MICROWAVE RADIOMETRY AS A TOOL TO CALIBRATE TROPOSPHERIC WATER-VAPOR DELAY*

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ABSTRACT

The spectrum of atmospheric emission contains an emission line due to the water-vapor molecule at a frequency of 22.2 GHz. The strength of the line is proportional to the amount of water vapor along the line-of-sight. In principle, measurement of this line strength provides an independent estimate of water-vapor induced delay that can then be used to correct the interferometrically observed group delay. We have used borrowed radiometers for the past 5 years to refine our understanding of this technique to measure water vapor. Four separate field tests have been completed in which we have compared the radiometer to other techniques that measure water vapor. We have attempted to schedule these experiments at times and locations that would test the validity of our assumptions relating radiometer output (i.e., brightness temperature) to integrated water vapor content. We believe that we can estimate water-vapor induced delay with an accuracy of ±2 cm for elevation angles above 17°. We are currently constructing seven water vapor radiometers for use at very long baseline interferometry (VLBI) stations. These new instruments are being designed to be compatible with the Mark III data acquisition system. We believe that the technique is ultimately capable of a 1-cm accuracy, and further tests are planned to investigate this possibility. In addition, we plan a re-design and re-packaging of the radiometer with the goal of reducing the total cost.

*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

In the previous paper by Claflin and Resch, you heard how water vapor introduces an error in VLBI measurements. The most cost effective method for calibrating the water-vapor induced errors appears to be the use of microwave radiometry to estimate the total amount of water vapor along the line-of-sight by measuring the strength of the water-vapor emission line at 22.2 GHz. Figure 1, taken from Waters (1977), shows the spectrum of the atmosphere for two conditions. The lower curve is the brightness temperature versus frequency for an atmosphere with no water vapor. The upper curve is calculated for an atmosphere containing 2 gm/cm^2 of precipitable water vapor. This corresponds to a delay of 12.2 cm at the zenith – a fairly high zenith delay. Our new radiometers operate at 21 GHz on the shoulder of the emission line and at 31 GHz, which is well off the wing of the line. The brightness temperatures that we typically measure are in the range 20° to 100°K. The 21 GHz brightness temperature is proportional to the total amount of water vapor in the beam plus the background emission. The 31 GHz channel is used to subtract out the background and is particularly useful for removing the effect of clouds.

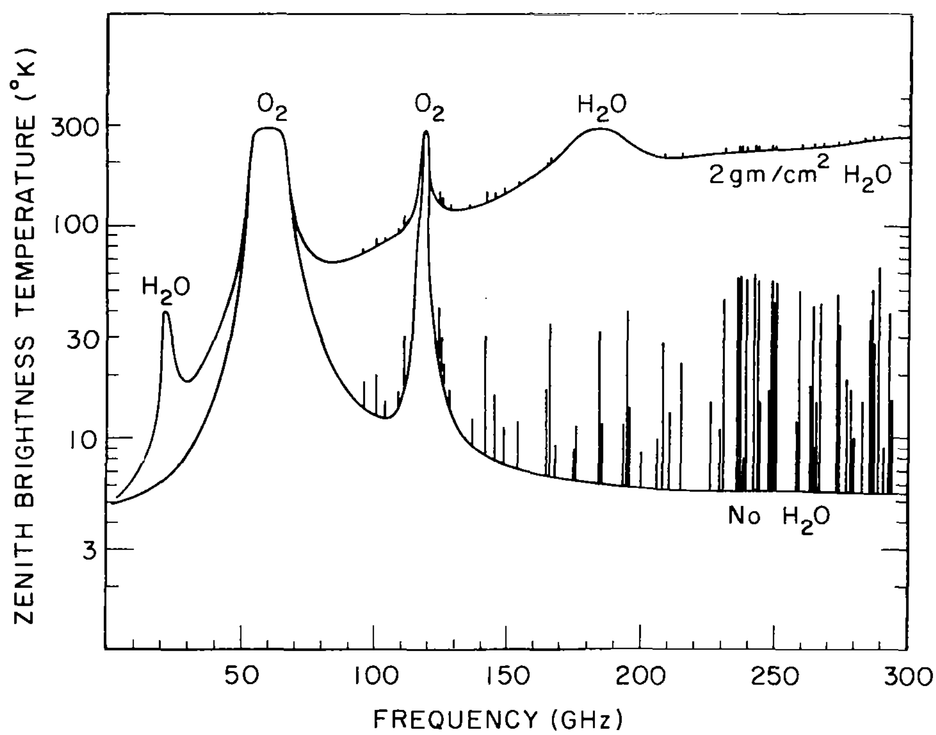

Figure 1.

