DSN Water Vapor Radiometer Development — A Summary of Recent Work, 1976-1977

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A water vapor radiometer (WVR) has been developed which measures the atmospheric noise temperature at two different frequencies. These noise temperatures are used in empirical-theoretical equations which yield tropospheric range delay, in centimeters, through the atmosphere along the beam of the WVR. This range correction is then applied, as needed, to measurements concerning spacecraft range and to VLBI baseline determinations. The results of the March 1976 Pt. Mugu tests are given and equipment modifications and JPL tests since that time are discussed.

I. Introduction

The water vapor radiometer (WVR) has undergone a number of developmental changes since its first field operation at El Monte Airport in May, 1975. The present instrument (Ref. 1) has a lower noise temperature, better waveguide matches, better stability and resolution, and more accurate absolute calibration than that which existed two years ago. The presently configured WVR, operating as a noise-adding radiometer (NAR), has noise temperatures of about 700 kelvins on the 22.235-GHz channel, and 750 kelvins on the 18.55-GHz channel. Two frequencies are used in order to separate the effects of liquid water (clouds) which contribute to atmospheric noise temperature but not to tropospheric delay. With a five-minute integration time on each of the six source positions (sky, cold termination, and ambient termination at two frequencies), the stability is better than 0.5 kelvins over an 8-hour period. This corresponds to a tropospheric delay stability of ±0.2 cm for the same period, assuming a homogeneous and constant atmosphere. Figure 2 of Ref. 1 shows the WVR in its configuration during the Pt. Mugu tests. Figure 1 herein shows the WVR as it is presently configured. The air-driven expansion refrigerator which gave cold termination temperatures of about −80°C at Pt. Mugu has been replaced with a pumped fluorocarbon refrigerator capable of maintaining cold load temperatures of about −130°C. For absolute self-contained radiometer calibrations it is desirable to have as cold a reference termination as possible (noncryogenic, for cost and maintenance reasons), since the atmospheric noise temperatures measured by the WVR are generally in the 20 to 100 K range (−253 to −173°C). Figure 2 shows the block diagram of the present system; it is essentially the same as shown in Ref. 1 for the Pt. Mugu instrument.

II. Pt. Mugu Tests, March 1976

The Pt. Mugu tests at the U.S. Navy Pacific Missile Test Center were carried out with the two channels of the WVR operating at 22.235 and 18.0 GHz. Another microwave instrument, known as SMILE (Scanning Microwave Inversion Layer Experiment), was also operating there at the same time. Its operating frequencies were 22.235 and 31 GHz, because SMILE was originally a satellite instrument and 31 GHz is an atmospheric window, allowing visibility of the Earth's surface from orbit. Numerous "sky truth" instruments were used at Pt. Mugu to determine the real atmospheric properties such as the water vapor and refractive index altitude profiles.

During the period of the tests (about 10 days total) 23 rawinsondes[1] were launched, 34 meteorologically instrumented aircraft flights were made, and 12 microwave refractometer aircraft flights were made. These direct measurements of atmospheric parameters result in an inferred determination of tropospheric range delay. The radiometers probe the atmosphere along the line-of-flight of aircraft and rawinsonde; the microwave measurements are compared to the meteorological measurements and a relationship linking the two is developed.

The meteorological aircraft, provided by Meteorology Research, Inc. (MRI), flew only to an altitude of 3 km. Atmospheric measurements made by the on-board instruments were augmented with the upper-air measurements made with the rawinsondes. The rawinsondes normally send back information all the way up to an altitude of 30 km, but most of the water vapor (the critical parameter in the measurements as far as we are concerned) is below 3 km altitude and is measured by the aircraft instruments, which are much more accurate than the rawinsonde instrumentation.

The meteorological aircraft flew along atmospheric paths at elevation angles of 90, 30, 20, and 10 deg as seen by the WVR. This allowed measurements of tropospheric delay of as much as 6 times the zenith amount (at 10 deg elevation). The troposphere above 3 km altitude in the nonzenith flights was modeled by multiplying the rawinsonde-measured delay above 3 km by the factor 1/sine (elevation angle) to account for the increased atmospheric path length.

