The Effect of Gradients in the GPS Estimation of Tropospheric Water Vapor

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BIOGRAPHY

Anthea Coster has been involved with the analysis of the earth's ionosphere and troposphere for the past 20 years. She received a B.A. in mathematics from the University of Texas at Austin and an M.S. and Ph.D. in space physics and astronomy from Rice University. She has been in the satellite tracking group at the M.I.T. Lincoln Laboratory Millstone Hill Radar since 1984. Arthur Niell is a research scientist at the M.I.T. Haystack Observatory specializing in geodetic measurements using GPS and very long baseline interferometry (VLBI). He received a B.S. in physics from Caltech and a Ph.D. in applied physics from Cornell University. Fredrick Solheim holds a doctorate in Geophysics from the University of Colorado. He is President of Radiometrics Corporation, a developer and manufacturer of radiometers for atmospheric sensing. He is also a part-time researcher at the Research Applications Program of the National Center for Atmospheric Research. Virgilio Mendes received his Diploma in Geographic Engineering from the Faculty of Sciences of the University of Lisbon, Portugal, in 1987. Since then, he has been working as a teaching assistant at this university. In 1991, he enrolled as a Ph.D. student at the University of New Brunswick. He is involved in tropospheric delay modeling of radio signals and the application of the Global Positioning System to the monitoring of crustal deformation. Pieter Toor graduated in May 1995 with the "degree of engineer" cum laude from the Faculty of Geodetic Engineering, Delft University of Technology. Following graduation, he spent the summer at the University of New Brunswick participating in several GPS projects. He currently works for Racal Survey Ltd. Richard Langley is a professor in the Department of Geodesy and Geomatics Engineering at the University of New Brunswick (UNB), where he has been teaching since 1981. He has a B.Sc. in applied physics from the University of Waterloo and a Ph.D. in experimental space science from York University, Toronto. Dr. Langley has worked extensively with GPS, concentrating on error modeling and reduction. He is a co-author of the Guide to GPS Positioning and is a contributing editor and columnist for GPS World magazine.

ABSTRACT

The Westford Water Vapor Experiment (WWAVE) was designed to measure the temporal and spatial variability of the total precipitable water vapor over an area within a 25 km radius of the Haystack Observatory in Westford, MA. The main experiment was conducted from 15-30 August 1995, and a variety of different techniques were used to measure the water vapor, including: radiosondes, launched two to three times daily from one location; a water vapor radiometer (WVR); and eleven GPS receivers separated by 0.5 to 35 km. The WVR scanned continuously in azimuth and elevation. Line of sight measurements of the wet delay by the WVR were used to estimate spatial and temporal gradients in the water vapor distribution. GPS data were analyzed for correlations with times of large gradients.

INTRODUCTION

Typically, the water vapor distribution around a site will exhibit some inhomogeneous structure. During the WWAVE campaign, measurements of the water vapor distribution were obtained with a WVR that scanned continuously in azimuth and elevation. One of the GPS receivers used during WWAVE was located approximately 200 m from the WVR location. This receiver was an Allen Osborn Turbo Rogue receiver with a Dorne Margolin choke ring antenna. Another GPS receiver, an Ashtech Z12, was located approximately 10 km away. This receiver also had a Dorne Margolin choke ring antenna, although the antenna was covered by a radome.

This paper examines whether azimuthal asymmetry is observed in the GPS residuals, and if so, tries to ascertain whether these variations are correlated with the water vapor distribution observed in the WVR data. A gradient model is applied to both the WVR and GPS data, and the estimated parameters are compared.

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The final section of this paper summarizes the WWAVE observations.

