The Measurement of Atmospheric Water Vapor: Radiometer Comparison and Spatial Variations

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Abstract—We conducted two water vapor radiometer (WVR) experiments to evaluate whether such instruments are both suitable and needed to correct for propagation effects that are induced by precipitable water vapor (PWV) on signals from the Global Positioning System (GPS) and Very Long Baseline Interferometry (VLBI). WVR's are suitable for these corrections if they provide wet path delays to better than 0.5 cm. They are needed if spatial variations of PWV result in complicated, direction-dependent propagation effects that are too complex to be parametrized in the GPS or VLBI geodetic solution. In the first experiment we addressed the suitability of radiometers by comparing six WVR's at Stapleton International Airport in Denver, Colorado, for two weeks. While two WVR's showed an average wet path delay bias of only 0.1 cm, others were biased by 1–3 cm relative to each other and relative to radiosondes. The second experiment addressed the question whether radiometers are needed for the detection of inhomogeneities in the wet delay. Three JPL D-series radiometers were operated at three sites in Colorado approximately 50-km apart. The WVR's simultaneously sampled PWV at different azimuths and elevations in search of spatial variations of PWV. On one day of this second experiment we found evidence for spatial variations of the wet path delay as high as 20% of the total wet path delay.

I. Introduction

SPACE GEODESY uses the difference in microwave signal arrival times at two sites to determine very accurate baseline vectors between these sites. The microwave signals originate from satellites (GPS) or quasars (VLBI) and they experience propagation delays as they pass through the troposphere. This atmospheric delay has two main constituents: The dry path delay and the wet path delay. Since the dry delay depends mainly on the amount of air through which the signal travels, it is easily modeled with surface pressure measurements. The wet path delay depends on the amount of PWV in the column of air through which the signal travels. One millimeter of PWV causes a wet path delay of about 6.5 mm [1]. Wet path delays range from 2–30 cm for signals arriving from the zenith direction. A 1-cm error in the estimation of the wet zenith delay results, typically, in an error of ~3 cm in the vertical component of the estimated baseline [2]. The horizontal components are less affected. In many tectonic and oceanographic applications of GPS the vertical baseline component contains the most important information and must be determined with an error of no more than 1–2 cm. To achieve this accuracy, the wet path delay must be known to about 0.5 cm, and the determination of PWV is often the limiting error source.

Three methods have been used to remove the effect of tropospheric delays on geodetic data from GPS and from VLBI. The first and simplest of these methods computes the wet and dry path delays from surface measurements of pressure, temperature, and humidity using atmospheric mapping functions such as those published by Marini and Murray [3], Saastamoinen [4], [5], Hopfield [6], Davis *et al.* [7], Chao [8], and others. This first approach is very effective for estimating the dry delay [9], [10], but yields poor results for the computation of the wet delay because humidity profiles are not as predictable as pressure and temperature profiles. Hurst *et al.* [11] computed the difference between wet zenith delays based on WVR's (WZD_{WVR}) and wet zenith delays based on surface meteorology measurements (WZD_{SMM}) for over 1000 simultaneous WVR and surface meteorolgical measurements taken at five locations in the United States, Mexico, and the Caribbean. Assuming that the WZD_{WVR} is accurate, the rms error of WZD_{SMM} was computed by fitting a straight line to these differences. The differences, and thus the error of WZD_{SMM}, increased linearly with increasing WZD_{SMM} according to:

$$\begin{aligned} RMS_{error} &= RMS\,(WZD_{WVR} - WZD_{SMM}) \\ &= [0.08\ WZD_{SMM} + 1.25]\ \text{cm}. \end{aligned}$$

For example: If WZD_{SMM} is computed to be 25 cm, then this correction will, on the average, be in error by 3.25 cm in the zenith direction. This error may result in a vertical baseline error of as much as 9 cm.

