On Ultrahigh-Precision GPS Positioning and Navigation

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ABSTRACT

In most GPS applications based on carrier-phase measurements, our first interest is to resolve the integer carrier-phase ambiguities because, once the ambiguities are fixed correctly, the carrier-phase measurements are turned into high-precision range measurements and hence it is possible to achieve centimetre-level positioning solutions. However, resolving the ambiguities is just one necessary step for high-precision positioning solutions. Correctly fixed ambiguities do not always guarantee centimetre-level positioning solutions due to errors in the carrier-phase measurements. In order to attain consistent high-precision positioning results with carrier-phase measurements, errors unspecified in the functional and stochastic models must be correctly detected and removed or otherwise handled at the data-processing stage. In this respect, reliability testing must be implemented as another necessary step for high-precision positioning solutions.

We introduce in this paper an ultrahigh-performance GPS positioning and navigation system for gantry crane auto-steering. The system differs from conventional systems in terms of the positioning accuracy and precision it can achieve. Aside from ambiguity resolution and reliability, many error sources (such as phase wrap-up, antenna phase-center variation, instrumental group delay bias, receiver clock jumps, residual tropospheric delay, *etc*.) must be handled precisely to attain ultrahigh-precision positioning solutions. We also introduce an optimal inter-frequency carrier-phase linear combination of the L1 and L2 measurements which can reduce the effects of the quasi-random errors such as multipath, diffraction, ionospheric scintillation, *etc*. A practical approach to estimating realistic receiver system noise is also introduced.

INTRODUCTION

One of the many benefits of GPS is that it provides positioning solutions for a wide variety of users. By and large, there are two extreme kinds of GPS users – the traveler who is satisfied with positioning accuracies of a few tens of metres and the geodesist who struggles with those of a few millimetres. The terms such as real-time, kinematic, and navigation usually go along with the ‘traveler’ community of GPS users while the ‘geodesist’ community is familiar with the terms such as post-processing, static, and positioning. Although they share the same GPS technology, the level of complexity of the hardware and software needed by these two kinds of GPS users is much different.

RTK (real-time kinematic) is a GPS technique pioneered by surveyors and geodesists for efficiently determining the coordinates of points with centimetre-level accuracy. GPS carrier-phase measurements must be used to attain the required positioning accuracies. Although the level of complexity of the hardware and software is still much different, this technique has gradually narrowed down the distinctions between the ‘traveler’ community and the ‘geodesist’ community in terms of GPS applications. One good example is machine control using the RTK technique. Machine-control applications such as a gantry crane auto-steering system require positioning accuracies better than a few centimetres with extremely high reliability in a real-time kinematic mode.

The University of New Brunswick (UNB) has developed ultrahigh-performance GPS RTK software for gantry crane auto-steering. The UNB RTK system currently determines the position of the crane every one

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tenth of a second (*i.e.*, at a 10 Hz update rate commensurate with the dual-frequency data rate) with accuracy better than 2 centimetres with extremely high reliability. Actually, there are two GPS receivers on each crane so that the control computer on the crane can determine the crane's orientation as well as its position. We introduce new cutting-edge GPS technology for a gantry crane auto-steering system in this paper. Technical and scientific aspects of the system are discussed.

FUNDMENTAL CONSIDERATIONS

One dilemma in developing a practical and fully operational RTK system is that correctly fixed ambiguities do not always guarantee a-few-centimetre-level high-precision positioning solutions due to errors in the carrier-phase measurements. We might be embarrassed by such a dilemma happening in real world situations because our first interest is to resolve the integer carrier-phase ambiguities in most GPS applications based on carrier-phase measurements and furthermore, we tend to believe that it is always possible to achieve a-few-centimetre-level high-precision positioning solutions once the ambiguities are fixed correctly.

In conventional high-precision GPS applications such as establishing geodetic control networks, monitoring dam deformation, and measuring the Earth's rotation, errors in the carrier-phase measurements as small as a few millimetres can be important. The same is true in many RTK applications including machine control. Such errors may include phase wrap-up, antenna phase-center variation, instrumental group delay bias, residual tropospheric delay, ionospheric scintillation, satellite orbit error, multipath, diffraction, receiver clock jumps, cycle slips, and so on. We will discuss some of the errors of interest in the following section.

To achieve the required positioning accuracies and consistent high-precision positioning results with carrier-phase measurements, systematic errors must be modeled very carefully or preferably avoided in the first place. Unfortunately, we cannot remove all the errors completely. As usual in relative positioning, by single-differencing (SD) the measurements between satellites or double-differencing (DD) the measurements (that is, differencing between receivers followed by differencing between satellites or vice versa), the common effects at satellites (or both satellites and receivers) can be removed. However, the residual effects of some error sources can be significant enough to make a difference in high-precision GPS applications. Most of the error sources can cause faulty solutions. In this respect, robust quality control such as reliability testing (which refers to the ability to detect such errors and to estimate the effects that they may have on a solution) must be implemented as another necessary step for high-precision positioning solutions.