BACKGROUND

Precipitable water vapor (PWV) is defined as the height of liquid water that would result from condensing all the water vapor in a column from the surface of the Earth to the top of the atmosphere. PWV is an important parameter in monitoring changes in the Earth's climate, and it can be used to improve weather forecasting. It has been shown by Kuo, et al., (1996) that when a PWV time series was introduced into the NCAR/Penn State mesoscale model, the accuracy of short-range precipitation forecasts improved significantly. Since 1992 scientists have been investigating the use of GPS for the determination of total precipitable water vapor (Bevis, et al., 1992; Bevis, et al., 1994; Rocken, et al., 1993; Rocken, et al., 1995; Dodson, et al., 1995; Coster, et al., 1996).

The primary meteorological measurement produced by GPS is the tropospheric path delay at zenith. The zenith tropospheric path delay is estimated from the various line of sight tropospheric delays corresponding to the different GPS satellites in view. Each of these various tropospheric delays is mapped to zenith using an elevation dependent mapping function. The tropospheric delay is further composed of two parts: a hydrostatic delay term, dependent on atmospheric pressure and temperature, and a wet delay term, dependent on the partial pressure of water vapor and temperature. These two terms can be separated given an accurate estimate of the surface barometric pressure. An error of 0.5 mb in the pressure measurement will cause a 1 mm error in the zenith wet delay (Rocken, et al., 1995). The zenith wet delay (ZWD) is related to PWV by a factor Π that is approximately 0.15 (Bevis et al., 1994). This factor varies by 20% and is a function of the weighted mean temperature of the atmosphere. It can be determined to about 2% when it is computed as a function of surface temperature, and to about 1% if data from numerical weather models are used. The zenith wet delay, ZWD, in the Westford, Massachusetts, area ranges from near 0 to approximately 40 cm, corresponding to a PWV of 0 to 6 cm.

Rocken et al. (1993) presented evidence that GPS could be used to measure the precipitable water vapor with an accuracy of 1 mm. Analysis of the WWAVE data set produces similar results when comparing GPS estimates of the zenith wet delay to those from radiosondes, a water vapor radiometer, and very long baseline interferometry,VLBI, (Coster, et al., 1995a, Coster, et al., 1995b, Niell, et al., 1995)**.** The WWAVE GPS estimates of zenith wet delay (ZWD) agree with measurements by WVR and radiosondes to within 6-12 mm, corresponding to 1-2 mm of precipitable water vapor (PWV). Elevation cutoffs of 5 degrees were used in all of the GPS data processing. The precision of the GPS measurement of ZWD is better than 6 mm (1mm of PWV), based on comparison of three GPS systems separated by about 1 km.

This paper is primarily concerned with the few time periods during the WWAVE experiment where the WVR estimates of the zenith wet delay do not agree very well with the GPS estimates of ZWD. Discrepancies were evident on three separate days during the WWAVE campaign: day 236, day 239, and day 244. All of these days show evidence of some amount of rainfall as detected by the liquid WVR measurement. Discrepancies between the WVR and GPS estimates of ZWD can be caused by any one (or some combination thereof) of four different factors: 1) the presence of liquid water on the mirror of the WVR; 2) incorrect retrieval coefficients used in the WVR estimation process of water vapor, (Niell, et al., 1995, Coster, et al., 1995b); 3) error in the GPS estimation of other quantities, such as satellite clock, receiver clock, GPS orbit, etc. (perhaps caused by the presence of multipath); and finally, 4) the presence of gradients in the water vapor distribution (which to first order appears as a spatial gradient).

Gradients in the water vapor distribution around a site do exist, and their presence will affect the estimated zenith wet delay. During the WWAVE campaign, a WVR was positioned approximately 200 meters from one of the central GPS sites (MHR0) and approximately 625m from the radiosonde launch site. This WVR scanned continuously in azimuth and elevation. A complete scan took approximately 15 minutes and included 8 azimuths (separated by 45 degrees) and 5 elevations, (90, 45, 27, 19, and 14). Note that GPS data were included down to 5 degrees elevation.

Until recently, water vapor gradients have not typically been modeled in the GPS estimation of zenith wet delay. Bar-Server (1997) has included a gradient model in GIPSY/OASIS and has reported improvements in position estimation due to its inclusion. Obviously, the ability to detect gradients in the water vapor distribution with a single GPS station would greatly increase the utility of GPS data.

