ESTIMATING THE RESIDUAL TROPOSPHERIC DELAY FOR AIRBORNE DIFFERENTIAL GPS POSITIONING (A SUMMARY)[†]

J. Paul Collins and Richard B. Langley
Geodetic Research Laboratory
Department of Geodesy and Geomatics Engineering
University of New Brunswick, Fredericton, N.B. E3B 5A3 Canada

ABSTRACT

When post-processing dual frequency carrier phase data, the residual tropospheric delay can easily be the largest remaining error source. This error can contribute a bias in height of several centimetres even if simultaneously recorded meteorological data are used. This is primarily due to the poor representation of the water vapour profile in the tropospheric delay models. In addition, a lack of real-time meteorological data would force the scaling of either surface values or standard atmosphere values; these are also unlikely to accurately represent the ambient atmosphere.

To obtain the highest precision in kinematic GPS some advantage may be obtained by estimating this error source along with the position solution. The simple tests reported in this paper removed biases of several centimetres in height when estimating the residual tropospheric delay from GPS data recorded at an aircraft in flight. However, important limitations exist in the geometry of the satellite coverage which must be considered before the full reliability of the technique can be quantified.

INTRODUCTION

This paper provides a brief summary of our investigations into estimating the residual tropospheric propagation delay from GPS signals. This parameter is the remaining part of the tropospheric delay not predicted by empirical models. In post-processed dual frequency carrier phase data, it can easily be the largest remaining error source. Unlike most applications of the technique, we have used data recorded at an aircraft in flight. This idea was motivated by the fact that highly accurate aircraft positions are required for gravimetric, altimetric and photogrammetric surveying purposes. Increasingly, GPS is being used to provide the decimetre-level accuracy required for some of these techniques. This level of precision can be achieved using carrier phase observables, but we will show that unmodelled tropospheric effects could potentially contribute a bias of a similar magnitude.

When processing GPS observations, a value for the tropospheric delay is predicted using empirical models which must be provided with meteorological values of the ambient

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temperature, pressure and relative humidity. Unfortunately, even with accurate values, these models rarely predict the true delay with a high degree of accuracy. In theory the hydrostatic component of the delay can be predicted in the zenith to the millimetre level, however the highly variable nature of atmospheric water vapour means that the accuracy of the non-hydrostatic delay is at the centimetre, or even decimetre level.

In addition, when recording GPS data at an aircraft, it is often the case that no meteorological information is recorded at the same time. When processing this data, assumed meteorological values must be used, and in addition to the poorly modelled wet component, there could also be a bias contributed by the hydrostatic component.

The results presented here are a subset of those presented in *Collins and Langley* [1997b] in which results using a wider set of models are presented.

MODELLING CONSIDERATIONS AND DATA PROCESSING

A least-squares positioning model using double-differenced, dual-frequency, GPS carrier phase observations is implemented in the KARS processing software [*Mader*, 1996]. The code has been modified at UNB to allow for the estimation of the tropospheric delay as a scale factor at either the roving receiver or at both the rover and the reference receiver.

Unfortunately, there is a problem with using differenced data to estimate the residual tropospheric delay over short baselines. For this situation, there exists a strong mathematical correlation between the partial derivatives of the tropospheric delay. For baseline lengths up to several hundred kilometres the elevation angles to a particular satellite will be similar and hence so will the partial derivatives (but with opposing signs). Even if the meteorological conditions are drastically different at the ends of such a baseline, it is difficult for a least-squares model to separate the two contributions. The usual technique to overcome this problem is to fix the tropospheric delay at the reference station and to estimate the *relative* delay at the secondary station. We have used real-time meteorological data at the reference station to help minimise the error in the estimated residual delay.