The microwave refractometer aircraft, provided by the Navy, flew to 3 km altitude and measured the index of refraction of the atmosphere directly. Conceptually, this instrument would have provided the best direct measure of tropospheric range delay, but unfortunately, problems in instrument calibration prevented the use of this most valuable data.

Figures 3 and 4 show tropospheric delay measurements on the four days when both radiometers, the meteorological aircraft, and the rawinsonde were all operating. Figure 3 shows the zenith measurements (with aircraft measurements augmented by the rawinsonde). Figure 4 shows delay measurements made along an atmospheric path at 10 deg elevation. The consistency among these measurements is remarkable, although it must be mentioned that the Pt. Mugu measurements were used to calibrate the WVR and then this calibration was folded back into the raw data, giving the very good agreement in the results shown. Whatever the case, a single set of regression coefficients linking tropospheric delay to microwave measurements was developed which yields consistently correlated values over a wide range of atmospheric conditions. On day 070, the sky was full of dark, threatening clouds, and a moderate amount of drizzle was experienced throughout the day. Two days later on day 072, Santa Ana winds arrived at 7 a.m. and the amount of water vapor in the atmosphere dropped by a factor of about 3, as seen in the drop of zenith tropospheric delay from 9 to 3 cm. For comparison, a normal day (68°F and 40% relative humidity) has a zenith tropospheric delay of about 7 cm. The 10-deg elevation plot shows the same delay variations and consistency of data. It can be seen by comparing the zenith and 10-deg graphs that evidence of horizontal inhomogeneity (nonstratification) of the atmosphere existed during the days shown. The zenith delay numbers of 9.0, 3.3, 8.5, and 7.2 cm should be multiplied by the factor 5.76 (1/sin(10 deg)) to model delay values to 10 degree elevation. These values turn out to be 51.8, 19.0, 49.0, and 41.5 cm, and the daily modeling errors become 3 cm, 5 cm, 5 cm, and 2-5 cm, respectively. This shows the value of direct line-of-sight microwave measurements rather than modeled zenith values.

The equation linking tropospheric delay and microwave measurements (as determined by the Pt. Mugu measurements) is presently

$$\Delta L = 2.640 + 0.273T_{22} + 0.000424T_{22}^2 + 0.0858T_{18} + 0.00659T_{18}^2$$

where T_{22} and T_{18} are the "water noise temperatures" (due to vapor and liquid only) and are derived from the measured antenna noise temperatures by subtracting out the cosmic and oxygen noise temperatures at the particular elevation angle of interest. As an example of the use of the above equation, antenna temperatures of 30.5 and 20.9 K at 22 and 18.5 GHz, respectively, at an elevation angle of 30 deg, result in water noise temperatures of 21.6 K and 12.7 K, and a ΔL of 10.9 cm.

Following the Pt. Mugu tests, numerous equipment changes were made; and it is not believed that these affected the "Pt. Mugu coefficients" in the above expression. But, since Pt. Mugu is at sea level, these coefficients may be valid only at

[1] A rawinsonde is a radiosonde that is tracked in azimuth and elevation in order to gain information about wind direction and velocity.

that elevation. Further tests and studies will be made to determine the effects of altitude change.

III. JPL Tests

A large number of radiometer measurements were made from the roof of a building at JPL during the last part of 1976 and first part of 1977. These measurements monitored the results of equipment improvements and also helped to exercise the data reduction methods, which were vastly improved since the Pt. Mugu tests.

Figure 5 shows a typical radiometer determination of tropospheric delay during four days of March, 1977, using the Pt. Mugu coefficients. The radiometer pointed toward the west at an elevation angle of 30 deg and operated unattended during this period. The peak in tropospheric delay toward the end of day 62 indicates an influx of moisture-laden air into the Los Angeles area; and indeed, rain was reported at many locations west of Los Angeles, although none fell on the radiometer itself. The most stable atmospheric period is around day 65.0, where the tropospheric delay shows variations of at most ±0.2 cm over an 8-hour period. It is clear that the radiometer tracks small changes in atmospheric moisture content as seen in the variations at day 63.5. The absolute accuracy of the instrument is not known, as there were no rawinsondes or other meteorological instruments nearby with which to verify the delay values given.