BIASES AND ERRORS OF INTEREST

The quality of GPS positioning is dependent on a number of factors. To attain high-precision positioning results, we need to identify the error sources impacting on the quality of the measurements. Some of the error sources have systematic characteristics while others have quasi-random characteristics. For example, the effects of cycle slips and receiver clock jumps can be easily captured either in the measurement or parameter domain due to their systematic characteristics. Their systematic effects on the carrier-phase measurements can be almost completely removed once they are correctly identified. On the other hand, multipath, diffraction, ionospheric scintillation, etc. have temporal and spatial characteristics which are more or less quasi-random. These quasi-random errors cannot be completely eliminated. Instead, they must be handled using a rigorous mathematical approach to isolate their effects as much as possible from parameter estimates.

In terms of data processing, therefore, it is important to know whether we can remove error effects by means of suitable procedures such as the SD or DD process. If we know that some errors cannot be removed completely, it is also equivalently important to know whether the residual effects of the errors are negligible under certain circumstances. Otherwise, we may fail to attain high-precision positioning results because the error sources can deteriorate the quality of the measurements and subsequently, the quality of positioning results. In ultrahigh-performance positioning for gantry crane auto-steering, we were interested in assessing the following errors:

- carrier phase wrap-up induced by rotating GPS receiving antennas
- antenna phase-center variation
- instrumental group delay bias
- receiver clock jump
- residual tropospheric delay
- multipath, diffraction, ionospheric scintillation.

Although some error sources mentioned above may turn out to be irrelevant to specific applications such as the gantry crane auto-steering application, our intention was to investigate all potential error sources which are apt to be omitted in the functional and stochastic models. Brief discussions on the effects of individual error sources (and how we handle such effects) in the gantry crane auto-steering application are given in the section "Considerations for System Design".

Phase wrap-up. A circularly polarized antenna's phase response depends directly on the antenna's orientation with respect to the carrier source. As described in Tetewsky and Mullen [1997], a rotational effect must be accounted for if the platform is spinning. This effect is the change in the GPS carrier phase caused by rotation of a circularly polarized receiving antenna relative to a circularly polarized GPS signal. The effect of rotating a base-mounted circularly polarized antenna is an apparent phase shift. The "geodesist" community has long known this and models antenna orientation accordingly in its high-precision data analysis software [Wu *et al*., 1993]. Because the phase plots are independent of depression angle, this phase shift is common to all channels. By double-differencing the measurements, therefore, this common phase shift can be removed. For rotating a circumference-mounted circularly polarized antenna, however, the phase term appears to be the sum of the common phase shift plus some small perturbation that increases as the depression angle deviates from the spin axis. This residual spin-modulation term causes additional errors for circumference-mounted antennas and cannot be cancelled by the double-differencing operation.

Antenna phase-center variation. For a GPS receiving antenna, antenna phase center is the point to which the receiver's phase measurements actually refer. Ideally, a GPS antenna's phase center is independent of a signal's direction of arrival. Since a real antenna is not an ideal point source, however, its equiphase contour will not be perfectly spherical, and hence, when used as a receving antenna, the center of curvature may vary with the azimuth and elevation angle of an arriving signal [Langley, 1998].

For a well-designed antenna, the phase center's mean horizontal position usually coincides with the antenna's physical center. The phase center's vertical position with respect to an accessible physical plane through the antenna must be established by anechoic chamber measurements [Schupler and Clark, 2001]. If one employs a mixture of antennas of different make and/or model on a baseline or in a network, then the data-processing software must know the heights of the antennas' mean phase centers with respect to the physical reference points on the antennas so that it can make the appropriate corrections. Some users are applying azimuth and/or elevation angle-dependent phase center corrections in processing GPS data using different or widely spaced antennas [Mader, 2002]. Since antennas of the same make and model will typically show similar phase-center variations, their effects in relative positioning can be minimized by orienting antennas on short baselines to the same direction while one employs antennas of the same make and model.

Instrumental group delay bias. The signals traveling from the antenna through the receiver experience a small delay. This delay (that is, the instrumental group delay bias of the receiver) is the same for the signals simultaneously received from different satellites (assuming no inter-channel bias). However, this delay is slightly different for the signals with different frequencies *(i.e*., L1 and L2). A similar delay occurs in the signals traveling from the satellite transmitter to the satellite antenna. Thus the signals transmitted from different satellites have different satellite instrumental group delay biases of the satellites [Coco *et al*., 1991]. However, these delays can be removed by double-differencing the measurements.

