Improving GPS surveying with modeled ionospheric corrections

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Abstract. We model the ionospheric delay of Global Positioning System (GPS) signals with high precision and use it to correct single frequency (L1) GPS baseline estimations. We find that baselines up to 30 km in length are more precisely determined using corrected L1 data than using dual frequency data. The high resolution ionospheric modeling technique (called HiRIM in this paper) is demonstrated with 195 days of data from a 25-site GPS network at ~1 km spacing in central Japan. The network was designed for high vertical precision tectonic studies. We compute ionospheric corrections using data from a surrounding grid of nine GPS sites spaced ~50 km. Based on the observations from the surrounding grid, epoch and satellite specific ionospheric delays are interpolated to correct L1 observations from the internal sites. HiRIM has potential post-processing and real-time applications in navigation, surveying, and GPS meteorology.

Introduction

The ionosphere causes GPS signal delays proportional to the total electron content (TEC) along the path from the GPS satellite to a receiver. High accuracy GPS surveying routinely uses dual frequency observations (called L1 and L2) to form a linear combination (called L3) to correct for this dispersive delay [Spilker, 1978]. Over very short baselines, higher precision results are obtained using single frequency (L1) differential GPS data than with dual frequency data. This has two reasons. First, ionospheric effects at the two ends of a short baseline are very similar and cancel in differential processing. Second, observational noise of the L3 linear combination is larger by a factor of ~3 than for L1 observations only. The linear combination amplifies random phase measurement noise and, in addition, noise due to multipath and antenna phase pattern and monument differences. Thus the baseline length for which L1 solutions are more precise than L3 solutions is determined by ionospheric conditions and noise characteristics (including site and antenna effects) of the GPS stations.

Figure 1 shows the vertical component vs. time for a 300 m baseline using L1 and L3 data. The ends of this baseline have different monument and antenna types. The L3 processing [Rothacher et al., 1996] includes tropospheric parameter estimation. Thermal noise and systematic errors due to signal multipath and mismodeling of the antenna phase center are amplified when the L3 linear combination is formed. Clearly the L1 results are significantly more precise than the L3 results. L1 tropospheric estimation would cause a slight increase in L1 baseline scatter but would still be significantly more precise than the L3 results for this short baseline.

The results in Figure 1 are not affected by orbit, ionospheric or tropospheric errors because the baseline is so short. Therefore, these results represent a lower limit of the achievable precision with this type of GPS setup. Thus, if it were possible to model the ionospheric delay with sufficient accuracy, L1 baselines should be more precise than L3 baselines over longer distances than the demonstrated 300 m baseline as well.

Figure 1. Height scatter relative to the mean for a 300 m baseline at Tsukuba, Japan, using L1 and L3 processing.

Ionospheric Correction Model

Ionospheric models are usually computed by determining the TEC in the direction of all GPS satellites in view from a ground GPS network. The line of sight TEC measurements are scaled to the vertical direction (TECV). These TECV are attributed to the intercept point of the slant path with an infinitesimally thin shell that is typically placed at a height of 350-400 km. Next all the TECV values observed over some time are fit by a surface in a Sun-fixed reference frame [e.g. Mannucci et al., 1998; Schaer, 1999]. The Sun-fixed frame is chosen because the ionosphere rotates with the Sun. Modeling of the ionosphere in this way (called the standard model in this paper) does not capture small scale and high frequency ionospheric disturbances. We model these fluctuations as small correction planes to the standard ionospheric model as illustrated in Figure 2.

We can either import an ionospheric model or use the Bernese software to compute an ionospheric model assuming a shell at 350 km height and using ionospheric GPS observables computed from the linear combination L4=L1-L2 [Schaer, 1999, Rothacher et al., 1996]. We process double differences (dd) which include observations along 4 different paths (from 2 observation sites to 2 satellites), so that carrier phase cycle ambiguities can be resolved. Ambiguity resolution is important and improves the results because it reduces the number of estimated parameters and ensures that there is no correlation between ambiguity parameters and the ionospheric model and residuals. The dd analysis provides post fit dd residuals and an ionospheric model that approximately describes TEC in the region of our network. Residuals include noise plus the double differences of delays that could not be modeled with the iono-
spheric model. Noise sources that affect the residuals are primarily measurement noise, site multipath effects, and antenna phase center errors.

![Diagram](image_url)

Figure 2. Standard and observed ionospheric delays (line height above Earth’s surface represents model TECV) and ionospheric delay interpolation in the direction of an observed GPS satellite. Ionospheric delay values for each monitoring site, satellite and epoch (represented by the thin black lines) are used to estimate the best plane fit. The ray path intersection from L1 sites (dotted line) with this plane is used to compute the ionospheric correction.

