KINEMATIC GPS POSITIONING WITH NETWORK-DERIVED IONOSPHERIC DELAYS

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ABSTRACT ... Currently, fast and accurate long baseline positioning in kinematic mode is a challenging topic, but positional accuracy can be improved with the help of the network-derived external ionospheric corrections. To provide not only ionospheric corrections, but also their variances, satellite-by-satellite interpolation for the ionospheric delays is performed using the least-squares collocation (LSC) method. Satellite-by-satellite interpolation has the advantage in that the vertical projection used in single-layer ionospheric model is not required. Also, more reliable user positioning and the corresponding accuracy assessment can be obtained by providing not only external ionospheric corrections but also their variances. The rover positioning with and without the external ionospheric delays in both rapid-static and kinematic mode was performed and analyzed. The numerical results indicate that the improvement in the positioning quality is achieved using the proposed method. With the TAMDEF network in Antarctica, 18 % improvement in mean time-to-fix in kinematic mode was achieved.

KEY WORDS: GPS positioning, Ionospheric delays, Least-squares collocation

1. INTRODUCTION

In precise relative positioning, the ionospheric effect on GPS signals is the largest error source in the observation equation, so that it must be properly modelled, especially for long-baseline applications. Improvement in the positioning quality can be obtained once the carrier phase ambiguities are successfully resolved in the double-difference approach using, for example, wide-lane and narrow lane, or wide-lane and L2, etc. The problem is that there exists a high correlation between the ionospheric delay and the integer ambiguity in the GPS observation equation; so, measurements over a certain time span are required to resolve the ambiguities. To obtain a converging solution within a short time span, the use of external ionospheric information derived, for example, from a permanent GPS network, such as Continuously Operation Reference Stations (CORS), has been investigated and analyzed (Odijk *et al.*, 2000; Rizos, 2002; Yi and Grejner-Brzezinska., 2003; Wielgosz *et al.*, 2005). Both static and kinematic modes require external ionospheric information for fast convergence of the solutions.

Several methods to generate ionospheric corrections from the GPS network have been developed and can be categorized into single layer or tomographic model approaches. The single layer model is two-dimensional (2-D), whereas the tomographic model is three-dimensional (3-D). In the single layer model, there is an assumption that all the free electrons are contained in a shell of infinitesimal thickness at an altitude of approximately 350-450 km. Therefore, this assumption may cause errors because the actual ionosphere covers a region that stretches between 50 km and 1,000 km above the Earth's surface, and the electron density encountered along a signal path depends on the azimuth and elevation angle at the ionosphere piercing point (IPP). To overcome the limitations of the 2-D ionosphere model, 3-D tomographic approaches have been proposed (Raymund *et al.*, 1994; Liu and Gao, 2001; Hansen, 2002; Spencer *et al.*, 2004). However, the system of equations to be solved requires more coefficients than in the 2-D case, and this often leads to an underdetermined system (Blanch *et al.*, 2004). To reduce or eliminate the error sources when using the thin-shell model, Sparks *et al.* (2004) proposed a conical domain approach, so that a direct slant delay map is estimated for each satellite. This approach is the most attractive one because the simplicity of the 2-D model is still retained and no error sources due to a thin-shell assumption are introduced. However, precisely modelled stochastic information on the predicted value is not available in this case, so that least-squares collocation (LSC) method is selected in this study to provide not only ionospheric delays but also their variances to the rover location. Then, they can be used as constraints in the estimation procedure for the improvement of the rover positioning quality. The analyses of the positioning results are performed with the Transantarctic Mountains Deformation (TAMDEF) sub-network, located in Antarctica.