GPS Processing

WWAVE used improved P-code GPS receivers and specific antennas to reduce site multipath. The two GPS receivers discussed in this paper both used Dorne Margolin choke ring antennas. These antennas were designed to minimize the multipath problem, and their use allowed the inclusion of GPS data down to 5 degrees in elevation. In this paper, the GPS estimates of the zenith wet delay were computed using JPL's GIPSY/OASIS software (Webb and Zumberge, 1995) and the JPL determined precise orbits were used. These orbits are predicted to be accurate to 20 centimeters, although recent modifications have improved the orbits to 10-15 cm (Lichten,1996). The precise point positioning technique was used (Zumberge et al., 1997). GIPSY/OASIS was updated with the Niell tropospheric mapping function (Niell, 1996).

Water Vapor Radiometers

A ground based water vapor radiometer (WVR) is an instrument that scans the sky and measures the brightness temperature (radiation energy) of all water vapor along the line of sight. For WWAVE, a Radiometrics™ Corporation WVR-1100 portable water vapor radiometer was used. It operates at two frequencies. One channel is at 23.8 GHz the other is at 31.4 GHz. The 23.8 GHz channel is dominated by water vapor but contains some cloud liquid signal, and the 31.4 GHz channel is dominated by cloud liquid but contains some vapor signal. The contributions can be separated algebraically. The techniques used to convert the WVR measurement to zenith wet delays are described by Elgered, (1993).

The T_{mr} and retrieval coefficients were computed by linear regression analysis of the previous year's radiosonde data for July, August, and September from the NWS sites of Chatham, MA, Grey, ME, and Albany, NY. This analysis assumes a model for the molecular absorption of water vapor. There is some evidence that the NWS sondes produce PWV estimates that are too large (Coster, et al., 1995b).

Errors in the WVR estimate of ZWD can be introduced in the retrieval algorithms, in the absorption models for water vapor emission at the WVR frequencies, and/or in the calibration uncertainties of the radiometer. S. J. Keihm (1995) estimates that one can expect PWV retrieval biases of 1mm in PWV for dry conditions (6.5 mm zenith wet delay) and 2.5 mm of PWV (16-20 mm zenith wet delay) for very humid conditions. It may well be that some of the discrepancies we see in the WWAVE data are due to these very humid conditions.

OBSERVATIONS

The overall analysis of GPS derived estimates of ZWD are shown in Figure 1.

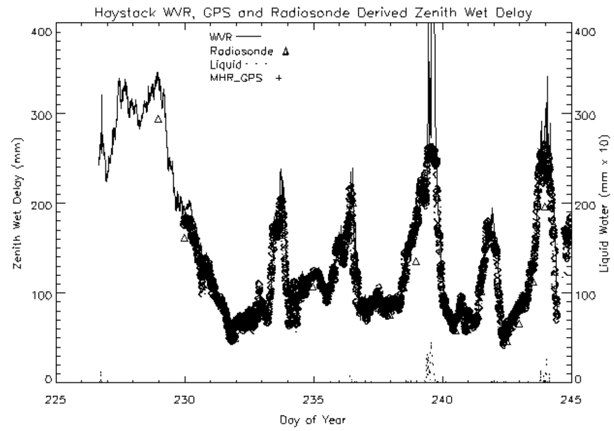

Figure 1. Haystack Radiosonde, WVR, and GPS Derived Zenith Wet Delay

With the exception of the time periods associated with rain, it is clear that the estimates of the zenith wet delay from the various techniques agree very closely. The three days of concern are 236, 239, and 244. Looking at these days individually we see the following.

