

PRECISE KINEMATIC APPLICATIONS OF GPS: PROSPECTS AND CHALLENGES

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ABSTRACT

GPS kinematic positioning in the post-processed or in the real-time mode is now increasingly used for many surveying and navigation applications on land, at sea and in the air. Techniques range from the robust pseudo-range-based differential GPS (DGPS) techniques capable of delivering accuracies at the few metre level, to sophisticated carrier phase-based centimetre accuracy techniques. The distance from the mobile 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. For carrier phase-based techniques reliable ambiguity resolution becomes an even greater challenge. In the case of DGPS, more appropriate implementations such as Wide Area DGPS become necessary.

In this paper, the challenges, progress and outlook for high precision GPS kinematic positioning for the short-range, medium-range and long-range cases, in both the post-processing and real-time modes will be discussed. Although the focus will be on carrier phase-based systems, some comments will also be made with regards to DGPS systems. Several applications of kinematic GPS positioning will be considered, so as to demonstrate the engineering challenges *in addition to GPS*, that have to be addressed.

INTRODUCTION

The standard mode of precise *differential* positioning is for one reference receiver to be located at a station whose coordinates are known, while the second receiver's coordinates are determined relative to this reference receiver. In addition, the second receiver may be static or moving, and carrier phase measurements must be used to assure high positioning accuracy. This is the basis for pseudo-range-based differential GPS (DGPS for short) techniques. However, for high precision applications, the use of carrier phase data comes at a cost in terms of overall system

complexity because the measurements are *ambiguous*, requiring that *ambiguity resolution* (AR) algorithms be incorporated as an integral part of the data processing software.

Such high accuracy techniques are the result of progressive R&D innovations, which have been subsequently implemented by the GPS manufacturers in their top-of-the-line "GPS surveying" products. Over the last half decade or so several significant developments have resulted in this high accuracy performance also being available in "real-time" -- that is to say, 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. Real-time precise positioning is even possible when the GPS receiver is in motion, through the use of "on-the-fly" (OTF) ambiguity resolution algorithms. These systems are commonly referred to as RTK systems ("real-time-kinematic"), and make the use of GPS-RTK for many *time-critical* applications such as machine control, feasible GPS-guided earthworks/excavations, automated haul truck operations, and other autonomous robotic navigation applications.

CHALLENGES IN CARRIER PHASE-BASED GPS KINEMATIC POSITIONING

If the GPS signals were continuously tracked (loss-of-lock never occurred), the integer ambiguities resolved at the beginning of a survey would be valid for the whole GPS kinematic positioning span. However, the GPS satellite signals are occasionally shaded (e.g. due to buildings in "urban canyon" environments), or momentarily blocked (e.g. when the receiver passes under a bridge or through a tunnel), and in these circumstances the integer ambiguity values are "lost" and must be *redetermined* or *re-initialised*. **This process can take from a few tens of 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 (see Figure 1). In addition, the longer the period of tracking required to ensure reliable on-the-fly AR (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.

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, which typically deliver positioning accuracies of 1-10 metres. 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. For medium-range or long-range precise GPS kinematic positioning, the distance-dependent biases, such as orbit bias, ionospheric delay and tropospheric delay, will become significant problems.
- Determining how long the observation span should be for reliable AR is a challenge for real-time GPS kinematic positioning. The longer the observation span is required, the longer the "dead" time during which precise positioning is not possible (see Figure 1). 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.
- AR techniques normally requires five or more visible satellites and expensive dual-frequency GPS instrumentation in which the geometric constraints and combination of dual-frequency observations make AR easier.
- 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 many 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. Quality control procedure are not only applied for carrier phase-based GPS kinematic positioning, but also for pseudo-range-based DGPS positioning. However, the quality control or validation criteria for AR is a significant challenge.

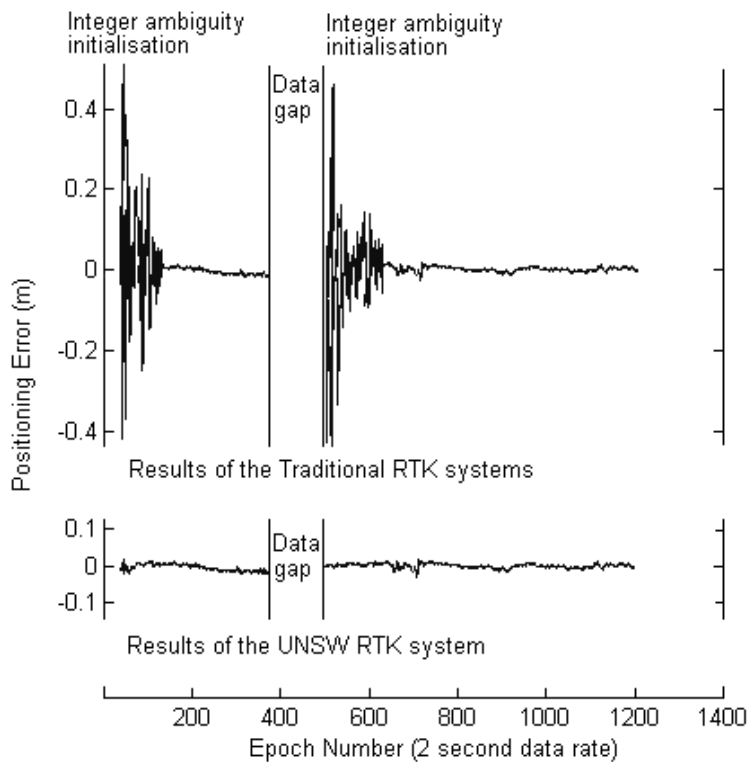


Figure 1. Comparison of RTK performance using standard OTF-AR techniques and the instantaneous OTF-AR technique used by the UNSW system.

PROGRESS IN PRECISE GPS KINEMATIC POSITIONING

Over the last few years several important developments have occurred that appear to have overcome some of the constraints for carrier phase-based positioning:

- (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.
- (b) Reliable OTF-AR in the shortest period of time possible, even with just one measurement epoch, has been demonstrated.
- (c) Given very short periods of 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 the normal mode of kinematic positioning for *all epochs*.
- (d) Improved multipath mitigation *within* the GPS receivers themselves.
- (e) For certain applications single-frequency GPS instrumentation can be used.
- (f) The release of several commercial integrated GPS-GLONASS receivers.

The two most significant algorithm improvements therefore have been in: (a) overcoming the baseline length constraint, and (b) shortening the "time-to-AR" to just one epoch of data. However, advances in receiver hardware have had to be made in concert.

Short-range (<15km) IOTF-AR has been reported by Han (1997a, 1997b), Han & Rizos (1996d) and others. Developments in fast ambiguity resolution algorithms and validation criteria procedures, together with improvements in the observation stochastic modelling and the application of careful quality control procedures, have generally been responsible for this increased level of performance (see "Instantaneous Ambiguity Resolution Algorithm").

Carrier phase-based medium-range GPS kinematic positioning has been reported for baselines several tens of kilometres in length (Wanninger, 1995; Wübbena, et al., 1996). IOTF-AR has also been reported for medium-range GPS kinematic positioning (Han, 1997a; Han & Rizos, 1997). 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, multipath and observation noise. These are exciting developments that will require testing and implementation in operational positioning systems.

In the case of long-range kinematic positioning several innovative concepts have been reported. Colombo & Rizos (1996) report results of decimetre accuracy navigation over baselines up to a thousand kilometres in length. Although it is not yet possible to resolve ambiguities OTF for baselines of several hundreds of kilometres in length, ambiguity re-initialisation or *ambiguity recovery* is achievable (Han, 1995; Han & Rizos, 1995a). In other words, if 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. A new long-range precise positioning technique that does not require AR has also been suggested by Han & Rizos (1996c). The technique is best described as "*GPS traversing*", in which the *relative* positions of successive GPS stations are determined to high accuracy, not the positions in relation to a distant reference receiver.

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: 1597-1617 MHz; L2 in the range: 1240-1260 MHz).

- Each satellite transmits a different frequency on L1 ($=1602 + K \times 0.5625$ MHz; $K \in [-7, 24]$) and L2 ($=1246 + K \times 0.4375$ MHz; $K \in [-7, 24]$).
- 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 (PPS) and a Standard Positioning Service (SPS), as in the case of GPS.
- No Selective Availability is implemented.