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Next we convert the dd ionospheric delay residuals to zero-difference (zd) residuals. The zd or slant delay residuals correspond to the unmodeled delay between 1 observation site and 1 satellite. This dd to zd conversion is described and validated by Alber et al. [2000] and Braun et al. [2000]. The zd method depends on two assumptions: (1) the weighted sum of all single differences (differences of observations from 2 stations to 1 satellite) observed from a station pair at one epoch is equal to zero, and (2) the weighted sum of all zero differences in the direction of one satellite observed by the entire monitoring network at one epoch is equal to zero. This step of the analysis provides \( zd(t_k, \text{lat}_j, \text{lon}_j) \) for satellite \( j \) at station \( i \) with horizontal geodetic coordinates \( \text{lat}_i \) and \( \text{lon}_i \) at epoch \( t_k \).

Next (if \( i \geq 3 \)) we fit a plane to the \( zd(t_k, \text{lat}_j, \text{lon}_j) \) residuals for each satellite \( j \) at each measurement epoch. The sum of the standard ionospheric correction (which can be computed from the standard model at time \( t_k \) at the location of the ray intercept point and angle with the ionospheric shell) plus the value of the epoch and satellite specific plane for a station’s known longitude and latitude is the ionospheric correction that we use to correct single frequency observations.

Similar plane fits to ionospheric double differences were first described by Wanninger [1995]. In that study the planes were fit directly to the full ionospheric dd residuals. The dd correction terms were then interpolated and applied to improve ambiguity resolution and single frequency processing results. The advantage of the method described here is that we compute the corrections based on zero differences from a monitoring network and apply them to data collected by another network. Wanninger’s method requires common reference sites and reference satellites between monitoring and L1 networks, our method does not. This distinction is important because the new technique is easier to implement, avoids antenna mixing issues if the monitoring network uses different antennas than the L1 network, and lends itself to potential real-time applications.

We generate a file that contains the parameters of a plane for every satellite observed by the monitoring network at every epoch. This file plus the standard ionospheric model are provided to the analysis of the L1 network. In this paper we process the L1 network with double differences and apply these corrections. Any bias of the epoch specific correction planes introduced by the assumptions in the dd to zd conversion cancels when applied in double difference processing.

**Results**

The network to evaluate the HiRIM technique is shown in Figure 3. Corrections were applied to GPS data observed near solar maximum conditions. The monitoring network is a subset of the 1,000-station Japanese national GPS network GEONET (http://mekira.gsi-mc.go.jp/). The corrections are applied to a subnetwork of sites that is called the High Vertical Accuracy Network (HVAN). The maximum height difference between HVAN sites is 80 m. The HVAN sites use dual frequency receivers mounted on 2.5 m stainless steel monuments. We process L1 data from this network with HiRIM corrections to obtain more precise geodetic results than are possible with L3 solutions.

![Diagram](image_url)

Figure 3. Monitoring network sites (open diamonds) and HVAN sites (black dots) in Japan.
In Figure 4 we compare dual frequency and HiRIM L4 ionospheric values for one site and one satellite. Plotted L4 values were obtained by first computing dd residuals relative to the standard ionospheric model for the network. L4 dd residuals were then converted to slant residuals using the zd method described above [Alber et al., 2000]. Ambiguity parameters were estimated and resolved where possible.

Figure 4. Comparison of HiRIM corrections (thick) with L4=L1-L2 zero difference residuals (thin)

The good agreement in Figure 4 is typical for H VAN processing and shows that small-scale ionospheric fluctuations can be corrected with HiRIM. Ionospheric model plus HiRIM corrections represent absolute unbiased ionospheric delays only if the assumptions that we apply in the dd to zd inversion are correct. If these assumptions are in error the HiRIM corrections for an epoch and a satellite are biased. The comparison values in Figure 4 may thus be biased, but they are biased by the same amount because they are obtained from the same dd to zd conversion step. Such biases can be caused, for example, by a bias in the ionospheric model above the network. It is very important to note that this bias, if it occurs, will always be the same at all stations for a given epoch and satellite. Therefore this bias cancels when HiRIM corrections are applied in dd GPS processing for geodetic or atmospheric applications.

To determine the effect of the HiRIM corrections on geodetic surveying precision we processed the data from the H VAN network in five different modes. For days 078 to 285, 1999, we computed 195 daily L1 solutions using an ionospheric model and including no tropospheric estimation (L1 NT), 3-hr. tropospheric estimation (L1 3T), and 3-hr. tropospheric estimation with HiRIM corrections (HR 3T). In addition, we computed L3 solutions with no tropospheric estimation (L3 NT), and with 3-hr. tropospheric estimation (L3 3T).