The second method for determining the wet path delay of geodetic signals is to use WVR's to measure the integrated PWV along the line of sight path. WVR's measure the brightmess temperature of the atmosphere at two or more radio frequencies near water vapor resonance spectral features (see Table I). These brightness temperatures can be used to determine PWV and the wet path delay [12], [13]. While some studies have shown evidence that WVR's can help to correct the wet path delay [14], there is still lack of compelling evidence that WVR's are appropriate or needed for high-accuracy geodesy. The instruments are expensive (> $100K), have high-power consumption, and

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TABLE I
RADIOMETER COMPARISON*

WVR	F1 (GHz)	F2 (GHz)	Data Type	Calibration Mode
D2 D3	20.7 20.7	31.4 31.4	orthogonal tip curves	frequent tip curves + noise diodes
NOAA WPL	20.6	31.65	zenith observations	tip curves (1 per month) strict temperature contl.
RADIO-METRICS	23.9	31.4	tip curves	frequent tip curves + noise diodes
J03	20.7 22.2	31.4	tip curves + zenith observations	frequent tip curves + temperature control + noise diodes

*This table summarizes the primary differences between the five radiometers that were compared in this study. The frequencies at which the instruments measure atmospheric brightness temperatures, the data types that were used in the comparison, and the calibration modes of the various instruments are listed. For the D-series and RAD instruments, we used only the data from frequent tip-curve calibrations. This was done because these instruments are not thermally controlled and noise diodes are required to account for gain changes between tip curves. While the D-series and RAD radiometers are equipped wih noise diodes, we excluded radiometric measurements that depended on noise diodes, because we noticed a temperature dependence of these noise diodes. For the NOAA instrument we used only zenith observations. The NOAA WVR is thermally a very stable instrument and requires re-calibration with tip curves on the order of once per month only. J03 data were taken from tip curves and from line-of-sight observations. This instrument is thermally controlled, uses frequent tip curves for re-calibration, and, in addition, has noise diodes to account for gain changes between tip curves.

are in general not designed for field use in remote locations. Thus they will not be used with space geodetic surveys unless their advantage has been established beyond any doubt.

The third method of determining the wet path delay is to directly estimate it as a parameter during the reduction of the geodetic data. This approach to solving the wet path delay problem has cast further doubt on whether radiometers are actually needed for high-accuracy GPS and VLBI. Results from Tralli and Dixon [15] and Lichten and Kornreich [16] indicate that estimation of tropospheric zenith delay parameters yields baseline accuracies that are comparable to those obtained with WVR corrections.

All tropospheric estimation schemes have thus far assumed that the zenith tropospheric delay is a function of time, and that the delay in all other directions can be scaled as a function of the zenith delay. Recent attempts by Davis and Elgered [17] to model not only the temporal, but also the spatial variations of the wet tropospheric delay look promising, but are limited to very simple geometries.

In summary: While the use of surface meteorological measurements does not, in general, provide zenith tropospheric corrections of sufficient accuracy, these corrections can be obtained by estimating zenith tropospheric delays as parameters during the GPS (VLBI) data inversion. Such computed zenith corrections can accurately account for the temporal changes of the zenith delay, but they do not account for spatial variations. These variations can be directly measured with WVR's. Radiometers can therefore help to improve the accuracy of GPS surveys if they provide wet path delay values accurate to within 0.5 cm, and if spatial variations in the wet delay are present. In this paper we describe two experiments which were conducted to (i) compare results obtained from different WVR's, and (ii) detect spatial variations in the wet delay.

II. WVR COMPARISON EXPERIMENT

The comparison test was conducted jointly with NOAA, the Jet Propulsion Laboratory (JPL), the Goddard Space Flight Center (GSFC), and the Radiometrics™ cooperation (RAD) between August 22 and September 5, 1988 at Stapleton International Airport in Denver, Colorado.

The following six WVR's were involoved in the test: Two JPL D-series instruments (D2 and D3), one J-prototype from JPL, one RAD prototype, one J-series instrument J03 [18] from GSFC, and one NOAA WVR [19]. In addition, there were two radiosonde launches each day and two solar hygrometers operating at the site. Neither the data from the J-series prototype nor from the solar hygrometers were available for this comparison. Table I summarizes the primary differences between the compared radiometers.

