Continuously Operating GPS Reference Station Networks: New Algorithms and Applications of Carrier Phase-Based, Medium-Range, Static and Kinematic Positioning

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ABSTRACT & INTRODUCTORY REMARKS

Continuously operating GPS networks have been used for many years to address two types of positioning applications. The first, perhaps best known application, is in relation to geodetic objectives such as the determination of crustal motion on a variety of spatial scales - from the measurement of the broad kinematics of tectonic plates to deformation monitoring of local areas undergoing subsidence (e.g. due to fluid extraction and underground mining), surface inflation (e.g. due to magma intrusion under volcano domes), or the complex faulting in seismically active zones. Currently, permanent GPS stations around the world which have been established to address such geodetic applications number well over a thousand. Hundreds of these stations are now formally part of the global network organised under the auspices of the International Association of Geodesy (IAG) as the well-known International GPS Service (IGS). Data from this network is collected on a daily basis, centrally archived at data centres and is available via the Internet to users. Many of these users, through the application of special carrier phase processing techniques, are able to achieve relative station coordinate accuracies at the "few parts per billion" level (sub-centimetre accuracy for receiver separations perhaps a thousand kilometres or more).

The second class of applications that have traditionally been addressed by continuously operating GPS receiver networks are those that require real-time, differential GPS (DGPS) services to determine coordinates to accuracies of the order of a few metres. Local Area DGPS systems rely on a single reference station generating correction messages, which are transmitted to users over a wireless link. The DGPS corrections to pseudo-range data can also be determined at groups of permanent GPS stations, to service wide continental or oceanic regions. This mode of positioning is therefore generally referred to as Wide Area DGPS (WADGPS). Such WADGPS services are offered by several multinational companies, who own and operate networks of reference stations, and who use communications satellites to deliver the DGPS corrections to their customers.

The population of continuously operating GPS receivers is growing rapidly. Some are being established to address a single application, e.g. crustal deformation measurement, for atmospheric monitoring, to support precise real-time navigation, etc. Less frequently, GPS networks are designed for multifunctional use. In some countries permanent GPS stations are intended to support local surveying users. However, the GPS reference receivers, because of their high cost, cannot be established in a dense enough configuration to satisfy all user requirements. For example, GPS surveying typically requires receiver separations of less than 30km (and even <20km for high efficiency OTF-kinematic and rapid static positioning techniques). In this paper three scenarios for user positioning which are optimised for permanent GPS reference receiver separations of the order of 50-100km are introduced. (These implementations are referred to here as addressing "medium-range" positioning applications in Surveying and Geodesy.) The techniques all use a linear combination observation model based on the

double-differenced phase observations between user receiver (either moving or stationary) and multiple GPS reference receivers. In such a model the orbit bias and ionospheric delay can be largely eliminated, and the tropospheric delay, multipath and observation noise can be significantly reduced.

One geodetic implementation is a form of "densification" of a network of dual-frequency GPS receivers in which a permanent array of low-cost, single-frequency GPS receivers is deployed to increase the receiver network spatial resolution. Such an implementation would benefit, for example, deformation monitoring applications. Another implementation allows for the use of cost effective operational procedures based on short station occupation times (as in the "rapid static" GPS Surveying technique). The configuration requires two types of GPS receivers: (a) the permanent, continuously operating, dual-frequency, reference receiver network, and (b) the *mobile*, single-frequency receivers which are used to visit a large number of benchmarks for short periods of time. Data from some stations of Japan's Geographical Survey Institute and Taiwan's Institute of Earth Sciences, Academia Sinica, permanent GPS networks have been used to test these algorithms, and the results are presented here.

In addition to such *static* positioning applications in Geodesy, centimetre-level accuracy kinematic GPS positioning with the aid of a sparse continuously operating GPS reference receiver network is also possible. This paper describes how an integrated ambiguity resolution method (with improvements to the real-time stochastic model, new criteria to verify the selected ambiguity set, and a fault detection and adaptive procedure), when used with the proposed multiple GPS reference station observation model, permits the integer ambiguities to be resolved using as little as a single epoch of data, even for receiver separations of several tens of kilometres. Such an enhanced carrier phase-based technique can be used for real-time positioning applications when implemented within a multiple GPS reference station network such as is being currently established in Singapore, in a collaborative R&D project for The University of New South Wales (UNSW) and the Nanyang Technological University (NTU). What makes this network comparatively unique is that the data from the four permanent GPS reference receivers are continuously delivered by dedicated high speed datalinks to a single control station, in a manner analogous to the pseudo-range-based WADGPS systems.

