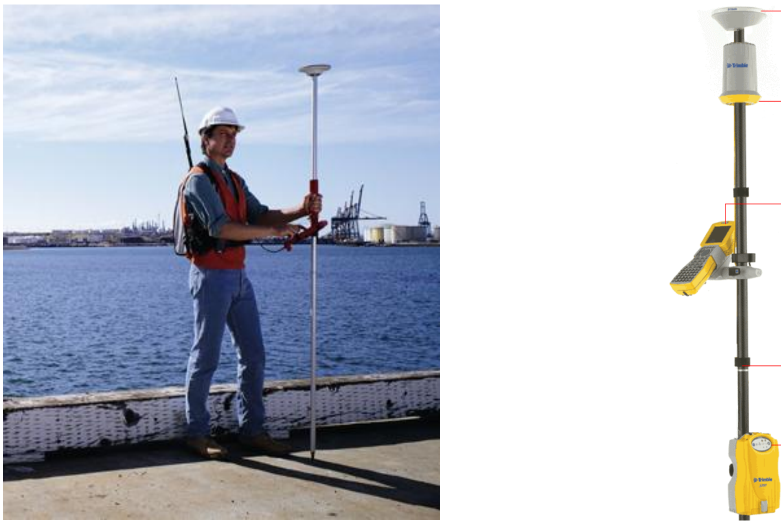

Figure 1: Typical top-of-the-line GPS Surveying products capable of RTK using OTF-AR algorithms. The Leica System 530 (left) and the Trimble 5700 (right).

2.2 The Issue of 'Time-to-Ambiguity-Resolution'

Although RTK systems represent the 'state-of-the-art' in GPS commercial-off-the-shelf (COTS) technology, able to deliver centimetre-level accuracy in real-time using a pair of GPS receivers, there are several conditions (or constraints) that must be fulfilled. These constraints may be so restrictive that they may hinder the widespread adoption of precise GPS technology for both engineering surveys (a traditional application of carrier-phase-based GPS techniques), as well as for new applications such as navigation in support of vehicle guidance/control.

If GPS signals were continuously tracked and loss-of-signal-lock never occurred, the integer ambiguities determined at the beginning of a survey would be valid for the whole period that GPS was being used. However, the GPS satellite signals can be shaded (for example, due to buildings in "urban canyon" environments, or when the receiver passes under a bridge or through a tunnel), in which case the ambiguity values are 'lost' and must be redetermined. This process can take from a few seconds up to a few minutes with present GPS COTS systems, *but only when the reference-to-user receiver distance is less than about 20km*. During this "re-initialisation" period centimetre accuracy positioning is not possible, and hence there is 'dead' time until sufficient data has been collected to "resolve the ambiguities" (see Figure 2). If interruptions to the GPS signals occur repeatedly, then ambiguity "re-initialisation" is at the very least an irritation, and at worse a significant weakness of GPS COTS carrier phase-based systems. In addition, the longer the period of tracking required to ensure reliable OTF-AR, the greater the risk that cycle slips will occur during this crucial "re-initialisation" period. These shortcomings are also present in any system based on data post-processing as well. Figure 2 also illustrates the situation when the OTF-AR algorithm is so optimised that it can operate on a single epoch of data, i.e. IOTF-AR (Rizos & Han, 1998).