The data set used in this paper consists of dual-frequency GPS data recorded at a two second interval at a reference station and an aircraft in flight. The flying time was approximately 103 minutes up to a maximum distance of 210 kilometres from the reference station at St. John's, Newfoundland (see Figure 1). A set of fixed integers for all satellites on both frequencies was derived. This was done by processing the flight data at various elevation cut-off angles while resolving the ambiguities "on-the-fly". Comparing the ambiguities from these solutions with ambiguities computed for the short static period before the flight, has enabled stable sets of integers to be selected. While confident that these are the correct values, without actually estimating these values in flight, we can only confirm this by examining the residuals of the positions solution to see if they diverge over time.

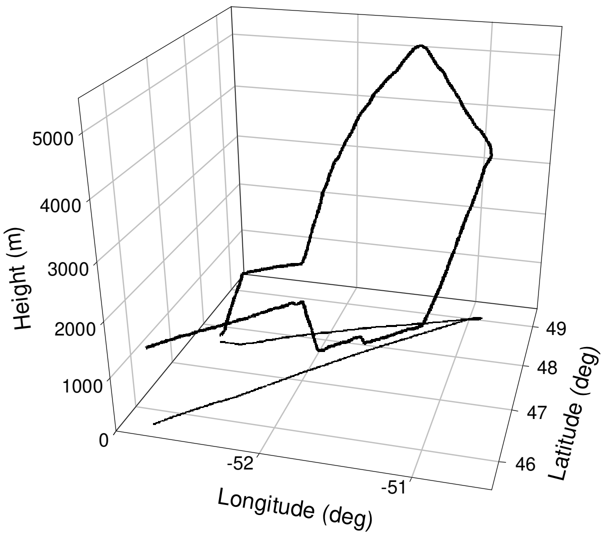

Figure 1. Flight path of aircraft for data used in this study.

Of the remaining error sources, the primary one is the satellite position error. To minimise it as much as possible, International GPS Service for Geodynamics (IGS) precise orbits were used. This leaves multipath and noise which should be of the order of centimetres or less for the carrier phase observable.

The solution was computed estimating the three-dimensional positions of the aircraft along with the residual tropospheric delay as a scale factor. No filtering was applied and no a-priori constraints were placed on any of the parameters. Each epoch provided an independent solution.

RESULTS

The results presented here used one tropospheric zenith delay and mapping function combination at the reference station and the aircraft. These were the *Saastamoinen* [1973] zenith delays using simultaneously recorded meteorological data and the mapping functions of *Niell* [1996] which only require position and day-of-year information. This model is denoted as SAANf in this paper.

Solution Residuals

Considering first of all the root-mean-square (rms) of the double-differenced carrier phase residuals after the least-squares adjustment, examination of Figure 2 shows the general improvement gained by estimating a residual tropospheric delay parameter. Overall a small improvement has been made, indicating that estimation of the residual tropospheric delay has reduced the impact of the errors in this model on the solution.

Residual Delay Estimates

Turning to the actual residual delays estimated, Figure 3 shows the residual delay estimated over the flight. The plot can be considered in two halves — before and after the 45 minute epoch. Consideration of the elevation angle trace shows that before this point in the flight there are no satellites at low elevation angles (< 10 degrees). As is well known in GPS, this limits the potential for adequately estimating the tropospheric delay. The wide variation in the first half of Figure 3, coupled with the large negative magnitude could mean that the residual estimates for this time span are unreliable.