Receiver clock jump. Most receivers attempt to keep their internal clocks synchronized to GPS Time. This is done by periodically adjusting the clock by inserting time jumps. As described in Kim and Langley [2001b], at the moment of the clock correction, two main effects are transferred into the code and phase observables. The effects of the geometric range corresponding to the clock jump are common to all measurements at the moment of the clock jump at one receiver. By double-differencing the measurements, therefore, this common clock jump effect can be removed. However, the effects of the geometric range rate corresponding to the jump (that is, the first order effects of clock jump) are different for each observation. They can reach the level of a few centimetres when a satellite is close to the horizon and at the same time the receiver experiences high dynamics. They cannot be cancelled by the double-differencing operation. Instead, Doppler frequency or carrier-phase difference measurements should be used for correcting such effects.

Residual tropospheric delay. When processing GPS data, a value for the tropospheric delay is typically predicted using empirical models which in general must be provided with measured or default values of the ambient temperature, pressure and relative humidity. Unfortunately, even with accurate values, these models rarely predict the true delay with a high degree of accuracy. The residual tropospheric delay is the remaining part of the tropospheric delay not predicted by empirical models. It can be the largest remaining error source in dual-frequency precision positioning [Collins and Langley, 1997]. Like many other spatially-dependent error sources, the effects of the tropospheric delay are usually negligible in relative positioning in short-baseline environments. If there are large height differences (or rapid height variations) between the base and remote antennas, however, the effects may be significant according to meteorological conditions and cannot be cancelled by the double-differencing operation.

Quasi-random errors. Multipath, diffraction, ionospheric scintillation, *etc*. have temporal and spatial characteristics which are more or less quasi-random. These quasi-random errors cannot be completely eliminated and are apt to be omitted in functional and stochastic models. Since least-squares estimation, when errors are present, tends to hide (reduce) their impact and distribute their effects throughout the entire set of measurements, it is better to handle systematic errors separately from quasi-random errors. To detect and remove quasi-random errors, they must be handled using a rigorous mathematical approach to isolate their effects from parameter estimates.

CASE STUDY: GANTRY CRANE AUTO-STEERING

Machine-control applications such as a gantry crane auto-steering system require positioning accuracies better than a few centimetres with extremely high reliability in a real-time kinematic mode. Since the level of system performance required is so high in such applications, we have to consider all of the aspects mentioned in the previous two sections. A brief description on the gantry crane auto-steering system is given in this section.

Fig. 1 – Rubber-tired gantry cranes (RTGCs) tracking line marks.

The crane control system has been developed to improve container-handling productivity and operational safety at a busy container terminal of a trading port. The auto-steering system, as a sub-system of the crane control system, is used to keep the wheels of a rubber-tired gantry crane (RTGC) moving along a track (Figure 1) – either a painted line or an electrical guide wire – and prevents it from hitting containers or other cranes in the tightly packed yard. For that purpose the auto-steering system must consistently identify the line mark and calculate the corresponding deviations of the RTGC's front and rear wheels. The calculated deviations are fed into a programmable logic controller so that it can adjust the speed of the left and right wheels to keep the crane on track (Figure 2).

Fig. 2 – Aligning the wheels of an RTGC to the line mark (yellow).

Several technologies for identifying the line mark – such as induction-loops, transponders, and charge-coupled device cameras – have been adopted for RTGC auto-steering systems. Since these technologies are highly dependent on environmental factors (such as surface reflection and line mark condition) and have limited effective ranges, there is a growing concern that they may not provide the greatest possible system reliability and economic efficiency. On the other hand, to build an auto-steering control system independent of environmental factors, we need to use a technology not based on physical line marks in the container yard. This can be accomplished using an electronic map with virtual lines and a GPS receiver to precisely locate an RTGC on the map. The control system can then compare the crane's position as reported by the GPS receiver with the virtual lines and steer the crane accordingly. GPS RTK technology provides the most efficient and reliable way to accomplish this.

The most significant challenge in this application is that a fully operational and safe RTGC auto-steering system requires GPS RTK software with high levels of accuracy, integrity, continuity, availability, and computational efficiency.

Accuracy. For this application, the horizontal accuracy requirement of GPS positioning solutions is 1.5 centimetres at a 95 percent confidence level. This enables the integration of GPS with the auto-steering control system and is almost the highest real-time accuracy level currently attainable from GPS. While this accuracy level is generally achievable in short-baseline and static applications, it is very challenging to achieve it in kinematic mode due to the dynamics of the moving platform and the problem of multipath (produced by the crane itself and any lighting towers or other cranes in the vicinity).

Integrity and Continuity. For the system to be safe, the GPS RTK software must include a self-diagnosis routine able to detect failures when the positioning accuracy degrades beyond what could be expected from the GPS observations the system is using. For that purpose, two parameters — integrity and continuity — should be considered rigorously. The risk associated with equipment latency or design failure is specified by an integrity parameter while the risk associated with unscheduled function interruptions is specified by a continuity parameter.

Availability. In general, the system's availability parameter depends on the visible GPS constellation (that is, the number of satellites available at the site at a particular time with a given mask angle profile). This parameter affects the GPS data processing software design because a minimum number of satellites commonly observed by both base and remote receivers should be available at the site all day.