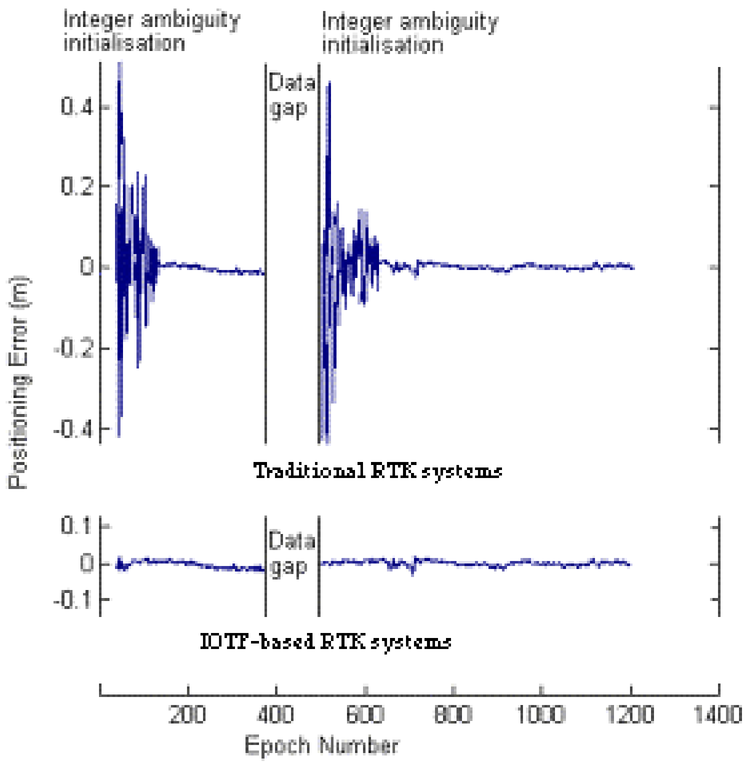

Figure 2: Comparison of RTK performance using standard multi-epoch OTF-AR techniques and the instantaneous OTF-AR technique. Note the 'dead' time (when accuracy is degraded) during which AR is being undertaken in upper plot, compared to lower plot for IOTF-AR.

2.3 Improvements in AR & ValidationTechniques

Several ambiguity search procedures for OTF-AR have been suggested during the 1990s, including the FARA, FASF, Cholesky, Hatch, and U-D decomposition methods (Han & Rizos, 1997b). However, the most optimal procedure uses the LAMBDA transformation (Teunissen, 1994; Han & Rizos, 1995b) in combination with the U-D decomposition search procedure. Although these are all search techniques in the estimated ambiguity domain, when combined with search procedures in the measurement and coordinate domain single-epoch OTF-AR is possible (Han, 1997a). Although new search algorithms are still being researched at universities, all commercial OTF-AR algorithms use the LAMBDA method in one form or another. Furthermore, the most significant improvements will come from increasing the *reliability* of AR, as well as minimising the 'time-to-AR'. This requires careful attention to issues such as statistical testing, quality assurance (QA), and AR validation procedures.

There is no "magic" algorithm for single-epoch (or IOTF) ambiguity resolution. The AR procedure is a rather straightforward one, though a relatively unstable procedure when using small amounts of data, with a high chance that incorrect ambiguities will be resolved (particularly when there is multipath disturbance of the GPS signals), hence significantly biasing the baseline results. To improve the computational efficiency and to improve the reliability (or AR success-rate) of the procedure, advances in data modelling, parameter estimation and statistical testing have had to be made. None on their own can deliver the performance required, but the sum of the suggested improvements has resulted in a success-rate for the IOTF-AR algorithm that is greater than 98% (see, e.g. Han, 1997a; and others). For example, an on-line stochastic model determination method and an adaptive procedure was described in Han (1997b). The 'conventional wisdom' is that the reliability of the OTF-AR algorithm for single-baseline techniques is improved under the following conditions:

- Good satellite-receiver geometry, characterised by a PDOP of less than 5.
- Maximising the number of tracked satellites, with 6 or more being preferred.
- Constraining the length of the baseline, the shorter the better.
- Minimising the multipath effect on signal tracking and data processing.

Even though research is still underway on the refinement of the stochastic model, and on QA/validation procedures, several commercial products have been released. For example, the Ashtech Z-Extreme claims IOTF-AR (or at the very least a few seconds of data) under conditions when satellite geometry is particularly favourable, the number of GPS satellites is greater than 7, and the baseline length is shorter than 10km. Even if IOTF-AR is not possible, e.g. due to longer baselines, it is claimed that the reliability of AR has been significantly improved. This trend to either an improvement in the reliability of OTF-AR (in order to accommodate different scenarios) even sacrificing a very short 'time-to-AR', or ever more restrictive conditions for IOTF-AR, is expected to continue. One means of breaking this 'either-or' condition is to consider multiple reference receivers (Section 3). Another significant development is the broadcast of an additional civilian signal on L5 will significantly improve the reliability of AR if using 'triple-frequency' receivers (Han & Rizos, 1999; Hatch et al., 2000).