The water-vapor delay correction can be related to the brightness temperature by a very simple linear relation as shown in figure 2. The quantities T'_C, A_0,A_1, and A_2 in this expression are actually functions of surface temperature, pressure, and relative humidity as explained by Claflin, Wu, and Resch (1978). We have determined the constant terms in these functions from a regression analysis against radiosonde and instrumented aircraft measurements at some particular site. We believe that we know the functional dependence on temperature, pressure, and relative humidity well enough to allow us to transport the radiometer to other geographical locations or climates and still retain the instrumental calibration. The quantities T′ (22 GHz) and T′ (31 GHz) are the brightness temperatures that have been corrected for opacity and adjusted to an absolute temperature scale.

$$\Delta L_V \,\bar{=}\, (A_0 M - T_C') + A_1 T'(22\ \text{GHz}) + A_2 T'(31\ \text{GHz})$$

T_C = COSMIC BLACKBODY BACKGROUND TEMPERATURE = 2.8°K

M = AIR MASS

Figure 2. WVR path delay algorithm.

When we initially contemplated the use of this technique to support VLBI measurements, we noted two important difficulties: (1) it seemed to require an instrument well calibrated on the absolute temperature scale – this is difficult and expensive, and (2) the measurement of antenna temperatures in the 20° to 100°K range implied a cold internal calibration load would be necessary – this is also operationally difficult and expensive. Both difficulties were eased by using a calibration technique suggested by Water (1975).* This technique is illustrated in figure 3. The instrument is tipped from the zenith (air mass = 1) to different elevations (higher air mass) and the observed brightness temperature is plotted versus the air mass as shown by the dotted line. In general, this line implies a negative brightness temperature at zero air mass – a nonphysical result. We assume that this nonphysical result is due to two causes: (1) nonlinearity of the tipping curve (i.e., opacity effects), and (2) lack of proper instrumental calibration. We then perform a simple iteration calculation to estimate the opacity and instrumental correction term that would cause the tipping curve to have the proper intercept at zero air mass; i.e., 2.8°K, the cosmic blackbody background temperature. By using this tipping curve calibration method, we have found that we can forego the cold internal calibration load in favor of a hot load that is much more convenient to operate.

In order to determine the constants that appear in the equation relating brightness temperature to delay, we have used the radiometers in several calibration sessions as shown in figure 4. We have used two different radiometers and compared them against radiosondes, instrumented aircraft, LIDAR (laser radar), and a microwave refractometer mounted in an aircraft. Some typical results are shown in figure 5. Here, we plot the delay determined by the water vapor radiometer (WVR) along the vertical axis and the delay determined by an instrumented aircraft along the horizontal axis. The aircraft flight pattern was an approximation to the line-of-sight at elevation angles of 10°, 20°, and 30°, and the zenith. The WVR could not tip down to elevation angles of 10° so we had to extrapolate from data taken at 17°. This data shows a relatively wide range of path delay. Typical of all our data, the RMS of the fit is a bit better than 2 cm. This is one way to demonstrate the WVR – compare it with an independent method of measuring water vapor. Another way, one that probably means more to VLBI practitioners, is to demonstrate that VLBI data improves with WVR calibrations.

*J. W. Waters, private communication, 1975.

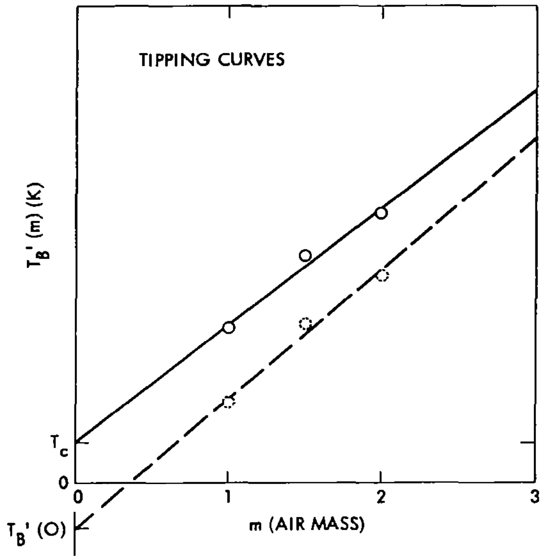

Figure 3.

MAY 1974 EL MONTE, CA.	SMILE	VS. RADIOSONDE
MAY 1975 EL MONTE, CA.	SMILE, NEMS	VS. RADIOSONDE, AIRCRAFT
FEBRUARY 1976 PT. MAGU, CA.	SMILE	VS. RADIOSONDE, AIRCRAFT
JUNE 1978 HAMPTON, VA.	NEMS	VS. LIDAR, REFRACTOMETER

Figure 4. WVR calibration sessions.