Computational Efficiency. Since the system works in real time and, furthermore, must be capable of measuring the off-track deviation of an RTGC with an update interval of less than 150 milliseconds, data processing speed needs to be fast enough to handle observations obtained at a 10 Hz data rate. In this case, the latency of data communication and the computational efficiency of the GPS data processing software are crucial. It is important to keep the system latency as short as possible to minimize the auto-steering response time. A longer response time results in larger wheel deviations.

CONSIDERATIONS FOR SYSTEM DESIGN

To satisfy the required system performance of the gantry crane auto-steering system, we designed the RTK software system carefully. First of all, we investigated the effects of the biases and errors in the measurements under the given application environment (that is, short-baseline, multipath-rich and high-dynamics due to vibrations and jerks) so that we could decide whether they should be estimated as unknown parameters or could be considered negligible and ignored.

Since the gantry crane auto-steering system operates under the short-baseline environment of a few kilometres, some of the biases and errors could be removed by double-differencing the measurements in the data processing software. The removed ones include the instrumental group delay bias, geometric range corresponding to the clock jump and any other errors common at both the base and remote antennas such as the satellite and receiver clock biases. The residual effects of these errors are, if any, insignificant so that they are ignored in our application.

We could also ignore the effects of the residual tropospheric delay in the double-differenced measurements because there were no significant height differences between the base and remote antennas. After implementing the system at site, antenna height differences ranged from seven to nine metres.

At the beginning of the system design, we thought that we must take care of the carrier phase wrap-up induced by rotating GPS receiving antennas. Fortunately, we could remove this error term too because of the way the cranes operate. RTGCs' operators turn the crane's wheels only to make ninety-degree changes to its direction of movement and only when the crane is stationary at special low-friction turning pad (the crane frame, and hence the antennas, does not rotate). And hence, there are no rotational effects on the antennas on the cranes.

To minimize the antenna phase-center variation, we used the same make and model of antenna at both ends of a baseline. Since the crane changes its direction by rotating its wheels, the antenna orientation on the crane and at the base station is always the same. This allowed us to ignore the effects of the antenna phase-center variation in the measurements.

Since the first order effects of the receiver clock jump are different for each receiver, they cannot be removed by double-differencing the measurements. Instead, Doppler frequency or carrier-phase difference measurements should be used for correcting such effects. Such effects are usually significant in the measurements obtained from receivers having millisecond-level clock jumps. As an exceptional case, we have found that such effects are negligible in the Navcom NCT-2000D receivers because they have a-few-microsecond-level clock jump at every second. Figures 3 and 4 illustrate typical examples of the millisecond- and microsecond-level clock jumps. The spikes in the triple-difference (TD) (that is, at two adjacent data collection epochs, differencing the DD measurements) time series disclose that the first order effects of the millisecond-level clock jumps are significant. On the other hand, the effects of microsecond-level clock jumps seem to be buried in the noise of the TD measurements.

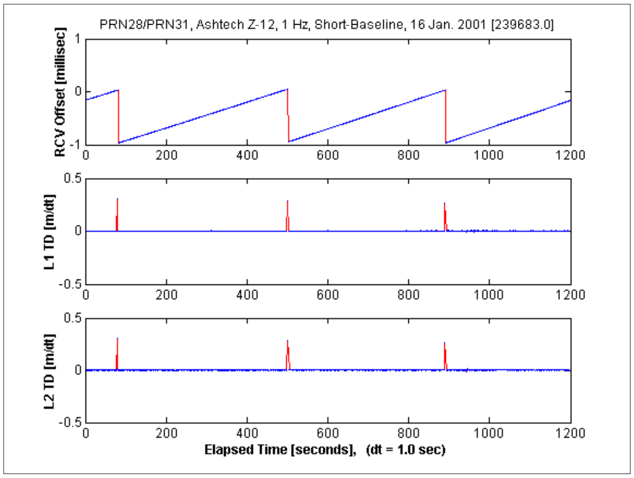

Fig. 3 – First order effects of millisecond-level receiver clock jumps (Ashtech Z-12): the receiver clock offset estimates (top); and the L1 and L2 TD measurements disclosing the significance of the first order effects (middle and bottom). The number in square brackets is the GPS Time of the first observation; 'dt' is the observation sampling interval.

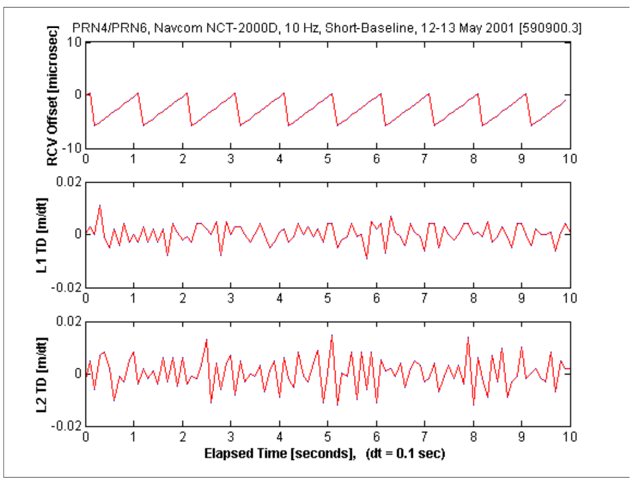

Fig. 4 – First order effects of the microsecond-level receiver clock jumps (Navcom NCT-2000D): the receiver clock offset estimates (top); and the L1 and L2 TD measurements hiding the first order effects of the jumps (middle and bottom).