2. METHODOLOGY

The noise level of the code pseudo-range measurements is relatively high, so that the geometry-free phase-smoothed code pseudo-range (GSC) observations are frequently used for the ionosphere modelling (Schaer, 1999; Wielgosz *et al.*, 2003). The geometric range, tropospheric delay, and satellite and receiver clock errors will be eliminated in the GSC observation as shown in Eq. (1).

$$E\{\widetilde{P}_i^k\}=F\frac{I_i^k}{f_1^2}+\Delta b^k+\Delta b_i \tag{1}$$

$$F=\left(1-\frac{f_1^2}{f_2^2}\right)$$

where $E\{\cdot\}$ is expectation operator, $\widetilde{P}_i^k$ is GSC observation between receiver i and j, f_1 and f_2 are carrier frequencies of L1 and L2, respectively, I_i^k/f_1^2 is ionospheric delay, Δb^k and Δb_i are satellite and receiver DCBs, respectively.

The GSC observation consists of scaled ionospheric delay and constant bias terms. Therefore, receiver and satellite DCBs should be properly modelled to obtain undifference (UD) ionospheric delay from the GSC observation. The receiver DCB can be obtained efficiently by using the method proposed by Hong (2005). However, determination of the satellite DCB is not required because the interpolation of ionospheric delay at the rover location will be performed on satellite-by-satellite basis. This means that the satellite DCB remains as a common bias term in the GSC observations from all the receivers, as a consequence, biased UD ionospheric delays due to un-modelled satellite DCB will be obtained. Once ionospheric delays (possibly biased due to satellite DCB) are obtained from all the receivers, prediction of ionospheric delays to the rover location through LSC is performed. Then, the predicted DD ionospheric delays are formed from the UD ionospheric delays as shown in Eq. (2). It should be mentioned that the satellite DCBs will be cancelled out by differencing operator in this step.

$$\tilde{I}_{ir}^{k\ell}/f_1^2=\begin{bmatrix}1 & -1 & -1 & 1\end{bmatrix}\begin{bmatrix}\tilde{I}_i^k/f_1^2\\ \tilde{I}_r^k/f_1^2\\ \tilde{I}_i^\ell/f_1^2\\ \tilde{I}_r^\ell/f_1^2\end{bmatrix} \tag{2}$$

where $\tilde{I}_{ir}^{k\ell}/f_1^2$ is the predicted DD ionospheric delay at the rover location, $\tilde{I}_i^k/f_1^2$ is the predicted UD ionospheric delay for the satellite k at the location of reference receiver i, $\tilde{I}_i^\ell/f_1^2$ is the predicted UD ionospheric delay for the satellite ℓ at the location of reference receiver i, $\tilde{I}_r^k/f_1^2$ is the predicted UD ionospheric delay for the satellite k at the location of rover r, $\tilde{I}_r^\ell/f_1^2$ is the predicted UD ionospheric delay for the satellite ℓ at the location of rover r.

Finally, rover positioning in DD mode are performed with following DD GPS observation equation:

$$E\{\mathbf{y}\}=\mathbf{A}_1\boldsymbol{\xi}_1+\mathbf{A}_2\boldsymbol{\xi}_2 \tag{3}$$

where $\mathbf{y}$ is DD observed minus computed values, $\boldsymbol{\xi}_1$ is DD ionospheric delay parameters to be estimated, $\boldsymbol{\xi}_2$ is all other parameters to be estimated including user coordinates and DD ambiguities, $\mathbf{A}_1$ and $\mathbf{A}_2$ are design matrices associated with $\boldsymbol{\xi}_1$ and $\boldsymbol{\xi}_2$, respectively.

The network-derived DD ionospheric delays will be introduced as additional constraints for the improvement of rover positioning quality with following form:

$$E\{\mathbf{z}_0\}=\boldsymbol{\xi}_1 \tag{4}$$

where $\mathbf{z}_0$ is pseudo-observations, i.e., network-derived DD ionospheric delays interpolated to the rover location.