PROGRESS IN CARRIER PHASE-BASED GPS POSITIONING

Since the early 1980s several innovations to GPS carrier phase-tracking hardware, data processing software and field procedures have made precise GPS positioning a comparatively routine activity. The standard mode of precise differential positioning is for one (or more) GPS reference receivers to be located at stations whose coordinates are known, while other GPS user receivers are located at points of interest. All GPS receivers simultaneously track the L-band carrier waves transmitted by the GPS satellites and, following sophisticated data processing, the coordinates of the GPS user receivers are determined relative to those of the reference receiver(s). Carrier phase-based GPS positioning is now extensively used for many geodetic, surveying and precise navigation applications on land, at sea and in the air.

GPS Geodesy: Techniques & Applications

We may distinguish the techniques and applications of *GPS Geodesy* from those of standard *GPS Surveying*. GPS Geodesy typically can be characterised by the following:

(a) ***Hardware*** - receivers and high quality antennas able to make carrier phase and pseudo-range measurements on both L-band frequencies.
(b) ***Software*** - sophisticated computer programs to process the collected GPS data.
(c) ***Field Procedures*** - simultaneously tracking instruments, recording data over a lengthy observation session, with static (non-moving) antennas.

(d) ***Specialist Applications*** - typically those requiring relative positioning accuracy of 0.1-0.01ppm, and stable reference datum connections.

(1ppm is equivalent to a centimetre accuracy for a 10km reference-user receiver separation.) GPS Geodesy techniques have been progressively refined in order to address the *constraints* of carrier phase-based GPS positioning. The two most significant constraints which GPS Geodesy has been able to dramatically overcome are: (a) ppm-level accuracy, and (b) reference-user receiver spacing. Nowadays, as a result of increasing sophistication in measurement modelling, better satellite tracking coverage, a global network of permanent GPS tracking stations belonging to the International GPS Service (IGS), a well-defined global reference frame such as the International Terrestrial Reference System (ITRS), and the availability of dual-frequency GPS instrumentation, significantly higher *relative accuracies of the order of 0.01ppm are commonplace*. Furthermore, such accuracy is achieved for receiver separations ranging from tens of kilometres to several thousands of kilometres, when large numbers of receivers are used simultaneously (some at reference datum sites with ITRS coordinates).

The quintessential *GPS Geodesy technique* is that which has been refined since the early 1980s, and typically used to establish national (and global) geodetic control networks, to measure the movement of tectonic plates, or to monitor the long-term stability of station benchmarks. At the heart of the technique is sophisticated software which can process the data collected by a network of dual-frequency GPS receivers deployed at fixed benchmarks. The quintessential *GPS Geodesy application* is the measurement, or monitoring, of 3-D station velocities to a high accuracy. Station motion being due to, for example, global geodynamics and regional tectonics, ground subsidence as a result of water or oil extraction, or underground mining activities, volcano and hill slope instability, and even movement of engineering structures such as dams, bridges, buildings, open cut mine walls, etc. An experiment can be established in order to measure the rate of deformation, by using GPS to measure the change in length (as well as height difference and orientation) of baselines connecting receivers in a carefully monumented station network. Although GPS techniques which address such applications are generally implemented on a *field-campaign* basis, implying the periodic (often annual) re-survey of a network of station benchmarks, there is increasing interest in the use of *permanent, continuously operating GPS stations*. These are now deployed globally by the IGS, although regional GPS networks have also been established in the USA, Japan, Europe, and many other countries, to address a variety of crustal motion monitoring applications.

The range of GPS Geodesy applications that can be addressed using GPS Geodesy techniques is growing rapidly and includes:

- establishment of national geodetic datums,
- maintenance of the ITRS, including the determination of earth orientation parameters,
- determination of the magnitude and pattern of regional and global crustal motion, both in the horizontal and vertical sense,
- local (ground or structural) deformation monitoring,
- precise determination of the coordinates of benchmarks, or the trajectory of receivers, in a well-defined reference frame, in support of a number of specialist applications,
- precise determination of satellite orbits, and
- atmospheric studies, including water vapour measurement and the monitoring of ionospheric activity.

There is, in addition, intensive R&D into *new* GPS Geodesy techniques which challenge a number of further constraints to precise carrier phase-based positioning. These include techniques that are applicable when the GPS antennas are in motion (as in so-called "kinematic geodesy"), the length of observation sessions are significantly shortened, the positioning results need to be determined in "real-" or "near-real-time", the density of points to be surveyed is very high, and so on. Some of these techniques require multiple GPS reference stations.

High Productivity GPS Surveying

GPS Surveying requires a minimum of two GPS receivers, and until recently the cost of such technology has been quite high. What has made GPS Surveying technology expensive, apart from the high capital cost of the instrumentation, was the inflexible field procedures which required that the antennas be stationary (over a groundmark) for periods of up to several hours, as well as the complex post-mission data processing.

