WATER VAPOR AS AN ERROR SOURCE IN MICROWAVE GEODETIC SYSTEMS: BACKGROUND AND SURVEY OF CALIBRATION TECHNIQUES*

E. S. Claflin and G. M. Resch

Jet Propulsion Laboratory

ABSTRACT

At microwave frequencies, the delay imposed by tropospheric water vapor becomes a limiting error source for high accuracy geodetic systems. The mapping of tropospheric induced errors into "solved-for" parameters depends upon baseline length and observing strategy. Simulation analysis (and experience) indicates that in some cases, errors in estimating tropospheric delay can be magnified in their effect on baseline components. We have surveyed the various techniques by which tropospheric water can be estimated or measured with particular consideration to their possible use as a calibration technique in support of VLBI experiments. The method of remote sensing using a microwave radiometer seems to be the most cost effective way to provide an accurate estimate of water vapor delay.

*The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS7-100, sponsored by the National Aeronautics and Space Administration.

Refractivity — $N = (n - 1) \times 10^6$

$$= \frac{77.6\,P}{T} + 1722\,\frac{\rho_V}{T}$$

"Electrical" Length — $L = \int_o^{\ell} n\,ds$

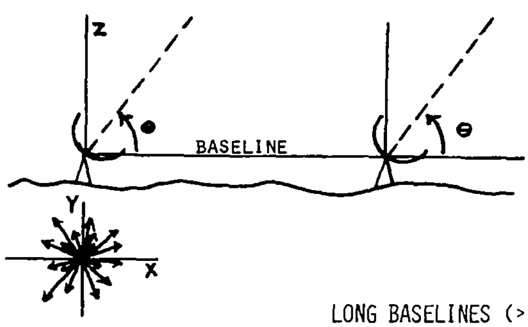
Path Delay — $\Delta L = \int_o^{\ell} (n - 1)\,ds = L - \ell$

Water Vapor Path Delay — $\Delta L_V = k \int \left(\frac{\rho_V}{T}\right) ds$

Precipitable Water Vapor — $V = \frac{1}{\rho_W} \int \rho_V\,ds$

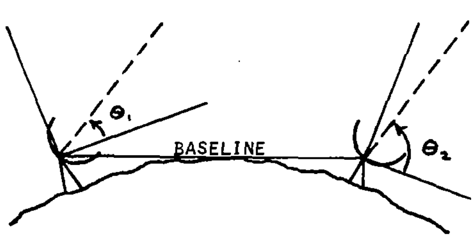
Ratio — $\Delta L_V / V \approx 6$

Figure 1. Refractivity and path delay.



- LOCAL VERTICALS NEARLY PARALLEL.
- WATER VAPOR ERROR AFFECTS ONLY LOCAL VERTICAL COORDINATE.
- STRONG COMMON MODE REJECTION.
- WATER VAPOR DELAY CANNOT BE SOLVED FOR.

LONG BASELINES (> ~ 1000 KM)



- LOCAL VERTICALS NOT PARALLEL.
- WATER VAPOR ERROR ENTERS ALL COMPONENTS OF BASELINE.
- NO COMMON MODE REJECTION.
- WATER VAPOR DELAYS CAN BE SOLVED FOR.

Figure 2.

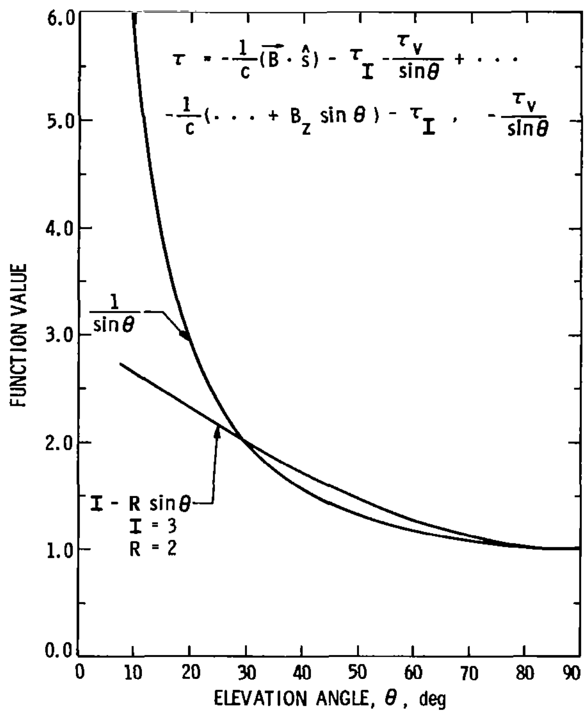


Figure 3. Similar functions: $(\mathrm{Sin}\ \theta)^{-1}$ and (I-R Sin θ).