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 concerning which there are 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. GLONASS was declared operational (with 24 satellites in orbit) in 1996.

GLONASS positioning results are of higher accuracy than GPS because no Selective Availability is implemented. Autonomous (single receiver) horizontal accuracy at the 95% confidence level is therefore significantly enhanced in the case of GLONASS-only (20m) and GPS+GLONASS (16m) receivers, compared to GPS-only systems (100m). Differential accuracies are quoted as being of the order of 1m and 75cm for differential GLONASS (DGLONASS) and DGPS+DGLONASS receivers, respectively. DGLONASS is implemented through special messages within the RTCM differential correction transmission format.

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 trying to develop optimal GLONASS data processing techniques. One technique is to determine the GLONASS carrier phase ambiguity "float" solution and to then try to "fix" the GPS carrier phase ambiguities (Rossbach & Hein, 1996; Landau & Vollath, 1996). Another method is determine the GLONASS carrier phase

ambiguities by either correcting the receiver clock bias, or estimating the small component of the ambiguities (e.g. Raby & Daly, 1993; Leica et al., 1995).

INSTANTANEOUS AMBIGUITY RESOLUTION ALGORITHM

There is no "magic" algorithm for single-epoch or instantaneous OTF ambiguity resolution. The ambiguity resolution 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, hence significantly biasing the baseline results. To improve the computational efficiency and to improve the reliability (success-rate) of the procedure, advances in data modelling, parameter estimation and statistical testing had to be made. None on their own could deliver the performance required, but the sum of the suggested improvements has resulted in a success-rate for The University of New South Wales (UNSW) algorithm that is greater than 98% (Han, 1997a). These are briefly discussed below.

Integrated Functional Model

The traditional functional model for ambiguity resolution only used carrier phase observations because the C/A pseudo-range data was not precise enough to contribute very much to improving the ambiguity-float solution. This meant that quite a long observation session (a few minutes in the case of dual-frequency receivers, or more than 15 minutes for single-frequency receivers) was typically required to obtain an ambiguity-float solution accurate enough for the reliable resolution of the integer ambiguities. However, the new generation GPS receivers output precise pseudo-range data on L1 and L2, and these observations will significantly improve the ambiguity-float solution using only a short period of data, at an extreme, even using a single-epoch of data (Han & Rizos, 1996d).

The ambiguity-float solution will have no contribution coming from the carrier phase measurements if only one epoch of data are used. Hence, relative positioning using the pseudo-range data on L1 and/or L2 will be used to initially

estimate the coordinate parameters \hat{X}_C and the co-factor matrix $Q_{\hat{X}_C}$. The ambiguity-float solution for \hat{X}_N can then be computed with variance-covariance matrix $Q_{\hat{X}_N}$. (Consult the reference *ibid*, 1996d, for computational details.)

Real-Time Stochastic Model Estimation

Reliable Least Square results require the correct definition of both the functional and stochastic models. The stochastic model may change subtly due to variations in the data quality, which is itself influenced by many factors. Hence, the most efficient method of changing the stochastic model is one based on *empirical* analysis of the data itself, rather than deriving a complex formula-driven stochastic model. For example, GPS data may be separated into different segments, and the previous data segment can be used to estimate the stochastic model for the current

segment. The segment length may be as short as just a few minutes in length. Two different methods for the real-time estimation of a stochastic model are summarised below.

The first model is based on the fact that the noise of the one-way observation is dependent on the satellite elevation E . This "noise" includes measurement noise, multipath, residual atmospheric delay, etc., but excludes the biases which can be eliminated by double-differencing (those which are the same for all carrier phase observations, or pseudo-ranges, related to all satellites for the same receiver and at the same time; and those biases which are the same for carrier phase observations, or pseudo-ranges, related to all receivers for the same satellite at the same time). The standard deviation of the one-way L1 observations can be approximated as:

$$\sigma = s \cdot (a_0 + a_1 \cdot \exp(-E / E_0)) \quad (1)$$

where a_0 , a_1 and E_0 are empirical derived values, with typical magnitudes of 0.3cm, 2.6cm and 20° for carrier phase, and 7.0cm, 60.0cm and 20° for pseudo-range data for an Ashtech Z12 GPS receiver (Han, 1997b). The scale factor s can be estimated from the quadratic form of the double-differenced residuals of the previous segment of data, and applied to the current segment of data. The variance-covariance matrix can then be formed for the Least Squares estimation.

Alternatively, the variance-covariance-components of the double-differenced observations can be estimated directly using the previous segment of data. The elements of the symmetric variance-covariance matrix of the double-differenced observations can be considered to be the same within a segment (of a few minutes in length) and estimated using the variance-covariance-component estimation method. The estimated variance-covariance matrix can then be applied to the current epoch.

Fast Ambiguity Search Procedure

The ambiguity search is based on

$$R_k = (\hat{X}_N - N_k)^T Q_{\hat{X}_N}^{-1} (\hat{X}_N - N_k) = \min \quad (2)$$

under the condition:

$$(\hat{X}_C - \tilde{X}_{C,k})^T Q_{\hat{X}_C}^{-1} (\hat{X}_C - \tilde{X}_{C,k}) \leq t \cdot m_0^2 \cdot \xi_{F_{t,n-t-m}; 1-\alpha} \quad (3)$$

where \mathbf{N}_k is the candidate of the integer ambiguity vector, m_0^2 is the a posteriori variance factor and $\xi_{\chi^2_{t, n-t-m}; 1-\alpha}$ is the one-tailed boundary of the $1-\alpha$ confidence interval for the Fisher's distribution statistic with t and $n-t-m$ degrees of freedom. The other solution vectors are for the coordinate parameters and the real-valued ambiguity parameters referred to earlier. Equation (2) is equivalent to the minimum of the quadratic form of residuals.

In the UNSW software, the Least-squares AMBIGUITY Decorrelation Adjustment (LAMBDA) method is used to form the ambiguity transformation matrix which transforms the original (real-valued) ambiguity vector $\hat{\mathbf{X}}_N$ into the transformed ambiguity vector whose variance-covariance matrix has much smaller diagonal elements (Teunissen, 1994; Han & Rizos, 1995b). The Cholesky decomposition method is then used to search the transformed integer ambiguities, and then transform it back to the original ambiguity vector (Landau & Euler, 1992).

Validation Criteria and Adaptive Procedure

Using the above mentioned model, the real-valued ambiguities can be estimated and the integer ambiguity search procedure then used to determine the correct integer ambiguity set (that which generates the minimum quadratic form of the residuals). The ratio test of the second minimum and the minimum quadratic form of the residuals is normally used to *validate* the correct integer ambiguity set. New validation criteria were derived by Han (1997b), which assume that the integer ambiguity set generating the minimum quadratic form of the residuals is correct, but which detects the outlier of the integer set generating the second minimum quadratic form of the residuals. If this outlier can be detected, the integer set generating the minimum quadratic form of the residuals is considered to be the correct one. On the other hand, the sequence generated by differencing the double-differenced ionospheric delay on the L1 and L2 carrier phase can also be used as a validation criteria. If this sequence has a slip (or "jump") at the current epoch, this confirms that the ambiguity resolution at this epoch is incorrect.

If ambiguity resolution fails, and six or more satellites are observed at the current epoch, an *adaptive procedure* can be applied using a satellite elimination procedure, starting with the one satellite with the lowest elevation angle with respect to the receiver, repeating the process until ambiguity resolution is successful. If all possible sets of five or more satellites are combined and the ambiguity test still fails, the ambiguity resolution step is considered to have failed.

REAL-TIME IMPLEMENTATION ISSUES

Implementing DGPS or RTK in real-time is a significant engineering challenge. Some of the issues relating specifically to real-time GPS kinematic positioning are discussed below.

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 greatest consideration for the DGPS data link is the rate of update of the range corrections. Selective Availability errors vary more quickly than any other bias (such as orbit error, atmospheric refraction, etc.), hence they are the primary concern and the major constraint for real-time DGPS communications options. The correction to the pseudo-range and the rate-of-change of this correction are determined and transmitted for each satellite. If the message "latency" (or age) is too great then temporal decorrelation occurs, and the benefit of the DGPS corrections is diminished.

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.