We computed component solutions for all possible baselines in the H VAN network. The daily vertical baseline solutions in Figure 5 show that the HiRIM results are more precise than the dual frequency solutions for almost all baselines up to 30 km in length.

Next we compute linear fits to the rms of the daily vertical solutions for baselines up to 30 km and for the longer baselines (Figure 6). The 10 km breakpoint is chosen somewhat arbitrarily based on the break in slope seen by the eye. A different choice in a reasonable range (7-10 km) would not significantly affect the key results described below. In Figure 6 we see that vertical HiRIM solutions are more precise than L3 solutions for baselines up to 30 km in length. The L1 solutions are slightly better than the HiRIM solutions for baseline lengths shorter than 1 km, and are better than the L3 solutions for baselines shorter than 2.5 km. Estimation of tropospheric parameters does not improve the L1 solutions for any baseline length, implying that tropospheric estimation cannot reduce the ionospheric error. The vertical rms is higher for L3 solutions with tropospheric estimation up to 5 km, and for baselines longer than 5 km tropospheric estimation improves vertical precision. The effect of tropospheric estimation on the L1 and L3 results is an interesting result by itself, but will not be discussed in this paper which focuses on ionospheric modelling. The key result is that HiRIM solutions provide the most precise vertical baselines for the entire H VAN network. Averaged over all baselines the vertical 195-day rms scatter is improved by 1.2 mm with HR 3T compared to L3 3T. Horizontal components computed with HiRIM do not show a significant difference compared to L3 3T (0.05 mm average rms improvement in the North and -0.02 mm average rms worsening in the East) and are not shown here.

Figure 5. Vertical solutions for all H VAN baselines. Each dot is the rms of 195 daily solutions. All L3 3T rms values above 8 mm can be attributed to 3 sites. Height scatter relative to the mean for a 300 m baseline at Tsukuba, Japan, using L1 and L3 processing.

Figure 6. Linear fits to daily baseline vertical rms vs. length for the 5 solution types.

**Atmospheric Sensing**

GPS networks have potential applications in atmospheric sensing [Ware et al., 2000]. For example, single path phase
delays can be used to model three dimensional water vapor fields [MacDonald and Xie, 2000]. In particular, dense L1 arrays are being evaluated for use in defining high resolution water vapor fields. If the L1 array is located inside of a sufficiently dense dual frequency GPS grid, HiRIM could be applied to correct for ionospheric effects. This approach could provide lower cost and higher accuracy GPS atmospheric sensing.

Conclusions

For baselines up to 30 km the ionospheric delay can be modeled as an epoch and satellite specific plane to a high level of precision. Single frequency networks using this model can provide better GPS surveying results than dual frequency networks, even during solar maximum conditions. This is possible because the L1 observations are lower in noise than dual frequency observations. In addition multipath and uncorrected antenna phase center errors at the dual frequency monitoring sites can be considered uncorrelated and are filtered when the ionospheric correction planes are estimated. The quality of the HiRIM corrections depends on ionospheric conditions and on the spacing of the monitoring network. As long as ionospheric residuals can be modeled accurately as satellite and epoch specific planes the technique works. HiRIM models the ionosphere at a higher resolution than previous ionospheric models because it covers only those areas of the ionosphere that are pierced by network-to-satellite rays. There is no interpolation between pierce points for different satellites like in traditional ionospheric models. Additional improvement of the technique can be expected if we introduce weighting of corrected observations based on the quality of each plane fit. Extrapolation of our results to monitoring networks with larger spacing and to different ionospheric conditions (i.e. tropical ionosphere) requires additional experimental and analysis work. Because we do not know the ground truth for the HVAN network we cannot assess the effect of HiRIM on surveying accuracy.

Our results show that lower cost L1 GPS networks can provide more precise surveying than more expensive dual frequency networks over baselines less than 30 km in length. L1 networks will not only be cheaper, but can also be more precise as long as HiRIM corrections are provided by three or more dual frequency monitoring sites that surround the L1 network. Monitoring networks could be established for population centers and, in principle, HiRIM corrections could be computed and broadcast in real time to extend the range of precise real-time kinematic surveying.

Acknowledgements. This work was supported by the Geographical Survey Institute of Japan, the development of the dd to zd method was supported by the Office of Naval Research, Dr. Scott Sandgathe, Code 322MM.

References


Braun, J., C. Rocken, and R. Ware, Validation of single slant water vapor measurements with GPS, Radio Science, accepted for pub., July 2000.