The analysis of the effect of network-derived ionospheric delays on the rover positioning quality is performed in terms of the ambiguity success ratio and the time-to-fix for ambiguity resolution (AR) in kinematic mode. The Least square AMBiguity Decorrelation Adjustment (LAMBDA) method is selected for the AR because it is known to be the most successful of all the AR methods from both theoretical and practical point of view (Hofmann-Wellenhof *et al.*, 2001). Also, W-ratio test is used for the validation of AR (Wang et al., 1998). The empirically determined critical value 4 is selected for the validation of AR. This means that the ambiguity is considered to be successfully resolved once W-ratio passes the pre-selected critical value 4.

3. DESCRIPTION OF THE TEST DATASETS

To analyze the performance of the proposed algorithm, GPS measurements were obtained from the Transantarctic Mountains Deformation (TAMDEF) project. The TAMDEF is a joint USGS/OSU project with the primary objective of measuring the crustal motion in the Transantarctic Mountains of Southern Victoria Land using GPS techniques. More details on the project and the collected datasets used for the project can be found at the web site http://www.geology.ohio-state.edu/TAMDEF/. The 24 hours of test data were collected on Jan. 5, 2006, from the TAMDEF GPS stations and one International GNSS Service (IGS) station. Eight stations from the TAMDEF network, and one station from the IGS network were selected. Thus, nine stations in total were used to analyze the performance of the proposed algorithm. Figure 1 shows the locations of the GPS stations selected in Antarctica. The MCM4 station was selected among the IGS stations in Antarctica, because it is one of the closest to the TAMDEF network with published station coordinates. Figure 1 shows the location map for the selected GPS stations.