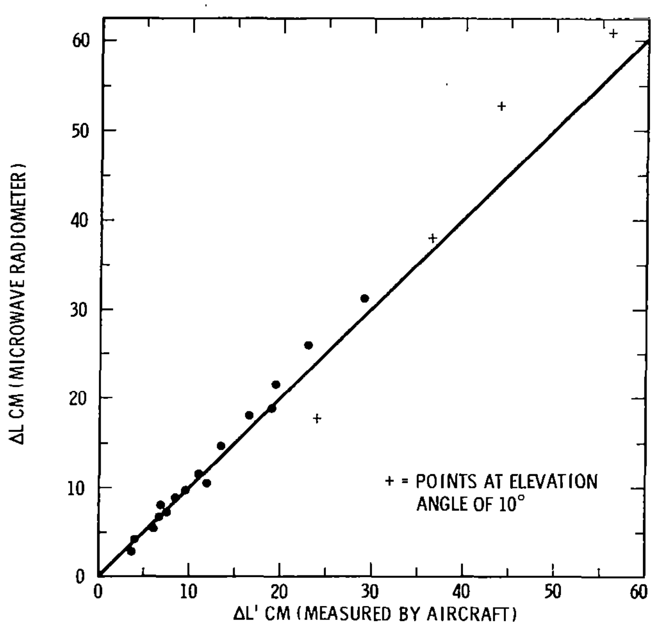

Figure 5. Excess path delay due to water vapor as measured by a microwave radiometer and an instrumented aircraft.

Figure 6 is the first suggestion that the WVR does indeed positively contribute to a VLBI result. We have plotted the results from three experiments that were performed in June 1977 between OVRO and the 9-m ARIES antenna that was then located near the Golden Gate Bridge in San Francisco. The coordinate system chosen was local to the 9-m antenna. The reference point was arbitrary but located near the intersection of antenna axis. The data was reduced using two different types of water vapor calibrations. The unfilled squares indicate a solution in which the tropospheric water vapor was estimated from surface meteorological measurements. The filled circles indicate a solution in which the tropospheric water vapor was estimated by using the WVR. The WVR did not observe along the line-of-sight to each radio source, but merely estimated the zenith water-vapor path delay. To the best of my knowledge, this was the first set of experiments in which WVR's were used at both ends of the baseline.

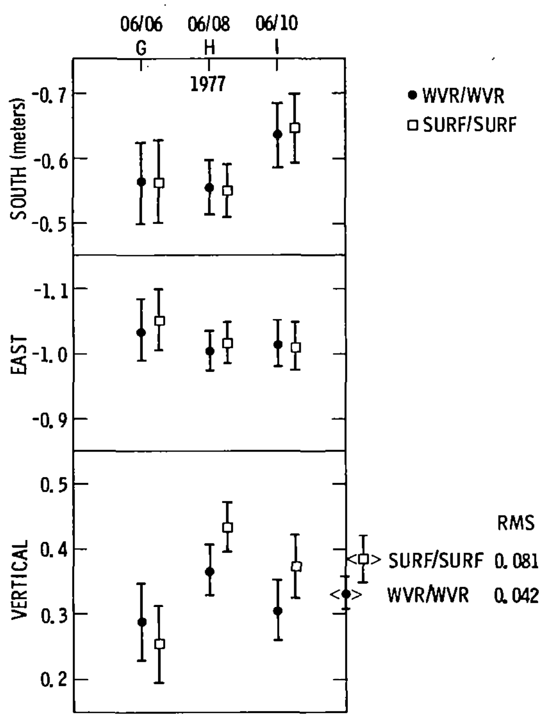

Figure 6. Troposphere calibration comparison OVRO/San Francisco.

In the earlier paper by Claflin and Resch, it was pointed out that propagation medium errors have little effect on the determination of local horizontal coordinates. As you can see in figure 6, the North-South and East-West baseline components are not affected by the choice of tropospheric calibration. However, as we would expect from the previous discussion, the scatter in the local vertical component does improve with the WVR calibration. If we can attach any significance to the RMS of three data points then the "RMS" improves by almost a factor of two by using the WVR calibration – at least the scatter in the data did not get worse. Obviously, the case for the WVR must be established by many more data points. During the past year our main objective has been to complete seven WVR's so that this data can be collected on a variety of baselines.