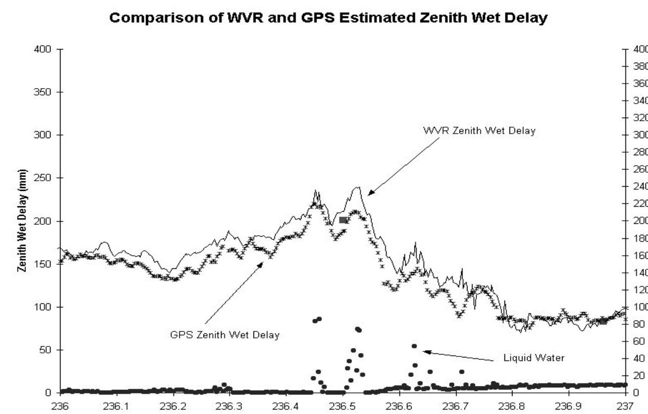

Figure 2. WVR and GPS Estimate of ZWD, Day 236

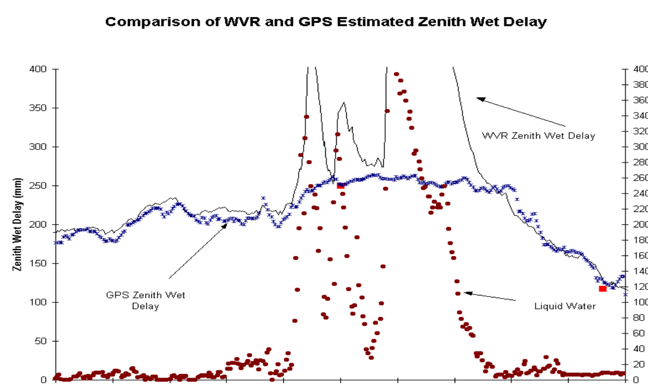

Figure 3. WVR and GPS Estimate of ZWD, Day 239

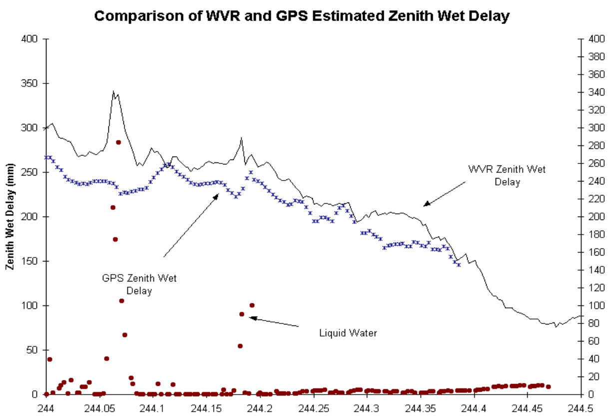

Figure 4. WVR and GPS Estimate of ZWD, Day 244

Each of these days (Figures 2-4) represent different conditions. It is clear that the difference in the zenith wet delay on day 236 (Figure 2) is greater towards the middle of the day when liquid water appears to be present. The average difference is about 10-15 mm of zenith wet delay. It is equally obvious that both the WVR and the GPS estimate of ZWD show the same smaller scale pattern of variation in the zenith wet delay, perhaps caused by gradients.

On day 239 (Figure 3), the WVR and GPS estimates of the zenith wet delay agree very well at the beginning and end of the day. The exception is during the middle of the day, when extremely large values of the zenith wet delay are observed during a time period associated with rain. Note that the GPS estimate of the ZWD is relatively constant (and much smaller) during this entire period.

Finally, on day 244 (Figure 4), large variations in the estimates of ZWD, on the order of 30 mm, were observed between the GPS and WVR. In addition, the small scale structure in the ZWD estimates does not appear to correspond between the two data sets as it does on day 236. It is worth noting that this is the most humid day of the three, with GPS estimates of the ZWD sometimes measuring greater than 250 mm.

