Evaluation of Different Strategies for Mitigating Azimuthally Asymmetric Tropospheric Delays

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1. Introduction

The asymmetric nature of the earths atmosphere, if neglected, can cause troposphere delay errors on the order of 50 mm for low elevation angle observations. In order to achieve mm accuracy in station height using space geodetic techniques, it is necessary to model these asymmetries. Currently, the International Earth Rotation and Reference System Service (IERS) recommends estimating linear horizontal gradients via the geodetic observations. However, due to the increased number of parameters and the possibility of these parameters absorbing other errors sources, this technique is less than optimal. We investigate different strategies for modeling the asymmetric delay for space geodetic data. We assess these different solutions using a precise point positioning (PPP) campaign, and investigate their impact on the position results, troposphere zenith delay and convergence time of the solution.

2. Strategies for Modeling Asymmetric Delay

Below are the descriptions of the various approaches for describing the asymmetric delay. The approaches are listed in order of their reliance on external data sources (ie. numerical weather models (NWM). As a bench mark we have chosen to include as the standard solution, the symmetric mapping function case which simply neglects any asymmetric troposphere delay.

Standard Approach with Gradient Model (IERS Conventions)

- Estimate gradient parameters using GPS observations

$$D_L^i(t;\varepsilon,\alpha) = m_h(t;\varepsilon)D_h^Z + m_{nh}(t;\varepsilon)D_{nh}^Z + m_\Delta \cot(\varepsilon)(G_N \cos\alpha + G_E \sin\alpha)$$

- Apriori Hydrostatic delays derived from NWM (ECMWF)
- Site-dependent Symmetric Mapping Functions – VMF1
- Gradient mapping function equal to wet mapping function

Gradient Scale Factor Estimation

- Estimate a gradient scale factor γ, using GPS observations

$$D_L^i(t;\varepsilon,\alpha) = m_h(t;\varepsilon)D_h^Z + m_w(t;\varepsilon)D_{nh}^Z + \gamma\left[m_\Delta \cot(\varepsilon)(G_N \cos\alpha + G_E \sin\alpha)\right]$$

- Gradient terms derived from NWM – LHG (Boehm et al., 2007)
- Could possibly use a simple apriori gradient model

Prediction + Estimation of Residual Zenith Delay

- Ray-traced slant factors derived from ray-tracing through NWM

$$D_L^i(t;\varepsilon,\alpha) = k_h^i(t;\varepsilon,\alpha)D_h^Z + k_{nh}^i(t;\varepsilon,\alpha)D_{nh}^Z \quad \text{where the slant factor:} \quad k_j^i = \frac{D_j^i(t;\varepsilon,\alpha)}{D_j^Z(t;90,0)}$$

- Apriori hydrostatic zenith delays derived from NWM for every epoch
- Estimate wet zenith delay using NWM derived non-hydrostatic slant factors

Prediction-Only

- Ray-traced slant factors derived from ray-tracing through NWM

$$D_L^i(t;\varepsilon,\alpha) = k_h^i(t;\varepsilon,\alpha)D_h^Z + k_{nh}^i(t;\varepsilon,\alpha)D_{nh}^Z \quad \text{where the slant factor:} \quad k_j^i = \frac{D_j^i(t;\varepsilon,\alpha)}{D_j^Z(t;90,0)}$$

- Hydrostatic and non-hydrostatic zenith delays derived for every epoch
- No estimation of residual delay

– LESS Reliance on NWM MORE +

3. Why Ray-traced Slant Factors?

Rather than applying the ray-traced delays directly to the observations, slant factors were computed due to several advantages they present: 1) Fewer modifications to PPP software; used much the same way as traditional mapping functions; 2) Possible to estimate residual zenith delays using same stochastic model; 3) In the future, the use of an external source of zenith delays is possible (ie. Network- derived GPS zenith delays for example).

4. PPP Processing

GAPS
http://gaps.gge.unb.ca/gaps_summary.txt
GPS Analysis and Positioning Software

Daily RINEX files for a two week period from January 1st – 14th , 2008 were processed using GAPS, a PPP software developed at UNB. The processing interval was set to 5 minute epochs and a cutoff angle of 5 degrees was used when possible. Along with the other standard PPP error models, atmospheric pressure loading corrections were applied daily, at the coordinate level (Petrov and Boy, 2004). When residual troposphere delay and gradient parameters were estimated, they were done so at each epoch employing a random walk model of 5mm/√hr and 0.3mm/√hr respectively. The observation variances were modeled as $C_0^2/\sin^2(\text{elev})$.