2.4 The Issue of Baseline Length

Short-range (<10km) IOTF-AR has been reported by a number of university-based investigators, including Han (1997a, 1997b), Han & Rizos (1996b), and others. Developments in very fast AR algorithms and validation criteria procedures, together with improvements in the observation stochastic modelling and the application of careful QC/QA procedures, have generally been responsible for this increased level of performance. Such a development is welcomed by the GPS surveying community, as it allows GPS to be used for short-baseline applications that were previously addressed using 'total station' (electronic tacheometer) technology.

Carrier phase-based 'medium-range' GPS kinematic positioning has been under development for baselines several tens of kilometres in length in universities since the mid-1990s (see, e.g. Wanninger, 1995; Wübbena, et al., 1996; Han & Rizos, 1997a). IOTF-AR has also been reported for medium-range GPS kinematic positioning (Han & Rizos, 1996d; Han, 1997a). Such *medium-range* performance requires the use of multiple reference stations in order to mitigate the orbit bias, as well as the ionospheric and tropospheric biases (Rizos et al., 1997, 1999; Raquet & Lachapelle, 2001). These are exciting developments and the first commercial systems are currently undergoing testing (see Section 3.2).

In the case of *long-range* kinematic positioning several innovative concepts have been reported. One of the first tests of such a kinematic positioning concept was reported by Colombo & Rizos (1996), who demonstrated the feasibility of decimetre-level accuracy navigation over baselines up to a thousand kilometres in length! Research in this area is continuing, principally in order to address long-range applications such as the precise positioning of airborne sensors such Laser Scanners (see, e.g., Han et al., 1999). Although it is not yet possible to resolve ambiguities OTF (i.e. while the receiver is in motion) for baselines of several hundreds of kilometres in length, ambiguity "re-initialisation" or *ambiguity recovery* is possible (Han, 1995; Han & Rizos, 1995a). In other words, if signal loss-of-lock occurs, the

AR algorithm can 'recover' the ambiguities as long as any 'data gap' is less than a minute or so. Initial AR must be carried out using traditional techniques, including static initialisation.

2.5 The GLONASS Alternative?

The Russian Federation's Global Navigation Satellite System (GLONASS) was developed for the Russian military, and is at present the only satellite-based positioning system which is a natural competitor to GPS. GLONASS has the following characteristics (Kleusberg, 1990):

- 21 satellites + 3 active spares.
- 3 planes, 8 satellites per plane.
- 64.8° inclination, 19100 km altitude (11hr 15min period).
- Dual-frequency (L1 in the range: 1597-1617MHz; L2 in the range: 1240-1260MHz).
- Each satellite transmits a different frequency on L1 (=1602 + Kx0.5625MHz; $K\in[-7,24]$) and L2 (=1246 + Kx0.4375MHz; $K\in[-7,24]$).
- Spread-spectrum Pseudo-Random Noise code signal structure.
- Global coverage for navigation based on simultaneous pseudo-ranges, with an autonomous positioning accuracy of better than 20m horizontal, 95% of the time.
- A different datum and time reference system to GPS.
- There is a Precise Positioning Service and a Standard Positioning Service, as in the case of GPS.

Although some of the characteristics of GLONASS are very similar to GPS, there are nevertheless significant technical differences. In addition, the level of maturity of the user receiver technology and the institutional capability necessary to support the GLONASS space and control segment are significantly less than in the case of GPS. GLONASS will continue to be viewed by many user communities as a technically inferior system to GPS, a system that has many question-marks regarding its long-term viability. This uncertainty is stifling much needed market investment in new generation receiver hardware. Yet to dismiss GLONASS as a serious candidate for a 21st century satellite positioning technology because it cannot *compete* with GPS technology is too simplistic an analysis. Although GLONASS has the potential to rival GPS in coverage and accuracy, this potential is unlikely to be realised in the medium term, and hence for the foreseeable future GLONASS should be considered a *complementary* system to GPS (at least until Galileo becomes operational around the end of this decade). GLONASS was declared operational (with 24 satellites in orbit) in 1996, however less than 8 satellites are operating at present (May 2001).