From the initial investigation, we established that many of the biases and errors were insignificant in the application and eventually concluded that the crane auto-steering application is very similar to the normal short-baseline application where the only significant parameters except for ambiguities and receiver's position, are the quasi-random errors and the receiver system noise. In the long run, we brought forward two main issues to tackle:

- optimal inter-frequency linear combination to reduce the effects of the quasi-random errors
- realistic receiver system noise estimation.

The fundamental idea on the optimal inter-frequency linear combination to reduce the effects of the quasi-random errors was briefly described in Kim and Langley [2001c]. Figure 5 illustrates the reduction of the effects of the quasi-random errors by the optimal combination. As shown in Figures 6 and 7, one of the promising aspects of this approach is that the positioning solutions of the optimal combination are always bounded by those of the L1 and L2 measurements.

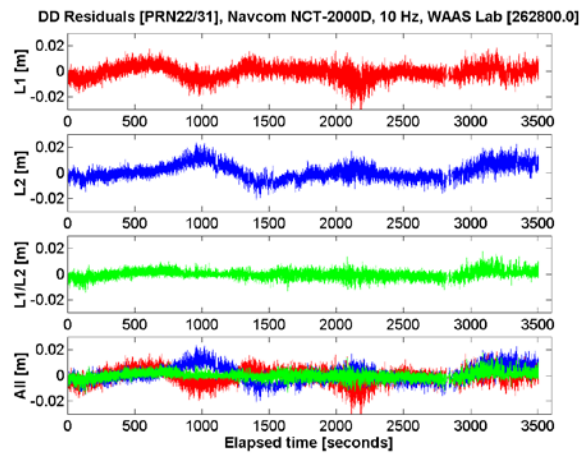

Fig. 5 – Residuals of the double-differenced L1, L2 and the optimal inter-frequency linear combination (L1/L2) for PRN22 and PRN31 over an hour on a five-metre baseline. Overlapped plot (all three solutions) is in the bottom panel.

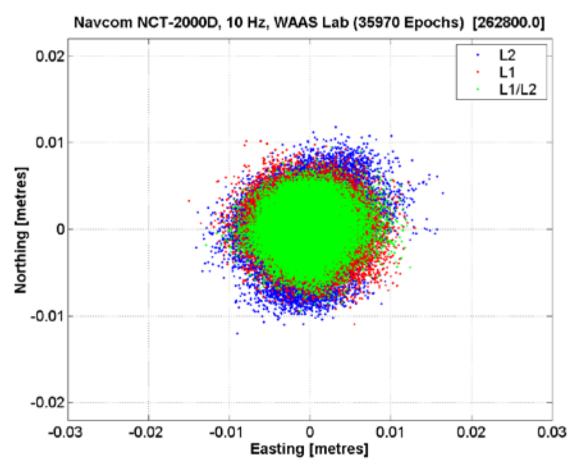

Fig. 6 – Horizontal scatter of the positioning solutions given by the L1, L2 and L1/L2 double differences over an hour on a five-metre baseline.

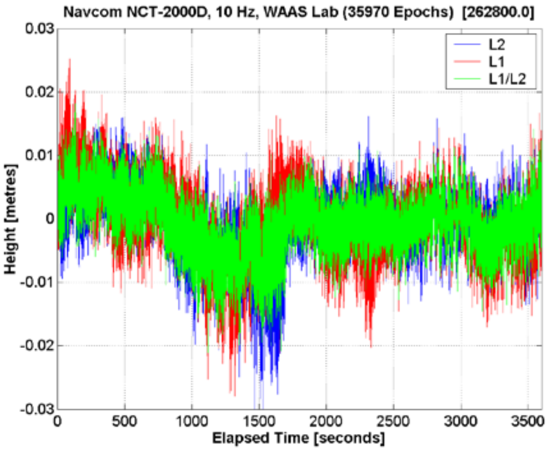

Fig. 7- Height solutions of the L1, L2 and L1/L2 double differences over an hour on a five-metre baseline.

Since statistical testing and reliability analysis can only be efficient if the stochastic models are correctly known or well approximated, it is not an overemphasis to obtain more realistic receiver system noise estimates for use in the stochastic model (see Langley [1997] for a general discussion on receiver system noise). The "differencing-in-time" method described by Kim and Langley [2001a], which corresponds to a high-pass filtering technique, has been successfully tested and implemented in our RTK software. This approach performs extremely well in real-time kinematic applications operating at a high data rate (e.g., 10 Hz or higher) as well as static applications at even lower data rates.