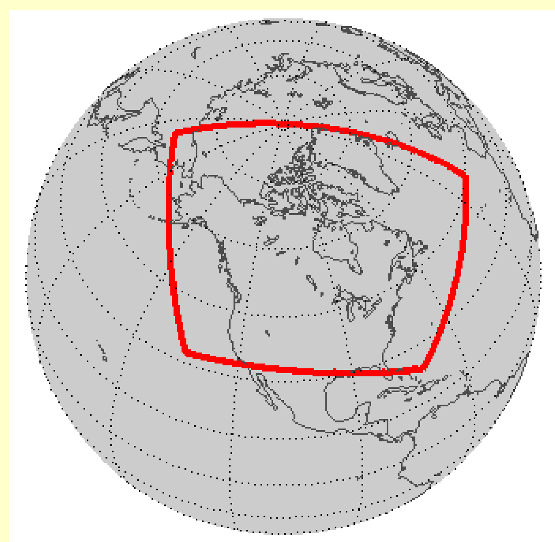

Figure 1.0 Extent of the Canadian Regional NWM produced by the Canadian Meteorological Center

Ray-tracing was performed through the Canadian Meteorological Centre's Regional NWM. Grid resolution is 15km at N60°, 28 pressure levels + surface temporal resolution of 3 hours.

10 stations from the Canadian Active Control Stations (CACS) network used in the campaign.

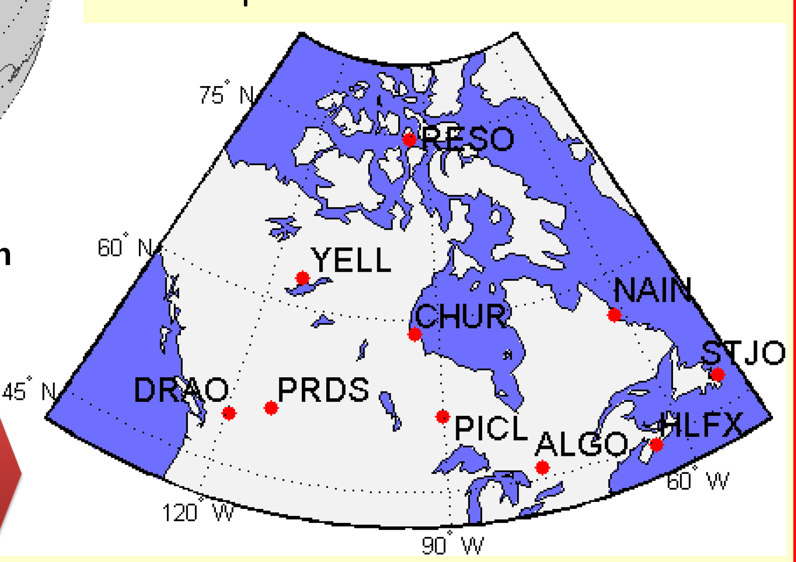

Figure 2.0 GPS network of CACS

5. Results and Analysis

Figure 3.0 shows the time series of the station displacements for a station with low troposphere variability (RESO) and a station with higher variability (HLFX). All solutions perform equally well in the horizontal component but in the height component the prediction-only case has higher variability which is due to the station height parameter absorbing any errors in the prediction of the tropospheric delay.