The development of integrated GPS-GLONASS receivers which measure carrier phase offers special challenges, not the least being that the signals to the different GLONASS satellites are of different frequency, making the standard GPS data processing strategies based on double-differencing inappropriate. However, the extra satellites that can be tracked should make precise positioning a more robust procedure. During the last few years several research groups has been working to develop optimal GLONASS data processing techniques. See Leick et al. (1995), Landau & Vollath (1996), and Wang et al. (2001), for details of integrated GPS-GLONASS data processing.

2.6 Towards 'Plug-and-Play' Carrier Phase-Based Positioning

The goal of all GPS manufacturers is to develop the *ideal* real-time precise GPS positioning system, able to deliver positioning results, on demand, in as easy and transparent a manner as is presently the case using pseudo-range-based DGPS techniques. For example, the DGPS technique is robust, implemented in real-time via the transmission of correction data, and there is negligible delay in obtaining results. However, there are significant challenges for the developers of a similarly reliable "plug-and-play" positioning system that is capable of sub-decimetre accuracy:

- Residual biases or errors after double-differencing can only be neglected for AR purposes when the distance between two receivers is less than 15-20km (shorter in the case of IOTF-AR). For medium-range or long-range precise GPS kinematic positioning, the distance-dependent biases, such as orbit bias, ionospheric delay and tropospheric delay, remain significant problems which require special treatment.
- Determining how long the observation span should be for reliable AR is a challenge for GPS kinematic positioning. The longer the observation span, the longer the 'dead' time during which precise positioning is not possible (see Figure 2). This can happen at the ambiguity "initialisation" step if the GPS survey is just starting, or at the ambiguity "re-initialisation" step if the GPS signals are blocked causing cycle slips or data interruptions.
- Data latency is a challenge for many time-critical applications. The data latency is normally caused by the data transmission and the data processing, both of which cannot be avoided. Even if the data latency is only of the order of a few tenths of seconds, it may restrict certain applications.
- Quality control of the GPS kinematic positioning results is a critical issue and is necessary during all steps: data collection, data processing and data transmission. QC/QA procedures are not only applied for carrier phase-based GPS kinematic positioning, but also for pseudo-range-based DGPS positioning. However, the development of validation criteria for AR remains a significant challenge despite progress in the last five years (Han & Rizos, 1996a; Han, 1997b; Han & Mok, 1997).

In the last few years, a variation of the single-epoch OTF-AR for RTK positioning has been implemented. The application is deformation monitoring of a structure such as a building, dam or bridge, using carrier phase-based GPS positioning (see, e.g., Hudnut & Behr, 1998; Mok, 1999). (This can be referred to as "GPS Engineering Geodesy".) Several implementations resolve ambiguities each epoch, on a continuous, 24hour basis. However, the IOTF-AR algorithm is aided by knowledge that the coordinates have not changed very much from the previous epoch (certainly less than the effect of one cycle change in one or more of the double-differenced ambiguities). However, it is debatable if such IOTF-AR is truly independent from epoch-to-epoch.

In summary, the two most significant AR algorithm improvements have been in: (a) shortening the 'time-to-AR' to just one epoch of data, and (b) overcoming the baseline length constraint with respect to AR. The implementation of RTK carrier phase-based positioning is also a significant engineering development, as discussed in Section 4.

3. NETWORK-BASED PRECISE KINEMATIC POSITIONING TECHNIQUES

Since the mid-1990s university researchers have been investigating the use of multiple reference stations for improved static and kinematic positioning in support of a range of non-geodetic applications. Only very recently has there been commercial implementations of such a positioning methodology.

