HOW CAN MY POSITION ON THE PADDOCK HELP MY FUTURE DIRECTION?

Chris Rizos
School of Geomatic Engineering
The University of New South Wales
Sydney NSW 2052
Tel: 02-93854205, Fax: 02-93137493
Email: c.rizos@unsw.edu.au

Abstract

GPS is the positioning technology of choice for a wide range of land-based applications. Since the mid-1990s GPS products have been on offer for the 'agricultural market'. GPS *on its own* does not appear to contribute much to improving agricultural productivity. Hence 'precision agriculture' has generally referred to the intergation of GPS within a total system that, for example, uses spatial information on soil quality to deliver variable quanitities of fertiliser. Hence, the GPS technology is just one element of a total vehicle-borne system, and may not even be the most expensive or problematic component. If crop yields do indeed improve through the application of such a system, then one would expect the GPS technology to be wholeheartedly embraced. Trends in the GPS receiver technology necessary for positioning at the few metre accuracy level will be reviewed. However, GPS-guided agricultural vehicles place similar demands on precise positioning (centimetre to decimetre level accuracy) technology that mining, excavation and industrial vehicles do. Hence, precise GPS positioning developments in areas such as field robotics are expected to deliver improved performance for agricultural vehicles as well.

Introduction

The Global Positioning System

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 community in the early 1980s. The range of applications of GPS is enormous and encompasses a wide spectrum of hardware and operational procedures principally designed to address varying accuracy requirements. It is the *user accuracy requirement* that more than anything else differentiates the various GPS equipment and procedures, and is responsible for the enormous differences in the cost (capital and operational) of GPS technology. It is possible to categorise GPS according to three classes:

(1) *Standalone navigation receivers*, characterised by:
- single-frequency (L1 signal);
- low-cost; typically a few hundred dollars for the receiver;
- use of a single-point positioning (SPP) algorithm, based on the processing of pseudo-range data;
- capable of horizontal accuracy of 5-10m (95%), 2-3x worse for vertical accuracy;
- offered in many form-factors, including: handheld, OEM, 'smart antenna', etc.; and
- the product of rapid innovation in the 'mass market' for SPP receivers, driving cost, size and power requirements ever lower.

(2) *Differential SPP receivers*, characterised by:
- single-frequency (L1 signal);
- moderate-cost; typically a few hundred dollars for the receiver, but additional cost for Differential GPS (DGPS) message receiver and service subscription;
- use of a single-point positioning (SPP) algorithm, based on the processing of differentially-corrected pseudo-range data;
- capable of horizontal accuracy of 1-5m (95%), 2-3x worse for vertical accuracy;
- various form-factors, including: handheld, OEM, 'smart antenna', etc.; and
- benefitting from the product innovation mentioned above, but dependent on the available DGPS services.

(3) *Differential carrier phase-based receivers*, characterised by:
- single-frequency (L1 signal) or dual-frequency (L1 and L2 signals);
- high-cost; typically thousands to a few tens of thousand dollars for the receiver, but additional cost for base station receiver and/or specialist service subscription;
- use of carrier phase processing algorithm, with or without resolved ambiguities;
- capable of horizontal accuracy of 2-50cm (95%), 2-3x worse for vertical accuracy;
- offered by a significantly smaller number of GPS companies than in the case of SPP receivers, and
- benefitting from developments in receivers and techniques appropriate for high precision surveying and machine guidance/control applications.

It can be seen that the first two categories are well suited for soil and landform mapping, geo-referencing of remote sensed images, vehicle tracking/navigation, and for controlling broadacre operations such as variable fertiliser application, etc. In such cases the cost of the GPS technology is unlikely to be a deterrent to its use. On the other hand, GPS systems capable of centimetre-decimetre levels of accuracy are relatively expensive. The capital cost of such equipment, together with the complex operational procedures necessary to ensure high precision, is a big impediment to the widespread adoption of such technology for vehicle guidance or control. The status, challenges, constraints and prospects of the GPS technologies represented by the above three categories, in relation to agricultural applications, will be discussed is later sections.