Our "guess-estimate" of the error budget for a two-channel WVR is shown in figure 7. The bar on the far left is due to system noise and the cross-hatched area indicates that this error can normally be reduced by averaging. The bar labeled instrumental corrections indicates that the technique of using tipping curves to determine the instrumental constants is itself noisy. The technique error is due to the approximations that we make in deriving our simple algorithm. These errors are roughly proportional to the total amount of water vapor. Also, when we calibrate the instrument by comparing it to an independent method of measuring water vapor, this independent method usually is subject to errors that are roughly proportional to total water vapor content. The root-sum-square of these assumed independent error sources is shown by the bar on the far right. At low values of path delay, the error budget is dominated by system noise. At larger values of path delay, the error is more like a percentage value of the path delay. For the range of typical delay values likely to be encountered in a VLBI experiment, we feel the WVR errors will be no larger than 2 cm.

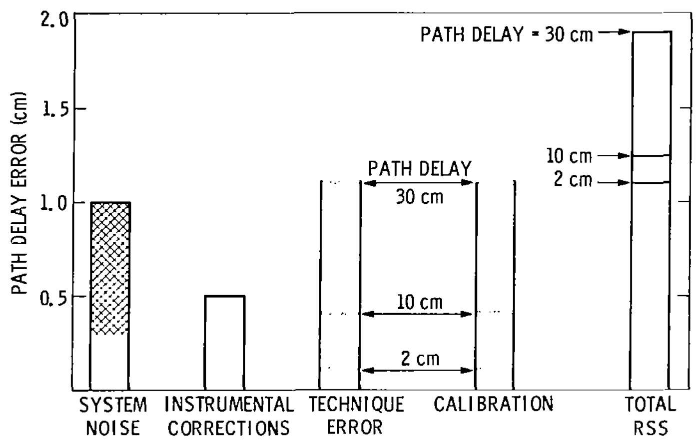

Figure 7. Two-channel WVR error budget.

Even with a 2-cm calibration accuracy, water vapor is likely to be a major error source to the VLBI systems that evolve during the next decade. Simulations of WVR performance suggest that the instrument may be capable of 1-cm accuracy. Figure 8 summarizes the research and development tasks that we feel need work. The priority task is to develop an independent calibration method that is intrinsically more accurate than the WVR. A good possibility is a method that utilizes an optical/microwave device. The basic principal of the device has been described by Thompson (1971). It utilizes a microwave signal to modulate a laser and then transmits both the optical and microwave signals. The optical signal suffers a group delay that is, to first order, proportional to the dry component. The microwave signal is retarded by both dry and wet component. An observer who detected the two signals some distance away would note a phase difference that is proportional to the total amount of water vapor along the propagation path. If we can mount either the transmitter or receiver end of this device in an aircraft and fly it at 20,000 feet (above 98 percent of the tropospheric water vapor), it would provide a subcentimeter calibration of the WVR and practically eliminate a large contributor to the overall WVR error budget.

- OPTICAL/MICROWAVE CALIBRATION TECHNIQUE
- MEASURE LINE SHAPE 18 - 26 GHz
- ESTIMATE EFFECTIVE ATMOSPHERIC TEMPERATURE USING 54 GHz RADIOMETER
- DESIGN AND PACKAGING CONSIDERATIONS
  - LOWER FABRICATION COST
  - REDUCE DEW ACCUMULATION
- DEFINE OPERATIONAL LIMITS IN PRECIPITATION
- INHERENT ACCURACY OF THE TECHNIQUE USING NUMERICAL METHODS
- FLUCTUATION STUDIES

Figure 8. WVR R&D tasks.

Algorithm error could be reduced by building a new type radiometer that was frequency agile and could measure the line shape. The addition of a 54 GHz channel would also be useful to estimate the effective atmospheric temperature which would improve the accuracy of the algorithm. There are some design and packaging features that could be improved. It may be possible to use a single frequency agile channel which would appreciably lower the fabrication costs. With the present package design, we have trouble often in the early morning hours with dew accumulation. Liquid droplets form on the covering of the horn antennas and give large brightness temperature errors. We will have to experiment with different methods to remove this dew accumulation. The algorithm that relates the brightness temperature to path delay is not valid in heavy precipitation. We need to do more work in order to properly define the operational limits of the technique.

We are continuing our work on the inherent accuracy of the remote sensing technique using simulation methods. Our preliminary conclusion is that the WVR should be capable of 1-cm delay accuracy under most conditions. Now that we have several dedicated radiometers we will pay much more attention to fluctuation studies. This is important for several reasons. First, we must be able to separate instrumental and real atmospheric fluctuations. Second, we must examine our assumption that the spatial average of water vapor over the large solid angle of the WVR antenna is equivalent to the longer temporal average over the duration of a VLBI observation. Finally, we must investigate the homogeneity of tropospheric water. This will tell us how to construct an observing strategy with the WVR in both time and space coordinates. The latter point is particularly relevant to a SERIES type network where the spacing between points is a few tens of kilometers. If we do not need a WVR at each of these points, there would be a big cost impact in the initial cost per station.

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