3.1 Bias Mitigation and the Use of Reference Station Networks

Medium-range kinematic positioning based on OTF-AR (Section 2.4) requires that baseline length dependent biases be mitigated. The most important of these are the satellite orbit, ionospheric and tropospheric biases. Multiple reference stations surrounding the area of survey can serve to generate empirical correction terms for the static or moving user GPS receiver (Wanninger, 1995; Wübbena et al., 1996; Raquet & Lachapelle, 2001). The advantage is that the distances between reference receivers can be many tens of kilometres without compromising the level of performance expected from current short-range RTK (i.e., very fast OTF-AR, even IOTF-AR under ideal conditions). This means that a large area (e.g. a metropolitan city) can be 'serviced' by a smaller number of GPS reference receivers than would be the case of the 10km spacing was enforced (as in the Hong Kong network, Figure 4).

Typically a "linear combination model" for the reference receiver measurements is used, which can model (and then be used to eliminate) satellite orbit bias, ionospheric and tropospheric delay (one example of such a model, used for IOTF-AR, is described in Han, 1997a; Han & Rizos, 1997a; Rizos et al., 1999). The basis of such an approach is that the data from the reference receiver network can be used to generate corrections to the double-differenced carrier phase data (and pseudo-range double-differences as well) formed between a user receiver and one (or more) 'real' or 'virtual' reference receiver. This is not unlike the concept of Wide Area DGPS, except that it involves carrier phase measurements rather than pseudo-range measurements. Dai et al. (2001) has investigated such a network-based methodology for combined GPS-GLONASS reference receiver networks.

It must be emphasised that there are a number of research groups investigating the optimal combination model, as well as engineering issues related to implementing such a scheme in an operational system. Many of the approaches differ only in the details. However, all must address the not insignificant challenge of very fast AR for the double-differenced parameters associated with the reference receivers (located up to 100km apart) when a new satellite rises, or after a long data gap (see, e.g., Chen et al., 2000; Dai et al., 2001).

3.2 Researching and Implementing Network-Based Techniques

The critical resource for research into network-based techniques is access to a multiple base station infrastructure. Figure 3 shows the Singapore Integrated Multiple Reference Station Network, comprising four permanent GPS reference receivers linked by dedicated telephone lines to a central server. This facility is jointly operated by the Nanyang Technological University and The university of New South Wales, and is a valuable GPS "test laboratory". In addition to testing new network-based algorithms (for reference receiver, as well as user-reference receiver, processing), it permits research into the real-time (operational) aspects of such a network. It must be emphasised that number of other networks have been established in developed countries, but the Singapore facility is perhaps unique in that it has been established, and is controlled, by university researchers.

Network-based techniques can, in principle, be implemented wherever a continuously-operating reference receiver network has been established. In general, such networks are designed and implemented to support single-baseline (user-reference receiver) techniques across a wide area. The spacing is planned such that a user receiver may be at most, say, 10km from the nearest base station (and it is the data from this station that is used to determine the user-reference receiver baseline), as in the case of the network currently being commissioned in Hong Kong (Figure 4).

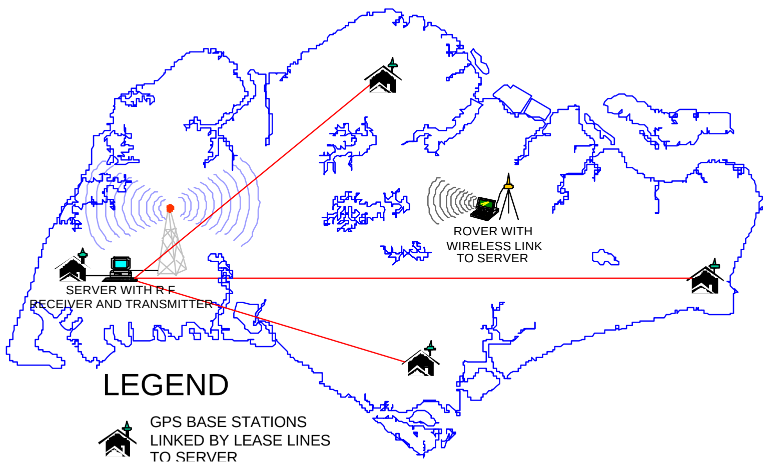

Figure 3: The Singapore Integrated Multiple Reference Station Network (locations approximate).