Precision Agriculture

At the heart of so-called 'precision agriculture' is the GPS technology. Without GPS it is difficult to imagine the implementation of elements of what is nowadays understood as 'precision agriculture', which is generally considered to include such elements as:

(1) The *customisation* of soil and crop management practices to fit the various conditions found within a farmer's field. A GPS antenna/receiver is placed on any agricultural machinery and provides location information which can be linked to yield monitoring devices, soil and pest sampling, remote sensing, and information such as topography, soil type, water patterns, etc. As these parameters vary within a field, *maps* of such variability allow the farmer to individually, rather than uniformly, manage areas within the field. When these maps are incorporated within a Geographic Information System (GIS), a farmer can organise, manipulate and analyse this data. Map accuracy at the few metre to dekametre level is sufficient.

(2) GPS and GIS together make possible *variable rate treatment* (VRT) for a field. In essence, VRT allows for varying the crop inputs according to need in order to improve farming efficiency, and hence potentially to maximise economic returns while minimising possible environmental damage. For example, the fertiliser, pesticide or irrigation application rates can be varied as GPS location information, linked to soil nutrient, pest infestation or soil mositure data within a GIS, triggers the appropriate action on the farm machinery. Location accuracy at the few metre level is sufficient.

(3) *Farm machinery guidance/control* is an additional desirable application. GPS guidance will aid the farmer to plow, seed, apply fertiliser/pesticide, water, and finally harvest fields in an efficient manner. That is, ensuring that such row operations do not 'miss' parts of the field, or preventing an overlap of such operations. In such cases decimetre level accuracy is needed. However, sub-decimetre accuracy would be required if vehicle guidance (and ultimately control) must ensure true 'parallel tracking' across the field, so that the machinery tyres always travel down the same 'ruts'. This is the most challenging of the GPS applications in 'precision agriculture'.

It can be seen that the GPS accuracy requirements for 'precision agriculture' fall neatly into two broad groups: few metre to dekametre accuracy for mapping and VRT, and cm-dm accuracy for machinery guidance/control. The former can be satisfied using SPP or DGPS pseudo-range-based techniques, while the latter requires carrier phase-based techniques.

Pseudo-Range-Based GPS Techniques

Single-Point Positioning (SPP)

The announcement by the then former U.S. President Bill Clinton to turn off 'Selective Availability' (SA) at midnight (Washington DC time) on 1 May 2000 has had a significant impact on users all over the world. Although the instantaneous accuracy of Single-Point Positioning (SPP) was limited by many errors, including satellite ephemeris error, satellite clock bias, atmospheric effects, receiver noise and multipath, SA had been the dominant error since its introduction on 25 March 1990. The improvement in the accuracy of GPS SPP since SA was 'switched off' has been commented on by many investigators, and is generally conceded as being of an order of magnitude, that is accuracies are now better than 10m. An analysis of 7 days of continuous SPP results of a pillar at The University of New South Wales confirmed horizontal accuracies in the approximate range of 3 to 7m and vertical accuracies 5 to13m (at the two-sigma level, considered here to be equivalent to a 95% Confidence Interval), depending on such factors as whether single- or dual-frequency observations were processed, and whether precise orbits were used in place of the broadcast satellite ephemerides (Rizos & Satirapod, 2001a). (As expected, the highest accuracy was for the dual-frequency/precise orbit option, and the lowest accuracy was the standard single-frequency/broadcast ephemerides option implemented in low-cost GPS hardware.)

A huge selection of SPP hardware are available, ranging from small handheld receivers to OEM boardsets and packages. Examples of the former ("Garmin eTrex") and the latter ("Rojone GPS Genius") are shown in Figure 1. While these are very modestly priced, installation within a farm vehicle, the incorporation of operator screens and/or integration with VRT and GIS technologies would drive costs up into the thousands of dollars.