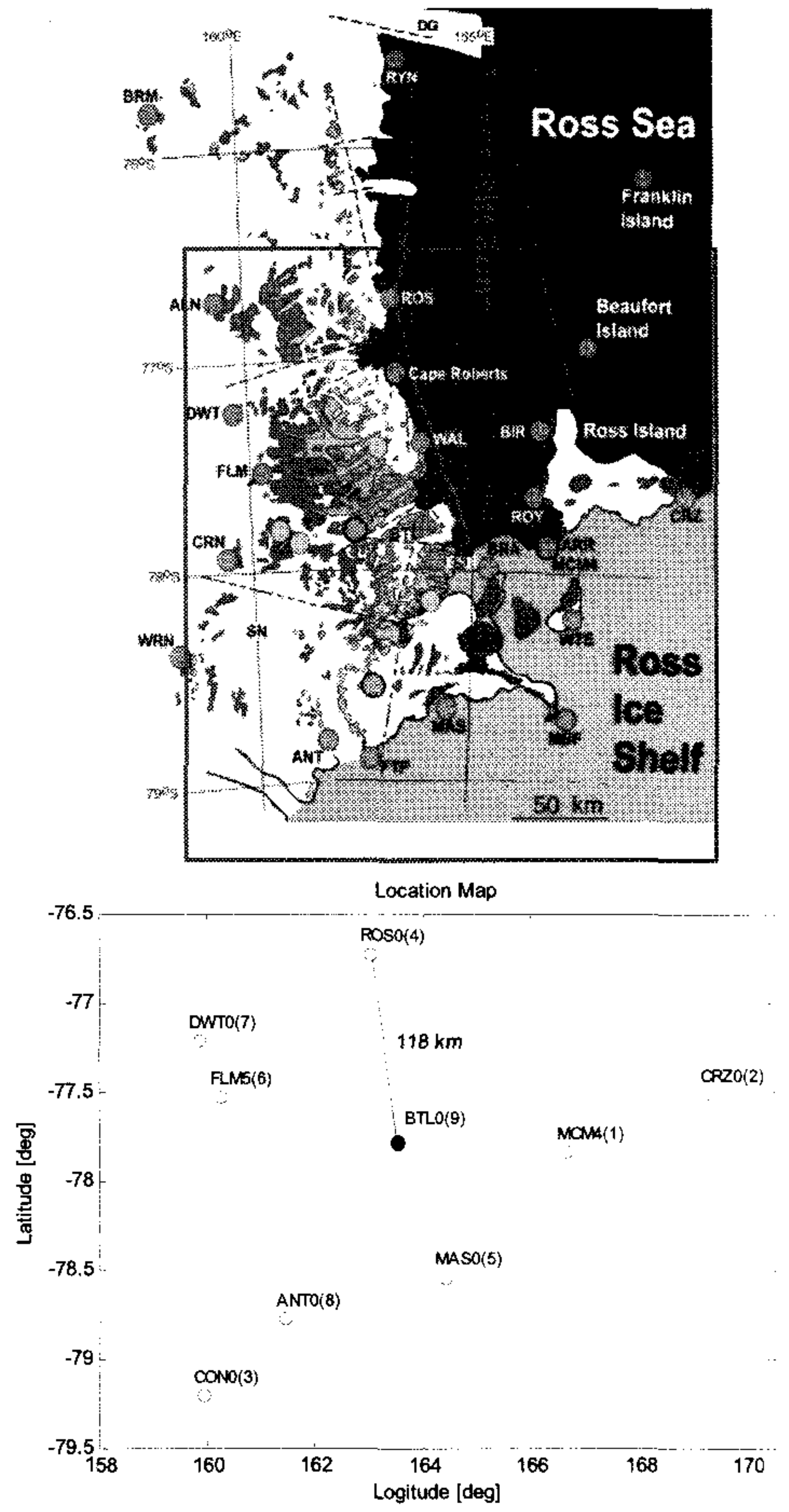


Figure 1. Location map of selected GPS stations in Antarctica (http://www.geology.ohio-state.edu/TerryWilson/research_gps.htm).

Published coordinates of the TAMDEF GPS stations were not available, so the coordinates of the selected stations were estimated, together with the total zenith delay (TZD) at each station, to obtain the reference coordinates. To estimate the coordinates of the TAMDEF sub-network stations, the coordinates of the MCM4 station were tightly fixed to the published values, and the coordinates of the other stations were estimated. It should be noted that, in the following analysis, ROS0 is selected as a reference station while BTL0 station is assumed to be the simulated rover. Also, the TZDs of both stations were fixed with the estimated values for the following analysis.

4. RESULTS

In the first step, UD ionospheric delays from the TAMDEF network were used for the prediction of UD ionospheric delays together with their error standard deviations through LSC method. Figure 2(a) shows one example of UD ionospheric delays observed from all the stations for PRN01 at specific epoch. Figure 2(b) and Figure 2(c) present predicted UD ionospheric delays and their error standard deviations at each grid point over the network, respectively. As can be seen in Figure 2(b), predicted ionospheric delays vary smoothly over the network. It should be noted that the interpolation will be required at the rover location only in real applications. This procedure was applied for all the satellites observed at each epoch for the generation of UD ionospheric corrections. Then, DD ionospheric delays were formed from the predicted UD ionospheric delays for the rover positioning.

