Real-Time Carrier Phase Ambiguity Resolution for GPS/GLONASS Reference Station Networks

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BIOGRAPHY

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ABSTRACT

Real-time high precision GPS surveying and navigation applications have been constrained to 'short range' due to the presence of distance-dependent errors in the between-receiver single-differenced observables. Over the past few years, the use of a GPS reference station network, to extend the inter-receiver distances (user-to-reference station), has attracted great interest. This network-based approach can be extended to include GPS/GLONASS receivers. In order to model the distance-dependent errors such as the ionospheric and tropospheric biases, the ambiguities in the GPS/GLONASS reference station network should first be fixed to their correct integer values. However, even with precisely known station coordinates, it is still a challenge to fix the ambiguities in reference station networks, especially when a new satellite rises above the horizon.

In this paper two procedures for ambiguity resolution, suitable for real-time implementations, in GPS/GLONASS reference station networks are suggested. The first procedure is single-epoch ambiguity resolution after an ambiguity is initialized. As the distance-dependent errors (atmosphere errors and orbit errors) exhibit a high degree of temporal correlation for short time spans, the double-differenced residuals can be represented as a linear function of time for short periods of up to a few minutes. On an epoch-by-epoch and

satellite-by-satellite basis these systematic errors (or biases) can be estimated using previous measurements with fixed ambiguities, and precisely predicted for use in ambiguity resolution during the following measurement epochs. The second procedure is suitable for a newly risen satellite, or after a long data gap. Atmospheric biases also exhibit strong spatial correlations between satellite pairs. The atmospheric delay information derived from other satellites, with fixed ambiguities, can be used in predicting the atmospheric bias for a newly risen satellite, and for those satellites that have unknown ambiguities associated with them.

A test data set from a GPS/GLONASS reference station network was used to evaluate the performance of these procedures. The experimental results show that the proposed procedures can reliably and efficiently resolve the integer ambiguities of reference station networks, in real-time, on a single-epoch basis.

INTRODUCTION

Because of the presence of distance-dependent errors, such as atmosphere bias and orbit bias in the between-receiver single-differenced measurements, real-time high precision GPS surveying and navigation applications have been mostly constrained to the short baseline case. Over the past few years, the use of the GPS reference network-based approach, to extend the inter-receiver distances (user-to-reference station), has shown great promise, and has since been implemented in a commercial product by Trimble. The double-differenced, satellite-by-satellite, distance-dependent error models, generated and transmitted by a GPS reference station network, can be applied to GPS users located within the network region to mitigate the distance-dependent errors (see, e.g., Wanninger, 1995; Wubbena et al., 1996; Han & Rizos, 1996; Raquet, 1997; Gao et al., 1997). A detailed review of a variety of multi-reference station methods for real-time kinematic positioning can be found in Fotopoulos & Cannon (2001)

In order to model the ionospheric and tropospheric biases, the ambiguities in GPS reference station networks should be resolved to their correct integer values. Various ambiguity resolution methods have been proposed, for example, among others, Gao et al. (1997), Rabah & Leinen (1998), Hernández-Pajares et al. (1999), Schaer et al. (1999), Sun et al. (1999), Chen (2000), Chen et al. (2000), Vollath et al. (2000). The challenging issue here is to fix the ambiguities in real-time for the comparatively long baselines (up to 100km) between reference stations, especially when a new satellite rises above the horizon. A recent review of the existing real-time ambiguity resolution procedures for use in the case of GPS reference station networks is given in Dai et al. (2001).

With the combination of GPS and GLONASS, the volume of observations will be increased. This will enhance the reliability of the multiple reference station applications, and will provide an improved ability for modelling residual atmospheric errors. Hence higher success rates for ambiguity resolution in reference networks should be expected. However, due to the different frequencies of the different GLONASS satellites, there is a greater challenge in fixing the ambiguities in real-time (e.g., Wang et al., 2001).

In this paper two procedures for real-time ambiguity resolution in a GPS/GLONASS receiver network are proposed. The first procedure is used for single-epoch ambiguity resolution (after initialization), while the second procedure is designed to aid the resolution of the wide-lane and narrow-lane ambiguities for a newly risen satellite (or after a long data gap). The performance of the proposed procedures will be demonstrated through a case study example of a GPS/GLONASS reference station network.