Differential GPS (DGPS) Positioning

The standard mode of differential or relative positioning requires one reference GPS receiver to be located at a "base station" whose coordinates are known, while the second user GPS receiver simultaneously tracks the same satellite signals. For almost all users, the base station receiver is owned and operator by a *service provider*, who ensures that DGPS messages are broadcast to users so that DGPS positioning can be provided in real-time. The same hardware is used as for SPP (e.g. Figure 1), however the added complication (and expense) is the additional hardware to receive (and perhaps decode) the DGPS messages.

Figure 1: Typical low-cost SPP navigation-type GPS receivers: handheld, e.g. the Garmin etrex (left), and OEM receivers, e.g. the Rojone GPS Genius (right).

Special Committee 104, of the Radio Technical Commission for Maritime (RTCM) Services, was formed to develop 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. 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" reference receiver. The DGPS-corrected positioning accuracy is of the order of 2-3m in the horizontal, and 4-6m in the vertical component (both at the two-sigma level) (Rizos & Satirapod, 2001b). The accuracy is generally a function of distance from the nearest (broadcasting) base station. A generally accepted 'rule-of-thumb' states that over 100km from a base station the DGPS accuracy degrades by about 1m per 100km for so-called Local Area DGPS (LADGPS) implementations.

A range of communication options are available. From dedicated UHF/VHF links, through packet radio, MF beacons, mobile phone dialups, FM subcarrier, to satellite-communications and the Internet. The free-to-air LADGPS service provided by the Australian Maritime Safety Authority (AMSA, 2001) is restricted to the coast and the immediate hinterland, as the MF beacon transmissions are optimal for broadcast to maritime users up to 200 nautical miles offshore. In the U.S., the provision of beacon DGPS signals is being extended to cover the entire continent (NGPS, 2001), in part to address the needs of 'precision farming'. However, there are no plans to extend the AMSA service so that all farmers can take advantage of the signals, and in fact moves (so far unsuccessful) have been made to prevent non-maritime users from accessing the AMSA signals. There are several commercial DGPS service providers in Australia, one broadcasting LADGPS signals on the ABC's JJJ radio stations' FM subcarrier (AUSNAV, 2001), and two broadcasting DGPS signals via the Optus geostationary satellite (Fugro, 2001; Thales, 2001). The subscription costs are in the range of just over a thousand dollars to several thousand dollars per annum. The Fugro OmniSTAR and Thales (formerly Racal) Landstar services are examples of so-called Wide Area DGPS (WADGPS) services, where the RTCM message is optimised for the user's location by using the base station *network* to model the distance-dependent errors. Base station separations of many hundreds of kilometres are possible, with no degradation in accuracy as a function of the distance from the nearest base station.

Some GPS products already incorporate the receiver technologies to access some or all of the various DGPS signals (upon payment of the subscriptions of course): L-band (WADGPS), MF (LADGPS) and FM subcarrier (LADGPS), into one 'package'.

The debate concerning whether a government agency transmitting free-to-air DGPS signals should 'compete' with commercial DGPS service provider companies has already be raging as far as the maritime beacon signals is concerned. However, a potentially more farreaching development is the deployment over the next few years of the U.S. Federal Aviation Authority's Wide Area Augmentation Service (WAAS) for aviation users (FAA, 2001). This system, which includes a satellite-based and a ground-based component (Figure 2), is intended to support aviation navigation for the enroute through to precision approach phases of flight. The satellite-based component consists of several (up to four) geostationary satellites that will have two major functions, namely the transmission of GPS differential corrections to users and the provision of a ranging capability to improve availability, reliability and integrity over the United States. The geostationary satellite transmission will be on L1 using a C/A-code for ranging and a uniquely structured message to broadcast differential corrections and integrity information to users.