Over the last half decade, however, considerable R&D has been invested by instrument manufacturers to make the GPS Surveying technology more attractive. That is, if the antenna could be moving (that is, the so-called "kinematic positioning" mode), then new applications for the GPS technology could be addressed. If the length of time required to collect phase data for a reliable solution could be shortened, and if the results were available immediately (that is, the "real-time" positioning mode), then GPS carrier phase-based positioning *productivity* would significantly improve and the technology would be attractive for many more precise positioning applications. GPS Surveying is now a mature technology, capable of delivering relative accuracies of the order of a few parts per million (ppm) for reference-user receiver separations up to 10-20 kilometres using commercial-off-the-shelf (COTS) GPS products.

Present COTS "real-time kinematic" (RTK) GPS systems are: (a) able to be used in the kinematic positioning mode, (b) require comparatively short observation times, and (c) are capable of real-time operation (when provision is made for a communications link between the two GPS receivers). At the heart of <u>all</u> such high accuracy GPS systems is the Ambiguity Resolution (AR) algorithm. The challenge has been (and continues to be): *how to carry out AR quickly, reliably and with a minimum of constraints?* Addressing the constraints of AR in RTK systems is crucial if GPS is to be used for time-critical applications such as machine control, GPS-guided excavations, precision farming, automated container port operations, and so on.

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 (e.g. 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. The length of this "time-to-AR" may range from several tens of seconds up to a few minutes with present GPS COTS systems, *but only when the reference-to-mobile-user receiver distance is less than about 20km*. During this "re-initialisation" period centimetre accuracy positioning is not possible, and hence there is "dead" time until sufficient data has been collected for 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 "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, however implementing an RTK system is more challenging.)

The algorithm improvements that can address the baseline length constraint, <u>and</u> shorten the "time-to-AR" to just one epoch of data, for kinematic applications, rely on new multiple GPS reference station implementations and associated improvements to data processing algorithms.

GPS Geodesy has provided considerable impetus for: (a) improvements in instrumentation, (b) the development of the IGS infrastructure, and (c) the ITRS reference frame. GPS Surveying is (almost) capable of instantaneous centimetre-level accuracy positioning of moving antennas *if certain conditions are met*. The following constraints can be addressed via multiple GPS reference station implementations and associated improvements in data processing algorithms:

(1) Insistence on site occupations of several days for geodetic applications such as control network densification, and surveys undertaken for pre- and post-seismic network distortion measurement.

(2) Insistence on the use of high cost, dual-frequency instrumentation for geodetic applications such as deformation monitoring.

(3) Insistence on short reference-to-mobile-user receiver separations for kinematic applications using OTF-AR techniques, for both real-time and post-mission implementations.

In the scenarios described in this paper, the implication is that medium-range positioning (defined here as involving baseline lengths of the order of 50-100km) is carried out in such a manner that *baseline length dependent biases are mitigated*. For geodetic applications ((1) and (2) above) this means that sub-ppm accuracy can still be delivered even when the instrumentation (single-frequency receivers) and/or field procedures (short observation periods) deviate from those traditionally insisted upon. In the case of precise kinematic applications ((3) above), this implies that OTF-AR is just as easy and reliable as over short baselines.

The most important baseline length dependent biases are satellite orbit, ionospheric and tropospheric biases. Multiple GPS reference stations surrounding the area of survey serve to generate empirical correction terms for the user receiver in a manner analogous to Wide Area DGPS systems. A linear combination model has been proposed by Han (1997), Han & Rizos (1997), which can account for orbit bias and ionospheric delay, as well as mitigate tropospheric delay, multipath and measurement noise across the network. The basis of this approach is that the data from the reference station network can be used to develop corrections to the double-differenced carrier phase data formed between a mobile receiver and a *single reference receiver*, hence making it possible to implement it within COTS single-reference-receiver static and kinematic data processing software.

Geodetic Procedures Based on Multiple Reference Receivers

Four data sets were used in these experiments, three provided by the permanent GPS network of Japan's Geographical Survey Institute (GSI), and one from Taiwan's Institute of Earth Sciences - Academia Sinica (IESAS). These are located in Figure 1 (in Hokkaido, Tokai and Kyushu, in Japan, and on the east coast of Taiwan). For each geographical location, seven days of data (dual-frequency data with sample rate 30 seconds, 24 hour files), from four different seasons in 1997 (day-of-year: 001-007, 091-097, 181-187 and 271-277), from a total of about 30 stations, were used in the analysis. All station coordinates were determined using scientific GPS software in the ITRS, with respect to three IGS stations. These coordinates would be used for comparisons with alternative processing strategies proposed by the authors.