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 designed their own proprietary data transmission standards to overcome the RTCM problems. One of them, the which had been used by the Trimble RTK systems for several years, has recently

been proposed as an "industry standard" (Talbot, 1996). This format is referred to as the Compact Measurement Record format. It 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, 450-470 MHz. The maximum power is dependent upon the type of licence issued to the user, and may range from about 5 W for roving users, to 50 W 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 1 W transmitter operating within the UHF "land mobile" band, should be adequate if the site conditions are ideal.

Data latency problems for RTK can be resolved in either of the following two ways: (a) synchronise reference receiver data and mobile receiver data (which gives the maximum precision but a substantial delay), or (b) use the latest reference receiver data and extrapolate them to the time of the mobile receiver data (which will cause some additional error). The former is better for the carrier phase AR process, as all errors have to be minimised for maximum reliability and performance. However, the kinematic position will suffer due to a time delay of up to 1-2 seconds (which may be crucial for some real-time applications); the latter solution will introduce additional errors due to observation extrapolation. Experimental results show that the linear extrapolation model will introduce an additional double-differenced error of about 2cm for a 1 second delay and about 8cm for a 2 second delay. A quadratic extrapolation model will introduce an additional double-differenced error of about 4cm for a 2 second delay (Landau et al., 1995).

Communication Link Considerations

The following considerations must be addressed by DGPS/RTK communication links:

- **Coverage:** This is generally dependent on the frequency of the radio transmission that is used, the distribution and spacing of transmitters, the transmission power, susceptibility to fade, interference, etc.
- **Type of Service:** For example, whether the real-time DGPS/RTK service is a "closed" one available only to selected users, whether it is a subscriber service, or an open broadcast service.

- **Functionality:** This includes such link characteristics as whether it is a one-way or two-way communications link, the duty period, whether it is continuous or intermittent, whether other data is also transmitted, etc.
- **Reliability:** Does the communications link provide a "reasonable" service? For example, what are the temporal coverage characteristics? Is there gradual degradation of the link? What about short term interruptions?
- **Integrity:** This is an important consideration for critical applications, hence any errors in transmitted messages need to be detected with a high probability, and users alerted accordingly.
- **Cost:** This includes the capital as well as ongoing expenses, for both the DGPS/RTK service provider as well as users.
- **Data rate:** In general the faster the data rate, the higher the update rate for range corrections, and hence better positioning accuracy. Typically a set of correction messages every few seconds is acceptable.
- **Latency:** Refers to the time lag between computation of correction messages and the reception of message at the rover receiver. Obviously this should be kept as short as possible, and typically a latency of less than 5 seconds is suggested.

Wide Area DGPS (WADGPS)

It is possible to differentiate between *Local Area DGPS* (LADGPS) and *Wide Area DGPS* (WADGPS). The assumption made when a pseudo-range correction message is generated at a base receiver is that it is a valid calibration quantity representing the "lumped" satellite and propagation link biases as monitored at the base receiver: satellite clock error, satellite orbit bias, troposphere and ionosphere refraction. However, apart from the first bias quantity, this assumption breaks down as the separation of base and rover receivers increases. In addition, the chances that the constellation of visible satellites at both the base and rover receivers are the same diminishes as inter-station distances grow. Typically, a range of 100 km or so is considered the limit beyond which it is unreasonable to assume that biases will cancel when the pseudo-range corrections are applied. *Hence, LADGPS refers to real-time differential positioning typically over distances up to a few hundred kilometres using the DGPS corrections generated by a single base station.* The DGPS correction is generally delivered by some form of short-range terrestrial-based communications system.

Wide Area DGPS, as the name implies, is a DGPS technique that distributes the accuracy advantages of DGPS across a very wide region. This may be over a continental extent or, in the extreme case, could represent a global service. Although there are a number of different implementations of WADGPS (see, for example Mueller, 1994), all rely on a *network of base stations distributed across the region of interest* and a communications system with the requisite coverage and availability characteristics. In its crudest form WADGPS can be considered a

means by which *multiple* RTCM messages are received at the rover receiver (from each of the base stations within the WADGPS network) and the corrections are, in effect, "averaged" and input through the receivers I/O port as a "synthetic" RTCM message (this obviates the need for elaborate new software having to be embedded within the GPS receiver). This implementation is sometimes referred to as "Network DGPS". More sophisticated implementations model (in real-time) the spatial variation of errors due to atmospheric refraction and orbital bias so that the WADGPS message contains the values of model parameters and a special algorithm computes the rover receiver corrections on the basis of geographic location.

Global Navigation Satellite System (GNSS)

This is a system augmentation designed to improve: (a) accuracy, (b) integrity, and (c) availability. The impetus for this has come from civil aviation authorities who wish to replace traditional navaids by technology which is less expensive, more reliable and more versatile. The International Civil Aviation Organisation (ICAO) has developed the concept of the Future Air Navigation System (FANS). An important component of FANS is the Global Navigational Satellite System (GNSS) based on GPS, but enhanced in order to satisfy the varying requirements for accuracy, availability and integrity for the different phases of flight: en route navigation, airport approach and landing, and surface movement. Although motivated by aviation concerns, GNSS is important because it provides the first model of *extension* of the GPS satellite-based positioning technology. The augmentation that ICAO has in mind for the GNSS consists of three components:

- (a) Transmission of *differential corrections* by satellite to users over large areas.
- (b) Transmission of *integrity information* by satellite.
- (c) Transmission of *additional GPS-like signals* by other satellites.

The enhancements:

- improve accuracy, integrity, availability and continuity,
- represent a significant investment in additional space and ground infrastructure,
- are intended to service users across large areas of the world,
- will require agreement on global specifications for all components,
- will require modifications to GPS user hardware,
- are primarily intended for one applications sector,
- indicate a possible system architecture for the successor to the GPS system, and
- are expected to be operational in the U.S.A. in early 1998, with other countries following suit with some or all of the components, according to an agreed timetable.

Although there has been international agreement that GPS alone cannot fulfil all the requirements for a sole navigation aid for civil aviation (and hence GNSS is not just a synonym for GPS), there is not yet unanimous agreement on the

details of the augmentation. As a consequence, there will be different regional implementations of the augmentation, with the U.S.A. promoting its Wide Area Augmentation System (WAAS), the European nations have their European Geostationary Navigation Overlay Service (EGNOS), and the Japanese have proposed the Multi-Functional Transport Satellite (MT-SAT).

The combination of GPS and GLONASS as part of GNSS is being actively promoted in version GNSS-1 of the European EGNOS. Although there are GLONASS-only receivers available on the market, these are generally inferior to GPS products. However, there is a distinct trend to develop receivers that can track and process signals from *both* the GPS and GLONASS satellites. One of the first commercial GPS+GLONASS systems is the Ashtech GG24 receiver. A combined GPS+GLONASS receiver can track signals from a 48 satellite constellation, twice as many as the GPS-only constellation and therefore significantly improving *availability*. For example, simulation studies have shown that with a 45° obstruction to half the sky (as would be caused by a tall building), five or more GPS satellites are only available for about 33% of the day, and four or more satellites for about 85% of the day. However, there is 100% availability of five or more satellites when both GPS and GLONASS satellites are considered.

Real-Time DGPS Services

A variety of real-time DGPS services have been established over the last few years to address precise navigation and positioning applications on land, at sea and in the air. Such services may be characterised according to the following:

- LADGPS or WADGPS implementation.
- The type of communications link, whether it is terrestrial or satellite-based.
- Whether the service addresses a specific group of users (for example, marine), or is a general service.
- The nature of the organisation providing the service, is it a government agency, an academic institution or a private company?
- Whether the service is freely available, or whether it is operated as a commercial activity.
- Whether it is restricted to RTCM pseudo-range correction broadcasts, or the transmission of carrier phase data, or both.
- Whether the system supports post-processed DGPS by archiving the base station data.
- Whether the service uses a single base station, or is part of a network of DGPS base stations.
- The sophistication of the quality control measures that are in place.

It is instructive to review the situation in Australia with regard to DGPS services, cost structures, user profiles and dominant applications. Australia may be considered a representative example of what is happening in many other countries, because the majority of system developers and service providers are global companies operating across different geographic regions. There are four services,

all which are multi-site systems which between them effectively address almost 100% of all DGPS needs in the Australian region. Some are WADGPS, others LADGPS. Some are commercial systems, however one is a free "public service". Several of them are mature systems, while others will expand as additional base stations are established.