The ground-based segment includes some 25 reference stations, two processing sites (Wide-Area Master Stations – WMS), two Ground Earth Stations (GES) to uplink the GPS differential corrections to the geostationary satellites and timing information to the geostationary satellites, and software to calculate differential corrections as well as to perform various integrity functions. The specified accuracy of the system is 7.6m (two-sigma level). However, the actual accuracy is expected to be significantly better than this. The reliability of WAAS is near 100%, and the integrity, which is extremely important for aviation, is very high. GPS receivers will have to be 'WAAS-ready' in order to receive and use the WAAS message. However, WAAS is intended to be a public service and anyone equipped with a suitably modified receiver will have access to it. This means that for many applications requiring sub-metre level positioning accuracy WAAS may become a viable alternative to the commercial WADGPS services. For maximum benefit WAAS should, however, only be used inside the area defined by the ground-based segment.

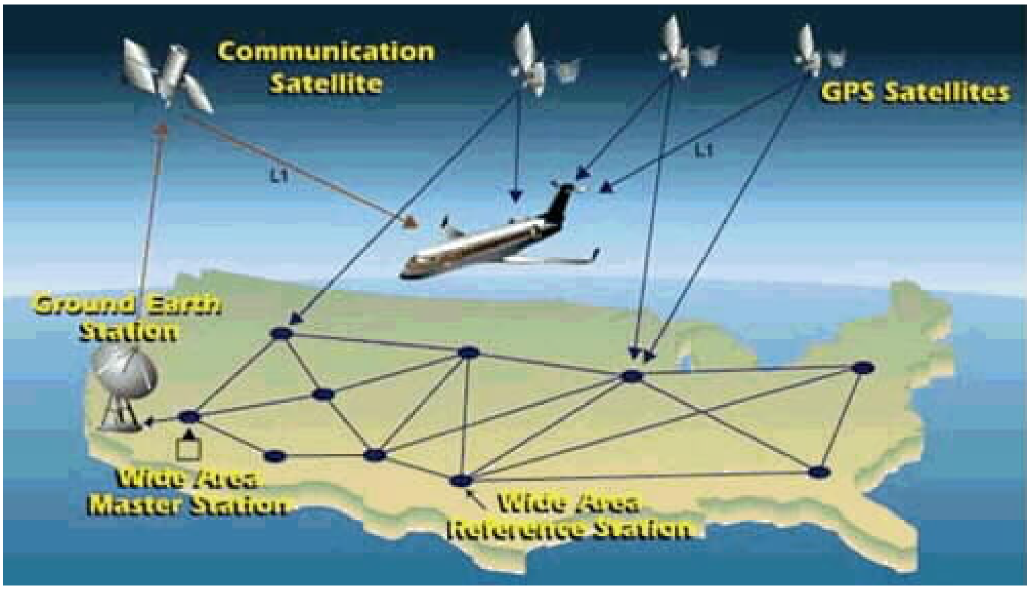

Figure 2: U.S. Federal Aviation Authority's WAAS concept.

Other countries or continents are also deploying similar augmentation systems. The European Geostationary Navigation Overlay System (EGNOS) and the Japanese Multi-Function Satellite-Based Satellite Augmentation System (MSAS) are prime examples of this effort. There will be no Australian equivalent of WAAS.

Carrier Phase-Based GPS Kinematic Techniques

These techniques are currently implemented in the differential mode, but the data processing has its own special challenges. 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 to a high accuracy. 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, including permitting it to be undertaken while the receiver is in motion, in the so-called "on-the-fly" (OTF) mode. 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 referred to as RTK systems ("real-time-kinematic"), and make feasible the use of GPS for time-critical applications such as GPS-guided excavations, farm machinery operation, open-cut mining, container port operations, etc.

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 – a prerequisite for very fast OTF-AR.
- 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, 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, able to track signals other than GPS, such as GLONASS signals, WAAS signals, 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'. With respect to the GPS system itself, two additional civilian frequencies will be transmitted by the Block IIR and Block IIF 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 the L5 carrier signal will also significantly improve the reliability of AR (Han & Rizos, 1999; Hatch et al., 2000).