SINGLE-EPOCH AMBIGUITY RESOLUTION ATFER INITIALIZATION

The GPS and GLONASS double-differenced L1 and L2 carrier phase observable can be expressed in units of metres as:

$$\begin{aligned}\Delta f_{j,n} l_{j,n} - \Delta f_{k,n} l_{k,n} &= \nabla\Delta r_{k,j} + \nabla\Delta N_{kj,n} l_{j,n} \\ &\quad - (l_{k,n} - l_{j,n})\Delta N_{k,n} + \frac{\Delta I_k}{f_{k,n}^2} - \frac{\Delta I_j}{f_{j,n}^2} \\ &\quad + \nabla\Delta d_{k,j}^{trop} + \nabla\Delta d_{k,j}^{orb} + \nabla\Delta d_{kj,n}^{mp} + e_{\nabla\Delta f_{kj,n}}\end{aligned} \tag{1}$$

where $\Delta f_{j,n}$ and $\Delta f_{k,n}$ are the single-differenced carrier phase observables expressed in units of cycles, and n=1,2 denote the L1 and L2 frequencies; $l_{k,n}$ and $f_{k,n}$ are the wavelength and frequency of the carrier wave for satellite k respectively; $\Delta N_{k,n}$ is the single-differenced integer ambiguity; $\nabla\Delta N_{kj,n}$ is the double-differenced integer ambiguity related to satellite pair k and j; $\Delta I_k / f_{k,n}^2$ and $\Delta I_j / f_{j,n}^2$ are the single-differenced ionospheric delay for satellite k and j respectively, where ΔI_k is a function of the Total Electron Content; $\nabla\Delta d_{k,j}^{trop}$ and $\nabla\Delta d_{k,j}^{orb}$ are the double-differenced tropospheric delay and orbit error respectively; $\nabla\Delta d_{kj,n}^{mp}$ and $e_{\nabla\Delta f_{kj,n}}$ are the multipath and noise for the carrier phase measurements respectively.

In Eq. (1), L1 and L2 GPS signals have the same frequencies ($f_1 = 1575.42MHz,\ f_2 = 1227.60MHz$) for all satellites. However, L1 and L2 GLONASS signals have different frequencies for different satellites:

$$f_{m,1} = (1602 + m * 9/16)MHz$$
$$f_{m,2} = (1246 + m * 7/16)MHz \tag{2}$$

where m is the frequency number in the range from 0 to 23.

Modelling the Temporally Correlated Biases

The biases (including atmospheric biases, orbit error, the single-differenced ambiguity bias and multipath) can be represented as:

$$Bias = \Delta f_{j,1}\, l_{j,1} - \Delta f_{k,1}\, l_{k,1} - \nabla\Delta r_{k,j} - \nabla\Delta N_{kj,1}\, l_{k,1} + e_{\Delta f_{kj,1}} \tag{3}$$

For a GPS/GLONASS reference station network, the biases in Eq. (3) can be easily computed after the double-differenced ambiguities are resolved. It should be pointed out that the single-differenced ambiguity bias would disappear for the GPS reference satellite, but will have constant characteristics for the GLONASS reference satellite (if no cycle slips occur).

Numerous studies have attempted to model the temporal correlation of the residual atmosphere biases and orbit errors in order to improve the performance of GPS positioning (see, e.g., El-Rabbany et al., 1992; Wang, 1999; Dai et al., 2000; Fotopoulos & Cannon, 2000). In these investigations it was shown that strong temporal correlation does exist in the measurements between adjacent epochs. The Han & Rizos (2000) study showed a strong temporal correlation of the multipath on pseudo-range and carrier-phase observations for static receivers.

As mentioned above, these biases exhibit a high degree of temporal correlation for short time spans, and hence this can be represented as a linear function of time for short periods of up to a few minutes. (For a detailed discussion see Dai et al., 2001.)

The bias modelling based on temporal correlation can be used for instantaneous ambiguity resolution for any linear combination, or L1, L2 frequencies (in this paper, double–differenced L1 and L2 are used). It should be noted that the proposed method can also be used to detect and repair cycle slips before an ambiguity is fixed. However, the predicted bias is significantly biased by the constant unfixed ambiguity term, and furthermore the 'absolute' double-differenced ambiguity cannot be fixed. In the following section the emphasis will be on real-time ambiguity resolution for newly risen satellites, or after a long data gap.

REAL-TIME AMBIGUITY RESOLUTION FOR A NEWLY RISEN SATELLITE

In the case of a newly risen satellite, its elevation angle is quite low. Generally, measurements with low satellite elevation angle will be serially contaminated by systematic ionospheric and tropospheric biases. Therefore, in GPS/GLONASS reference networks, it is a challenge to fix the ambiguities for newly risen satellites in real-time.