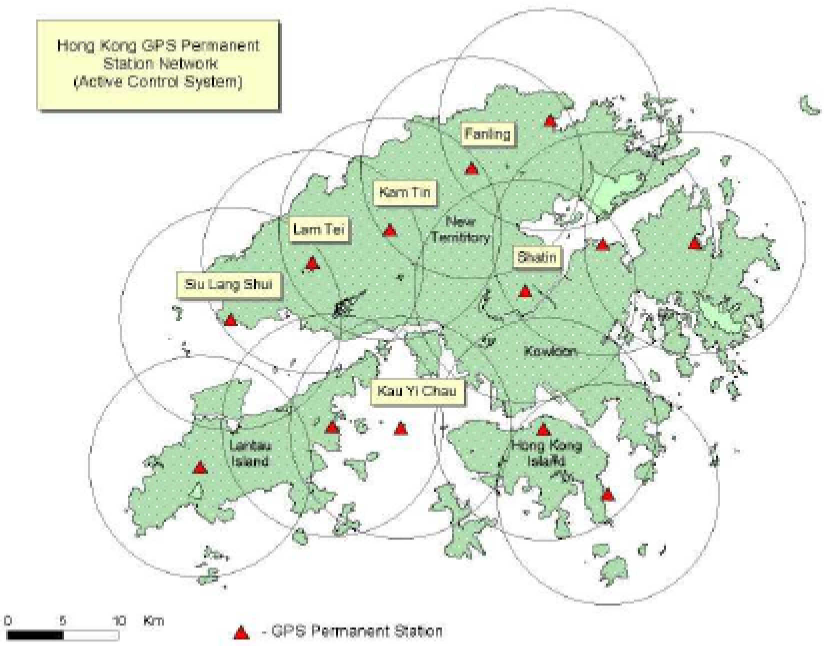

Figure 4: The Hong Kong GPS reference receiver network.

Such a density of receivers is generally difficult to justify for surveying and precise navigation users alone, therefore in the case of the state of Victoria a network (Figure 5) with an average base station spacing of 100km (with 50km spacing around the capital city) will be established (Talbot et al., 2001). While not able to support standard single-baseline positioning in as far as very fast OTF-AR is concerned (for which the Hong Kong network density is suited), it can be a candidate for upgrading to support true network-based positioning techniques. It is possible to implement the network-based approach for static and kinematic positioning in either the post-processed mode (e.g. via a Web-based processing "engine"), or in the real-time mode, or both. The greatest challenge is to network all the receivers so that all data is transmitted in real-time to a central server where the data processing occurs, and where the correction messages are generated and packeted for transmission to users. Both of these communication issues (intra-network, and network-to-user) are non-trivial.

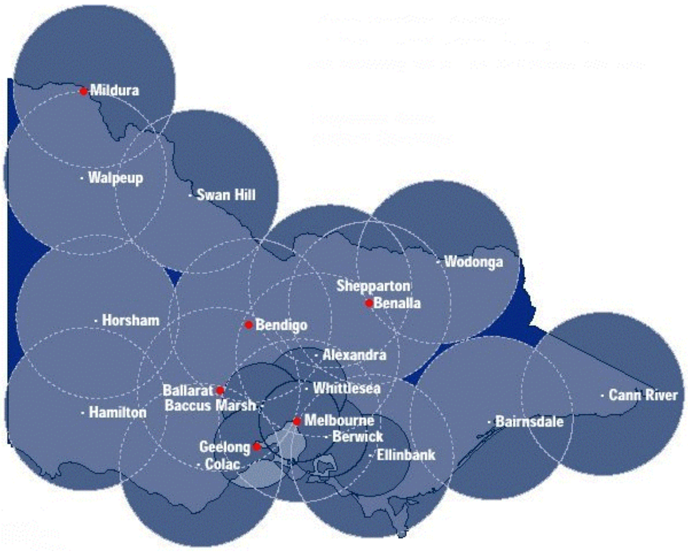

Figure 5: GPSNet Victoria. Note large circles 100km radius, small circles 50km radius.