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 10km*. 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 3).

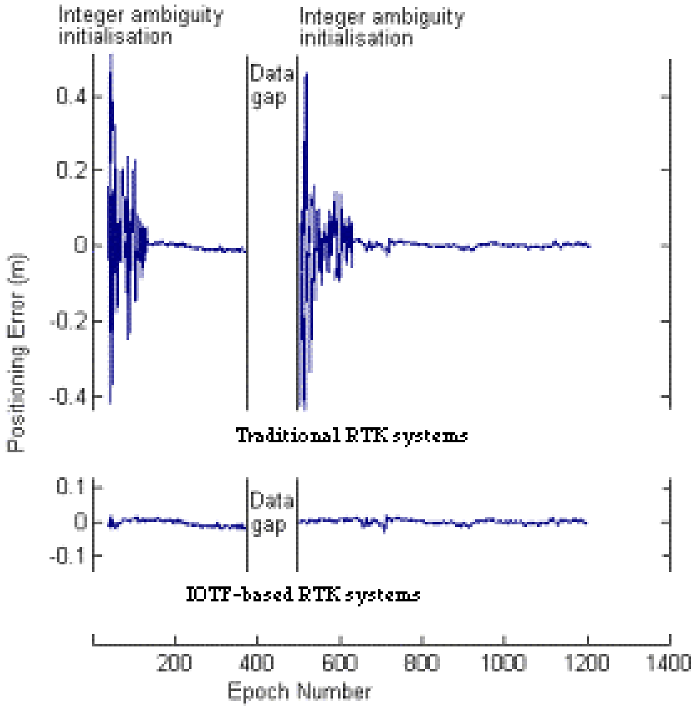

Figure 3: Comparison of RTK performance using standard multi-epoch OTF-AR techniques and the instantaneous OTF-AR technique. Note the 'dead' time (when accuracy is degraded) during which AR is being undertaken in upper plot, compared to lower plot for single-epoch OTF-AR.

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. Figure 3 also illustrates the situation when the OTF-AR algorithm is so optimised that it can operate on a single epoch of data.

Improvements in AR & Validation Procedures

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, 1997), the most optimal procedure uses the LAMBDA transformation (Teunissen, 1994) in combination with the U-D decomposition search procedure. 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 (Han, 1997).

There is no "magic" algorithm for single-epoch 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 single-epoch OTF-AR algorithm that is greater than 98%. 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-Xtreme claims instantaneous OTF-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 single-epoch OTF-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 single-epoch OTF-AR, is expected to continue. One means of breaking this 'either-or' condition is to consider the use of multiple reference receivers (or networks). Another significant development is the broadcast of an additional civilian signal on the L5 frequency which will significantly improve the reliability of AR if using 'triple-frequency' receivers.

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 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:

- 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.

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. 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.

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 single-epoch OTF-AR). For medium-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 3).
- 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.

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.

Medium-range kinematic positioning based on OTF-AR 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 a user's GPS receiver (Wanninger, 1995; Wübbena et al., 1996; Rizos et al., 1999; 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 single-epoch OTF-AR under ideal conditions). This is not unlike the concept of WADGPS, except that it involves carrier phase measurements rather than pseudo-ranges. Dai et al. (2001) has investigated such a network-based methodology for combined GPS-GLONASS reference receiver networks.

Network-based techniques means that a large area can be 'serviced' by a smaller number of GPS reference receivers than would be the case if 10km spacing of reference stations was enforced, a density of receivers that is generally difficult to justify for surveying and precise navigation users alone. Therefore in the case of the state of Victoria a network (Figure 4) with an average base station spacing of 100km (with 50km spacing in and around Melbourne) is being established (Talbot et al., 2001). While not able to support standard single-baseline positioning using a very fast OTF-AR algorithm, it can be a candidate for upgrading to support true network-based positioning techniques. 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.