IV. Future Work

Over the next year, a number of VLBI validation support tests will be made at Goldstone DSS 13. Interspersed between these tests will be calibration tests at Edwards AFB, wherein the WVR measurements may be compared to tropospheric delay measurements made by rawinsondes. Edwards AFB is an excellent location at which to calibrate the WVR because it is a desert location similar to Goldstone and has a similar altitude, although some altitude compensation is made in the WVR data reduction as far as oxygen noise contribution is concerned.

A new set of regression coefficients will be determined for the ΔL vs T_{22}, T_{18} equation (the "Edwards coefficients"). These will be compared with the Pt. Mugu coefficients to see if any differences are attributable to instrument change, altitude change, or some other pertinent variable. This determination will be necessary to ensure reliable portability of the WVR if measurements are to be made at a location other than Goldstone.

Reference

1. Batelaan, P. D., et al., "Development of a Water Vapor Radiometer to Correct for Tropospheric Range Delay in DSN Applications," *Deep Space Network Progress Report 42-33,* pp. 77-84, Jet Propulsion Laboratory, Pasadena, Calif., June 15, 1976.

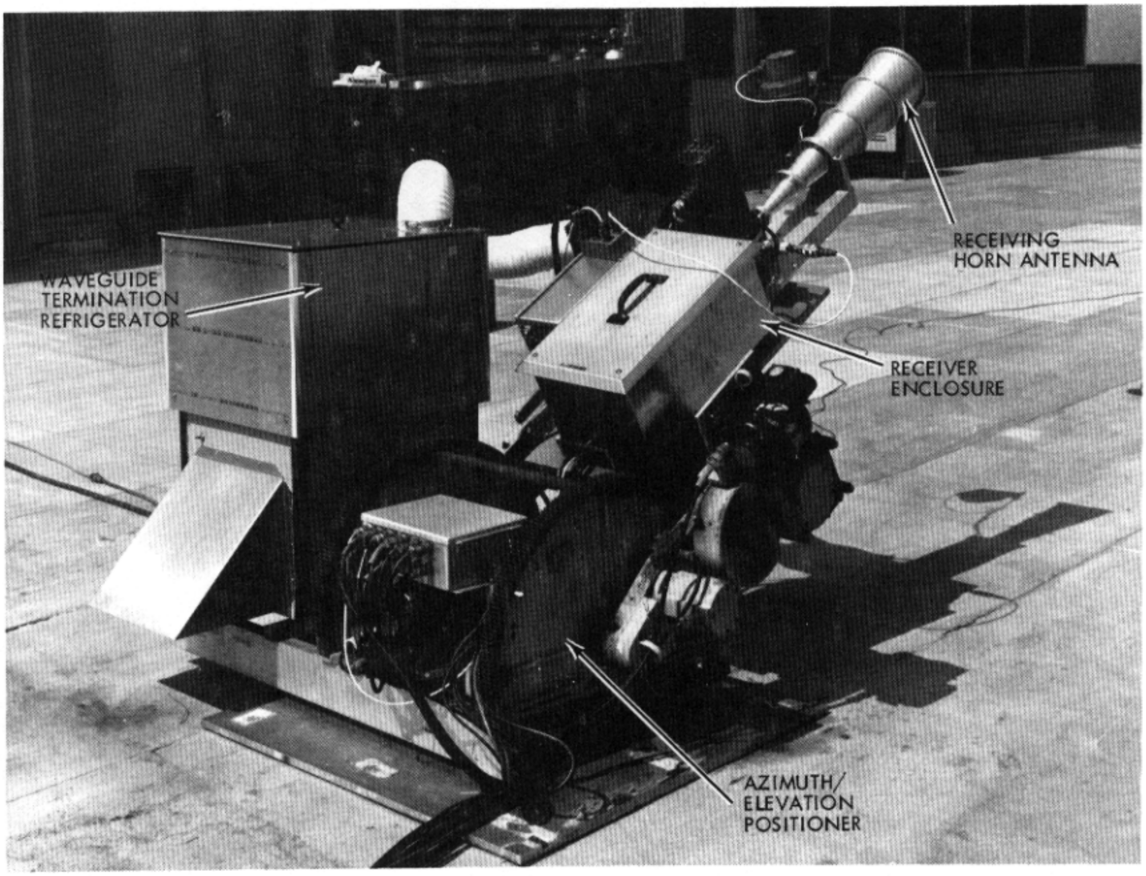

Fig. 1. Water vapor radiometer (present configuration, May 1977) mounted on the roof of Building 238 at JPL