The aim was to test the performance of the linear combination observation model based on double-differenced observations between a single-frequency (user) receiver and multiple GPS reference receivers. A variety of reference receiver network configurations, regions and seasons were chosen. The user-reference receiver baseline lengths ranged from about 24km to over 90km. Two experiments were conducted on all the data sets: (a) a test of rapid static, single-frequency surveys, and (b) a test of continuous GPS network containing both dual- and single-frequency receivers. The results are summarised below.

All baselines are first determined using dual frequency ionosphere-free combinations over seven days are considered and the results are considered true values for the according 7-day session. All GPS data sets are then split into files of 240 epochs (2hr length), resulting in 12 files per day per station (Rizos, et al, 1998). The 84 results for each baseline were derived and subsequently 84 differences can be derived. The mean value of the 84 differences and the standard deviation of the 2-hour session results are plotted in the left hand side of Figure 2 versus the baseline for four regions in the Autumn campaign. The solid circles (3 baselines), white squares (6 baselines), solid triangles (4 baselines) and white diamonds (1 baseline) represent the different networks: Hokkaido, Tokai, Kyushu, IESAS. The mean offsets of all 14 baselines are 2.8mm, 4.5mm, 14.1mm, 3.2mm for the latitude, longitude, height and baseline length components, respectively. It can be seen that the biases and standard deviation of the baseline results are almost baseline independent using the corrections from multiple reference stations. The right hand side of Figure 2 summaries all results over the four seasons. It notes that the variation of the 2 hour results deriving during the Summer period is larger than for other seasons. Further investigations on this issue are being undertaken.

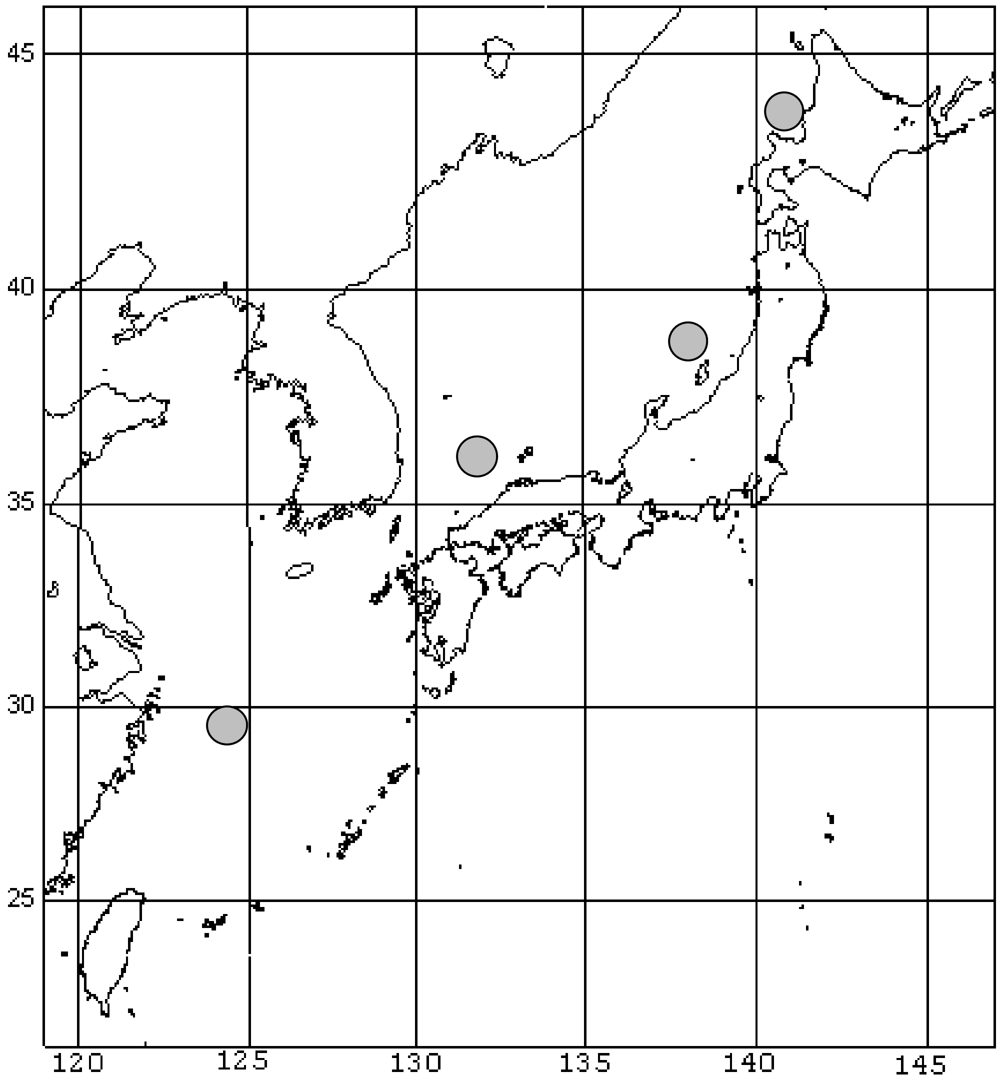

Figure 1. Four test areas of permanent GPS networks in Japan and Taiwan.