Because the GPS measurements are spatially correlated, it is expected that the residual atmospheric delay after double-differencing will exhibit a certain degree of spatial correlation. Based on this spatial correlation, the atmospheric delay information derived from other satellites, with fixed ambiguities, can be used to predict the atmospheric delay for newly risen satellites, and for those satellites that have unknown ambiguities associated with them.

Modelling Residual Ionospheric Bias

The double-differenced ionospheric measurements based on the L1 and L2 carrier phases can be computed after the ambiguities have been fixed to their correct integer values. Similarly, the double-differenced pseudo-range ionospheric measurements for all satellites in view can also be easily derived.

The question here is: how to quantify the spatial correlation between the double-differenced ionospheric delays? The assumption can be made that the greater the latitude and longitude differences between the reference satellite and the non-reference satellites, the larger the double-differenced ionospheric biases. In this study, the following linear model has been used:

$$\nabla\Delta L4 = C_0 + C_l \bullet \Delta l + C_b \bullet \Delta b \tag{4}$$

where C_0 is the constant coefficient; C_λ and C_β are the horizontal ionospheric gradient parameters; $\Delta\lambda$ and $\Delta\beta$ are the latitude and longitude differences between the reference satellite and non-reference satellite respectively.

The ionospheric gradient parameters C_λ and C_β are expected to absorb a significant amount of the spatially correlated ionospheric biases.

The double-differenced ionospheric measurements from carrier phase and pseudo-range can be used to estimate the ionospheric spatially correlated parameters via Eq. (4).

Modelling Residual Tropospheric Bias

Schaer et al. (1999) suggested 30-minute linear models for tropospheric refraction as a function of latitude, longitude and height of the user station. Then the corrections can be applied to each user station, for each epoch and each satellite. Zhang (1999) also discussed the estimation of the residual tropospheric delay for the purpose of predicting the tropospheric residual delay for a setting satellite, or newly risen satellite, using a network of reference stations. The residual tropospheric delay after double-differencing can be approximately represented as a function of the relative tropospheric zenith delay (RTZD) and a mapping function with respect to the elevation angle. The RTZD parameter can be assumed to be a first-order Gauss-Markov process or a random walk process (for a detailed discussion see Dai et al., 2001).

After careful selection of the reference stations, and using hardware and software multipath mitigation techniques, the influence of multipath can expect to have been significantly reduced in such networks. If the precise orbits (or real-time predicted orbits) are used and the reference station coordinates are precisely determined, and provided that the integer L1 and L2 ambiguities are correctly resolved, the residual double-differenced tropospheric bias can be derived from the ionosphere-free measurements. The RTZD parameter can then be estimated via the residual double-differenced tropospheric biases from the satellites with fixed ambiguities.

After the ionospheric and tropospheric bias modelling parameters are estimated, they can be used to predict residual ionospheric and tropospheric biases for a newly risen satellite or after a long data gap. With the aid of the predicted atmospheric biases, the wide-lane and narrow-lane ambiguities can be correctly resolved. The proposed ambiguity resolution procedure is illustrated in Figure 1.

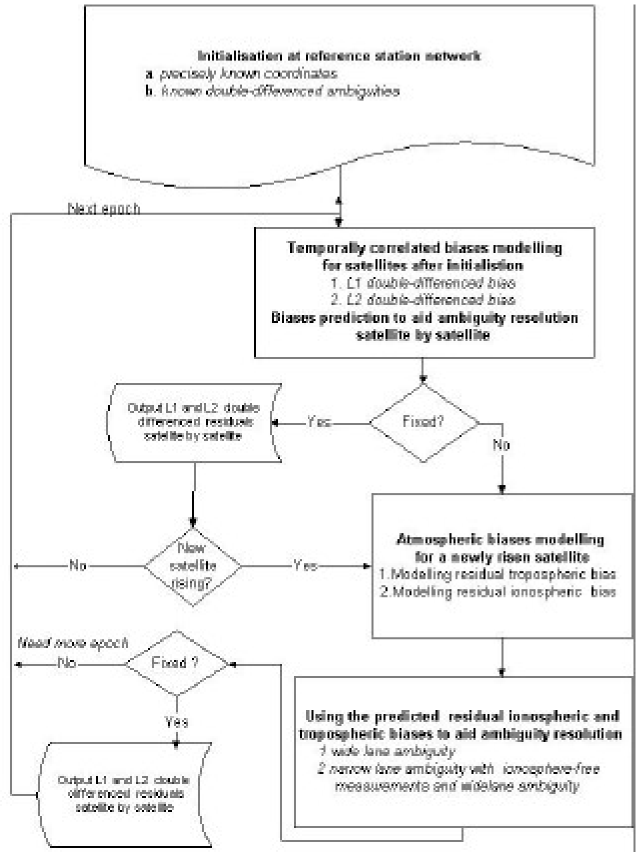

Figure 1. Flow chart for the proposed data processing steps within a GPS/GLONASS reference station network.