WVR's operate in two modes: (i) the calibration mode, and (ii) the observation mode. The calibration is required to relate the voltages from the video detector of the radiometer to atmospheric brightness temperatures. The most common calibration technique is the use of tip curves [19]. During a tip curve the radiometer antenna points at different elevations in the sky. In the zenith direction the radiometer points at 1 air mass, and at lower elevations at 1.5, 2, 3, etc., air masses. Based on a homogeneous model of the atmosphere, these measurements can be extrapolated to zero air mass. At zero air mass the radiometer must measure the cosmic background temperature. This known temperature is used to calibrate the WVR. In the observation mode a calibrated radiometer can measure zenith brightness temperatures or brightness temperatures in any given line of sight. The gain of the WVR may change between tip curve calibrations, mainly because of instrumental temperature changes. These gain changes can, in principle, be detected and corrected by the use of noise diodes, which inject a constant amount of white noise into the sky signal.

The radiometers were operated side-by-side within a 150-m radius for two weeks. During most of these two weeks the instruments took zenith observations. Several days were spent taking observations at lower elevation angles. These data were not included in this study because we wanted to minimize the effect of instrumental pointing errors. The data types that were included, and the reasons why we selected these data, are explained in Table I. For the D-series and RAD intruments we used only the data from frequent tip curve calibrations. For the NOAA instrument we used only zenith observations. J03 data were taken from tip curves and zenith observations.

III. ANALYSIS OF THE WVR AND RADIOSONDE DATA

The various steps that are required to process radiometer data for comparison are shown along with potential errors in Fig. 1. The radiometers all provide voltages or "raw counts" that are related to the brightness temperature of the atmosphere at the measurement frequencies. To determine this brightness temperature, the instrument has to be calibrated by use of tip curves and/or targets of known brightness temperature (blackbodies).

The data from the different radiometers were analyzed with different calibration algorithms. D-series tip-curve data were processed with the JPL-developed "123" software that is provided to operate these instruments. The data for the J03 radiometer were processed with the "TASK" software system, which was developed and extensively test at GSFC, and is also provided to operate the instrument. The NOAA data were processed with NOAA's software, and the data from the RAD prototype were analyzed with a tip-curve algorithm developed at

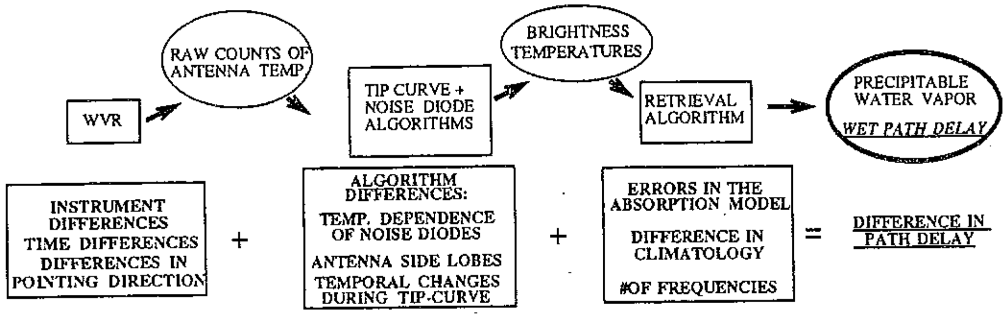

Fig. 1. Error sources in WVR comparison. This figure shows schematically the three steps that are involved in computing precipitable water vapor (PWV) or the wet path delay from raw radiometric observations. The three primary steps are shown in rectangular boxes: The data collection, the calibration algorithm, and the retrieval algorithm. The "products" of these steps are shown in the ovals. The WVR provides raw counts that are turned via a calibration (tip curve) algorithm into brightness temperatures, and via the retrieval algorithm to precipitable water vapor. The grey shaded areas show the various sources of error or differences between radiometers that can enter at each step.

the University of Colorado. WVR calibration algorithms are instrument-dependent in the way that they correct for the sidelobes of the antennas and model the behavior of noise diodes and blackbodies. Therefore it was not possible to use one algorithm for the comparison of all the instruments.

Once the raw counts were converted to brightness temperatures, these temperatures were used to compute the PWV, integrated cloud liquid (ICL), and the wet path delay. These calculations were done through the use of linear retrieval coefficients [12].