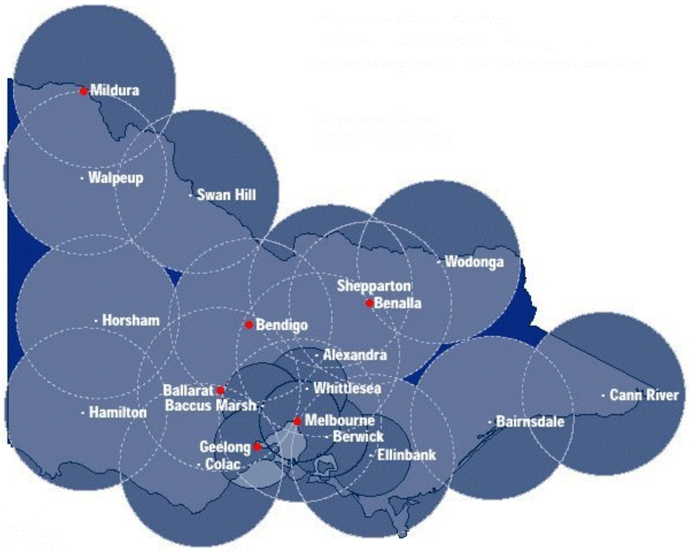

Figure 4: GPSNet Victoria. Note large circles 100km radius, small circles 50km radius.

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.

The first truly commercial product based on the multiple reference receiver approach is Trimble's "Virtual Reference Station" (Figure 5). The reference receiver network has inter-station distances of between 50-100km, the approximate spacing that allows good modelling of the atmospheric biases. 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).

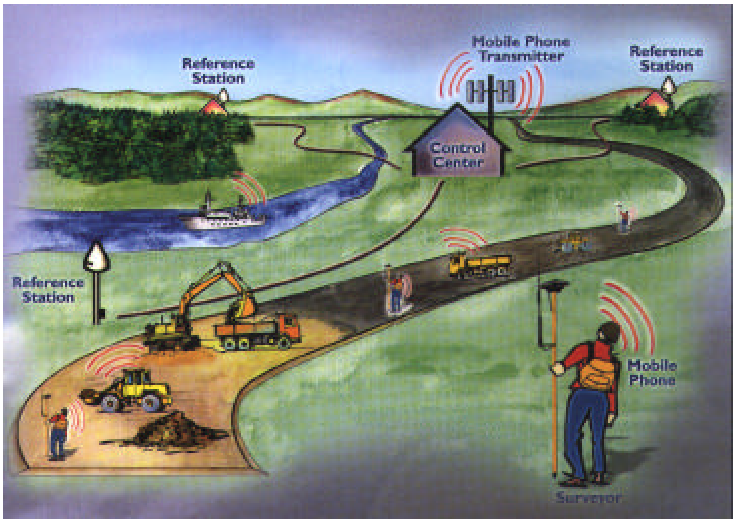

Figure 5: Trimble's Virtual Reference Station concept.

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 carrier phase-based GPS positioning.
- 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 welcomed.
- Advances in hardware, software and operational procedures has made possible very fast OTF-AR under restrictive conditions of satellite 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, to support a range of high precision positioning applications.

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. The development of a low-cost, reliable, cm-level accuracy positioning system to support 'precision agriculture' in the near future is assured.

References

AUSNAV, 2001, http://www.ausnav.com.au/

AMSA, Australian Maritime Safety Authority, 2001, http://www.amsa.gov.au/ns/dgps/dgps.htm

Dai, L., J. Wang, C. Rizos & S. Han (2001). Real-time carrier phase ambiguity resolution for GPS/GLONASS reference station networks. To be pres. *Int. Symp. on Kinematic Systems in Geodesy, Geomatics & Navigation (KIS2001)*, Banff, Canada, 5-8 June.