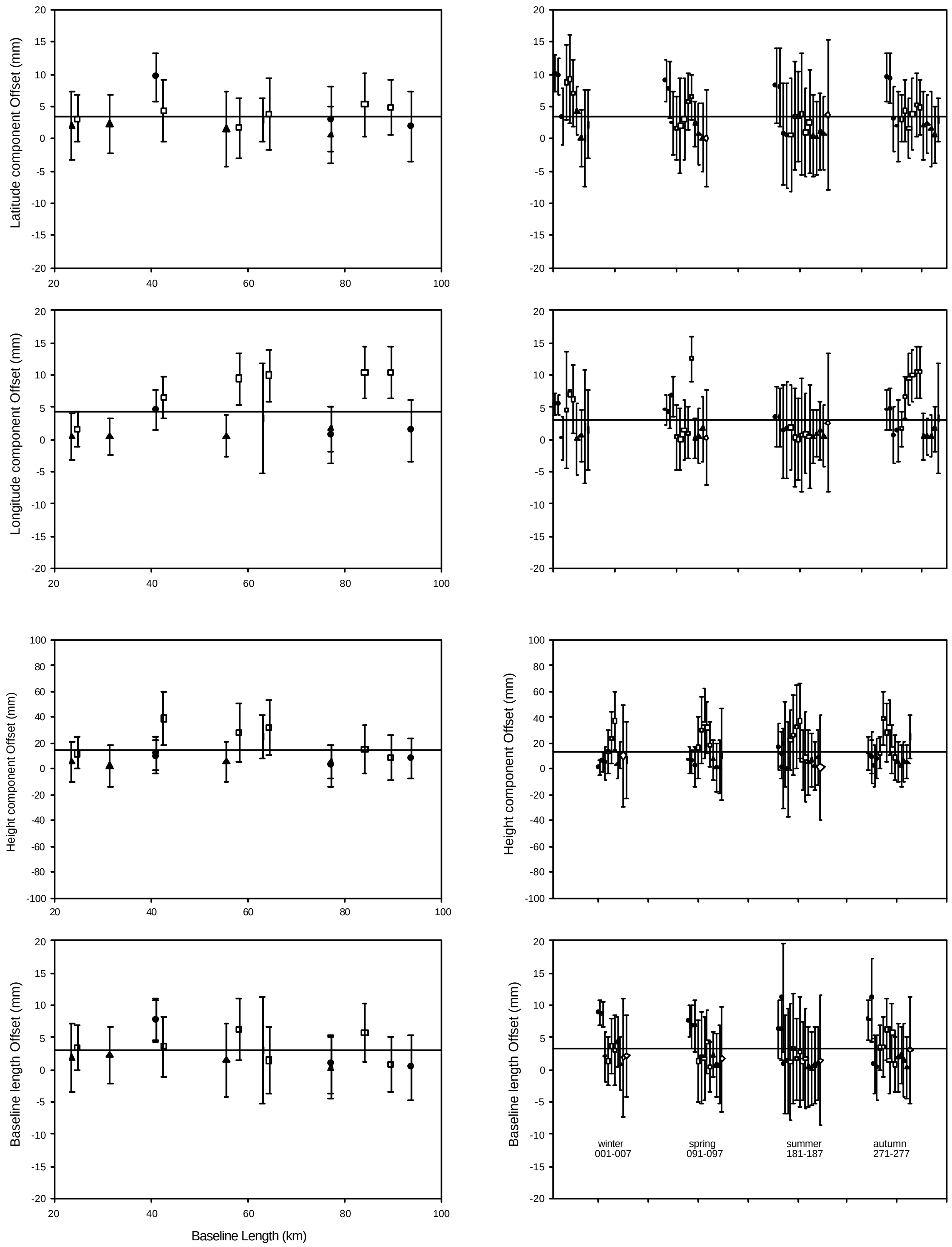

Figure 2. Mean baseline offsets (relative to the 7 day ionosphere-free results) and standard deviations of the 2 hour baselines. The results are shown for various user-reference receiver distances, in the different networks, in the lefthand column plots (the x-axis is distance in km) in the Autumn campaign, and in the righthand column plots over the four seasons. The symbols, ●, □, ▲, 7 represent the different networks: Hokkaido, Tokai, Kyushu, IESAS.