In order to ensure that each participant could use a consistent set of retrieval coefficients, these were computed by NOAA based on 15 years of Denver climatology and recently published absorption algorithms. The water vapor absorption models were taken from Liebe and Layton [20]. Rosenkranz [21] provided the oxygen absorption model, and the cloud absorption model was taken from Westwater [22]. Linear retrieval coefficients were obtained in a least-squares fit of radiosonde-derived integrated brightness temperatures to the corresponding radiosonde-derived integrated PWV. These retrieval coefficients, computed from 15 years of Denver radiosonde data, were then applied to the brightness temperatures, measured by the WVR's during our experiment, to obtain PWV. Wet path delays were computed by multiplying the PWV by a factor of 6.5 [1].

Data from National Weather Service (NWS) radiosondes were used for comparison with the radiometers. The zenith wet path delay obtained from the radiosonde data was computed at NOAA by evaluating the integrals for each complete sounding of pressure temperature and humidity. Radiosonde path delays cannot be considered as the "truth" against which the radiometers are tested. Comparisons of the NOAA radiometer and two kinds of radiosondes, carried out by Westwater *et al.* [23], showed that there was about as much difference between the two kinds of radiosondes as there was between the radiometer and radiosondes.

IV. Results of the Comparison

The data that were collected and used in the comparison are summarized in the left-half of Fig. 2. The zenith wet path delay varied between 5 and 20 cm during the two weeks of the experiment. Gaps in the D-series data result from times when we did not conduct tipping-curve calibrations. D3 had problems on day 239. Gaps in the data from J03 result from times when the instrument was not taking zenith observations; the same is true for the NOAA WVR which was pointing at nonzenith elevations on days 239–242. On day 237 the NOAA instrument was down with hardware problems. The data from the RAD instrument are sparse after day 239 because tip curves were carried out only once every 3 h. The connected points on top of each of the WVR plots show the zenith path delays as determined from radiosonde data. Radiosondes were launched twice daily, at 5 AM and 5 PM local time (11 and 23 UTC).

The right-half of Fig. 2 shows the zenith wet path delay from all the WVR's and from the radiosonde relative to D2. Except for D3, all WVR's and the radiosonde are biased relative to D2 above the 1-sigma level. A summary of all comparisons is shown in Table II, showing the bias and the 1-sigma scatter of the wet path delays for each comparison. We only compared radiometer measurements that were taken within 15 min of each other and interpolated linearly to a common time. Radiosonde and WVR delays were compared if measured within 30 min or less. Three-sigma outliers were excluded from all comparisons. Fig. 3 shows that the NOAA and D-series radiometers obtained wet path delays larger than the radiosonde, while J03 agrees well with the radiosonde, and RAD is about 1-cm lower than the radiosonde. The largest bias is 3.3 cm between the NOAA and RAD instruments. The two radiometers of identical design, D2 and D3, agree best with a bias of 0.1 cm and an rms scatter of 0.3 cm.

Table II shows that the standard deviations of the differences between radiometrically derived delays are significantly less than those obtained with radiosonde comparisons. This may reflect a higher degree of consistency between the radiometers, but it may also be due to the fact that radiometer–radiometer measurements were compared only if taken within 15 min, while we compared radiometer–radiosonde measurements within 30 min.

V. The Measurement of Azimuthal Variations

A second WVR experiment was carried out in Colorado between September 27–30, 1988. During the experiment, three D-series instruments were operated at three sites that were approximately 50-km apart: Boulder, Platteville, and Stapleton. Each radiometer performed two functions: (i) Co-pointing at GPS satellites which were observed simultaneously at the three sites with TI-4100 GPS receivers, and (ii) re-calibration with orthogonal tip curves every 10–15 min. Here we only discuss the data from the orthogonal tip curves.