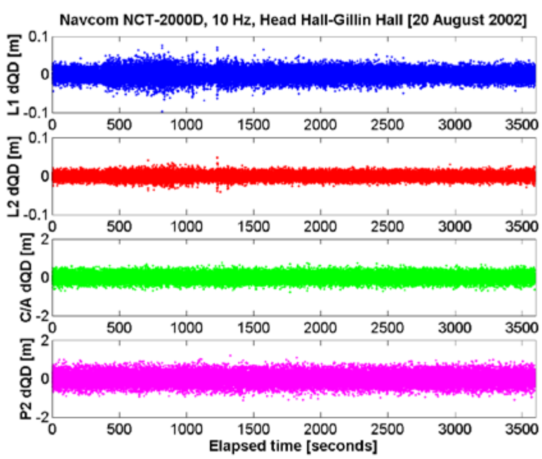

Fig. 8 – Quintuple-difference (dQD) time series to estimate the receiver system noise under static, short-baseline (about 60 metres) and multipath-rich conditions. The time series are bias-free and the level of the noise is clearly amplified in the differencing procedure. Plotted are dQD for all satellites available without imposing an elevation-angle cut-off.

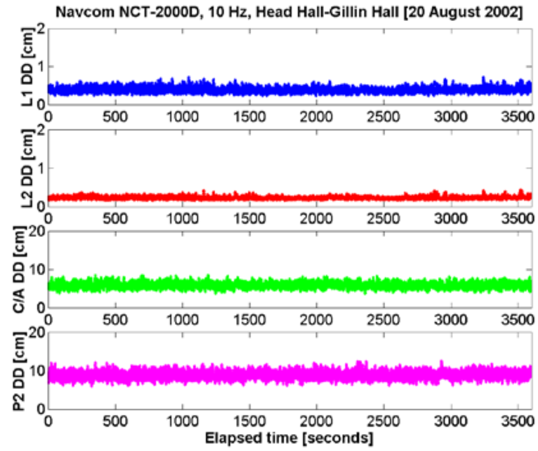

Fig. 9 – Receiver system noise estimates (1σ) in the DD measurements under the same conditions as those of Fig. 8. Each estimate value was computed using a 50-sample window of the individual DD time series.

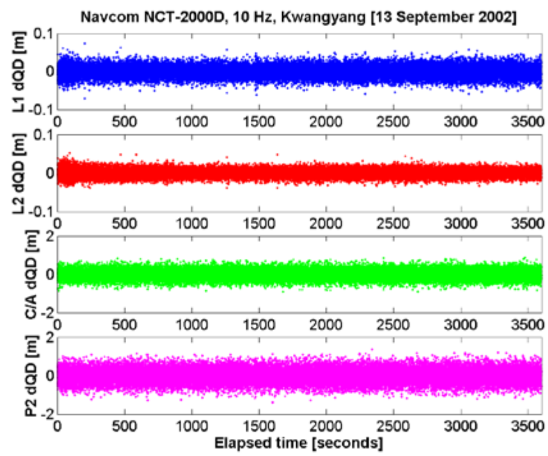

Fig. 10 – Quintuple-difference (dQD) time series under relatively high dynamics kinematic, short-baseline (up to 1 kilometre) and multipath-rich conditions.

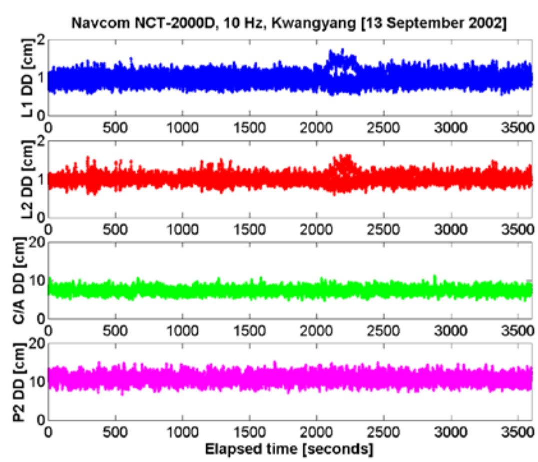

Fig. 11 – Receiver system noise estimates (1σ) in the DD measurements derived from the data shown in Fig. 10.

Figures 8 to 11 clearly show the levels of the receiver system noise for the observables in static and kinematic situations. Static test data were recorded on the roof of Head Hall and Gillin Hall at the University of New Brunswick. Kinematic test data were obtained on the cranes at Korea International Terminals' Kwangyang Port on the south coast of the Korean Peninsula. As was expected, we could confirm that the noise level of the measurements recorded in kinematic mode was higher than that of static mode. One thing of interest observed in the figures is the noise estimates of the L2 DD measurements. Unlike some other receivers, the Navcom NCT-2000D receivers provide lower-noise L2 measurements than L1. According to the manufacturer's reply to our inquiry on this subject, L2 is rate-aided from the L1 tracking loop, allowing the receiver to use a narrower loop on L2. If we do not consider this aspect in dual-frequency GPS applications, we may loose optimality in the inter-frequency linear combination and consequently, we may fail to obtain the most reliable solutions.