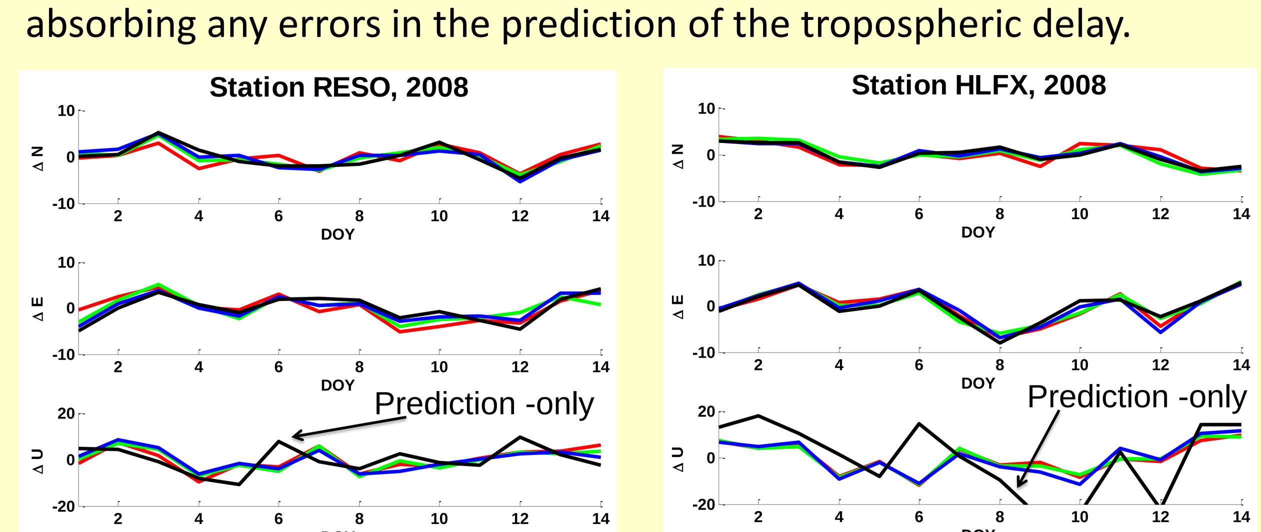

Figure 3.0 Time series of two stations, one which exhibited quiet troposphere variability (RESO) and higher troposphere variability (HLFX).

Figure 4.0 shows the repeatability for station height for all solutions. Overall the estimation of tropospheric gradients performed slightly better than the other approaches. The use of ray-traced slant factors with residual delay estimation performed almost as well with the added benefit of fewer parameters being estimated in the least squares estimation scheme. The improvement of the asymmetric models over the symmetric solution (Standard) was marginal but this is most likely due to January being a relatively quiet month for tropospheric variability in Canada. It is expected that the impact of modeling the asymmetric delay would be greater in locations or seasons which have more tropospheric variability.

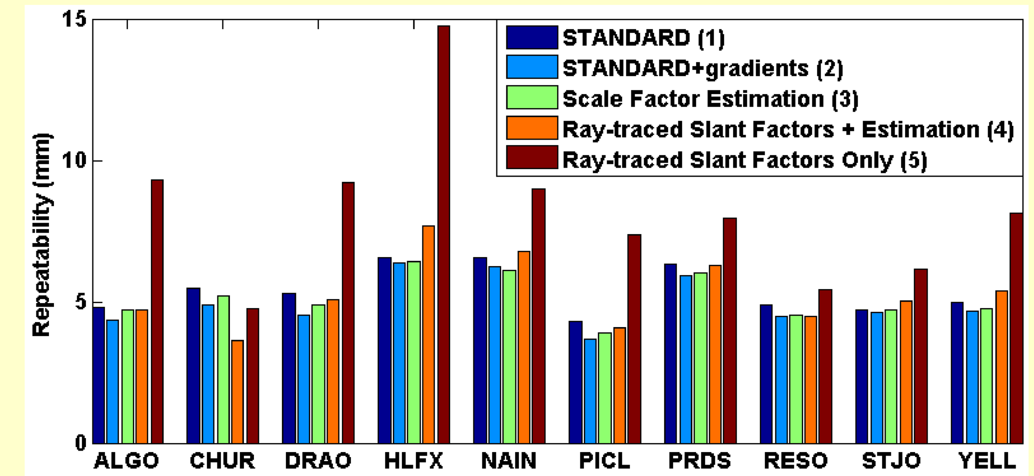

Figure 4.0 Repeatability of station solutions in up direction for Jan. 1-14, 2008

Repeatability (mm)			
Solution	N	E	U
1	2.5	2.9	5.4
2	2.4	2.8	5.0
3	2.2	2.9	5.1
4	2.1	3.1	5.3
5	2.1	3.2	8.2

Table 1.0 Summary of mean station repeatabilities for Jan 1-14, 2008

It was encouraging to see that even without any estimation residual delay parameters, cm level repeatability was achieved in the up direction. Additionally, we have the added benefit of a reduced convergence time, shown in Figure 5.0, with nearly 98% of the (daily) solutions converging to 10cm (3D) in 10 epochs (50 minutes) or less while the other approaches only achieved 82% convergence for the same time interval. The estimation of the gradient parameters did not significantly effect the convergence time which is due to the tight a priori constraints on the gradient parameters.