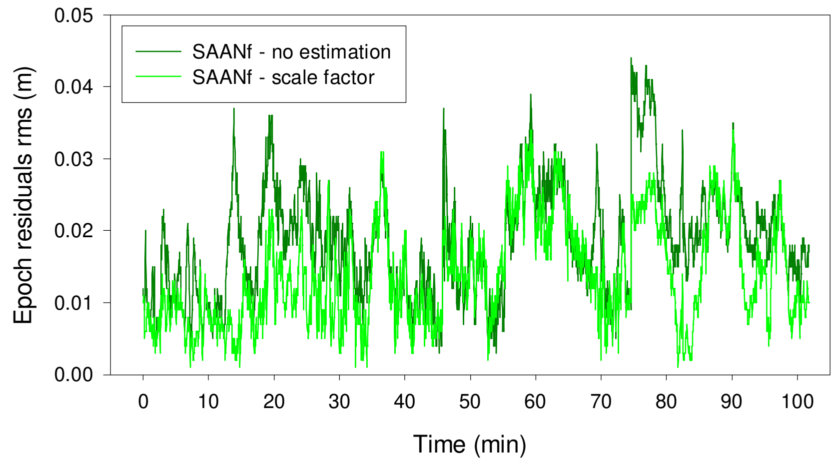

Figure 2. The rms double-difference carrier phase residuals with and without residual tropospheric delay estimation with real-time meteorological data.

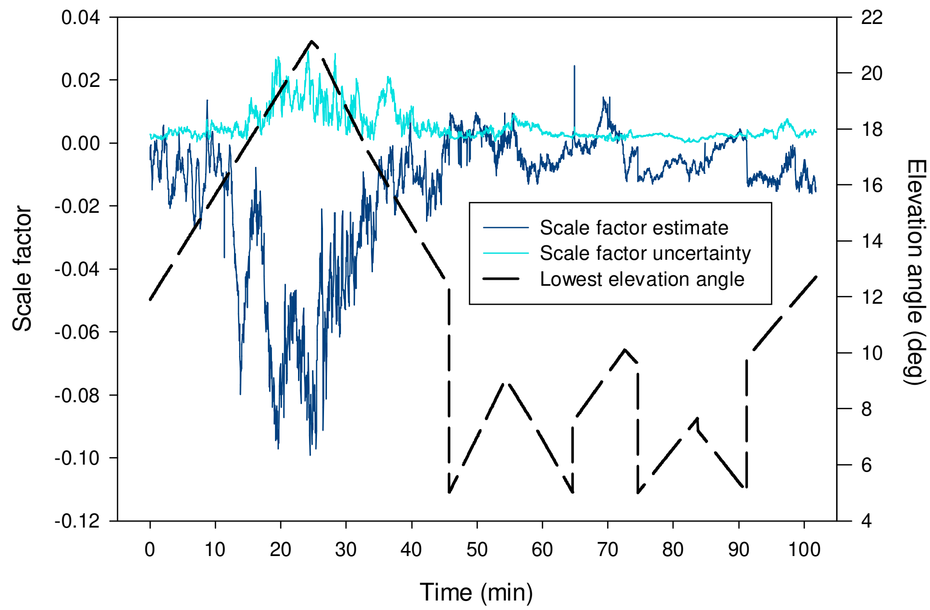

Figure 3. Comparison of residual tropospheric delay estimates and their uncertainty with the lowest elevation angle used in the solution.

Position Differences

Without residual delay estimation, we would consider the kinematic solution using SAANf to be the "best" obtainable because of its realistically-modelled zenith delays and mapping functions driven by real-time meteorological data. By estimating the residual delay we would hope to model any deviations from the average atmospheric structure implied by these models. Figure 4 shows the difference in the position components for solutions computed with and without residual tropospheric delay estimation. The difference in the height component is considerable: of the two sets of statistics for this data, even when considering only the “good” estimates after the 45 minute epoch, there is a mean bias in height of ~5 cm with an rms of ~9 cm.