ULTRAHIGH-PERFORMANCE RTK SYSTEM

To enable an RTGC to operate in automatic mode, we have developed ultra high-precision GPS RTK software, which satisfies the performance requirements discussed earlier. This software is able to provide navigation solutions in real time at a 10 Hz update rate commensurate with the dual-frequency data rate. The horizontal and vertical positioning accuracy guaranteed at essentially a 100 percent confidence level is better than 2 and 3 centimetres, respectively (see Figures 12 to 14). Figure 15 illustrates that the RTK solutions are available more than 99.9% of the time over the whole day.

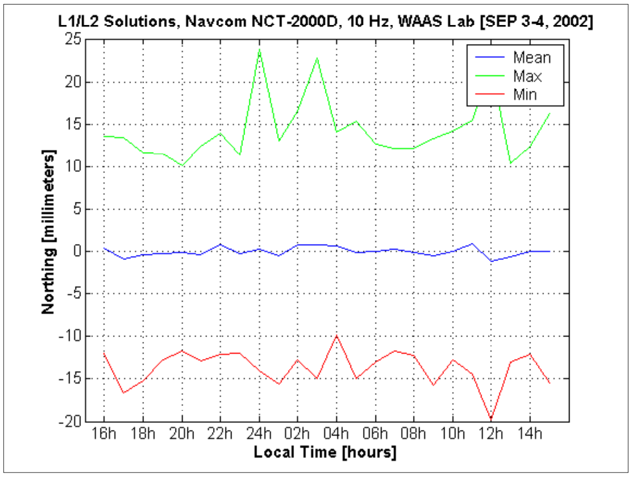

Fig. 12 – Example of the repeatability of RTK positioning solutions (northing component) over 24 hours on a five-metre baseline. Each hour's data was processed separately and the mean, maximum, and minimum values computed.

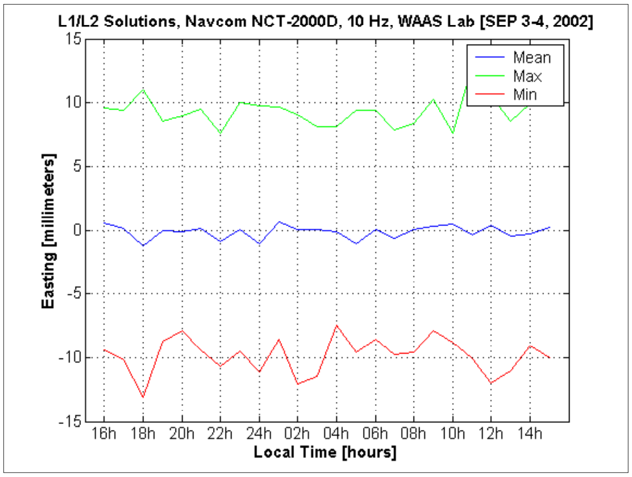

Fig. 13 – Example of the repeatability of RTK positioning solutions (easting component) as for Fig. 12.

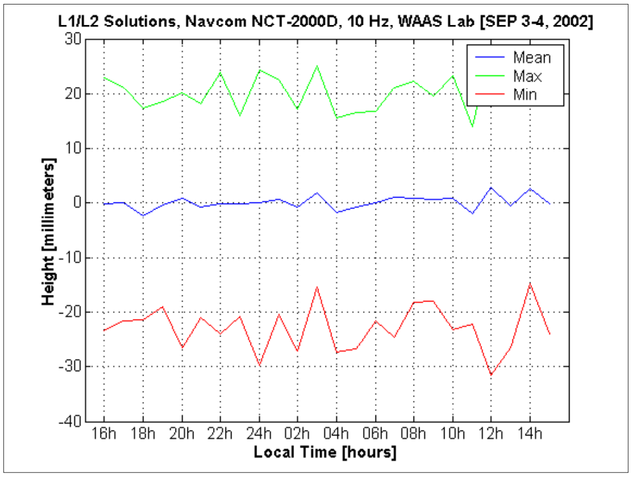

Fig. 14 – Example of the repeatability of RTK positioning solutions (height component) as for Fig. 12.

