GPS surveying with 1 mm precision using corrections for atmospheric slant path delay

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Abstract. Multipath and atmospheric effects can limit GPS surveying precision. We surveyed a 43 km baseline using large diameter choke ring antennas to reduce multipath and pointed radiometer and barometric data to correct for atmospheric slant delay. Based on 11 daily solutions, atmospheric slant delay corrections improved vertical precision to 1.2 mm rms and horizontal precision to sub-mm. Applications for high precision GPS surveying include deformation monitoring associated with earthquake and volcanic processes, subsidence, isostasy, and sea level measurements; monitoring of atmospheric water vapor for climate and global change research, and to improve the resolution of synthetic aperture radar; calibration of satellite altimeters; and precise satellite orbit determination.

Introduction

The 24 Global Positioning System (GPS) satellites broadcast signals at 1.6 (L1) and 1.2 (L2) GHz. GPS signal phases can be observed and analyzed to determine the vector between two or more sites [*Herring*, 1996].

Traditional GPS surveying [*Dixon*, 1991] can obtain ~2 to 5 mm horizontal and ~4 to 10 mm vertical precision over 1,000 km baselines. Atmospheric effects are corrected using a parameter estimated in the GPS analysis that maps approximately as the cosecant of the satellite elevation angle [*Niell*, 1996], defined as

$$\text{zenith delay} = 10^{-6} \cdot \int_{\text{antenna}}^{\infty} N(z)dz \tag{1}$$

where dz has units of length in the zenith direction, and

$$N = 77.6\frac{P}{T} + 3.73 \times 10^{5}\frac{e}{T^2} \tag{2}$$

approximates refractivity at a point with air pressure P (mb), water vapor pressure e (mb), and temperature T (K). The first or “dry” term in N contributes up to 240 cm to zenith delay and the second or “wet” term contributes up to 40 cm.

A more exact approach corrects for slant delay along the line-of-sight to each of the observed GPS satellites, where

$$\text{slant delay} = 10^{-6} \cdot \int_{\text{antenna}}^{\text{satellite}} N(s)ds \tag{3}$$

and ds has units of length along the GPS ray path. We use surface pressure and pointed radiometer data to calculate slant delay. We ignore cloud, rain, snow, and atmospheric particulate effects which are typically more than 20 times smaller than water vapor effects [*Solheim et al.*, 1997a].

Experiment Description

We observed with GPS, radiometers, and barometers from sites at Platteville and Table Mountain, Colorado, during fall 1995 and spring 1996. The sites are relatively free from obstructions above 10^{o} elevation and are separated by 43 km. We used Trimble^{TM} SSI GPS receivers and standard 35 cm diameter TurboRogue^{TM} choke ring antennas augmented with 85 cm diameter choke ring collars (Figure 1) mounted on pillars of reinforced concrete.

Figure 1. Ground reflected multipath was minimized using choke ring antennas augmented with ring shaped collars 25 cm in width.

The antenna collar can be fitted to the choke ring antenna without dismounting or repositioning the antenna. We found that choke ring antennas with collars have 10 db lower gain below the horizon than choke rings alone. Gains of the two antenna types vs. zenith angle are shown in Figure 2.

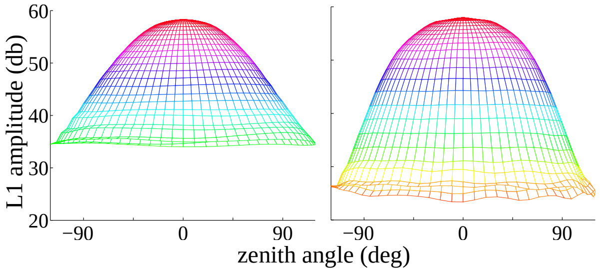

Figure 2. L1 gain of a 35 cm choke ring antenna alone (left), and with a 25 cm collar (right).

Single satellite GPS residuals computed using GIPSY software [*Webb and Zumberge*, 1993] are shown in Figure 3. The choke ring collar reduces ground reflected and other multipath by 40% [*Alber*, 1996; *Solheim*, 1997b].