FAA, U.S. Federal Aviation Authority, 2001, http://gps.faa.gov/Programs/WAAS/waas.htm

Fugro OmniSTAR, 2001, http://www.omnistar.com/

Han, S. (1997). *Carrier phase-based long-range GPS kinematic positioning*. PhD Dissertation, UNISURV rept. no. S-49, School of Geomatic Engineering, The University of New South Wales, 185pp.

Han, S., & C. Rizos (1997). Comparing GPS ambiguity resolution techniques. *GPS World*, 8(10), 54-61.

Han, S. & C. Rizos (1999). The impact of two additional civilian GPS frequencies on ambiguity resolution strategies. *55th National Meeting U.S. Institute of Navigation*, Cambridge, Massachusetts, 28-30 June, 315-321.

Hatch, R.R., J. Jung, P. Enge & B. Pervan (2000). Civilian GPS: The benefits of three frequencies. *GPS Solutions,* 3(4), 1-9.

Higgins, M.B. & N.C. Talbot (2001). Centimetres for everyone: Initial results from an Australian Virtual Reference Station network pilot project. To be pres. *5th Int. Symp. on Satellite Navigation Technology & Applications*, Canberra, Australia, 24-27 July.

Landau, H. & U. Vollath (1996). Carrier phase ambiguity resolution using GPS and GLONASS signals. *9th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation,* Kansas City, Missouri, 17-20 Sept., 917-923.

Langley, R.B. (1994). RTCM SC-104 DGPS standards. *GPS World*, 5(5), 48-53.

Leick, A., J. Li, J. Beser & G. Mader (1995). Processing GLONASS carrier phase observations - theory and first experience. *8th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation*, Palm Springs, California, 12-15 Sept., 1041-1047.

National DGPS Plan (2001). http://www.navcen.uscg.gov/dgps/NDGPS/

Raquet, J. & G. Lachapelle (2001). RTK positioning with multiple reference stations. *GPS World*, 12(4), 48-53.

Rizos, C., S. Han, H.Y. Chen & P.C. Goh (1999). Continuously operating GPS reference station networks: new algorithms and applications of carrier phase-based, medium-range, static and kinematic positioning. In "Quo vadis geodesia…?", Dept. of Geodesy & Geoinformatics, University of Stuttgart, ISSN 0933-2839, 367-378.

Rizos, C., & C. Satirapod (2001a). GPS with SA off: How good is it? *Measure & Map*, 12, 19-21.

Rizos, C., & C. Satirapod (2001b). GPS with SA off: How good is it? (Part 2). *Measure & Map*, 15, in press.

Talbot, N.C., K. Zhang, M. Hale & J. Millner (2001). GPSNet: A Victorian permanent GPS tracking network. To be pres. *5th Int. Symp. on Satellite Navigation Technology & Applications*, Canberra, Australia, 24-27 July.

Teunissen, P.J.G. (1994). A new method for fast carrier phase ambiguity estimation. *IEEE Position Location & Navigation Symp.*, Las Vegas, Nevada, 11-15 April, 562-573.

Thales (2001). http://www.thales-landstar.com/

Wang, J., C. Rizos, M.P. Stewart & A. Leick (2001) GPS and GLONASS integration: Modelling and ambiguity resolution issues. *GPS Solutions*, 5(1), in print.

Wanninger, L. (1995). Improved ambiguity resolution by regional differential modelling of the ionosphere. *8th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation,* Palm Springs, California, 12-15 Sept., 55-62.

Wübbena, G., A. Bagge, G. Seeber, V. Böder & P. Hankemeier (1996). Reducing distance dependent errors for real-time precise DGPS applications by establishing reference station networks. *9th Int. Tech. Meeting of the Sat. Div. of the U.S. Inst. of Navigation*, Kansas City, Missouri, 17-20 Sept., 1845-1852.