These time periods were chosen specifically as time periods possibly associated with gradients in the water vapor distribution. Gradients could result in erroneous estimates of the zenith wet delay. To examine this issue, two approaches were taken. The first was to plot as a function of azimuth and elevation the average ZWD estimate of the WVR. The GPS estimate of gradient in ZWD was computed from the postfit residual file produced by GIPSY/OASIS. This file contains the residual values in the GPS observations after all the modeled parameters have been removed. If one assumes that these residuals are due primarily to the unmodeled water vapor gradient, then they can be converted to a zenith estimate if a mapping function is applied. This was the procedure followed for several subsets of data from the days 236, 239, and 244, each consisting of approximately 30 minutes of data, from two WWAVE GPS sites: MHR0 and NVTO. Figures 5, 6, and 7 represent some of the better cases of agreement between the WVR estimate of ZWD and the MHR0 and NVT0 GPS estimates of ZWD. Data from the WVR are shown in Figure 5. MHR0 is the closest GPS site to the WVR, approximately 200 m away. Data from MHR0 are shown in Figure 6. The NVT0 GPS site is approximately 10 km to the southeast of the WVR. Data for this site are shown in Figure 7. In this case, it is clear that in all three plots, there is a maximum value of water vapor when looking towards the southeast and a minimum value of water vapor towards the northwest.

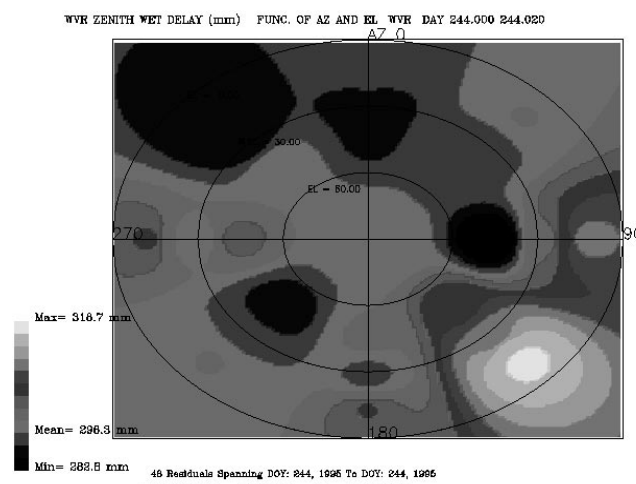

Figure 5. WVR Measurement of Zenith Wet Delay as a function of Azimuth and Elevation.

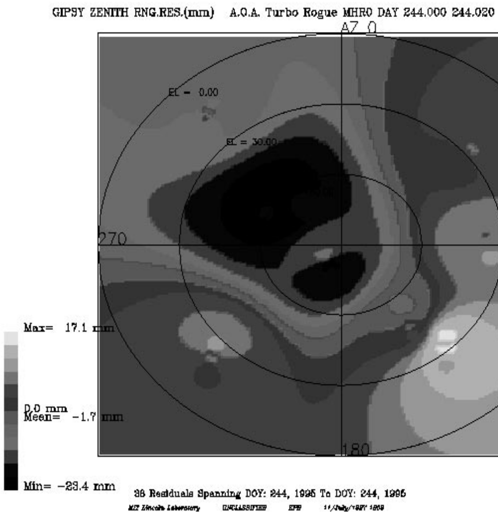

Figure 6. MHR0 GPS Measurement of Zenith Wet Delay as a function of Azimuth and Elevation.

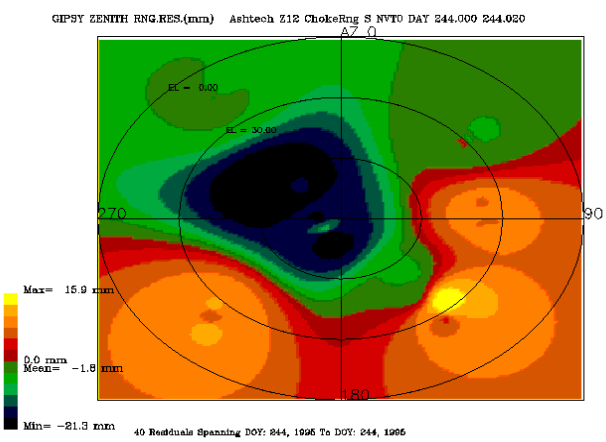

Figure 7. NVT0 GPS Measurement of Zenith Wet Delay as a Function of Azimuth and Elevation.