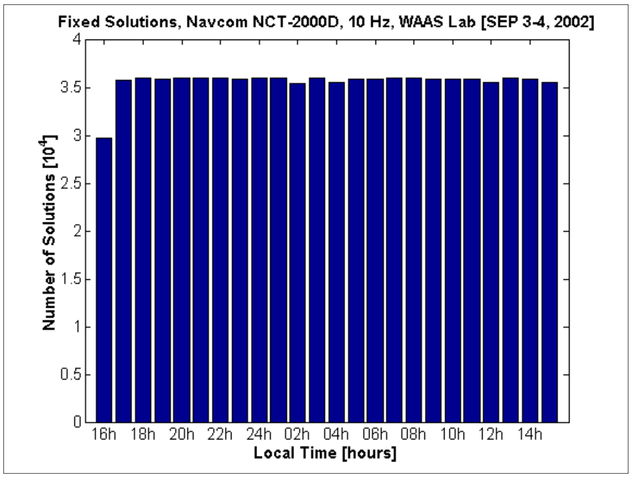

Fig. 15 – RTK system availability (the number of RTK positioning solutions determined using correctly fixed ambiguities). Each hour's data was processed

separately. During the first hour session, recording started about ten minutes after 16:00 local time.

The system tuning time (that is, the time to collect the required number of observations for the dQD time series) for stochastic modeling is normally set to 5.3 seconds. As soon as a stochastic model is available, the software can resolve GPS ambiguities using only current epoch measurements (i.e., epoch-by-epoch solutions). Therefore, the typical ambiguity resolution time of the software is 5.3 seconds, corresponding to the stochastic model tuning time. Actually, ambiguity resolution typically requires a minimum of six common satellites at the base and rover sites. When this number drops to five, as a constraint, a priori or recursively calibrated information such as the height and speed of the RTGC is automatically incorporated by the software with the GPS measurements in order to improve the performance of the ambiguity resolution process.

The level of system integrity is maximized through separate and independent ambiguity resolution on the widelane combination, L1, and L2. After fixing ambiguities, all separate solutions go through multi-level nested validation procedures, including the ambiguity constraint condition (that is, the widelane ambiguities should be the same as the differences of the L1 and L2 ambiguities), residuals analysis, reliability test, consistency test among positioning solutions and so on.

The kernel of this RTK software is UNB's OMEGA (Optimal Method for Estimating GPS Ambiguities) ambiguity search engine and the quality control routine which the first author conceived and developed. Typically, OMEGA is able to find the first- and second-best ambiguity candidates out of a potential 10^{18} candidates within 0.1 second using a 486/50 PC.

Unlike conventional approaches – such as a sequential least-squares estimator or Kalman filter, which uses the prediction values of the measurements for quality control – the quality control routine of this RTK software utilizes only the current epoch's measurements. Therefore, this approach attains high performance even when a receiver platform is maneuvering. Moreover, the quality control routine can handle cycle slips in low-quality measurements, so that we do not have to discard the measurements obtained at low elevation angles and from weak signals with low signal-to-noise ratios. As a result, this approach tends to increase observation redundancy and improve system performance in terms of integrity, continuity, accuracy, and availability.

Typically, the aggregate latency of our system, considering all factors, is less than a few milliseconds. Under the worst case scenario – that is, all 12 channels track satellites, the cycle-slip fixing routine searches a huge number of candidates due to low-quality measurements, the ambiguity search engine has intensive computational burden, and the real-time wireless LAN communication experiences a weak signal link – the aggregate latency of our system is typically still less than 60 milliseconds.

CONCLUSIONS

An ultrahigh-precision (or more generally speaking, ultrahigh-performance) GPS positioning and navigation software system for machine control, such as gantry crane auto-steering, has been developed. This system differs from the convention in terms of the positioning accuracy and precision, the levels of integrity and continuity, system availability and the update rate of positioning solutions that it can achieve. To build such a high-performance system, we need an efficient ambiguity search engine and a robust quality control procedure. In addition, many other error sources must be handled precisely.

The UNB RTK system initially developed for a gantry crane auto-steering system is fundamentally powered by UNB's OMEGA ambiguity search engine and quality control algorithms. Two subsidiary tools – an optimal inter-frequency carrier-phase linear combination of the L1 and L2 measurements, and receiver system noise estimation routine – support the system to attain ultrahigh performance GPS positioning and navigation.

We demonstrated the performance of the gantry crane auto-steering system at Korea International Terminals' Kwangyang Port in May 2002, achieving excellent results. This system is state-of-the-art and owes its unique capabilities mostly to the RTK software. Its development led to several remarkable achievements in GPS-based machine control, including:

- a real-time kinematic system using GPS dual-frequency carrier phases with high availability (available more than 99.9 percent of the time over the whole day even when satellite constellation geometry is sub-optimum)
- centimetre-level (horizontally better than 2 centimetres and vertically 3 centimetres at virtually a 100 percent confidence level) ultra high-precision navigation system
- high navigation solution update rate (10 Hz update rate commensurate with the dual-frequency data rate).

Currently, we are carrying out alpha and beta testing in different environments, including Kwangyang Port, jointly with the manufacturer of the crane control system. The manufacturer plans to replicate the system at other container ports and we hope to expand our efforts to explore the capabilities of the RTK software in new GPS applications.

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