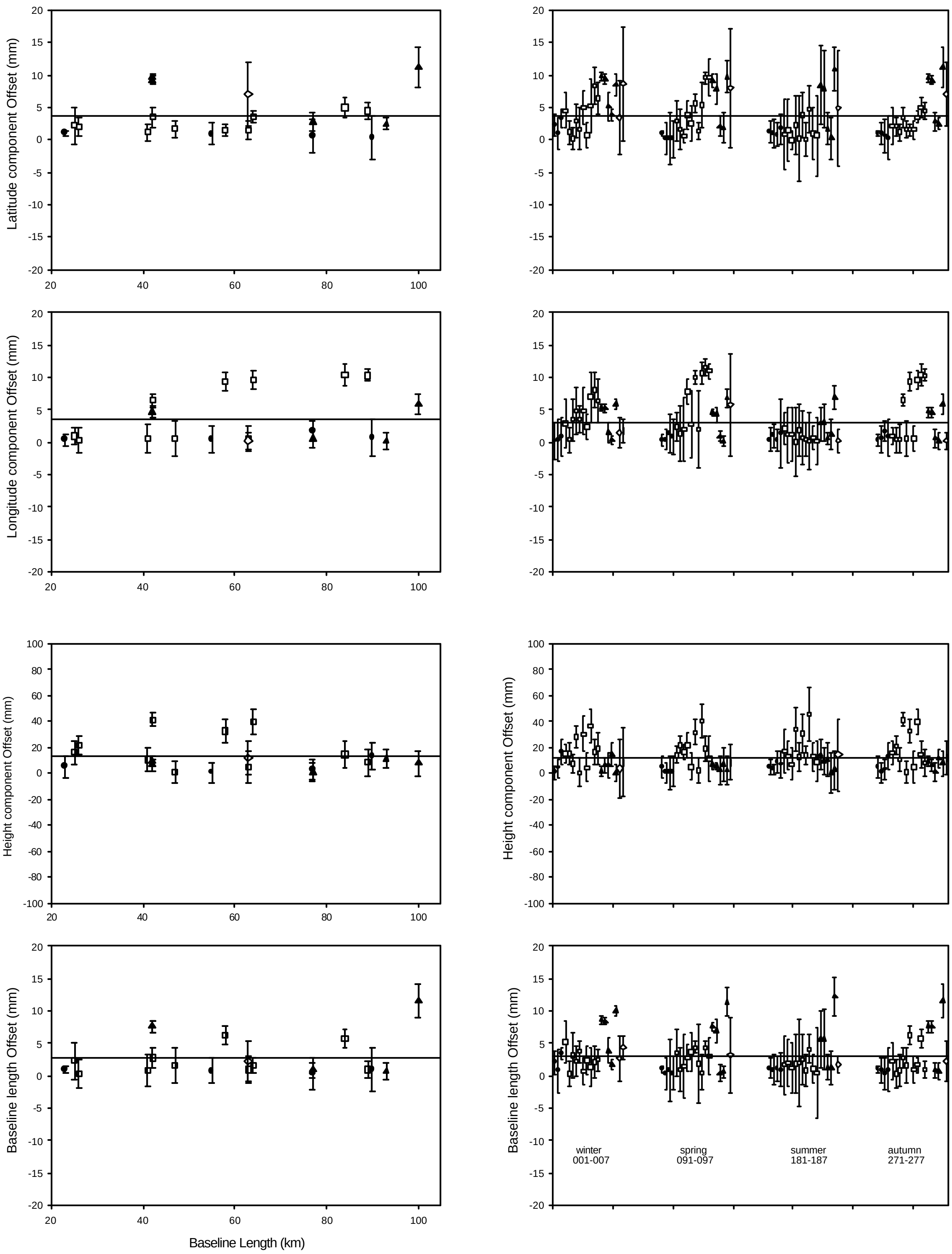

Figure 3. Mean baseline offsets (relative to the 7 day ionosphere-free results) and standard deviations of the 24 hour baselines. The results are shown for various user-reference receiver distances, in the different networks, in the lefthand column plots (the x-axis is distance in km) in the Autumn campaign, and in the righthand column plots over the four seasons. The symbols, ●, ☐, ▲, 7 represent the different networks: Hokkaido, Tokai, Kyushu, IESAS.

In summary, it appears that 1cm accuracy horizontal component and 3cm height determination is possible with single-frequency, rapid static techniques (2hr sessions) under certain conditions. Although these are the subject of ongoing investigation, it is obvious that, for example, larger errors (especially in the height component) are evident when the user receiver elevation is different from the surrounding network receivers (see Tokai network). It therefore appears feasible therefore that sub-ppm accuracy (ppm: 1cm accuracy over 10km receiver separation) is achievable using low-cost receivers and comparatively short observation sessions, for user-reference receiver separations of several tens of kilometres.