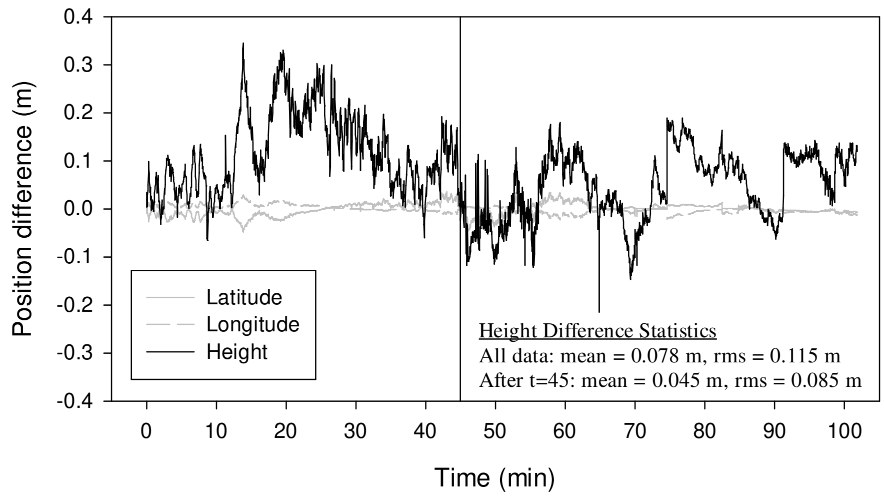

Figure 4. Difference in position solutions with and without residual delay estimation from predictions with real-time meteorological data.

It is possible under other conditions, for example using standard atmosphere meteorological values with the same zenith delay and mapping function combination, for the biases and differences shown in Figure 3 and Figure 4 to be much larger. However estimating the residual tropospheric delay appears to remove the impact of such biases. This is shown in Figure 5, where position differences between a solution computed with the “composite” tropospheric delay model UNB4 at the aircraft and the SAANf model solution are shown. (Note: UNB4 supplies meteorological data based on the 1966 U.S. Standard Atmosphere Supplements to the Saastamoinen and Niell algorithms. For more details see *Collins and Langley* [1997a]).

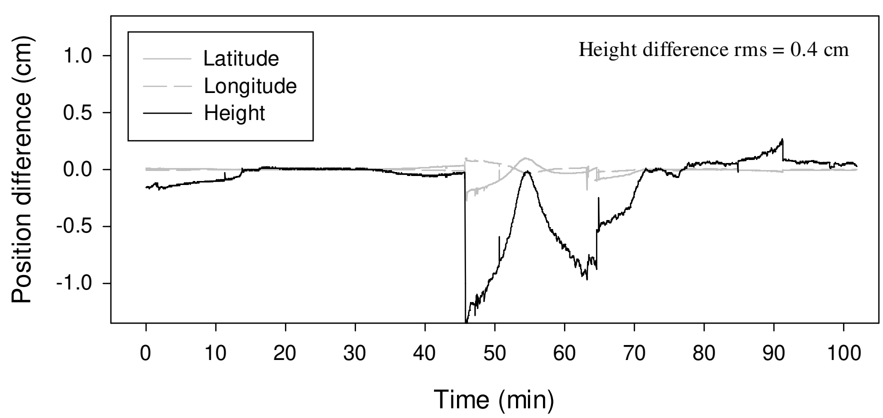

Figure 5. Position differences between the UNB4 solution and the SAANf solution. (Residual delay estimated in both solutions.)

CONCLUSIONS

We have presented in this paper a brief summary of our investigations into the effects of implementing residual tropospheric delay estimation from GPS data recorded at an aircraft in flight. The aim was to remove any unmodelled effects of the troposphere that cannot be predicted by empirical models, even when using meteorological measurements of the ambient atmosphere.

Estimating the residual delay appeared to almost wholly remove the impact of errors in the tropospheric delay model. However, the impact of the satellite geometry is important. It appears crucial that there exists data at low elevation angles (less than 10 degrees) for the tropospheric residual estimate to be meaningful. If the highest possible precision is required for aircraft positioning then estimation of a residual delay should be considered, otherwise biases of up to ten centimetres may be present in the solution.

This has been only a preliminary study and further work is required to study the condition of the normal equations of the least-squares adjustment and the reliability of the technique. New investigations could include the impact of antenna phase centre corrections, as the data is particularly sensitive to these at low elevation angles. Additionally, the implementation of a Kalman or other type of constraining least-squares filter could significantly enhance the technique by providing some a-priori constraints to the estimates.

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