Figure 6.0 shows the epoch-by-epoch difference between the estimated total tropospheric zenith delays (after convergence has been achieved) and the predicted zenith delays computed by ray-tracing through the CMC regional model. Overall, there were small biases of 2mm seen with a standard deviation of 1.7cm at the 99% confidence level. correcting the observations.

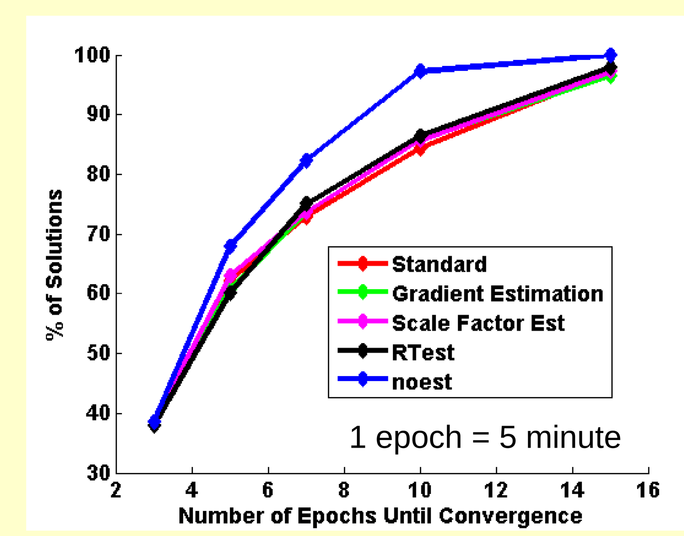

Figure 5.0 % of solutions which converged to 10 cm (3D) as a function of number of epochs.

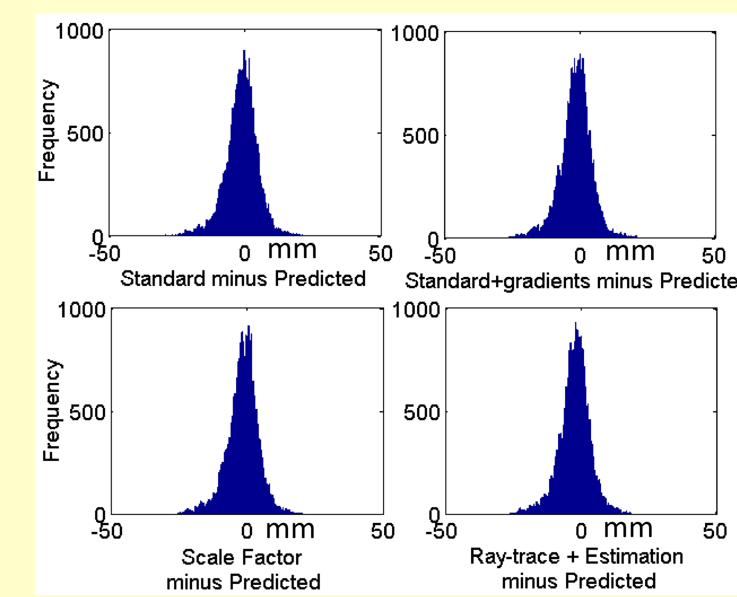

Figure 6.0 Distribution of estimated residual delays after convergence has been achieved (3 hours) w.r.t predicated delays. Units of mm.

6. Conclusions

The gradient estimated solution showed the best station repeatability although the use of ray-traced slant factors was shown to perform almost as well. We showed that the use of NWM predicted tropospheric zenith delays can allow for cm level station height repeatabilities, and lead to a significant improvement in convergence time. The use of the a priori gradients along with scale factor estimation was shown to be a valid method for modeling the asymmetric zenith delay although it was not as good as estimating both the direction and magnitude of the asymmetric delay. The improvement of the asymmetric cases over the standard, symmetric atmosphere approach was not as large as expected. This is most likely due to the low tropospheric variability during the month of January. Future work will include improving the stochastic models used in the scale factor estimation as well as extending the test period to include epochs when the troposphere is expected to have a larger impact on the position results.

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