EXPERIMENTS

In order to test the performance of the proposed algorithms for real-time ambiguity resolution within GPS/GLONASS reference station networks, a sample data set has been analysed.

An experiment was carried out on 15 May 2000, using three dual-frequency GPS/GLONASS JPS receivers to simulate a reference network (Figure 2). One of the reference stations was located on the roof of the GAS building, at The University of New South Wales. The other reference stations were located at Camden and Richmond. The distances between the reference stations were 55.9km, 48.2km and 49.5km. The experiment commenced at 8:30AM and finished at 12:30PM. A total of 4 hours of GPS and GLONASS measurements, with one-second sampling rate and 15^o cut-off angle, were collected. During the period, between 5 and 9 GPS, and between 3 and 5 GLONASS satellites were tracked.

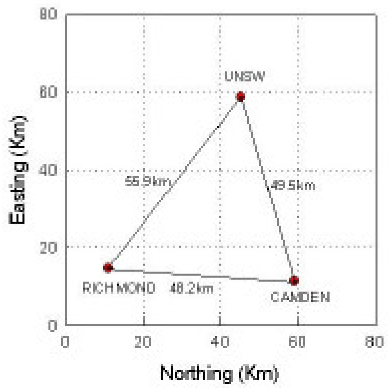

Figure 2: Configuration of the Sydney GPS/GLONASS reference stations experiment, 15 May 2000.

The reference station positions were precisely determined in the post-processing mode using the collected GPS and GLONASS measurements. The precise orbits from the Center for Orbit Determination in Europe (CODE) were used in the data processing. The ambiguities that were correctly resolved using the whole data set were used as the 'true values' to test the proposed algorithms.

Figures 3 and 4 show the L1 and L2 residuals for GPS satellite pairs 11-15 and 25-15, and GLONASS satellite pair 39-41 respectively. Black lines denote the original residuals. Red lines represent the residuals after the proposed bias temporal correlation model was applied. From Figures 3 and 4 it can be seen that the original residuals can reach up to 20cm for L1 and 30cm for L2. Therefore, the L1 and L2 ambiguities are difficult to resolve instantaneously (with one epoch of data). However, the residuals can be reduced significantly (to less 1cm) after the proposed model has been used. Therefore, ambiguities can then be correctly resolved by simply rounding-off to the nearest integer value. The results show that the double-differenced residuals do exhibit a high degree of temporal correlation and they can be estimated using previous residuals with fixed ambiguities, and precisely predicted for ambiguity resolution at subsequent measurement epochs.

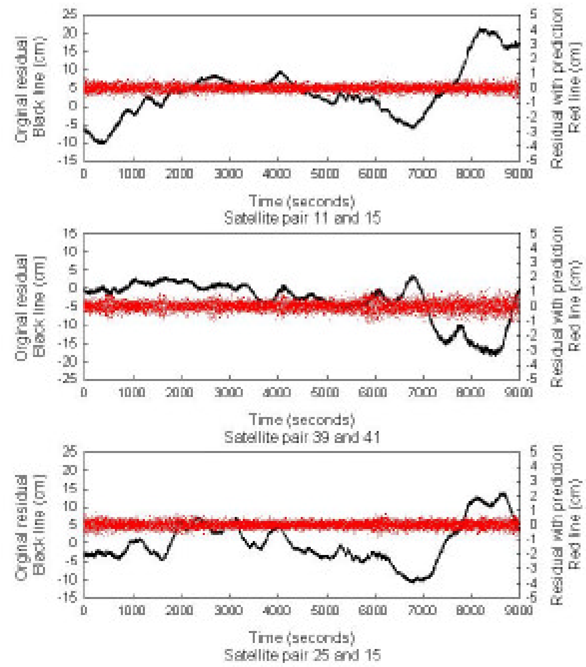

Figure 3: L1 residual for GPS satellite pairs11-15 & 25-15, and GLONASS satellite pair 39-41.

