Precise estimation of residual tropospheric delays using a regional GPS network for real-time kinematic applications

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Abstract. A new method called Trop_NetAdjust is described to predict in real time the residual tropospheric delays on the GPS carrier phase observables using the redundant measurements from a network of GPS reference stations. This method can not only enhance the effectiveness and reliability of real-time kinematic users within the network, but also provide a valid approach to tropospheric parameter variation forecasting. Trop_NetAdjust is theoretically based upon LS prediction criteria and enables the prediction of residual tropospheric delays remaining after a standard model has been applied to the raw GPS measurements. Two cases are analyzed, namely a first case when the delay is required for an existing satellite at a new point within the network and a second case when the delay is required for a new satellite. Field tests were conducted using data collected in a network of 11 reference stations covering a 400 x 600 km region in southern Norway. The results were analyzed in the measurement domain (ionospheric-free double-difference residuals) and showed improvements of 20 to 65% RMS errors using Trop_NetAdjust. The estimates of the Trop_NetAdjust prediction accuracy were also obtained using the covariance analysis method. The agreement was consistently better than 30% when compared with data from a real network.

Key words: GPS – Navigation – Real-time Kinematic Positioning – Meteorology – Ambiguity Resolution

1 Introduction

The troposphere is the part of the atmosphere closest to the Earth’s surface and is usually said to extend up to a height of 10 km. At GPS frequencies, the troposphere is a non-dispersive medium, so the delay effects of GPS signals are not frequency dependent, and therefore are the same for both code and phase measurements.

The tropospheric effect can be divided into a hydrostatic (dry) delay and a wet delay. The hydrostatic delay is caused by the transient or induced dipole moment of all the gaseous constituents of the atmosphere including water vapor. It is the larger of the two parts of delay. The hydrostatic delay typically reaches about 2.3 m in the zenith direction at sea level (Businger et al. 1996; Dodson et al. 1996). This part can be modeled and removed with an accuracy of a few millimeters or better using a surface model (including pressure, temperature, and humidity), so it is not much of a problem as far as its effect on GPS signals is concerned (Saastamoinen 1972; Tralli and Lichten 1990). However, the wet delay, which is mostly due to water vapor and is as small (zenith component) as a few centimeters or less in arid regions and as large as 35 cm in humid regions, is usually far more variable and more difficult to remove based on standard tropospheric models using surface measurements (Bevis et al. 1992; Duan et al. 1996; Darin et al. 1997). Significantly, the daily variation of the wet delay usually exceeds that of the hydrostatic delay by more than one order of magnitude, especially in temperate regions. Therefore, the residual delay remaining after applying a standard troposphere model is mostly due to the wet component. If this residual delay can be estimated or predicted in some way, GPS performance can be enhanced significantly, especially in the context of integer carrier phase integer ambiguity resolution for realtime kinematic (RTK) applications. If a network of reference stations is used instead of a single reference station, the ambiguities between any reference station and the user (mobile or static) can be resolved more effectively and over longer distances, provided the ambiguities between the reference stations can be resolved (Raquet et al. 1998). Accurate prediction of tropospheric delays becomes critical to the success of this approach. The redundant information available through the availability of multiple reference stations should intuitively be useful to improve the prediction accuracy.

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This paper focuses on developing and testing a methodology which uses a network of reference stations to accurately predict tropospheric delays in real-time. The two specific sub-objectives are as follows.

(a) Optimal prediction of residual tropospheric delays for existing stations at the user using satellite measurements available from the surrounding reference station network. This will result in a faster estimation of the integer ambiguities at the user since a large part of the carrier phase errors is due to the troposphere.

(b) Prediction of residual tropospheric delays for new satellites being observed by the network stations and user alike, using other satellite measurements available in the network. This implies that tropospheric delays between satellites and observation points are spatially correlated, which is indeed the case. This case is important in order to resolve quickly ambiguities involving new satellites. These satellites are initially relatively low and their tropospheric delays relatively high.

In the following, the residual tropospheric delays which can be partly estimated from carrier phase observables are first described. Then, a network adjustment approach referred to as Trop_NetAdjust is presented and applied to residual tropospheric delay prediction for user receivers and new satellites. Relative tropospheric zenith delays and associated stochastic characteristics are then analyzed using a sample GPS network located in Norway in order to calculate the covariance matrices. The effectiveness of the new method is demonstrated through the application of the method to test cases. Finally, the covariance analysis method is applied to estimate the prediction accuracy of Trop_NetAdjust and the results from the covariance analysis are compared with data from the real network.

2 Measurement of residual tropospheric delay

The delay remaining after applying a standard troposphere model and associated mapping function is called the ‘residual tropospheric delay’ and it is mostly due to the wet component. This delay can be expressed as follows:

\[ d_{\text{Trop}} = d_{\text{Trop}}(\text{model}) + d_{\text{Trop}}(\text{residual}) \]  

(1)

where \( d_{\text{Trop}} \) is the total tropospheric delay, \( d_{\text{Trop}}(\text{model}) \) is the predicted tropospheric delay using one of the standard models as well as an associated mapping function, and \( d_{\text{Trop}}(\text{residual}) \) is the remaining tropospheric delay after applying the standard models. The ionospheric-free combination of GPS carrier phase observations is a good measurement for this residual tropospheric delay computation.