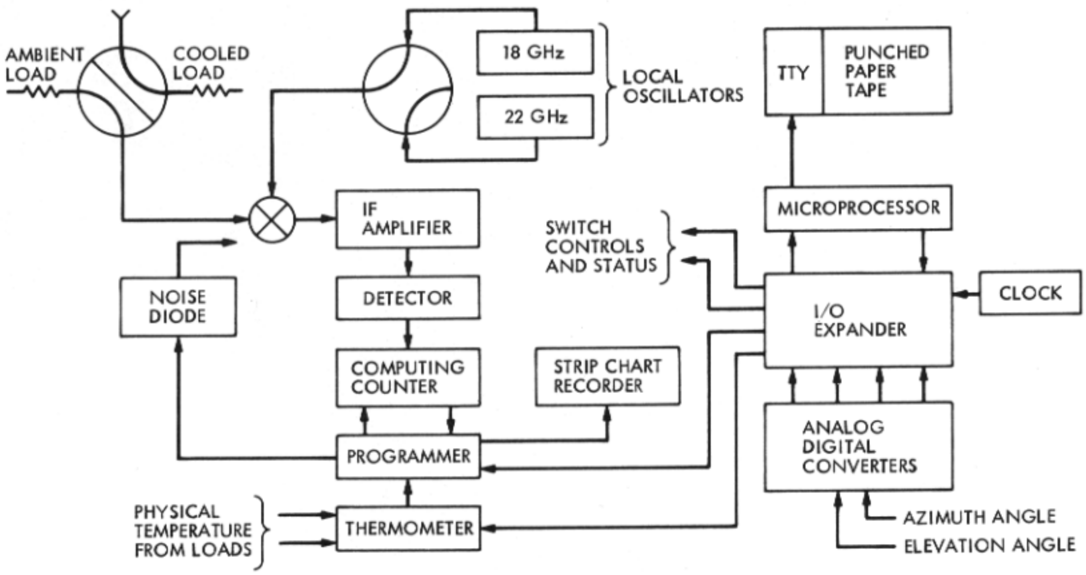

Fig. 2. Block diagram of water vapor radiometer

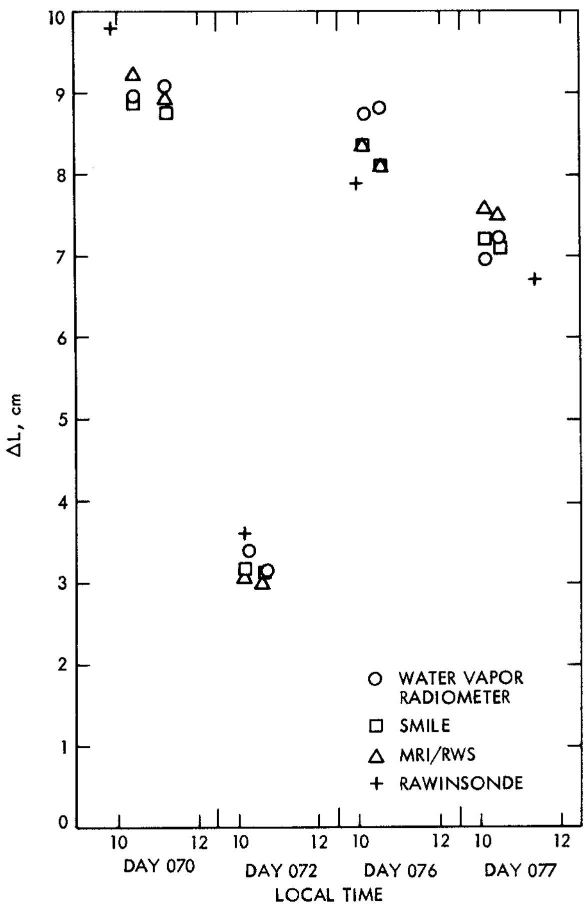

Fig. 3. Zenith tropospheric delay, Pt. Mugu, 1976