As is clearly evident here, the GPS data are fairly consistent. Note that NVT0 was a 12 channel Ashtech Z12 receiver, while the MHR0 was an 8 channel AOA Turbo Rogue receiver. In all data examined, this pattern of consistent GPS data is repreated. The WVR data, however, show no clear and consistent pattern of matching the structure observed in the GPS residual data. In addition, on average the excursions in the observed water vapor gradient is larger in the WVR data sets. In the above example of Figure 5, where the agreement between the different data sets is so close, this is not the case. The minimum WVR value plotted is 283 mm, while the maximum value is 319 mm, representing a difference of about 37 mm. The difference between the maximum and minimum value of the GPS residual is 40 mm. A more typical example is later during the day of 244 (at time 244.12-244.14). The difference between the maximum and minimum GPS residual is on the order of 22 mm, while the difference between the maximum and minimum estimate of the ZWD from the WVR is almost 60 mm. There is thus concern that the water vapor is being underestimated because of correlation with some other parameter in the GPS data processing.

GRADIENT MODEL

Following the gradient parameter estimation procedure of J. L. Davis, et al. (1993), the following six parameter model was fit to both the WVR and the GPS data.

$$L = Lo + V\,dt + G \cot E \cos(A - Ag) + Gdot\,dt \cot E \cos(A - Ar),$$

Where:

L	is the WVR-observed equivalent zenith delay,
Lo	is the zenith delay parameter at beginning epoch (of group) [mm],
V	is the Rate parameter [mm/min],
Dt	is the time from start of group,
G	is the Gradient term in [mm],
E	is the Elevation [deg],
A	is the Azimuth [deg],
Ag	is the Gradient azimuth [deg],
Gdot	is the Gradient rate [mm/min],
Ar	is the Gradient rate azimuth [deg].

In the case of the GPS data analysis, two solutions were computed, one with and one without an Lo term. This is because the Lo term corresponds to the zenith estimate of the ZWD. Since the GPS data set is composed of residuals, the Lo term should be zero. In fact, because the quantity was so small, it did not make a large difference whether or not this term was included in the fit. The results presented here did include this term.

Figures 8, 9, and 10 show the results of this fit. Each point represents 30 minutes of data used in the fit. The solid black line represents the MHR0 GPS estimate of the ZWD, while the light triangle above the GPS estimate represents the original WVR estimate of the ZWD. The Lo term solved for the WVR data is shown with the black diamond, and in all cases it closely matches the observed value of the ZWD. The open diamond in the lower part of the graph represents the estimated gradient terms from the WVR data. The small cross represents the estimated gradient term from the GPS data. Although the match is not perfect, it can be stated that where the data are reasonably well behaved, the two data sets produce similar size estimates for the "G" term. This is especially evident in the beginning and end of day 239, where the two gradient estimates seem to match up exactly. It is only in the middle of day 239, during the time period associated with rain, that large gradients are observed in the WVR data, but no gradients are observed in the GPS data.

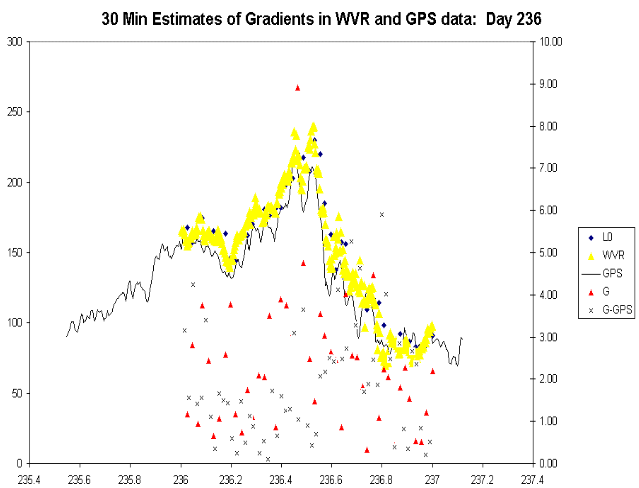

Figure 8. 30 Minute Estimate of Gradient Parameters in the WVR and GPS data: Day 236.