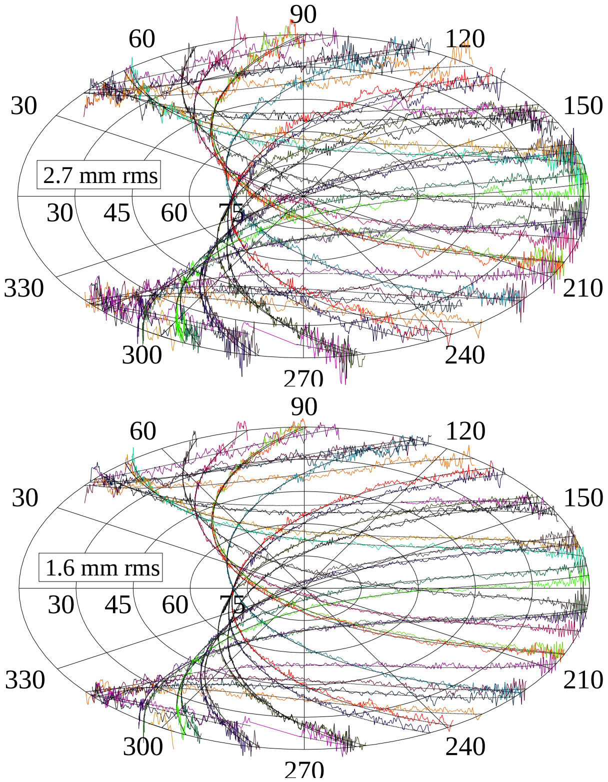

Figure 3. GPS residuals vs. azimuth and elevation angle. Antennas were mounted 10 m apart in a relatively high multipath environment on a laboratory rooftop.

Baseline component solutions vs. minimum satellite elevations are shown in Figure 4 [*Alber*, 1996; *Meertens et al.*, 1997]. Solutions are shown for 35 cm choke rings alone, and with the 25 cm collars added. The collars reduced baseline component variations for elevation cut-off angles between 10^o and 35^o by three times in the vertical and east components and by two times in the north component.

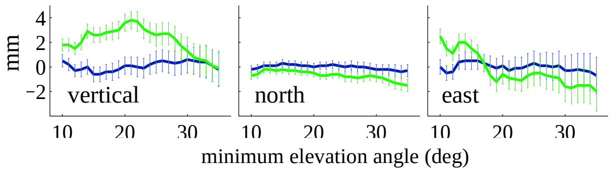

Figure 4. Daily baseline solutions and formal errors for pairs of 35 cm choke ring antennas with (blue) and without collars (green).

For our 43 km survey, we used an elevation cut-off angle of 20^o, logged barometric data accurate to 0.3 mb every min, and pointed Radiometrics WVR-1100^{TM} radiometers sequentially toward each of the GPS satellites in view. The radiometers observed at 23.8 and 31.4 GHz for 1 sec in the direction of each satellite during their ~8 min observation cycle, measuring slant wet delay with an accuracy of ~3 mm [*Ware et al.*, 1993].

Data Analysis

We analyzed the GPS data using Bernese software [*Beutler et al.*, 1996] and International GPS Service (IGS) precise orbits [*Neilan*, 1995]. The software computes double differences, defined as the difference in carrier phase of one satellite as observed from two sites, differenced again with a similar observation difference of a second satellite. Double differencing minimizes GPS transmitter and receiver clock errors.

The Table Mountain coordinates were constrained in the analysis to 50 mm horizontal and 70 mm vertical and the Platteville coordinates to 0.1 mm in all components. Solutions were computed using: (1) estimated zenith and (2) measured slant delay atmospheric correction methods. The zenith method estimates total (wet + dry) delays from the GPS observations in the traditional way. The slant method uses pointed radiometer data to correct for slant wet delay, and barometric data with a model [*Saastamoinen*, 1972] to compute slant dry delay.

Radiometer data were interpolated to the GPS observation times at 30 sec intervals. We required at least 22 hours of data for daily solutions. We excluded radiometer data degraded by moisture on the radiometer window and more than one week of spring observations due to a faulty GPS antenna connector. After these exclusions, we obtained daily solutions for eight 1995 fall days and three 1996 spring days.

Results and Discussion

We compare measured slant and estimated zenith delay corrected solutions in Figure 5 and in Table 1. The zenith correction method solves for zenith delays and coordinates. The slant correction method solves only for coordinates.

