

Utility of NOAA Ionosphere and Troposphere Models for Extending the Range of High-Accuracy GPS

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Introduction

High-accuracy (cm level), real-time dynamic positioning using Global Positioning System (GPS) satellites has been a reality for many years. The limiting factor to this accuracy, using this positioning method, is the distance of the roving (dynamic) receiver from the known base station (baseline length). When two GPS receivers are located relatively close together, nominally within 20 km, received radio signals traveling from the satellites, pass through similar atmosphere and, consequently, the effects of the atmosphere on those signals are similar. Therefore, errors associated with atmospheric effects can be estimated at the known base station and applied to the roving station in a process known as differential GPS. As the baseline length increases, the satellite signals pass through different parts of the atmosphere, and the effects of the atmosphere will begin to decorrelate between the base and roving receiver.

Two segments of the atmosphere have significant, and different, effects on GPS radio signals. They are the ionosphere and the troposphere. The conventional methods for dealing with these errors in real-time situations over long baselines (>20 km) are: differential GPS, closed-form troposphere models such as Saastamoinen, estimation of a Zenith Propagation Delay (ZPD) term in the position solution, and the creation of an 'ionosphere-free' observable by combining L1 and L2 observations.

The subject of this poster is the USM NGI study on the use of NOAA generated ionosphere and troposphere models to aid in long-range, high-accuracy differential GPS. Six Continuously Operating Reference Stations (CORS) sites from Louisiana have been selected for this study (see figure 1). Pairs of sites have been combined to create six baselines ranging from 25 to 300 km (see table 1). Four days with varying troposphere activity have been selected (June 29, July 5, 6 and 7, 2006). All of the data files have been acquired and processed. Data include:

- 30-second GPS observations
- NOAA troposphere wet delay maps
- NOAA USTEC ionosphere Total Electron Content (TEC) maps

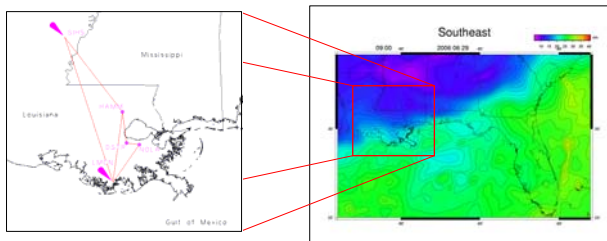
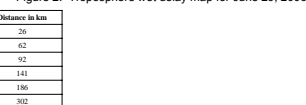


Figure 1: CORS stations and Baselines

Baseline	Distance in km
DSTR - NOLA (D-N)	26
DSTR - HAMM (D-H)	62
LMCN - NOLA (L-N)	92
LMCN - HAMM (L-H)	141
SIHS - HAMM (S-H)	186
LMCN - SIHS (L-S)	302

Table 1: Baseline lengths

Figure 2: Troposphere wet delay map for June 29, 2006



Processing

The USM GPS data processing software has been enhanced to include a Zenith Propagation Delay (ZPD) term to account for un-modeled troposphere errors and an algorithm to introduce high frequency ionosphere perturbations into the ionosphere models (known here as the Modified Doug P [MDP] solution). Each baseline, for each day, was processed multiple times with a variety of ionosphere mitigation methods and models, only a few of which are presented here.

Each of the processing methods was run using the Saastamoinen closed form troposphere model as well as the NOAA troposphere maps. Each of the processing and troposphere methods were also run with ZPD option on and off and the MDP option on and off. The total number of 24 hour processing runs was 1728. Error statistics (mean, standard deviation and root-mean-square [rms]) were determined by comparing the computed epoch-to-epoch positions with the known CORS position.

This poster depicts examples of the processing results for one day (day of year [DOY] 180, June 29, 2006), using the following ionosphere processing methods:

- Ionosphere-free (Iono Free), which combines L1 and L2 into a single observation that is free of the effects of the ionosphere, but has greater noise and removes the integer nature of the ambiguity.
- USTEC float (USTEC S), which keeps L1 and L2 as separate observations and applies the USTEC ionosphere model in a floating ambiguity solution.
- USTEC fixed (USTEC SF), which uses the USTEC float solution to attempt to resolve the integer ambiguities, which are then used in an ambiguity fixed solution.