The second scenario simulates a permanent network configuration that may be used for ground or structural deformation monitoring, based on a sparse network of 3 dual-frequency receivers surrounding a denser, inner network of low-cost, single-frequency receivers. The same four data sets were used for the tests with the exception that 24hr files were processed in place of the rapid static (2hr) results referred to above. Figure 3 contains the same information as Figure 2, and summarises the results of mean baseline offsets relative to the 7 day ionosphere-free results and standard deviations of the 24 hour baselines. The most noticeable difference is not in the overall accuracy (as indicated by the mean values), but in the standard deviations, which are lower. The conclusion that can be drawn is that when single-frequency data is processed in an optimal way, such that the reference receiver network is used to generate corrections to the double-differenced data between a user receiver and one of the reference receivers, the accuracy of the derived coordinate results are very high and may be adequate for addressing certain geodetic applications such as the monitoring of local ground deformation phenomena.

GPS Surveying Based on Multiple Reference Receivers

A test was carried out on 14 December 1996 (Han & Rizos, 1997). A permanent GPS station at The University of New South Wales (UNSW) was selected as one of the reference stations. The other two reference stations were located at Stanwell Park, to the south of Sydney, and at Springwood, to the west of Sydney. The mobile receiver was mounted on a car and the experiment started at the side of a highway, 31.44km, 34.11km and 46.5km distant from the UNSW receiver, Springwood receiver and Stanwell Park receiver, respectively. During the test the car-mounted receiver travelled along the highway, and then back to nearly the same point as the start point, collecting a total of 1903 epochs of data. Two algorithmic innovations were tested together: (a) the multiple GPS reference station methodology (Han, 1997), and (b) an integrated OTF-AR algorithm. The UNSW OTF-AR algorithm can be used with a single epoch of dual-frequency, carrier phase and pseudo-range data (Han, 1996). In addition to the standard AR search technique, it consists of three further refinements: (1) new criteria to validate the integer ambiguity set, (2) a real-time stochastic model, and (3) an adaptive procedure. The results in Table 1 have been separated to illustrate the improvements from applying these three steps. Firstly, the integrated method with step (1) is used, and the results displayed in row 2 of Table 1. Then, the integrated method with steps (1) and (2) is used, and the results displayed in row 3 of Table 1. Finally, the three-step UNSW OTF-AR algorithm (with multiple reference station corrections) is applied, and the results displayed in row 4 of Table 1.

This instantaneous OTF-AR methodology illustrates one of the benefits of using multiple GPS reference stations. Such OTF-AR performance, for baselines longer than 30km, would not be possible using a single GPS reference station. Conversely, multiple epoch OTF-AR could be a routine operation for baselines up to 100km in length were there a GPS reference network to surround the survey area. Finally, it is possible to implement such algorithms in real-time if the reference station network was *integrated* via high speed data links.

The implications of such medium-range positioning performance is worthy of comment. By overcoming the short-range AR constraint in this way the logistical costs associated with operating a close-by GPS reference station are reduced. Furthermore, if the operation of the GPS reference network were the responsibility of an agency (public or private), the user would be relieved of a considerable burden, and the costs of GPS surveys would be reduced further. The establishment of an appropriate multi-reference station infrastructure across a major city could therefore be a significant boon for all carrier phase-based GPS positioning applications, including challenging RTK implementations.

Table 1. Single epoch ambiguity resolution for medium-range, multi-reference station, GPS kinematic positioning, using the integrated UNSW OTF-AR methodology.

	Total	Fix Ambiguities		
	Epochs	Correct	Wrong	Reject
Integrated OTF-AR with (1)	1903	1840	0	63
Integrated OTF-AR with (1, 2)	1903	1849	0	54
Integrated OTF-AR with (1, 2, 3)	1903	1903	0	0

CONCLUDING REMARKS

Considerable R&D still needs to be undertaken in order to determine, for example, how closely spaced the network of reference stations should be in order to derive bias corrections with sufficient accuracy to resolve integer ambiguities, as well as investigate new configurations of precise static and kinematic GPS positioning systems. The critical resource for this research is a multiple GPS reference station infrastructure such as that being established to service researchers and users in the Republic of Singapore (see Figure 4). The project involves the installation of four permanent GPS reference receivers around the island, the leasing of dedicated telephone lines linking the receivers to a central computer server located at the Nanyang Technological University (NTU), and the development of software to manage day-to-day operations and the data flow within the network. Such an integrated facility will be crucial for testing possible real-time implementations of the "multiple GPS reference station approach" for GPS Surveying and GPS Geodesy.