DGPS by Satellite Communications Link: One service is offered by the huge Dutch conglomerate Fugro. They have a number of GPS base stations across Australia which are connected by landline to their head office, Fugro Starfix, in Perth. The DGPS corrections are uplinked to the Optus B1 satellite from where they are broadcast all over Australia and parts of S.E.Asia. The procedure is identical to that used by Fugro in other parts of the world except that instead of using the Inmarsat satellites (which require a gimbal-mounted directional antenna), they use Australia's L-band mobile satellite communication system which uses small whip omnidirectional antennas (a similar service is available in North America and Europe). The DGPS service, known as *Omnistar*, is a commercial operation and offers several levels of service. In its simplest (and cheapest) configuration it operates as a LADGPS (RTCM messages from one base station), which can deliver a few metres accuracy up to a few hundred kilometres from a base station, with accuracy degradation being a function of the distance from the nearest base station. A WADGPS option uses a proprietary Fugro format to combine the correction messages from several base stations, delivering sub-metre accuracy. The advantages of the service is that it is available anywhere in Australia (and offshore) using relatively compact hardware.

DGPS by satellite communications link is also offered by the British company, Racal Survey. As with the Fugro system, they have a number of GPS base stations across Australia which are connected by landline to their head office, also located in Perth. In every other respect the systems are direct competitors. The DGPS corrections are also transmitted by the Optus B1 satellite in the Australian region, and by Inmarsat satellites over the rest of the world. The DGPS service, known as *Landstar*, is also a commercial operation and offers both a LADGPS and WADGPS option.

DGPS by Radio Data Service (RDS) Link: This service is offered by the Australian Survey and Land Information Group (AUSLIG) in Canberra. They have established a large number of GPS base stations across Australia, mostly located in the capital cities or where there is a large (generally niche) local market for DGPS services. The DGPS corrections generated at each base station are sent to a local Australian Broadcasting Corporation FM radio station by landline, where they are encrypted and modulated on the sideband RDS signal. (RDS is a protocol for encrypting digital data on FM sidelobe signals.) Obviously this service takes good advantage of existing radio service infrastructure and allows for the use of very small, low cost FM receivers no larger than a pager, to receive and decode the RTCM message.

The DGPS range is limited to that of the FM signal reception range. The LADGPS service in Australia, known as *AusNav*, is a commercial operation aimed at small volume users, and users who cannot justify an expensive DGPS service such as that provided by the Racal or Fugro systems. The transmission of RTCM messages (and even carrier phase data) using the RDS principle is now being offered in many countries by two companies: Differential Corrections Inc. (as in the AusNav network) and PinPoint (or Accpoint Communications Corporation as it is known in the U.S.A.).

DGPS for Marine Users: This is a unique service because it is intended for only one class of user. It is patterned on a similar service offered in North America and Europe (where there are over a hundred DGPS base stations), and is in fact compatible with these international systems -- the marine users travel from country to country, and must be able to acquire and use transmitted messages wherever they go. In Australia the government agency tasked to provide this navigation service is the Australian Maritime Safety Authority (AMSA). It is a LADGPS service offered for free to users who can pick up an unused marine frequency -- about 304 KHz. AMSA is rapidly expanding the service and the network will eventually cover all coastal waters, and extend out to about 100-200 km from the coast. The signal can also give limited inland coverage, though the extent to which it could be used as an alternative to AusNav, in capital city environments, is not yet known.

A useful discussion on the future of "commercial" DGPS services can be found in Thompson (1996).

OUTLOOK FOR IMPROVEMENTS IN PRECISE KINEMATIC GPS

The dramatic improvements in carrier phase-based GPS kinematic positioning are the result of improvements and innovations in several areas. Some of these are highlighted below.

Improvements in AR Techniques

Several ambiguity search procedures for OTF-AR have been suggested during the last five years, including the FARA, FASF, Cholesky, Hatch, and U-D decomposition methods (Han & Rizos, 1996f). The U-D decomposition method was found to be the fastest. 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 IOTF-AR is possible. Suggestions on how to improve the Ambiguity Function Method (AFM) of AR (generally referred to as searching in the coordinate domain) were made by Han & Rizos (1996a). Although new search algorithms will continue to be developed, the most significant improvements to AR must come from increasing the *reliability* of AR as well as the speed of the AR algorithm (or minimising the time-

to-AR). This requires careful attention to quality issues such as statistical testing and various AR validation procedures.

Improvements in Quality Assurance and Validation Techniques

At the heart of reliable IOTF-AR are several innovations in quality assurance, stochastic modelling and result validation. For example, an online stochastic model determination method and an adaptive procedure are described in Han (1997b), and in the section "Instantaneous Ambiguity Resolution Algorithm" earlier. The validation procedure for AR in the ambiguity search domain was proposed in Han & Rizos (1996b), and the validation procedure for the AFM was described in Han & Mok (1997). Further research should be carried out on the refinement of the stochastic model and an adaptive procedure which can automatically adjust with changing environment.

Bias Mitigation and the Use of Multiple Reference Stations

Medium-range kinematic positioning based on OTF-AR requires that baseline length dependent biases be mitigated. The most important of these are satellite orbit, ionospheric and tropospheric biases. Multiple reference stations surrounding the area of survey serve to generate empirical correction terms for the moving GPS receiver (Wanninger, 1995; Wübbena, et al., 1996). A *linear combination model* has been proposed for instantaneous ambiguity resolution, which can eliminate orbit bias, ionospheric delay, as well as mitigate tropospheric delay, multipath and measurement noise across the area of survey (Han, 1997a; Han & Rizos, 1997). The basis of this approach is that the data from multiple reference stations can be used to develop corrections to the double-differenced carrier phase data (and pseudo-range double-differences as well) formed between a mobile receiver and one reference receiver. Figure 2 shows a typical double-difference correction series generated from a three reference receiver network during an experiment carried out in December 1996, in Sydney, Australia. (Details on how these corrections are computed can be found in Han & Rizos, 1997.)

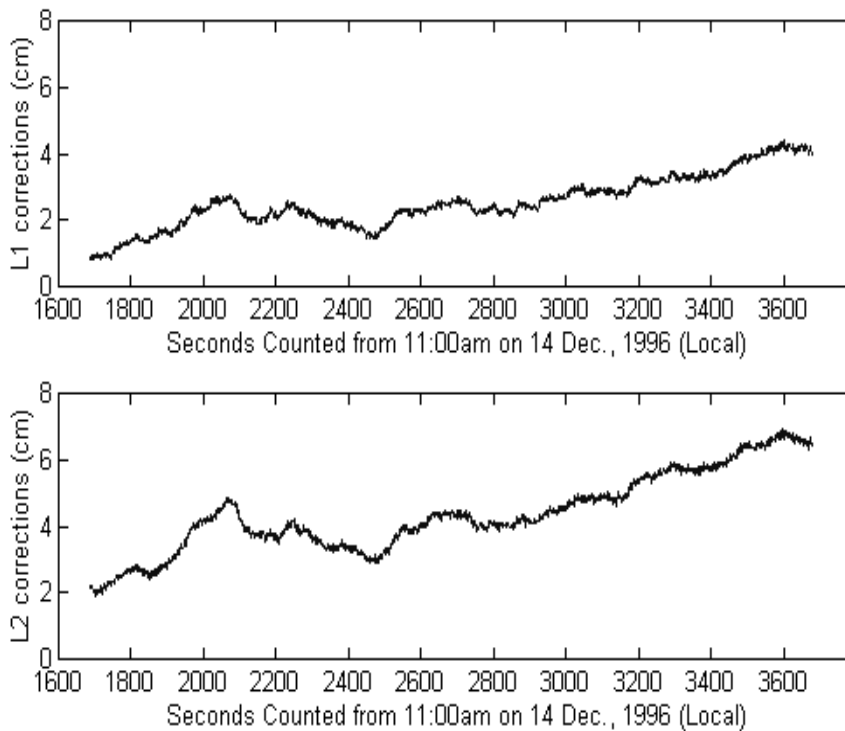


Figure 2: Example of corrections for double-differenced carrier phase observations for the satellite pair PRN 24 and PRN 9, on L1 and L2, generated from data collected in December 1997, in Sydney, Australia.