The troposphere map shown in figure 2 depicts the wet delay for 0900 hrs on June 29. This map clearly indicates a high gradient between the land and water, with very dry air on land and very wet air over the water. As a result, stations inland will have less effect from the troposphere than stations near the coast. Baselines where both stations are near the coast will experience similar troposphere delays, as will stations that are both further inshore (SIHS-HAMM). However, baselines that have one station inshore and one near the coast (LMCN-SIHS and LMCN-SIHS), will have vastly different troposphere effects.

Sample of results from short and medium baselines

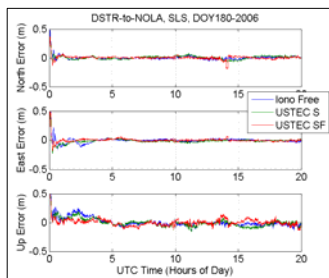


Figure 3: Short baseline north, east and up errors

	Bias	StdDev	RMS
Iono-Free	0.00	0.07	0.07
USTEC Float	-0.01	0.06	0.06
USTEC Fix	0.00	0.05	0.05

Table 2: Short baseline up (height) error bias, standard deviation (1 σ) and rms in meters

The three dimensional results for 20 hours of 30-second observations, from a short baseline (26 km shown in figure 3) and an intermediate baseline (62 km shown in figure 4), are presented here as examples. The time series plots depict the epoch-to-epoch position errors (north, east and up) relative to the known CORS station position. Both baselines were processed with the NOAA troposphere model, and with MDP and ZPD turned on. Beneath each plot are the resulting statistics (in meters) for the height error (see tables 2 and 3). These results indicate that the methods and models used in this study can achieve high-accuracy positioning over short and medium baseline

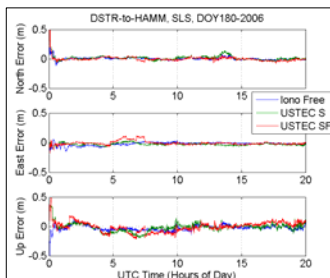


Figure 4: Medium baseline north, east and up errors

	Bias	StdDev	RMS
Iono-Free	-0.02	0.04	0.05
USTEC Float	-0.02	0.06	0.06
USTEC Fix	-0.01	0.08	0.08

Table 3: Medium baseline up (height) error bias, standard deviation (1 σ) and rms in meters

Sample of results for height from all baselines

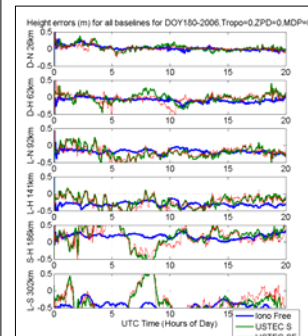


Figure 5: Height error for all baselines, in meters, using Saastamoinen troposphere model and ZPD and MDP off

The height results from all baselines, for 20 hours of 30-second observations, are shown in figures 5 and 6. Figure 5 shows the results from using the Saastamoinen closed form troposphere model and with MDP and ZPD turned off. Figure 6 shows the results from using the NOAA troposphere model, with MDP and ZPD turned on.

The ionosphere-free solutions are consistently the best for most baselines, in both figures, especially in the longer baselines. However, when using the ZPD and MDP (right figure) the USTEC float and fixed solutions come much closer. The MDP algorithm is not used in the ionosphere-free solution.

It is evident from the two figures that the solution improves considerably when using the NOAA troposphere model and with ZPD and MDP turned on. This is especially true as the baseline length increases. Bias improvements are very evident in the LMCN-SIHS and LMCN-HAMM baselines, which have both coastal and inland stations.

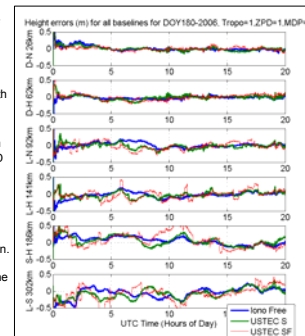


Figure 6: Height error for all baselines, in meters, using NOAA troposphere model and ZPD and MDP on

Evaluation of the effect of using NOAA troposphere model, MDP and ZPD

The following series of plots (figures 7 through 14) show the evaluation results from using the NOAA troposphere model as opposed to the closed form Saastamoinen model, as well as the effectiveness of using a Zenith Propagation Delay (ZPD) term and the Modified Doug P (MDP) algorithm. The figures show the height rms error (in meters) computed over 20 hours, plotted against the baseline length (see table 1 to correlate baseline length to stations). Figures 7 through 10 used the Saastamoinen troposphere model and figures 11 through 14 used the NOAA troposphere model. The ionosphere-free solution with the Saastamoinen troposphere model, and using a ZPD delay term was considered to be the 'conventional' solution and was included in all plots as a reference (IF SAAST ZPD). The optimum solution came from using the NOAA troposphere model, with MDP and ZPD on (see figure 14).