The double-difference (DD) equation of the carrier phase observable can be written as

\[ \Delta \nabla \phi_{ab}^\text{yy} = \Delta \nabla \rho_{ab}^\text{yy} + \Delta \nabla d^\text{yy}_{ab} - \Delta \nabla d^\text{yy}_{\text{iono}ab} + \Delta \nabla d^\text{yy}_{\text{Trop}ab} + \Delta \nabla m^\text{yy}_{\phi,ab} + \Delta \nabla v^\text{yy}_{\phi,ab} + \lambda \Delta \nabla N^\text{yy}_{ab} \]  

(2)

where subscripts \( a \) and \( b \) refer to receiver \( a \) and receiver \( b \). Superscripts \( x \) and \( y \) refer to satellite \( x \) and satellite \( y \). Every term in a unit of length. In this equation, each of the error sources is presented in the form of a double difference, namely

\[ \Delta \nabla \rho_{ab}^\text{yy} \] the double-differenced geometric range from satellite to receiver

\[ \Delta \nabla d^\text{yy}_{ab} \] the double-differenced satellite orbit error

\[ \Delta \nabla d^\text{yy}_{\text{iono}ab} \] the double-differenced ionospheric delay

\[ \Delta \nabla d^\text{yy}_{\text{Trop}ab} \] the double-differenced residual tropospheric delay after standard troposphere models

\[ \Delta \nabla m^\text{yy}_{\phi,ab} \] the double-differenced multipath error

\[ \Delta \nabla v^\text{yy}_{\phi,ab} \] the double-differenced receiver noise

\[ \lambda \] the wavelength of the GPS carrier phase

\[ N \] the carrier phase integer ambiguity.

In order to provide a clearer representation of the DD error sources, Eq. (2) can be rewritten in another form as

\[ \Delta \nabla \phi_{ab}^\text{yy} \text{(metres)} = \Delta \nabla d^\text{yy}_{ab} - \Delta \nabla \rho_{ab}^\text{yy} \]

\[ = \Delta \nabla d^\text{yy}_{ab} - \Delta \nabla d^\text{yy}_{\text{iono}ab} + \Delta \nabla d^\text{yy}_{\text{Trop}ab} + \Delta \nabla m^\text{yy}_{\phi,ab} + \Delta \nabla v^\text{yy}_{\phi,ab} + \lambda \Delta \nabla N^\text{yy}_{ab} \]  

(3)

where \( \Delta \nabla \phi_{ab}^\text{yy} \) is the phase measurement-minus-range observable.

Equation (3) can also be written in units of cycles as

\[ \Delta \nabla \phi_{ab}^\text{yy} \text{(cycles)} = \frac{1}{\lambda} \left( \Delta \nabla d^\text{yy}_{ab} - \Delta \nabla d^\text{yy}_{\text{iono}ab} + \Delta \nabla d^\text{yy}_{\text{Trop}ab} + \Delta \nabla m^\text{yy}_{\phi,ab} + \Delta \nabla v^\text{yy}_{\phi,ab} + \lambda \Delta \nabla N^\text{yy}_{ab} \right) \]  

(4)

Consider a linear combination of the \( L_1 \) and \( L_2 \) phase measurements

\[ \phi_{j,k} = j \phi_{L1} + k \phi_{L2} \]

(5)

where \( \phi_{L1} \) is the \( L_1 \) carrier phase measurement, \( \phi_{L2} \) is the \( L_2 \) carrier phase measurement, \( j \) and \( k \) are the linear combination coefficients for \( \phi_{L1} \) and \( \phi_{L2} \), respectively; and \( \phi_{j,k} \) is the combination of \( \phi_{L1} \) and \( \phi_{L2} \). After applying Eq. (4), the DD equation of the measurement-minus-range observable can be written as (Raquet 1998)

\[ \Delta \nabla \phi_{ab(j,k)}^\text{yy} = \frac{1}{\lambda_{j,k}} \left( \Delta \nabla d_{\text{Trop}ab}^\text{yy} + \Delta \nabla d_{\text{iono}ab}^\text{yy} \right) + \frac{j}{\lambda_1} \left( \Delta \nabla m_{\phi,ab1}^\text{yy} + \Delta \nabla v_{\phi,ab1}^\text{yy} \right) + \frac{k}{\lambda_2} \left( \Delta \nabla m_{\phi,ab2}^\text{yy} + \Delta \nabla v_{\phi,ab2}^\text{yy} - \frac{\Delta \nabla d_{\text{iono}ab}^\text{yy}}{c} \right) \]

\[ \times \left( \frac{f_2 + k f_1}{f_1 f_2} \right) + j \Delta \nabla N_1 + k \Delta \nabla N_2 \]  

(6)

where \( \Delta \nabla \phi_{ab(j,k)}^\text{yy} \) is the DD measurement-minus-range observable in cycles; \( \lambda_{j,k} = (\lambda_1 \lambda_2)/(j \lambda_2 + k \lambda_1) \) is the wavelength of the combined measurement term, \( f_1 \) is