During one orthogonal tip curve the radiometer points north, east, south, and west at the elevations of 30°, 42°, and 90°. Since the four azimuthal directions are identical at 90°, one orthogonal tip curve consists of four zenith measurements and

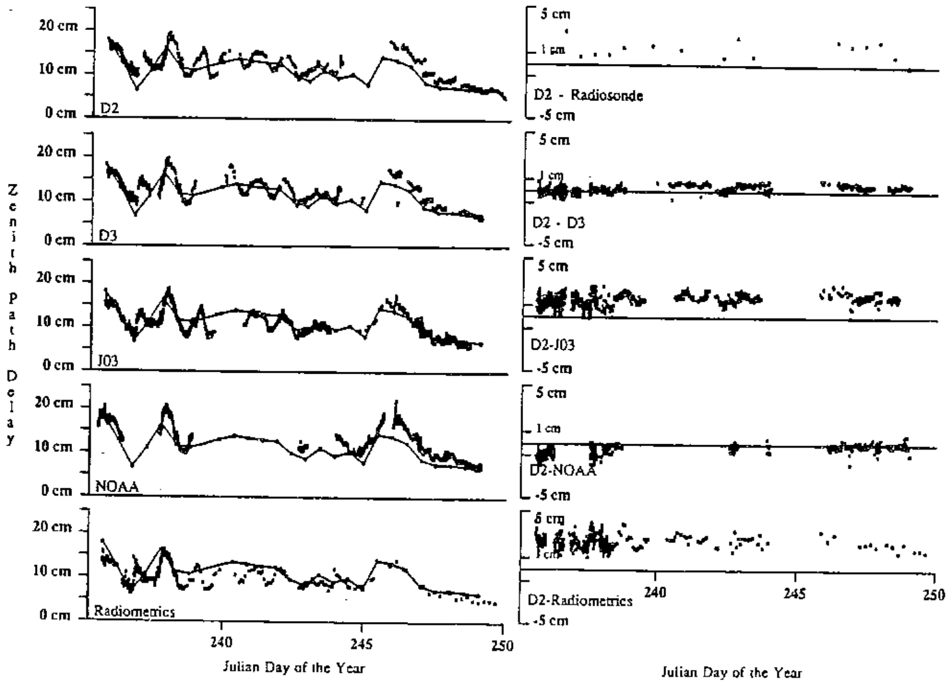

Fig. 2. Radiometer comparison—two-week data summary. The left-half of this figure shows the zenith wet path delay as measured using the five different radiometers that participated in this experiment. From top to bottom: D2, D3, J03, NOAA, and Radiometrics. The connected lines on top of the radiometer measurements are radiosonde path delays. The right-half of this figure shows the path delays of the radiosonde and the radiometers relative to D2. Bias and scatter for the different WVR's (and radiosonde) over the two-week experiment can be seen.

TABLE II
COMPLETE WET PATH DELAY COMPARISON*

DIFFERENCES + RMS IN [CM]					
	RAD	D2	D3	J03	NOAA
SONDE	1.13 1.15	−1.61 0.73	−1.40 0.66	0.24 0.84	−1.75 0.86
RAD	— —	−2.42 0.48	−2.41 0.48	−0.95 0.43	−3.28 0.60
D2	— —	— —	0.08 0.28	1.55 0.51	−0.85 0.37
D3	— —	— —	— —	1.45 0.46	−0.85 0.41
J03	— —	— —	— —	— —	−1.96 0.34

*For each instrument pair the top number shows the average two-week bias in centimeters, and the bottom number the rms scatter about this bias in centimeters.