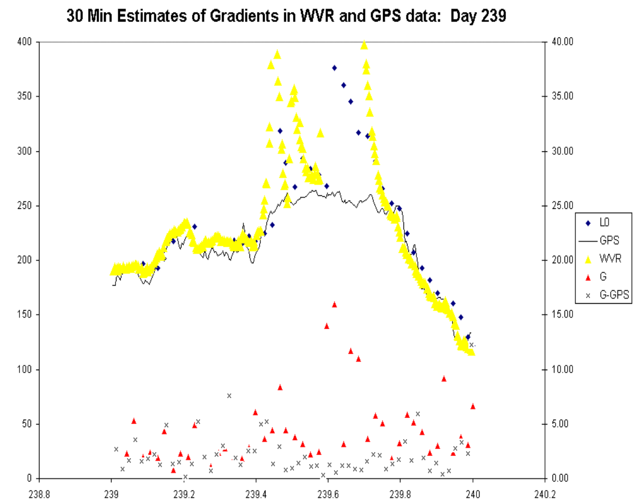

Figure 9. 30 Minute Estimate of Gradient Parameters in the WVR and GPS data: Day 239.

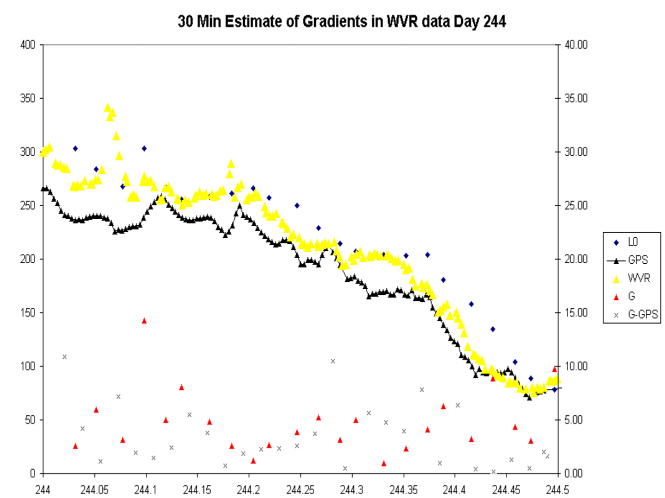

Figure 10. 30 Minute Estimate of Gradient Parameters in the WVR and GPS data: Day 244.

SUMMARY

In conclusion, data representing water vapor gradients from two GPS receivers and from one WVR have been examined for three separate days during the WWAVE experiment. Although some of the data look promising, the overall comparison between the two data types is relatively poor. This may be due to multipath related issues, or other antenna issues, such as antenna mounts. However, it should be pointed out the residuals between the two different receivers (NVT0 Ashtech Z12 and the MHR0 AOA Turbo Rogue) separated by 10 km are typically quite similar, indicating that the residuals are a function of some other term common to both sites.

Tropospheric gradient estimation is probably feasible with single GPS station but good receivers, antennas, and antenna mounts are essential . It is also clear that more research in these areas of GPS is needed. To obtain good estimates of water vapor distribution, extremely precise GPS orbit determination software (such as JPL's GIPSY/OASIS) is required. The GISPY/OASIS software may have to be tuned to allow for gradient estimation of the right size for the varying locations. Finally, the current gradient models may not be adequate for representing the true nature of the inhomogenities in the water vapor distribution. These models may also need to be updated or fine-tuned for specific locations.

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