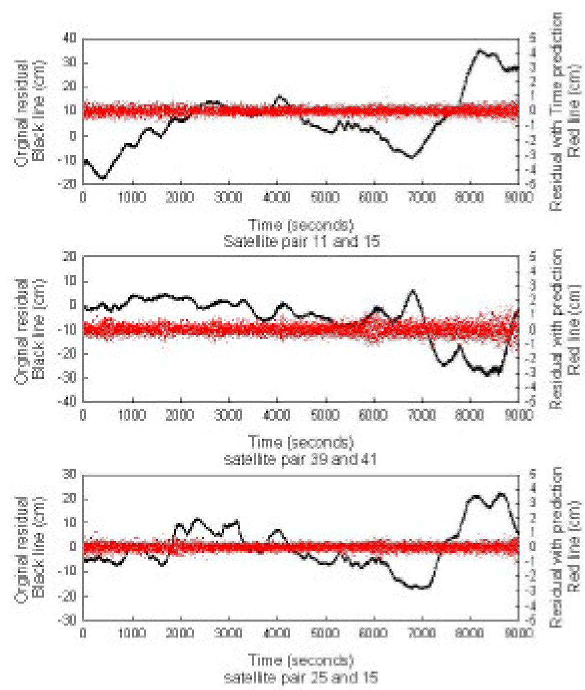

Figure 4: L2 residual for GPS satellite pairs 11-15 & 25-15, and GLONASS satellite pair 39-41.

Figure 5 shows the computed (black line), predicted (green line) wide-lane residuals and the difference (red line), for the newly risen satellite 19. It can be seen that the wide-lane ambiguity without the application of the residual ionospheric bias modelling cannot be fixed correctly for the first 15 minutes. Though this model cannot precisely predict the ionospheric bias for the newly risen satellite, it can aid wide-lane ambiguity resolution.

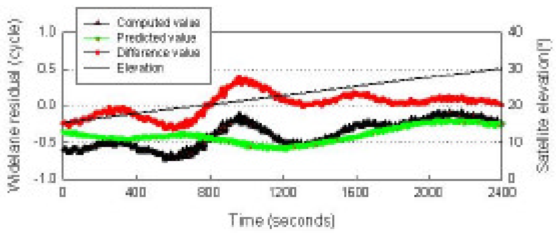

Figure 5: Residual ionospheric delay modelling for satellite pair 19-25.

Figure 6 shows the computed (black line), predicted (green line) troposheric delay and the difference (red line), for the newly risen satellite 16. It can be seen that the narrow-lane ambiguity without the application of the relative tropospheric zenith delay model cannot be fixed correctly at the beginning of the session. The results show that this model can precisely predict the tropospheric bias for the newly risen satellite, improve the ambiguity resolution success rate, and decrease the time required to resolve ambiguities.

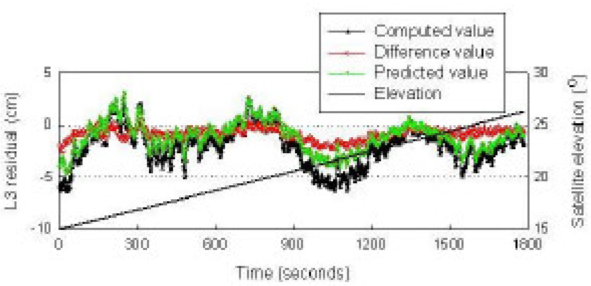

Figure 6: Residual tropospheric delay modelling for satellite pair 16-25.

The results from this experiment show that ambiguities can be easily resolved instantaneously, after initialization, using the proposed bias temporal correlation modelling procedure. The results also show that cycle slips have occurred more frequently for GLONASS satellites than for GPS satellites. Because the baseline length is not too long, all wide-lane ambiguities except one can be fixed correctly through a process of direct rounding-off. Fortunately, all can be fixed correctly after the residual ionospheric delay model was applied.

CONCLUDING REMARKS

In this paper two procedures for real-time ambiguity resolution for use in GPS/GLONASS reference station networks are suggested. The experimental results show that a bias prediction based on temporal correlations can be used for real-time ambiguity resolution. The average required time-to-fix the narrow-lane ambiguities can be significantly shortened, for example from 18.1 minutes to 5.5 minutes after the predicted relative tropospheric zenith delay model was applied. The conclusion can be made that the atmospheric delay information derived from other satellites, with fixed ambiguities, can be used to predict the atmospheric delay for a newly risen satellite, or after a long data gap, and hence can speed up the ambiguity resolution process.

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