Raquet & Lachapelle (1997) also report the use of reference receiver networks for long-range kinematic positioning. Further research needs to be undertaken in order to determine how closely spaced the network of reference stations should be in order to derive bias corrections with sufficient accuracy to resolve integer ambiguities. Investigations need to be made in order to ascertain the feasibility of carrying out carrier phase-based GPS kinematic positioning using WADGPS or WAAS differential corrections.

Instrumentation Issues

GPS equipment has undergone rapid improvement, and full wavelength L2 carrier phase and precise pseudo-range data can now be obtained from the new generation of GPS receivers, such as Ashtech Z12, Leica SR 399, Trimble 4000Ssi and NovAtel Millennium. The C/A pseudo-range accuracy can be derived at the 10cm level using so-called "narrow-correlator" technology (Fenton et al., 1991).

Multipath can also be reduced through the use of new antenna and improved receiver tracking loop design, such as Multipath Elimination Technology (MET) and the Multipath Elimination Delay Lock Loop (Townsend & Fenton, 1994). Other GPS manufacturers have also developed their own (patentable) multipath suppression tracking algorithms.

With respect to the GPS system itself, an additional civilian frequency could be transmitted by the Block IIF satellites early in the next century, and Selective Availability (SA) may be turned off in the next few years. The additional civilian signal will significantly improve the reliability of AR. Without SA, double-differenced carrier phase extrapolation will be possible to a higher accuracy, and the extrapolation period may be much longer than the current 1-2 seconds. GPS and GLONASS receivers such as the Ashtech GG24 will increase satellite availability, improve integrity and accuracy.

On the other hand, improvement can also be made in survey operations. The most dramatic improvements in AR have been reported when using the latest generation of dual-frequency GPS receivers, capable of both precise pseudo-range and carrier phase measurements on both L1 and L2. These instruments permit IOTF-AR for short and medium length baselines, and ambiguity recovery in the case of long baselines.

However, single-frequency instrumentation has a role to play in the so-called "*GPS traversing*" technique (Han & Rizos, 1996c), and for GPS-based attitude determination (Han et al., 1997).

Real-Time Implementation Issues

Real-time GPS kinematic positioning products (RTK) has been developed by several GPS manufacturers, with a few decimetres accuracy during integer ambiguity initialisation (Figure 1). The use of IOTF-AR when employed within such RTK systems can improve performance. For medium and long-range real-time kinematic positioning the challenge is to transmit the data over long distances beyond the range of UHS/VHF systems. Only satellite communications links seem to be feasible for such implementations. The general issues relating to real-time GPS kinematic positioning and the requirements for AR have been discussed in Han & Rizos (1996e), and Rizos et al. (1997a, 1997b). Further comments will be made when discussing selected applications of precise kinematic GPS positioning.

INTRODUCTIONARY REMARKS REGARDING APPLICATIONS OF KINEMATIC GPS POSITIONING

In summary, we can make the following comments:

- Carrier phase-based GPS positioning has evolved so that it can now position: (a) kinematically, (b) in real-time, and (c) instantaneously. Therefore there is 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. However, there are very real *constraints* to the universal use of GPS carrier phase-based positioning.
- There are several shortcomings with GPS that are very difficult to overcome. GPS is *not* the "ideal" system for all users, but there is a strong *temptation* to tackle these problems rather than abandon the view that GPS is the appropriate positioning technology.

Before analysing some applications of GPS it is necessary to consider the factors that influence the choice of positioning system solution, and in particular GPS.

They are:

- Operational issues,
- Data processing issues,
- Potential for product development, and
- Nature of technological constraints.

We will briefly discuss these below.

Factors Influencing GPS Solutions: Operational Issues

Precise positioning requires relative positioning, therefore a minimum of two GPS receivers are required, hence doubling the hardware cost, and resulting in increased complexity. What is required is therefore careful performance specification so as to ensure the operational issues do not interfere with the application.

Some comments regarding operational issues:

- DGPS accuracy is typically at the few metre level -- *generally insensitive to Base-Mobile receiver separation.*
- Carrier phase-based GPS at sub-decimetre level accuracy -- *tight constraints on Base-Mobile receiver separation.*
- Two sets of data can be processed in *real-time* or *post-mission.*
- Who runs the GPS Base Station(s)? -- which gives rise to issues such as *quality control, data pricing, value-added services, etc.*
- Compatibility issues -- *industry standard file and transmission formats required.*
- Datum issues -- *Base Station coordinates, applications, map references.*
- Multi-functional GPS infrastructure -- *Base Stations and datum to support all navigation, surveying and geodetic applications.*

Factors Influencing GPS Solutions: Data Processing Issues

Data requirements (in particular accuracy) "drives" the hardware configuration, but accuracy is dependent on many factors. Furthermore, the kinematic positioning mode is more challenging than static positioning, and there is a "universal truth" that higher positioning accuracy implies higher costs!

Some further comments regarding data processing issues:

- In-receiver processing of RTCM-transmitted GPS corrections.

- Real-time processing vs post-processing? -- *algorithm enhancements, coms link complications & costs.*
- Precise positioning requires OTF ambiguity resolution -- *state-of-the-art technology.*
- Highest positioning accuracy performance requires advanced GPS receivers - *new generation dual-frequency hardware.*
- Integrity issues -- *how to assure high accuracy results when real-time, carrier phase data processing?*

Factors Influencing GPS Solutions: Technological Issues

GPS technology can be treated largely as a "black box", therefore it is necessary to define the lowest level of system design, and consider incorporating external "value-added" components. However, GPS can be considered largely as a "plug-in" module in more complex systems, which can be developed to take advantage of, for example, industry standard NMEA output formats. It is fair to say that there is a general ignorance of the limitations and the capabilities of the GPS technology, not only within the general public but also the engineering community.

In relation to technological issues we can make the following comments:

- What basic GPS "package" will be used? -- *chipsets, boardsets, etc.*
- Carrier phase-based processing algorithms are still improving -- *in-receiver RT solutions now possible.*
- Innovative applications require external processing -- *attitude determination, GPS arrays, etc.*
- There are multi-level entry points for high-tech small to medium sized enterprises -- *intense competition for products at basic NMEA level.*
- There is only a small number of skilled personnel with a "deep" understanding of data processing -- *largely concentrated in universities and GPS companies.*

Factors Influencing GPS Solutions: Technological Constraints

It is important to understand the basic constraints impacting on GPS performance, such as Signal disturbances and blockage, and to take advantage of synergies offered by appropriate multi-sensor integration. However, ultimately the GPS system must address the application needs.

Therefore the following need to be considered:

- Satellite blockages due to foliage and buildings are a severe constraint for urban GPS applications -- *some form of GPS-Dead Reckoning integration may be necessary.*
- Multipath impacts severely the precision positioning applications.
- Integration of GPS and communications systems -- *real-time processing, transmission of coordinates to Base, etc.*
- GPS and GLONASS integration offers challenges -- *cost and complexity rise.*

- What about "standards & specifications"? -- *many applications must be quality assured.*
- Transformation to the required information format -- *graphical, road address, block number, etc.*

AN ANALYSIS OF SOME APPLICATIONS OF KINEMATIC GPS POSITIONING

In the following sections we will briefly describe several applications of the GPS technology, and analyse the technology components, constraints and remaining non-technical issues relating to the use of GPS. The four applications are:

- (1) Intelligent Transportation Systems
- (2) RTK products and applications
- (3) GPS-based machine guidance
- (4) GPS-based deformation monitoring

Intelligent Transportation Systems (ITS)

ITS is a global trend to improve ground transportation system "intelligence" so as to reduce road congestion, reduce air pollution, increase road safety and increase transport efficiency through the application of hi-tech solutions to environmental problems (Drane & Rizos, 1997). "ITS America" has identified the following user functions:

- (a) ATMS -- *Advanced Traffic Management Systems*
- (b) ATIS/ADIS -- *Advanced Traveller / Driver Information Systems*
- (c) AVCS -- *Advanced Vehicle Control Systems*
- (d) CVO -- *Commercial Vehicle Operations*
- (e) APTS -- *Advanced Public Transportation Systems*

From an engineering perspective *ITS can be criticised as being a technology-driven (as opposed to market-driven) movement.* The critical questions therefore are:

- Will the public buy such systems?
- Will institutional users subsidise system development?
- Will ITS be implemented in a piecemeal fashion?
- Can ITS be made more than the sum of its components?