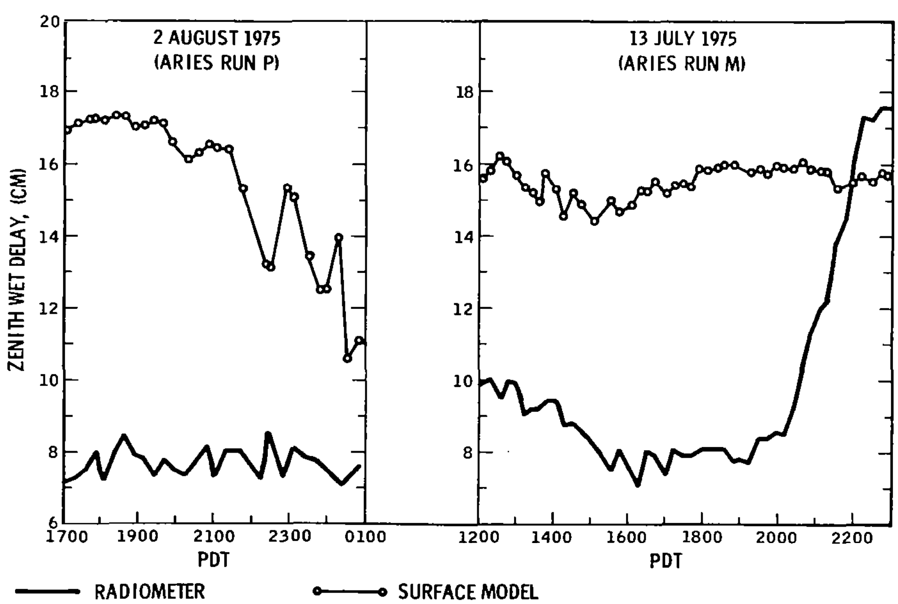


Figure 4. Zenith path delay during ARIES experiments as predicted by radiometer and a surface model.

I. IN SITU MEASUREMENTS

A. RADIOSONDES
B. AIRCRAFT
C. DRONES

II. TRANSMISSION MEASUREMENTS

A. SOLAR HYGROMETERS
B. 22 GHZ SATELLITE TRANSMITTER
C. OPTICAL/MICROWAVE TRANSMITTER

III. REMOTE SENSING

A. LIDAR
B. INFRARED WVR
C. MICROWAVE WVR

Figure 5. Water vapor measurement techniques.

PART I. IN SITU MEASUREMENTS

- RADIOSONDES - $50 K CAPITAL INVESTMENT, $100 PER LAUNCH.
  RECEIVING EQUIPMENT CAN BE AUTOMATED.
  PROVIDES MEASUREMENT AT "ZENITH".
  ACCURACY DIFFICULT TO SPECIFY.
  OPERATES DAY OR NIGHT AND DURING RAINFALL.

- INSTRUMENTED AIRCRAFT - EXPENSIVE ~ $1600 PER DAY.
  OPERATIONALLY INCONVENIENT.
  FLIGHTS RESTRICTED IN OVERCAST CONDITIONS.
  POTENTIAL CALIBRATION ACCURACY ~ 1 CM.

- INSTRUMENTED DRONE - $65 K CAPITAL INVESTMENT (RADIOSONDE RECEIVING EQUIPMENT).
  OPERATIONALLY INCONVENIENT.
  NOT SUITABLE FOR AUTOMATION.
  SAFETY HAZARD.
  POTENTIAL ACCURACY BETTER THAN SURFACE MODEL.

Figure 6. Water vapor measurement techniques.

PART II. TRANSMISSION MEASUREMENTS

- SOLAR HYGROMETER - INEXPENSIVE $\leq$ 12 K, CAN BE AUTOMATED.
  ONLY OPERATES IN SOLAR DIRECTION.
  INOPERATIVE UNDER CLOUDS OR AT NIGHT.
  ACCURACY PROBABLY BETTER THAN 3 CM AT ZENITH - DEPENDS ON SOLAR ELEVATION ANGLE.

- 22 GHz SATELLITE TRANSMITTER - VERY EXPENSIVE.
  ELECTROMAGNETIC POLLUTION.
  ONLY OPERATES IN DIRECTION OF SATELLITE.
  POOR ACCURACY POTENTIAL.

- OPTICAL/MICROWAVE TRANSMITTER - DIRECT MEASURE OF WATER VAPOR DELAY.
  EXPENSIVE OPERATIONALLY.
  NEEDS REPACKAGING FOR USE IN AERIAL PLATFORM.
  OPERATES DAY/NIGHT, BUT NOT UNDER CLOUDS.
  VERY HIGH POTENTIAL ACCURACY ~ 0.3 CM.

Figure 7. Water vapor measurement techniques.

PART III. REMOTE SENSING

- LIDAR (LASER RADAR) - EQUIPMENT INVESTMENT ~ $100 K.
  BULKY PACKAGING NOT SUITABLE FOR MOBILE OPERATIONS.
  GOOD SPATIAL AND TEMPORAL RESOLUTION OF VAPOR PROFILE.
  OPERATES DAY OR NIGHT, NOT UNDER CLOUDS.
  ACCURACY POTENTIAL BETTER THAN 1 CM.

- INFRARED WATER VAPOR RADIOMETER (WVR) - OPACITY TOO HIGH.

- MICROWAVE WATER VAPOR RADIOMETER (WVR) - COST ~ $85K.
  COMPACT PACKAGE CAN BE AUTOMATED.
  OPERATES DAY OR NIGHT, NOT DURING RAINFALL.
  POTENTIAL ACCURACY ~ 1 CM LINE-OF-SIGHT.

Figure 8. Water vapor measurement techniques.