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Test and Evaluation of Water Vapor Radiometers

Contract: NAS5-20975

Final Report

March 31, 1976 - February 29, 1980

Principal Investigator: Dr. James Moran

Prepared for

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt Road
Greenbelt, Maryland 20771

June 1980

Prepared by

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
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I. Introduction

The accuracy of very long baseline interferometry in geodetic and astrometric applications is primarily limited by the propagation delays through the troposphere. The part of this delay that is most difficult to predict is due to atmospheric water vapor which can contribute up to about 40 cm of excess propagation path at microwave frequencies. The water vapor content in the atmosphere is variable and is not well correlated with surface meterological variables. However, it has been well known for at least 13 years (Waters, 1967, and Shaper _et al_. 1970) that the brightness temperature measured near the transition of water vapor at 22.2 GHz and the propagation delay due to water vapor, or wet path length, are well correlated. This correlation is not perfect because the absorption coefficient and index of refraction do not have the same dependence on temperature and pressure. However, the water vapor has a scale height of only about 2 kilometers and the fractional variation of temperature over this range is small. Hence, the early theoretical studies showed that the wet path in the zenith direction could be predicted to an accuracy of ~ 1 cm from microwave radiometry data.

Several important theoretical refinements have been made in the last few years in establishing the best frequencies for microwave observations. With observations at many frequencies near the water line, estimates of the complete profile of water vapor versus height can be made (Hogg, 1980). This requires more instrumentation than is necessary to just measure the wet path. To estimate the wet path length, the integral of the refractivity, observations at two frequencies are sufficient. Observations exactly at the water line frequency are sensitive, giving T_B(°K) ~ 2 x Path (cm), but are not recommended. The opacity of the line is significant, up to 20 percent at zenith in some cases. This leads to saturation effects wherein the brightness temperature and path length are no longer linearly related. The frequency of 20.6 GHz is generally agreed to be a good choice because the absorption coefficient is independent of pressure (Westwater, 1978). The absorption coefficient is small enough, 1.6 GHz off the resonance, that saturation is not a problem. Since the brightness temperature contribution of clouds containing liquid water vapor is proportional to the square of the frequency, both the liquid and vapor contributions to the brightness temperature can be separated by using two widely spaced frequencies. Wu (1979) has shown that the best frequency to use, in addition to 20.6 GHz, is about 31.5 GHz. With these frequencies, the coefficients relating the brightness temperatures to wet path length are nearly independent of the details of the water vapor profile.

II. <u>Previous Work</u>

The early work on this contract from 1975 to 1976 has previously been reported by Moran and Penfield (1976). We rebuilt two water vapor radiometers originally constructed by

NRAO to measure brightness temperature at 19 and 22 GHz. We mounted them on search light mounts and built an analog-to-digital interface for data acquisition. We wrote computer programs to estimate brightness temperatures at various frequencies and the path length from radiosonde data using the equations of radiative transfer and the refractivity of air. We conducted a ten day experiment during which 45 radiosondes were launched and brightness temperature measurements were made with the radiometers at the Haystack Observatory. The rms deviation about the mean wet path length was 5.6 cm. Using surface meteorology, the wet path could be estimated to an accuracy of 3.2 cm, and using the radiometer data it could be estimated to an accuracy of 1.5 cm.

III. Current Work

We have kept the radiometers in operational order until the untimely dealth of the radiometer engineer, Joseph Hayes. Extensive data sets were obtained during most VLBI experiments over the contract period. The radiometers were interfaced to the Haystack Hewlett-Packard computer which controlled the pointing and received the data. Curt Knight wrote the software. The reduced data, in terms of zenith brightness temperatures, are available for analysis with the VLBI data. Unfortunately, data was never acquired simultaneously at any other location.

We also made several attempts to improve the NRAO radiometers. We replaced the noise tube calibration system with a load, cooled to the temperature of liquid nitrogen. While this calibration was more stable, tipping of the radiometers was ackward with open dewars. This technique was not used in routine operation.

We investigated the possibility of changing the frequencies of the NRAO radiometers. Wu (1979) gives several combinations of frequencies which produced flat weighting functions and therefore are insensitive to profile variations. The one frequency pair which was possibly within range of our radiometers was the one at 20.0/26.5 GHz. We measured the frequency response of all the radiometer components - circulators, Gunn oscillators, mixers, directional couplers, etc. The range of most of the components was 18 to 25 GHz. Above 25 GHz the responses of most components deteriorated rapidly. Since the stability and reliability of the radiometer was poor at the high frequency we decided not to retune the radiometers.

We reanalyzed our 1975 data, constraining the ratio of the regression coefficients to equal 1.37, the ratio of the observing frequencies. This constraint should tend to eliminate the effect of clouds. With this constraint the rms residuals increased from 1.5 to 2.4 cm, probably because of the decrease in the number of degrees of freedom and also because the ν^2 dependence in only approximate when the opacity is large since the opacities of the clouds and vapor do not add algebraically.

We have prepared a paper for publication in Radio Science describing our results. A copy is attached to this report.

I was greatly aided in this work by Joe Hayes who built the radiometer pointing system, maintained the radiometers and did all the laboratory tests. Joe Hayes died in December, 1979.

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