The first truly commercial product based on the multiple reference receiver approach is Trimble's Virtual Reference Station (Figure 6). The reference receiver network has inter-station distances of between 50-100km, the approximate spacing that allows good spatial modelling of the atmospheric biases. As can be seen, this is intended to support RTK operations. The reference receiver data, and the corrections messages generated from the real-time processing of the reference network data, are transferred to the user via the mobile phone infrastructure – note that the correction messages are computed for the user location (so to create a 'virtual' base station at the user's location, i.e. a very short baseline!). Currently trials are underway on a test network in the Brisbane area (Higgins & Talbot, 2001).

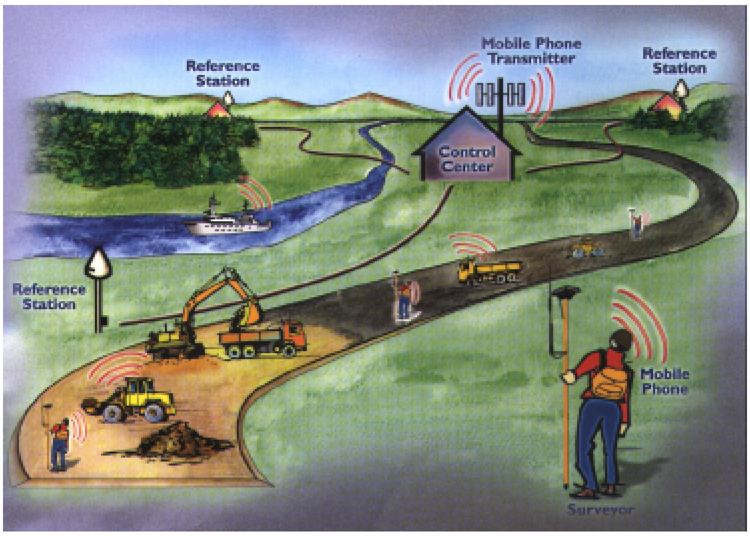

Figure 6: Trimble's Virtual Reference Station concept.

4. RTK IMPLEMENTATION ISSUES

In present 'point and click' world, the delivery of high quality GPS positioning services, on demand and with a minimum of constraints, could lead to an explosion in the use of carrier phase-based GPS positioning techniques. A good model is the current DGPS services. These have been provided for many years, and although the removal of Selective Availability has dented their 'market', government-run or commercial DGPS service providers continue to address the needs of users. Hence, what is required is a paradigm shift away from the 'own-and-operate-a-base-station' by an individual user mentality, to one based on contracting services.

4.1 Real-Time DGPS: Data Correction Transmissions

The United States body, the Radio Technical Commission for Maritime (RTCM) Services, is a group concerned with the communication issues as they pertain to the maritime industry. Special Committee 104 was formed to draft a standard format for the correction messages necessary to ensure an open real-time DGPS system (Langley, 1994). The format has become known as *RTCM 104*, and has recently been updated to version 2.2. According to these recommendations, the pseudo-range correction message transmission consists of a selection from a large number of different message types. Not all message types are required to be broadcast in each transmission, some of the messages require a high update rate while others require only occasional transmission. Provision has also been made for carrier phase data transmission, to support carrier phase-based RTK positioning using the RTCM message protocol. GLONASS differential corrections can also be transmitted within this protocol. Many message types are still undefined, providing for considerable flexibility.

The DGPS correction message format is patterned on the satellite navigation message, and was originally designed to operate with communication links with as low a data rate as 50 bps (bits per second). Almost all GPS receivers are "RTCM-capable", meaning that they are designed to accept RTCM messages through an input port, and hence output a differentially corrected position. RTCM is not instrument-specific, hence Brand "X" rover receiver can apply the corrections even though they were generated by a Brand "Y" base receiver.