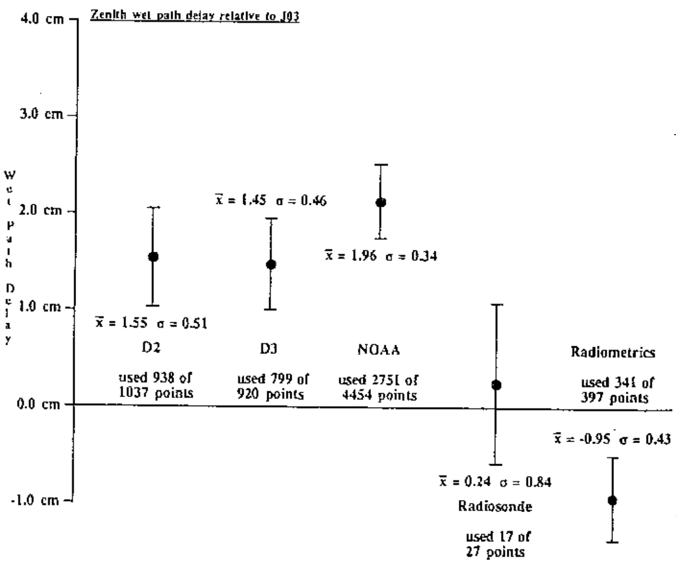

Fig. 3. Wet path delay difference between radiometers and radiosonde. This figure shows the offsets, rms scatter, and number of points used for the comparison of all radiometers and the radiosonde with respect to J03. From the figure it can be seen that D2, D3, and NOAA measured larger wet path delays than J03, the radiosonde, and Radiometrics. The error bars show the rms scatter about the offset relative to J03. A complete comparison of all the instruments involved in the experiment is shown in Table II.

one measurement in each of the four principal directions at the elevations of 30° and 42° (a total of 12 measurements).

In Fig. 4 we compare the wet path delays in the four directions at 30°, 42°, and 90° for measurements that were taken in Boulder and Platteville on September 27, 1988. The radiometer at Stapleton (D3) was not operating during most of the time on this day. Fig. 4 shows equivalent zenith delays, which are the measured delays at 30° or 42° scaled to zenith.

As explained above, during each orthogonal tip curve, which takes about 10 min to complete, the radiometer takes four zenith measurements. Differences between these zenith measurements, in the bottom panels of Fig. 4, are due to instrumental instabilities of the radiometer plus possible temporal changes of the zenith wet path delay during the time needed to complete an orthogonal tip curve. Thus the differences between the curves plotted for zenith observations are a measure of the noise level above which azimuthal variations may be detected. Differences between measurements in the four azimuthal directions at the lower elevation angles are clearly above the noise level defined by the zenith data. A north–south gradient of the wet path delay can be seen at both sites, Platteville and Boulder, at nearly the same time. This gradient reaches a maximum of about 3 cm in equivalent zenith path delay, which corresponds to a difference