The ITS technology components are:

- **Positioning** -- *GPS, DR, terrestrial systems, etc.*
- **Communications** -- *to and from vehicle*
- **Digital road data** -- *maps, points-of-interest, etc.*
- **Computing** -- *in-vehicle & central facilities*
- **Driver interface** -- *LCDs, HUDs, voice, etc.*
- **Road sensors** -- *traffic congestion, breakdown incident detection, etc.*

We can identify those applications which would need positioning, for example:

- In-vehicle navigation.

- Collection of probe vehicle data vital to support route guidance services.
- Positioning systems are a key element of computer aided dispatch systems.
- Use of radars for the purposes of collision avoidance.
- Many technologies will be used for automated cruise control.
- Automatic Traffic Control Systems must monitor traffic flow.
- Stolen vehicle recovery will be enhanced by systems that allow police to track cars.
- Efficacy of distress alarms will be greatly increased if location of an emergency is known.
- Dynamic bus/tram information systems able to predict arrivals improve service level of public transport systems.

Hence many elements of ITS cannot proceed without a positioning technology. This may be provided by GPS (with or without enhancements), or alternative positioning technologies including terrestrial-based systems. There are several "modes" of positioning, exemplified by queries such as "where am I?" (autonomous navigation mode), "where are you?" (vehicle tracking mode), and "where were you?" (inventory/data-logging systems). Restricting ourselves to GPS, there are several implementation strategies possible:

- Single receiver operation -- *100m horizontal accuracy (95%)*.
- DGPS -- *transmit corrections to vehicle, <5m accuracy*.
- "Reverse" DGPS -- *transmit data/position from vehicle to Base, 1-5m accuracy*.
- GPS + Dead Reckoning (DR) -- *because GPS coverage may be poor in urban areas*.
- Precise carrier phase-based positioning -- *for specialised applications*.

One of the most important issues in ITS is that coordinates are not necessarily the most appropriate form of expressing "position". They are not "user-friendly", and hence considerable effort has been expended in overcoming this shortcoming. At the heart of the position/location issue is the "map". There are several roles that map data, when combined with GPS-derived coordinate data:

- (a) Address Matching* -- *street address from coordinates (output), or coordinates from street address (input)*.
 - (b) Map Matching* -- *enhancement to GPS, or improving position display "aesthetics"*.
 - (c) Best Route Calculation* -- *in-vehicle or at Base? real-time or pre-journey? incorporate traffic congestion information?*
 - (d) Route Guidance* -- *turn-by-turn instructions*.
 - (e) Information-rich background -- *display location on electronic-map, display other fixed-feature details, low-cost & low-tech implementation*.
- (* require "intelligent", navigable map data)

Any discussion of ITS technology and applications is incomplete without making reference to the business opportunities, as they are major incentives for product development. We may remark on the "mass market" and the "niche market". With regard to the former we can make the following comments:

- ITS products must be cost-effective solutions to a complex engineering integration task.
- Over 200 systems developed -- *various configurations, most sophisticated are the combined GPS+DR+MapMatching systems.*
- Long term research -- *since early 1970's.*
- Japan very active -- *>1million cars with autonomous navigation, 10,000 in USA & Europe.*
- Private user systems are "packaged" -- *total "entertainment" systems (US\$2,000 - \$6,000), "car security" systems (<US\$1,000).*
- Many commercial systems available -- *especially tracking & dispatch systems.*
- Government sponsored pilot projects -- *EU projects, various city trials, Atlanta Olympics, etc.*
- Significant "customisation" necessary -- *com links, map databases, etc. -- less of a problem with CVO systems*

We can make the following comments as far as "niche market" is concerned:

- ITS products can also be developed by small to medium sized companies for niche applications.
- In-vehicle navigation extended to tracking & security applications -- *car theft recovery, more efficient road service, etc.*
- Enhanced map & attribute datasets -- *in addition to "standard" electronic-map datasets, tourist applications, etc.*
- Communication-positioning services -- *in-vehicle transactions, information services, etc.*
- Innovative Internet services -- *low cost, low volume tracking, mobile sensor systems (e.g. pollution, weather, traffic density, etc.).*
- New, increased precision vehicle positioning technology -- *GPS carrier phase+DR, etc.*
- Commercial & public transport systems -- *different features, display systems, interfaces, etc.*

We can see that ITS is a fruitful area for innovative engineering applications and products that address them. However, the accuracy generally required of these applications is not high. The main requirement is low-cost, moderate accuracy, instantaneous positioning system well suited to urban environments. Although GPS is far from the ideal system for ITS, it is generally the "first choice" system for engineers. Enhancements to GPS can overcome, to a degree, the constraints of the technology.

RTK Products and Applications

One of the main objectives of "real-time kinematic" (RTK) products is to *make GPS more competitive with traditional surveying technologies by:*

- Reducing the cost of GPS surveys.
- Reducing the complexity involved with traditional GPS surveying techniques.
- Obtaining the results in-the-field (that is, in "real-time").
- By reducing operational constraints on the use of carrier phase-based GPS.
- Increasing the flexibility of carrier phase-based GPS (being able to address "kinematic" applications).

Applications for RTK include:

- (a) Engineering surveys -- *building construction sites, preliminary-layout-asbuilt surveys, etc.*
- (b) Offshore engineering -- *dredging, offshore structures, support ocean-bottom surveys.*
- (c) Cadastral surveys -- *technology that "coordinates" property boundaries, ideal for establishing the Digital Cadastral Data Base, etc.*
- (d) Minor control surveys -- *rapid establishment of control for low accuracy applications.*
- (e) Specialised applications -- *vehicle-mounted video/GIS data collection, attitude determination, etc.*

From an engineering perspective *RTK is the most challenging of the commercial GPS technologies:*

- Requires state-of-the-art GPS hardware, including
- sophisticated AR software, with an
- ability to sense degraded conditions, however
- there are constraints that have to be applied to maximise high quality results.

These constraints are:

- Satellite coverage -- *require at least 5 satellites, but preferably more.*
- Short range -- *Base-Rover separation <20km.*
- Communication link restrictions -- *frequency allocation, power, datarate, etc.*
- No industry standards for phase data transmission -- *proprietary formats, no receiver "mixing" possible.*
- Require operation of both Base and Rover receivers -- *extra cost & logistical complexity.*
- High cost technology -- *significant obstacle to use by small private survey companies.*

As discussed earlier, several of these constraints appear to have been overcome. Commercial products do not yet have instantaneous OTF-AR, the

capacity for medium-range positioning, etc. The RTK product is, however, increasingly targeting the machine-guidance applications.

GPS-Based Machine Guidance

Several requirements must be fulfilled if GPS-RTK products are to be transformed into *automatic, on-line, active technology*. The technology must be robust and reliable, producing results with low latency and at a very rapid rate (>10Hz). Applications include:

- (a) Construction machinery -- *bulldozers, graders, etc.*
- (b) Open-cut mining -- *draglines, dumptrucks, etc.*
- (c) Precision farming -- *plowing, planting, fertiliser application, harvesting.*
- (d) Precision UAVs -- *unmanned airborne vehicles.*
- (e) Robotics -- *machine control, driverless vehicles!*

Although there are many *potential* applications, all are characterised by a requirement for extensive system integration and are *very intolerant of failure*. Hence several engineering challenges have to be addressed in terms of the technology:

- Advanced OTF ambiguity resolution techniques.
- Improved QC and validation procedures.
- Significant computer engineering.
- Appropriate user/machine interfaces.
- Interference-free communication links.
- Multipath (and residual bias) mitigation.
- Significant mechanical and mechatronic engineering component.

It is fair to say that GPS-based machine guidance has taken over from GPS-RTK surveying as a significant R&D driver with vast potential, and a source of high profits for GPS manufacturers!