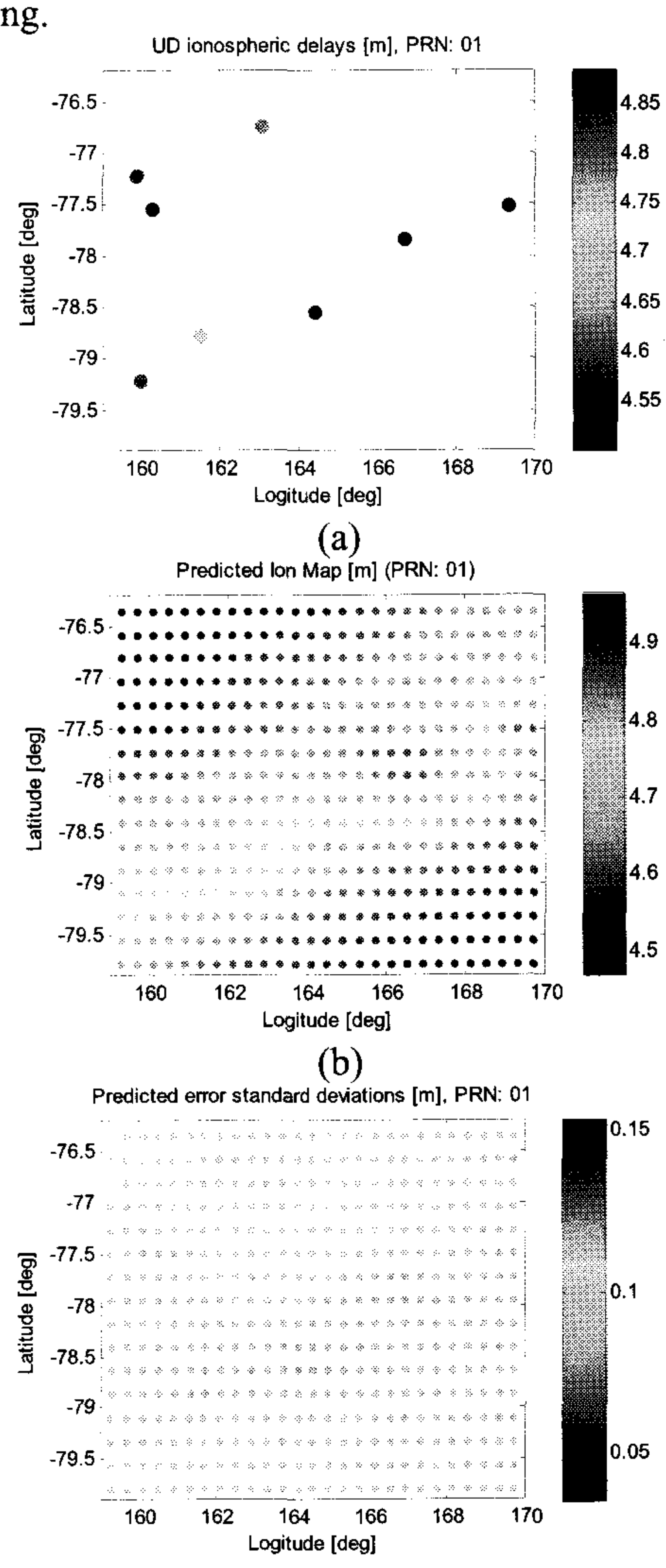
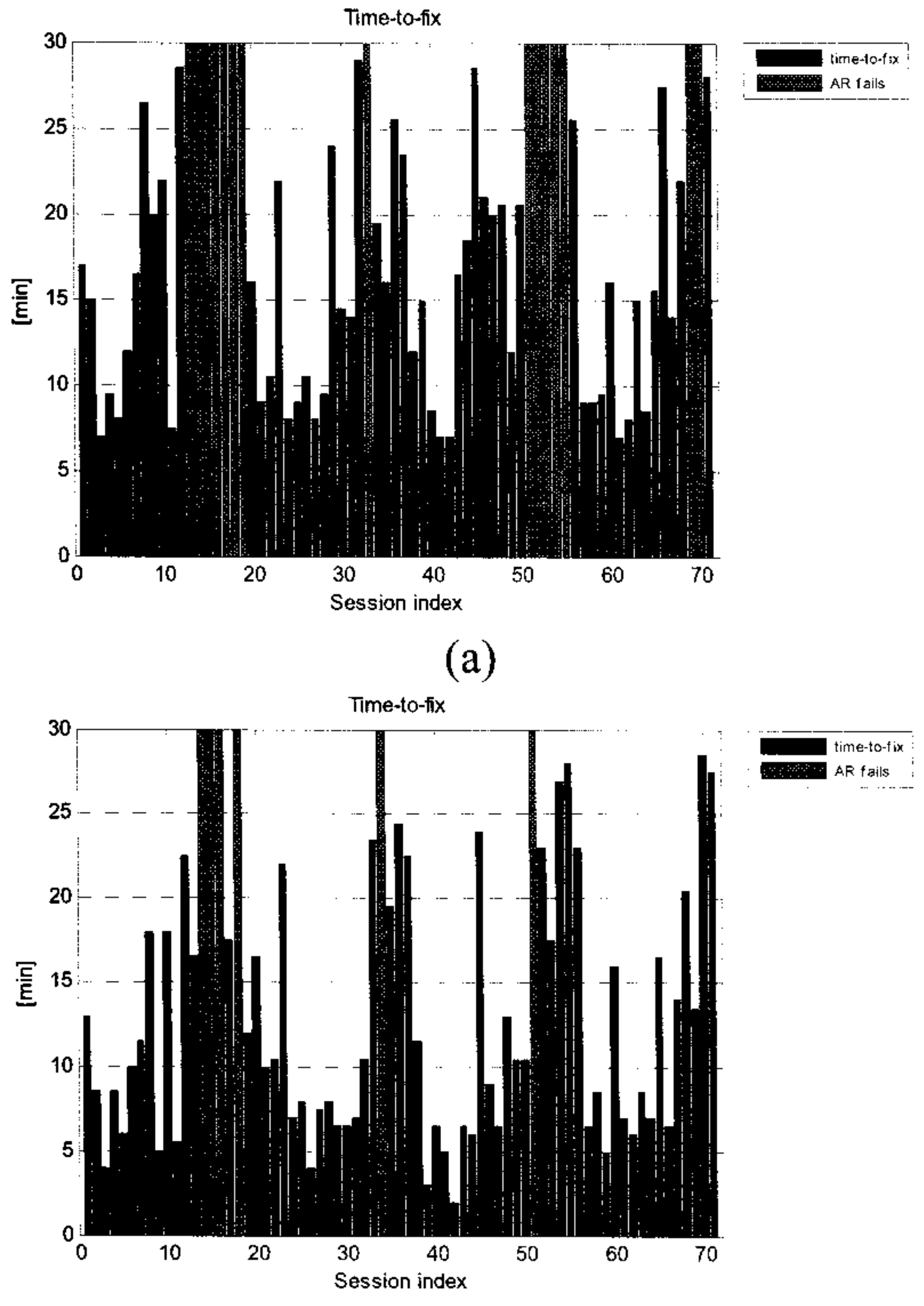