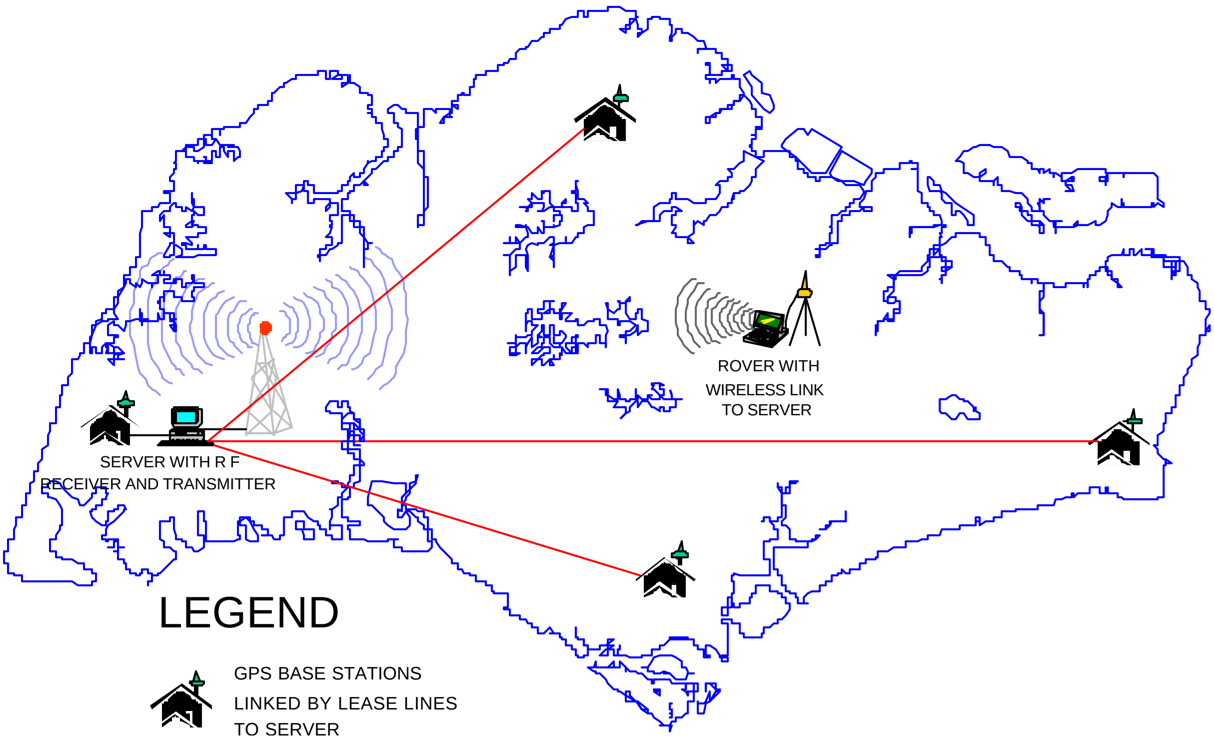

Figure 4. The integrated multiple GPS reference station infrastructure in Singapore (station locations only approximate).

Over the last decade, both the cost-effectiveness of GPS Surveying techniques and the accuracy and reliability of GPS Geodesy techniques has improved considerably. However, such performance has implied high cost, dual-frequency instrumentation and the use of rather rigid (and constrained) operational procedures. There are several new algorithms and implementation strategies that take advantage of multiple GPS reference networks which can overcome some of the constraints of medium-range positioning, using lower cost receiver hardware and/or less rigid field procedures, without "trading off" too much in performance (defined in terms of accuracy, time-to-survey, time-to-AR, reliability of AR, etc.). In this paper the authors have briefly described:

(1) The manner in which a "rapid static" surveying technique may be implemented using low-cost mobile GPS receivers to address "near-real-time" geodetic applications such as rapid surveys of large numbers of benchmarks in response to pre- or post-seismic activity.
(2) A scenario in which a dense network of single-frequency GPS receivers, in combination with a sparse network of permanent dual-frequency receivers, can be used cost-effectively for deformation monitoring applications.
(3) The scenario of a user owning only a single GPS receiver, and applying the "multiple GPS reference station approach", within an enhanced OTF-AR system that addresses the short-range AR constraint of present COTS systems.

Feasibility tests have been carried out at a number of network locations. However, over the next few years, an "open air laboratory" such as the NTU-UNSW GPS network in Singapore will permit engineering challenges (such as real-time implementations) to be addressed, as well as aid in identifying potential user applications of, and services for, such integrated networks.

ACKNOWLEDGEMENTS

The third author is supported by a study grant from the Republic of Taiwan's Institute of Earth Sciences, Academia Sinica, to undertake research towards a PhD at the School of Geomatic Engineering, The University of New South Wales.

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