GPS-Based Deformation Monitoring

This application is characterised by *slow* kinematic positioning, and can be addressed by an automatic, continuously operating GPS network of receivers. Apart from automatic operation, the technology needs to be robust and reliable as it may have to operate in hazardous or inhospitable environments. It shares a similarity to RTK in that a communications sub-systems is necessary to permit the transmission of carrier phase data from an *array* of GPS receivers to a "base" or "master" station. Applications of such GPS array systems include:

- (a) Engineering structure monitoring -- *bridges, dams, offshore structures, hill slopes, etc.*
- (b) Volcano monitoring -- *small scale geodynamics.*
- (c) Ground subsidence -- *oil or water extraction, underground mining, etc.*
- (d) Regional fault monitoring -- *medium scale geodynamics.*

There are several reasons why continuous monitoring by GPS is the best solution to the above application needs:

- Lower labour and survey costs.
- Continuous deployment of hardware.
- Real-time systems may operate as *alarm* systems as well as *monitoring* systems.
- Able to respond quickly in changing conditions.
- Continuous data may provide valuable insights into deformational phenomenon.
- High accuracy and free from line-of-sight constraints of traditional techniques.
- Potentially lower hardware costs.
- Upward scalability.

There are many different implementations possible, with different hardware configurations and data processing strategies. Some of the factors or characteristics that may vary include:

- Inter-receiver distances.
- Whether data is processed in kinematic or static mode.
- The number of GPS receivers in the array.
- The level of accuracy required.
- Whether an "off-the-shelf" solution is sought, or custom solutions.
- The degree of permanence of the array.
- Whether data is processed in real-time, or near-real-time.

Present off-the-shelf RTK-based solutions are not optimised for automatic deformation monitoring of slowly deforming networks. The challenge therefore is to develop an optimum technological solution for each application. This requires advances in the following:

- Use of low cost single-frequency GPS boardsets -- *and the development of appropriate data processing algorithms.*
- Ruggedised packaging -- *receiver and computer electronics, radio modem.*
- Power management sub-system -- *solar power, batteries, periodic powerdown.*
- Computer engineering -- *integration of software components for controlling receiver, data processing, communications, etc.*
- Software engineering -- *flexible operational modes from pure kinematic to static, continuous to intermittent.*
- Integration with external systems -- *other GPS receivers, com links, display systems, etc.*

The greatest challenge is, however, to develop low cost systems which can be reconfigured for different applications, and expandable to handle large numbers of receivers deployed across large areas. Han & Rizos (1996g) and Rizos et al. (1997c) describe a system architecture and data processing strategy for small-scale

GPS-based deformation monitoring based on a combination of a sparse network of dual-frequency GPS receivers ringed a larger number of low cost single-frequency receivers.

CONCLUDING REMARKS

The future of precise GPS kinematic positioning is dependent on a number of factors, including developments in receiver hardware, carrier phase data processing software, operational procedures, changes in official GPS policy, and also the augmentation of GPS with pseudolites or inertial navigation systems, WAAS system, and the combination of GPS with GLONASS. All of these will significantly improve the reliability, integrity, and accuracy of the position results. In the near future significant performance improvements can be expected with the strongest R&D motivation arising from new groups of applications such as ITS, machine guidance, and other real-time uses.

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**MAPEAMENTO DIGITAL DO SISTEMA AQUÍFERO
CÁRSTICO NO SÍTIO DE TRANQUEIRA REGIÃO
METROPOLITANA DE CURITIBA, FASE ATUAL**

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RESUMO

Com este trabalho, apresenta-se o estágio atual do Projeto de Mapeamento Digital do Sistema Aquífero Cárstico - MAPSAC -, que se iniciou em 1996 com a participação de um Grupo Multidisciplinar. A finalidade principal com o MAPSAC é explorar as informações e os dados espacialmente referenciados para obter um entendimento do Sistema Aquífero localizado em Tranqueira, próximo a Curitiba.

ABSTRACT

This paper describes the current stage of the project for digital mapping of the Karst aquifer system - MAPKAS. This project started in 1996 and is conducted by a interdisciplinary group. Its main objective is to explore spatially referenced data in order to understanding the structure of the aquifer system aiming at its future use without depleting it. The aquifer is located at Tranqueira site, near Curitiba. It is scrutiny and is expected to be used as one of the major sources of fresh water for the city.

1. INTRODUÇÃO

Em 1995, pela primeira vez, teve-se conhecimento de estudos que estavam sendo realizados por professores do Departamento de Geologia da UFPR e técnicos da SANEPAR sobre águas subterrâneas no Estado do Paraná.

Embora a água, como um elemento vital para a espécie humana, já apresente uma motivação natural para um trabalho de pesquisa, o que considerou-se como mais relevante foram as questões relacionadas com a utilização dos aquíferos como alternativa complementar ao abastecimento na região metropolitana de Curitiba.

Então em 1996, idealizou-se uma proposta para Mapeamento Digital do Sistema Aquífero Cárstico - MAPSAC, e submeteu-se ao Comitê Técnico do VIII Simpósio Brasileiro de Sensoriamento Remoto, que iria realizar-se em Salvador,BA.

Naquela época, concebeu-se o MAPSAC, como constituído por quatro sub-projetos: Posicionamento por Satélite (POS); Processamento de Imagens Digitais (PID); Interpolação Volumétrica (IVO) e Visualização e Análise (VISA). A idéia básica com isso, é que o MAPSAC seja na realidade o ponto de convergência de interesses, onde se integram de forma crescente equipes de trabalho multidisciplinar na busca de soluções e desafios.

2. OBJETIVO

Passado quase um ano entre a idealização do MAPSAC e a sua implementação, pretende-se com o presente trabalho, apresentar o estágio atual deste projeto e os principais aspectos metodológicos que foram importantes para os trabalhos até agora desenvolvidos, destacando-se as atividades de reconhecimento e rastreamento de referências de nível e a extração automática de canais de drenagem a partir de um DEM (*Digital Elevation Model*), respectivamente nos sub-projetos POS e PID.

3. O PROJETO MAPSAC

Com o MAPSAC, pretende-se estabelecer uma base de dados digitais que possa servir para a exploração e um melhor entendimento sobre o Sistema Aquífero Cárstico - SAC. Para tanto, a idéia básica é utilizar tecnologia GIS (*Geographic Information Systems*) para a integração e análise de dados.

O primeiro passo nesse sentido foi referenciar, espacialmente, 19 poços tubulares para os quais se dispõe de perfis litológicos e análises químicas e que estão distribuídos sobre a área. Na figura 1, apresenta-se a distribuição dos poços.

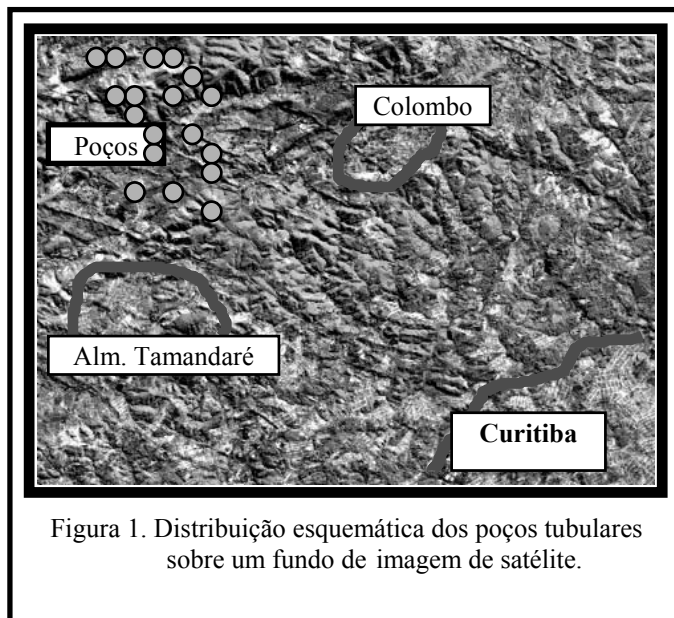


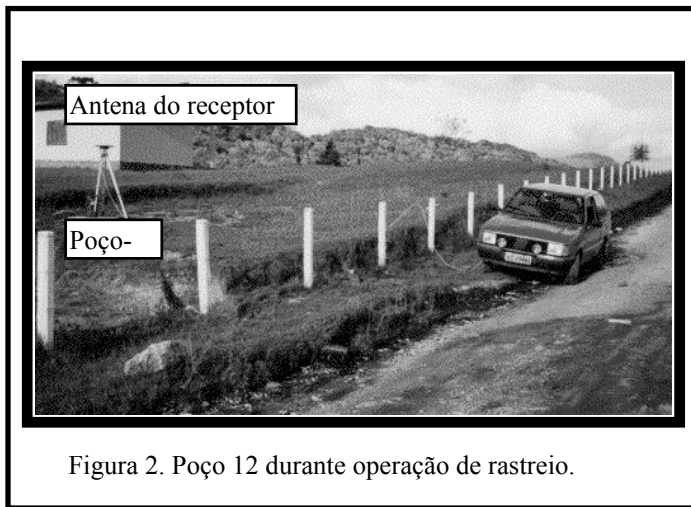
Figura 1. Distribuição esquemática dos poços tubulares sobre um fundo de imagem de satélite.