Figure 2. (a) original UD ionospheric delays (b) predicted UD ionospheric delays (c) error standard deviations of predicted UD ionospheric delays.

The performance of kinematic positioning with and without network-derived ionospheric delays was examined to analyze the effect of network-derived ionospheric delays on the rover positioning quality. The analysis was performed in terms of ambiguity success ratio and time-to-fix for AR. A total of 71 30-minute sessions were processed in kinematic mode, i.e., the estimation procedure started every 20 minutes, and each session was processed with and without external ionospheric delays, as a consequence, the solution of each data interval was obtained. Figure 3 shows the time-to-fix for AR for all sessions in kinematic mode. As shown in Figure 3, 56 sessions passed the W-ratio critical value when no external ionospheric delays are introduced, while 65 sessions passed the W-ratio critical value when external ionospheric delays are used for kinematic positioning. Hence, an 18 % improvement in time-to-fix was obtained when external ionospheric delays were used for the rover positioning.



(a)

(b)

Figure 3. Plot of time-to-fix for all sessions in kinematic mode (ROS0-BTL0 baseline, 118 km, 01/05/2006, dual-frequency receiver case); (a) without and (b) with external ionospheric delays.

5. SUMMARY AND CONCLUSIONS

In this paper, efficient and reliable prediction method of network-derived ionospheric delays for the rover positioning was proposed and demonstrated with TAMDEF GPS network in Antarctica. The effects of network-derived ionospheric delays on positioning quality were analyzed in terms of the ambiguity success ratio and the time-to-fix for AR. The numerical results showed that the improvements of 12 % and 18 % in the ambiguity success ratio and the mean time-to-fix were obtained, respectively, when network-derived ionospheric delays were introduced for the rover positioning..

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