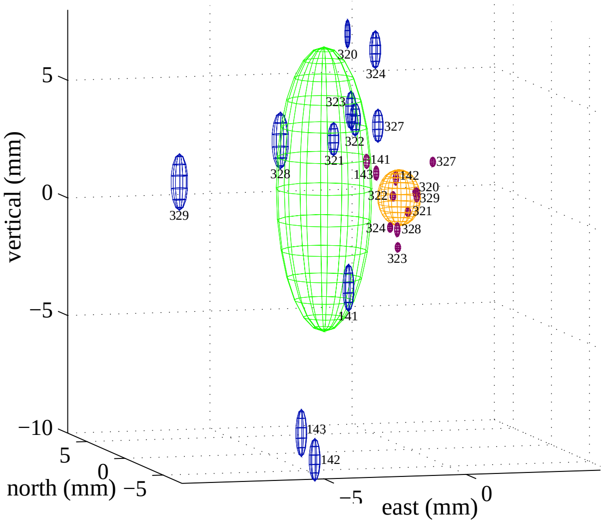

Figure 5. Daily slant (magenta) and zenith (blue) corrected solutions and formal errors using an elevation cut-off of 20^o, labeled by day of year. The 11 day, one sigma slant (orange) and zenith (green) corrected solution precisions are also shown. Days 320-329 were observed in 1995, and days 141-143 in

1996.

Table 1. Slant and zenith corrected survey precisions for 11 solution days. Also listed are offsets between the 11 day slant and zenith corrected solutions.

Atmospheric path delay correction method	Surveying precision and offset		
	vertical	north	east
slant (mm rms)	1.2	0.9	0.7
zenith (mm rms)	6.0	1.9	1.6
slant - zenith (mm)	0.3	0.9	-2.8

Slant corrected vertical precision is 1.2 mm, a factor of five better than the 6.0 mm obtained using estimated zenith corrections. Similarly, horizontal coordinate solutions are improved by a factor of two to sub-mm precision. Vertical and north coordinate offsets are sub-mm and the east coordinate offset is -2.8 mm. Coordinate precision for the two survey sets and the apparent coordinate movement (offset) over the six month time interval between surveys are listed in Table 2. The zenith corrected solutions show significant apparent vertical motion (12.2 ± 4.5 mm) that is not seen in the slant corrected solutions (1.5 ± 1.2 mm). This suggests a close relationship between atmospheric effects and apparent monument stability.

Table 2. Coordinate precision with slant and zenith corrections for fall ‘95 and spring ‘96 surveys. Also listed are the apparent coordinate movements (offsets) during the six month interval between the two surveys.

Correction method and time of survey		Surveying precision and offset		
		vertical	north	east
fall ‘95 8 days (mm rms)	slant	1.1	1.0	0.7
	zenith	2.2	2.0	1.9
spring ‘96 3 days (mm rms)	slant	0.5	0.5	0.7
	zenith	4.0	1.1	0.8
fall - spring (mm)	slant	1.5	0.5	-0.8
	zenith	12.2	-1.5	0.5

Radiometer observations at the two sites and their difference are shown in Figure 6. The difference is as large as 60 mm. Similar wet delay gradients were reported by *Rocken et al*. [1991] and by *Davis et al*. [1993] for a coastal site.

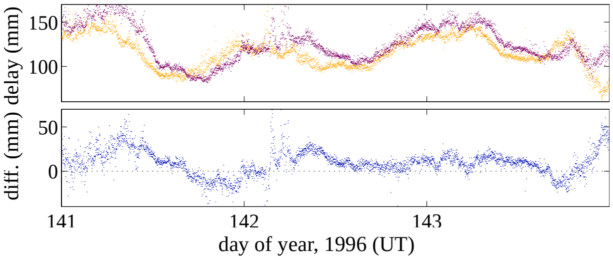

Figure 6. Radiometer sensed slant wet delays at Platteville (magenta) and Table Mountain (orange), projected to zenith, and their difference (blue). We attribute the scatter in each trace to wet delay gradients and the spikes to rain water on the radiometer windows.

We observed pressure gradients as large as 1 mb between the two sites during the experiment. This would induce a zenith dry delay gradient of ~3 mm. Thus, maximum delays resulting from wet gradients in this experiment are ~20 times larger than those from dry gradients. Similar wet and dry double difference delays were calculated by ray tracing through weather model data in Japan by *Ichikawa et al.* [1996].

GPS sensing of integrated water vapor along slant paths was first reported by *Alber* [1996], and later by *Ware et al.* [1997]. Typical examples of GPS and radiometer sensed double differenced slant wet delays are shown in Figure 7.