A range of communication options are available. From the UHF/VHF links, through packet radio, MF, mobile phone, FM subcarrier, to satellite-communications and the Internet. The commercial DGPS service providers in Australia use a combination of these options.

4.2 Real-Time Carrier Phase-Based Positioning

The RTCM SC-104 message types 18 to 21 provide for RTK service, however the awkwardness of the format and their message frame "overhead" make them relatively inefficient for RTK. For example, to satisfy once per second data transmission for RTK, a baud rate of 4800-9600 would be required (the higher baud rate would be required if DGPS correction messages are also sent), quite a technical challenge, and even more so if radio repeaters have to be used (for each repeater employed, the data rate must be doubled). As a consequence, GPS-RTK manufacturers have designed their own proprietary data transmission standards to overcome the RTCM problems. One which had been used by the Trimble RTK systems for several years, has been proposed as an "industry standard" (Talbot, 1996), and is now used by manufacturers other than Trimble. This format is referred to as the Compact Measurement Record format, and uses an efficient compression/decompression algorithm which makes it suitable for communications links that run at 2400 baud, and still deliver once per second GPS solutions.

Different countries have different regulations governing the use of radios, their frequency and power, hence there is considerable opportunity for confusion. In Australia, the Spectrum Management Agency is responsible for issuing permission on the use of selected radio frequency bands for data communication. In general, the UHF and VHF bands are favoured for RTK applications, in particular the "land mobile" band situated in the range 400-500MHz. The maximum power is dependent upon the type of licence issued to the user, and may range from about 5W for roving users, to 50W for fixed local sites. There is a complex relation between: height of transmitting antenna, the type of antenna used (Yagi or omnidirectional), transmitting power, cable length, tree cover and other intermediate objects; and the range of the radio. For test/demonstration purposes up to a few kilometres, a 1W transmitter operating within the UHF "land mobile" band, should be adequate if the site conditions are ideal.

Note that network-based RTK (Section 3.2) has been implemented using a dial-up mobile phone service. In Australia this is offered via the digital GSM phone service. Such a means of 'delivery' of RTK data is expensive, as call charges mount with increasing connect time. It is hoped that the arrival of the so-called 2.5 G system (the General Packet Radio Service – GPRS) will lead to economies, as GPRS call charges are expected to be a function of data 'volume' rather than connect time. As the quantity of data involved is comparatively modest, RTK services via GPRS should be significantly cheaper than the current GSM-based service. In fact, it may be economical to handle all intra-network communications via GPRS, obviating the need for dedicated or dial-up fixed telephone lines.

5. CONCLUDING REMARKS

In summary:

- Carrier phase-based GPS positioning has evolved rapidly over the last ten years so that it can now position: (a) kinematically, (b) in real-time, and (c) instantaneously.
- There is therefore a *blurring* of the distinction between precise GPS navigation and GPS surveying.
- If certain conditions are fulfilled, carrier phase-based positioning is almost indistinguishable from pseudo-range-based DGPS, but at a much higher accuracy.
- However, there are very real *constraints* to the universal use of GPS carrier phase-based positioning.
- If these constraints are accepted, then the trend to very fast OTF-AR is a welcome one.
- Advances in hardware, software and operational procedures has made possible very fast OTF-AR under restrictive conditions of satellite-receiver geometry and baseline length.
- Network-based techniques hold the promise of relaxing one of the critical constraints to very fast OTF-AR, permitting the maximum baseline length to be increased to many tens of kilometres.
- The establishment of continuously-operating GPS reference receiver networks is an important trend as it will permit the gradual implementation of network-based techniques, in the post-processed or real-time mode.

The future of precise GPS kinematic positioning is dependent on a number of factors, including developments in receiver hardware, carrier phase data processing algorithms and software, operational procedures, the Internet and mobile communications, as well as the *augmentation* of GPS with pseudolites and inertial navigation systems/sensors, implementation of the WAAS system, the combination of GPS with GLONASS, the development of the Galileo system, and the modernization of GPS to transmit a second and third civilian frequency. All of these will significantly improve the reliability, integrity, and accuracy of the position results.

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