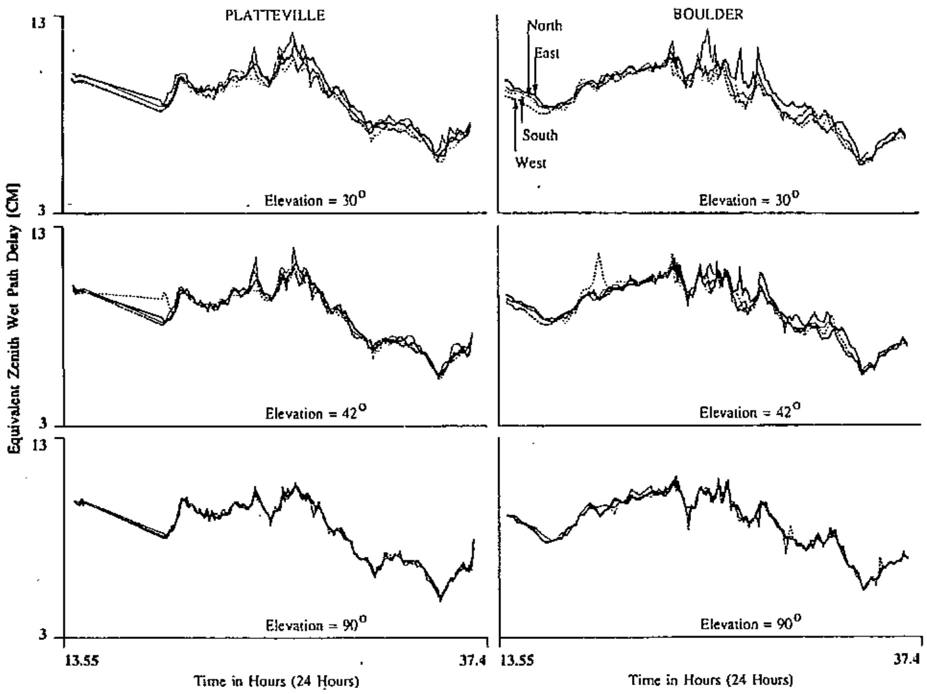

Fig. 4. Azimuthal variations, September 27, 1988. This figure shows 24 h of WVR data collected on September 27–28, 1988 in Platteville (D2) and Boulder (D1). Each plot contains 4 lines—corresponding to equivalent zenith wet path delays in the north, east, south, and west directions. Each point corresponds to the start-time of an orthogonal tip-curve. The bottom panels of the Platteville and Boulder measurements show the results of four zenith measurements taken during one tip-curve. The difference between the four lines is a measure of instrumental noise and temporal changes during one tip curve, which takes about 10 min to complete. The difference between the north, east, south, and west measurements at lower elevations (42° and 30°) results mostly from spatial variations in the wet path delay. North–south gradients of the delay of ~3 cm can be seen at 30° in Boulder in the middle of the data set. The spike for the Boulder and Platteville data at 42° at about 19 h is due to the radiometer pointing into the sun.

of 6 cm for the line of sight observations at 30°. After about 1 h this north–south gradient, with peak values of more than 20%, weakens, and the strongest difference is seen between observations to the north and the east. This change in direction of the highest path delay, which occurs at both sites, shows that the observed effect cannot result from pointing errors of WVR's that were leveled improperly.

A total of 1052 tip curves were collected during the 4-day experiment at the three sites. For each of these 1052 tip curves we computed the average equivalent zenith wet path delay for the four zenith, 42°, and 30° observations. The rms scatter of the four observations about this average was also computed. While the scatter of the zenith observations is a measure of the instrumental noise and temporal variations in the wet path delay, the scatter for the nonzenith observations is affected by spatial variations as well. The average rms scatter about the mean of all the zenith observations was 0.18 cm, the average rms scatter at 42° was 0.27 cm, and at 30° was 0.30 cm. The data shown in Fig. 4, along with these statistics computed from the entire data set, present evidence for azimuthal path delay variations in Colorado, even under rather dry and calm weather conditions.

VI. Discussion and Conclusions

The comparison of different WVR's showed biases between these instruments of up to 3.3 cm in the wet path delay. All radiometers, with the exception of J03, differed from radiosonde results by ~1 cm or more. The rms scatter of different radiometers about their average bias ranged from 0.3 to 0.6 cm. The best agreement between any two WVR's was seen between JPL's D2 and D3 radiometers, showing a bias of only 0.1 cm. Radiometers that agree as well as D2 and D3 may prove useful for the correction of the wet path delay in GPS and/or VLBI experiments.

Based on the biases that we observed, we warn against using radiometers of different design for the correction of the wet path delay. If different radiometer types are used, one needs to (i) compare the instruments before and after the experiments, or (ii) estimate a bias correction from the GPS/VLBI observations.

The source of the observed biases is not clear. Differences can enter our comparison in any of the three steps as symbolized in Fig. 1.

Step 1: Instrumental differences between different radiometers, such as different types of video-detectors, etc., cause fundamental differences. Differences can also occur because data are not taken in exactly the same direction and at exactly the same time. In our experiment, we minimized the latter errors by using zenith and tip observations only, and by synchronizing all radiometers to the same clock.

Step 2: Earlier we explained briefly how raw radiometer data are converted to brightness temperatures. In this step different algorithms are used for reasons explained above. Differences in these algorithms can introduce additional variations between the radiometers.

Step 3: The brightness temperatures are converted to PWV and wet path delay. The rms differences of PWV, as derived from 15 years of radiosonde data, and PWV retrieved from simulated brightness temperatures is about 0.7 mm [24]. This corresponds to a < 5 mm path delay. We believe that differences of much less than 5 mm are introduced in this step of the radiometer comparison because the retrieval coefficients used for each WVR were based on the same climatological data and the same absorption models.

The observed biases are therefore introduced in the first and second steps. It is important to understand the origin of these biases and to remove them. This is especially important since there may be a place for WVR's in high-accuracy space geodesy when azimuthal gradients of up to 20% of the wet path delay occur.

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J. M. Johnson, photograph and biography not available at the time of publication.

R. E. Neilan, photograph and biography not available at the time of publication.

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