Para estabelecer as coordenadas X,Y,Z de cada poço foi utilizada tecnologia GPS (*Global Positioning System*) no modo estático relativo, com o rastreamento sendo feito com receptores do tipo geodésico (modelo 4000 SST- Trimble), durante um período de observação de cerca de duas horas. Na figura 2, apresenta-se uma tomada fotográfica do poço-12, durante a operação de rastreamento.

3.1. Reconhecimento e rastreamento de RRNN

Embora alguns tipos de estudos hídricos não necessitem do conhecimento de altitudes ortométricas (desnível em relação ao nível médio dos mares), pressupõe-se que esta informação é fundamental para estudos subsequentes e,

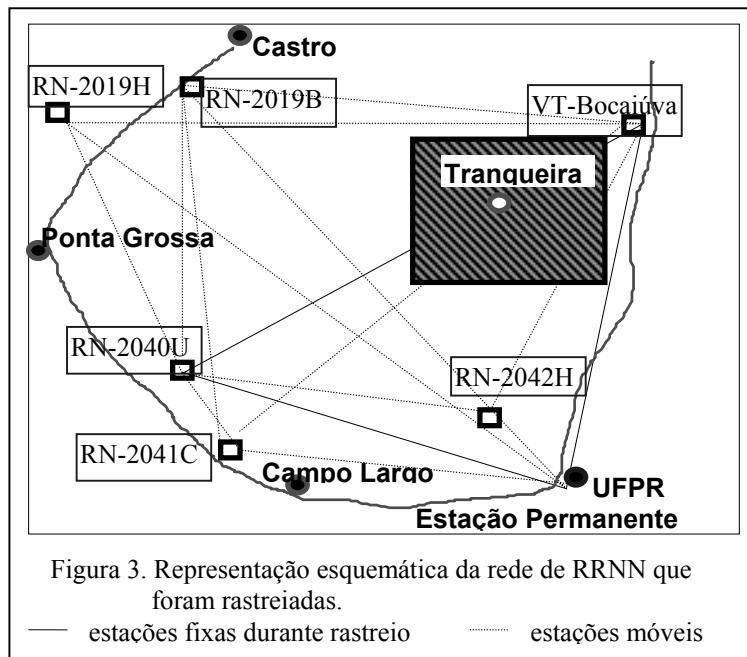
portanto, é desejável sua determinação. Mas como o GPS não fornece este tipo de altitude, ou seja, somente são determinadas altitudes geométricas, a alternativa adotada foi rastrear referências de nível (RRNN) que envolvessem a área do aquífero e a partir destas determinar um geóide local, para daí interpolar as altitudes para os poços.



Foram feitos reconhecimentos de quatro trechos de nivelamento geométrico do IBGE, embora só tenham sido encontradas RRNN relativas aos circuitos:

- a) Curitiba - Bocaiúva do Sul - Ribeira;
- b) Ponta Grossa - Campo Largo - Curitiba; e
- c) Ourinhos - Jaguariaíva - Castro - Ponta Grossa.

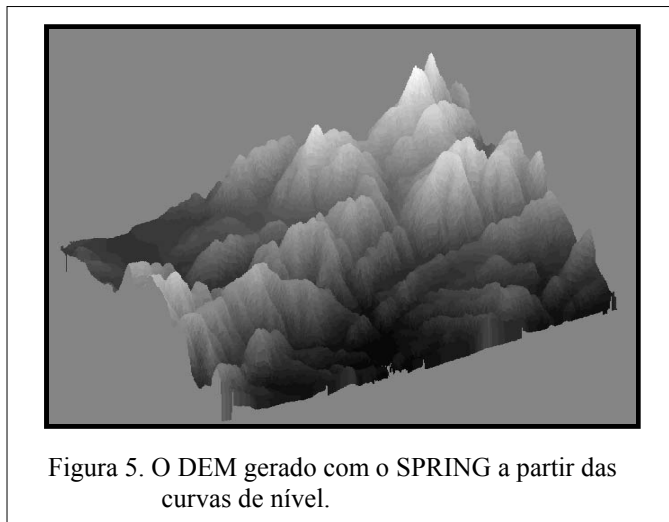
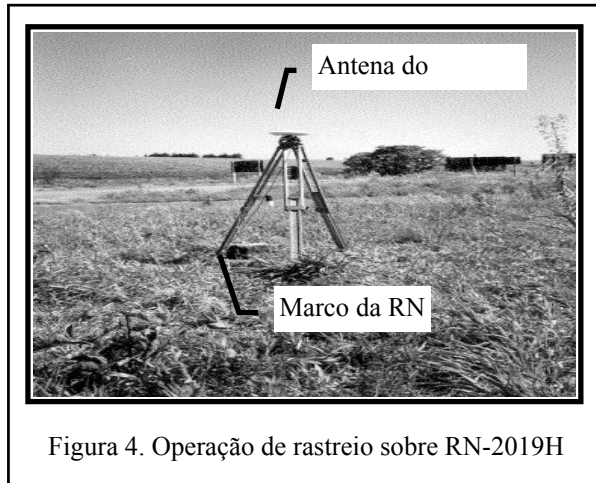
Para estes trechos foram encontradas oito, cinco e cinco RRNN, respectivamente nos circuitos (a), (b) e (c). Destas, selecionaram-se seis para formarem os pontos básicos para a determinação do geóide local. O critério utilizado foi selecionar RRNN que apresentassem um horizonte com um “mínimo” de obstáculos e que circundassem a área definida para estudo. Na figura 3, apresenta-se um esquema da rede de RRNN observada com GPS, onde para as posições VT-Bocaiúva, RN-2040U e Estação Permanente da UFPR, ficou-se em operação durante todo o período de rastreo (cerca de sete horas), para garantir uma simultaneidade de cerca de duas horas de rastreo com as RRNN: 2019B, 2019H, 2041C e 2042H.



Na figura 4, apresenta-se uma tomada fotográfica feita durante a operação de rastreamento da RN-2019H. Nesta campanha foram utilizados quatro receptores modelo Z12 Astech.

3.2. O DEM da área e a rede de drenagem

Para o segundo subprojeto, o PID, o objetivo foi obter o sistema de canais superficiais de drenagem (que seriam também importantes em estudos hidrogeológicos posteriores) a partir de um DEM. Para tanto, foram digitalizadas com o sistema MaxiCAD curvas de nível de cartas topográficas 1/10.000. Destas, produziu-se o DEM com o sistema SPRING, que é apresentado na figura 5.



A partir desse DEM, usou-se um método automático de extração de canais de drenagem, com base no programa SKEL, desenvolvido por pesquisadores da Universidade de Israel, ver Meisels-95. Na figura 6, apresenta-se um exemplo dos canais extraídos automaticamente do DEM (ver Delazari-96, para maiores detalhes).

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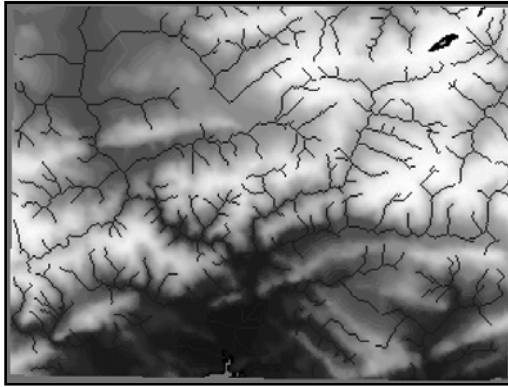


Figura 6. Canais de drenagem obtidos com o programa SKEL.

4. CONSIDERAÇÕES FINAIS

No que se refere aos sub-projetos de Interpolação Volumétrica (IVO) e Visualização e Análise (VISA), pode-se dizer que somente foram realizadas simulações sem resultados definitivos.

5. AGRADECIMENTOS

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