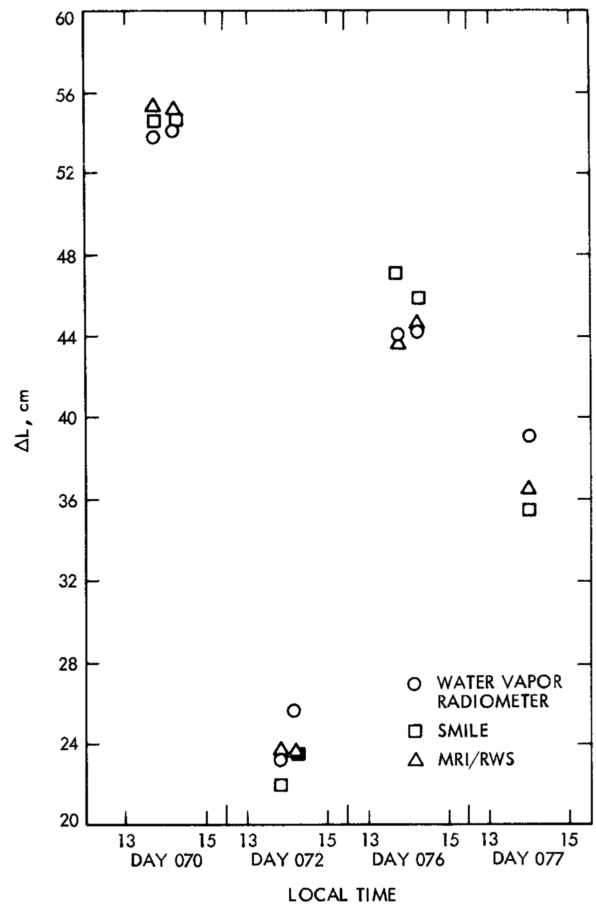

Fig. 4. 10-deg elevation tropospheric delay, Pt. Mugu, 1976

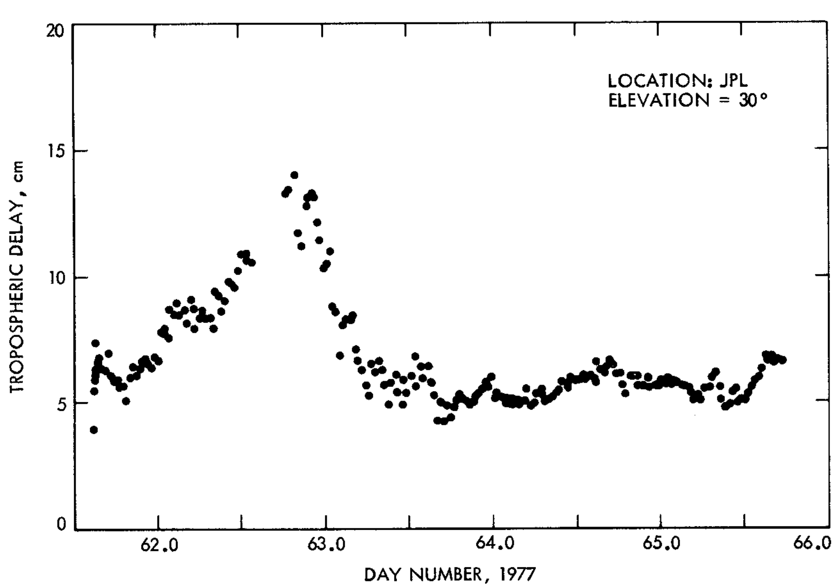

Fig. 5. Tropospheric delay results, JPL operational tests, March 1977