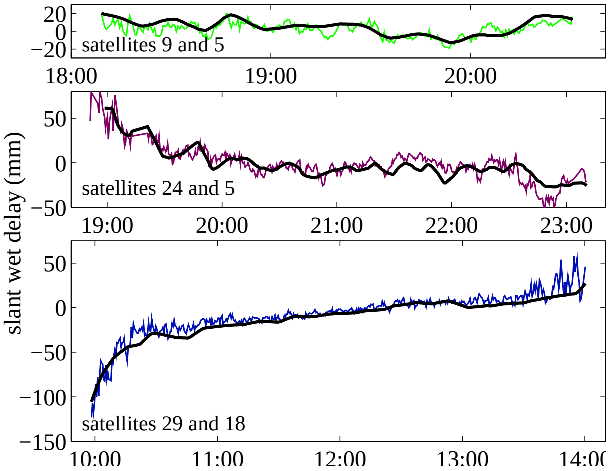

Figure 7. GPS (jagged, color) and radiometer (smooth, black) sensed double difference slant wet delay observations in Universal Time.

Ware et al. [1997] performed two dimensional ray tracing through a simulated 1 x 2 km cell of water vapor and found similarities to the high frequency variations seen in the GPS residuals in Figure 7. The high frequency variations are not seen in the radiometer data as they are smoothed by the 5^o beamwidth and 8 min sampling interval of the radiometers.

Sub-mm GPS surveying precision was reported by *Genrich and Bock* [1991]. They minimized atmospheric effects by surveying baselines less than 1 km in length and subtracted GPS residuals in sidereal time to reduce multipath effects.

Previous results using barometric and pointed radiometer data for slant delay correction are summarized in Table 3. The 1983 survey used Macrometer^{TM} GPS receivers and antennas, and pointed radiometers developed by NOAA. Only five GPS satellites were observed in this experiment and daily survey solutions included less than three hours of data. In spite of these limitations, slant delay corrections improved the vertical precision of the daily solutions in this experiment by a factor of three to 12 mm rms [*Ware et al.*, 1986].

Table 3. Slant corrected vertical GPS survey solutions vs. baseline length, number of solution days, and vertical precision improvement for slant compared to zenith corrected

solutions.

Date	Vertical precision (mm rms)	Improvement factor	Baseline length (km)	Number of solution days
1983	12	3	22	3
1992	2.6	2	47	19
1995	5	2	850	5
1996	1.2	5	43	11

The other experiments listed in Table 3 used Radiometrics WVR-1100s and observed 18 or more GPS satellites. The 1992 experiment used Trimble SST receivers and antennas and required a 20 hr minimum for daily solutions [*Ware et al*., 1993]. *Rocken et al*. [1993] identified ground reflected multipath in this experiment as the dominant source of error in wet delay estimates at 30 min intervals.

The 1995 experiment used a Trimble SSE ground plane antenna at a dry mountain site and a 35 cm choke ring antenna at a humid coastal site 850 km away [*Solheim et al*., 1995]. The use of mixed antennas, the combination of a dry inland and a humid coastal site, and the long baseline probably limited the precision in this experiment. Nevertheless, two times improvement in vertical precision was achieved using slant corrections. The 1995-96 experiment described in this paper and by *Solheim et al*. [1997c] used Trimble SSI receivers and 85 cm choke ring antennas.

These results demonstrate that slant corrections can improve GPS surveying precision by two to five times over 20 to 850 km baselines, even when mixed GPS antennas and humid coastal and arid mountain sites are included. They also show that one mm precision can be achieved if multipath is minimized. At this level of precision, errors associated with monument stability may become significant in GPS monitoring of crustal velocity [*Johnson and Agnew*, 1995].

Conclusions

We have demonstrated GPS surveying on a 43 km baseline with one mm precision using low multipath antennas and pointed radiometer slant delay corrections. The measured slant delay corrections improved vertical precision by a factor of five compared to estimated zenith delay corrections and horizontal precision to sub-mm. Similarly, a previous experiment demonstrated two times improvement in vertical survey precision for an 850 km baseline including mixed antenna types and a humid coastal site. Repeated or continuous surveys are needed over a number of years to better understand effects of slant delay, multipath, and monument stability in GPS monitoring of crustal velocity.

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