Note: MDP is never used in the ionosphere-free solution.

The most striking improvement came from using the NOAA troposphere model. This was evident from the large improvements in most of the baselines, over using the Saastamoinen model, (see figures 11 through 14). The greatest improvement occurred for the longer baselines that had both coastal and inland stations (140 and 300 km). The improvement would be almost linear with baseline length if not for the 186km baseline (SIHS-HAMM), for which both stations were inland and consequently had similar tropospheric effects. As shown in the figures there is very little improvement from using the ZPD term, this is especially apparent from the ionosphere-free solution of figure 7, where the error when using ZPD (IF SAAST ZPD) is only slightly less than when it is not used (Iono Free). Both the USTEC float and fixed solutions showed a little improvement when using ZPD, but showed much greater improvement when using the MDP algorithm (see figures 9 and 13). The USTEC float solution improved to the point where it was comparable to the ionosphere-free solution.

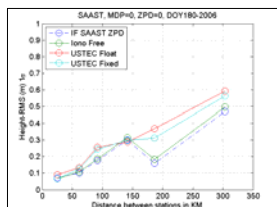


Figure 7: Saastamoinen, MDP off, ZPD off

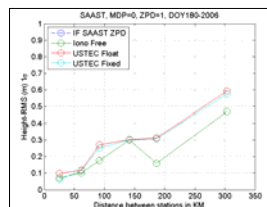


Figure 8: Saastamoinen, MDP off, ZPD on

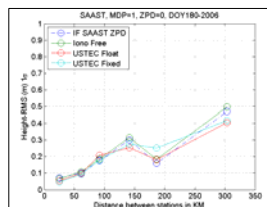


Figure 9: Saastamoinen, MDP on, ZPD off

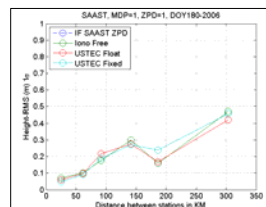


Figure 10: Saastamoinen, MDP on, ZPD on

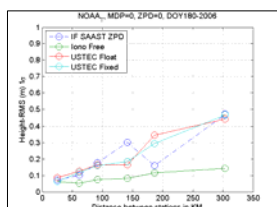


Figure 11: NOAA, MDP off, ZPD off

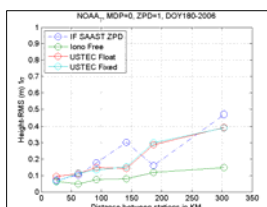


Figure 12: NOAA, MDP off, ZPD on

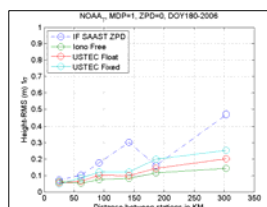


Figure 13: NOAA, MDP on, ZPD off

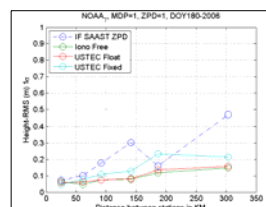


Figure 14: NOAA, MDP on, ZPD on

Conclusions

The evaluation to this point indicates that using the NOAA troposphere model greatly improves the position accuracy, especially when dealing with highly variable weather conditions between the base and roving stations. The ionosphere-free solution, which does not use any ionosphere model, overall produces the best results. However, the float solution using USTEC (USTEC S) and MDP comes very close, and it is the only method that can lead to a reliable ambiguity fixed solution (USTEC SF). Using ZPD does help the solutions, but only marginally. Using MDP with the USTEC ionosphere model greatly improves the float solutions, which improves the software's ability to create a reliable fixed solution. The fixed solutions (USTEC SF) perform well for the short baseline, but the accuracy starts to degrade with baseline length because the software occasionally fixes on the incorrect set of ambiguities.



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