

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

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### 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.

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

$$= \frac{77.6 P}{T} + 1722 \frac{\rho_v}{T}$$

“Electrical” Length —  $L = \int_0^{\ell} n \, ds$

Path Delay —  $\Delta L = \int_0^{\ell} (n - 1) \, ds = L - \ell$

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.

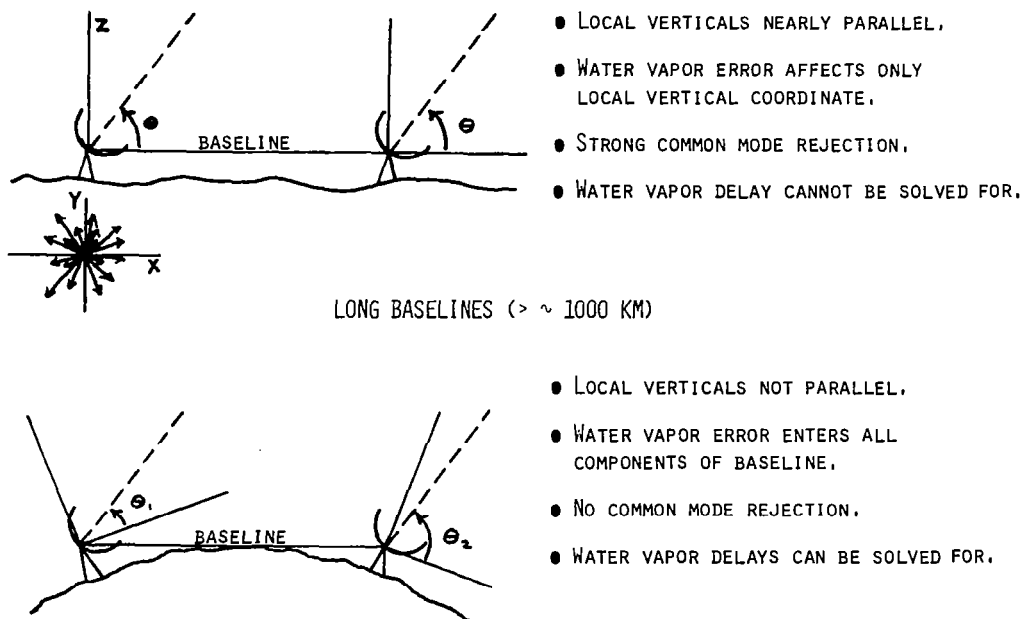


Figure 2.

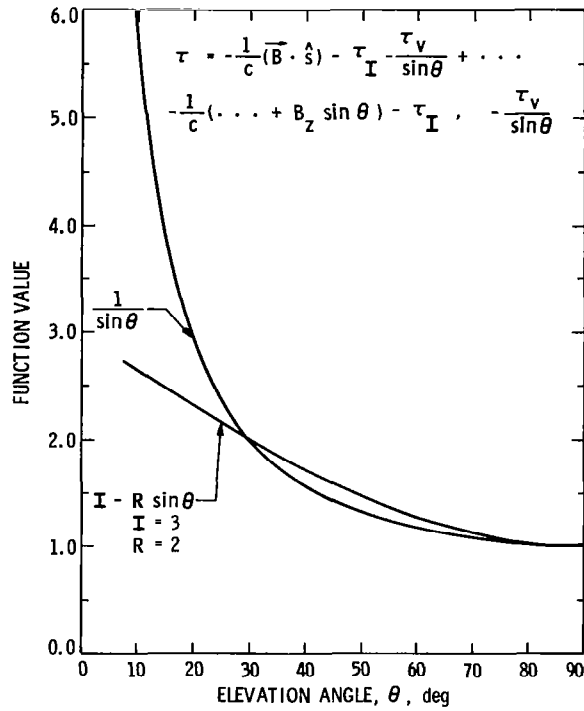


Figure 3. Similar functions:  $(\sin \theta)^{-1}$  and  $(I-R \sin \theta)$ .

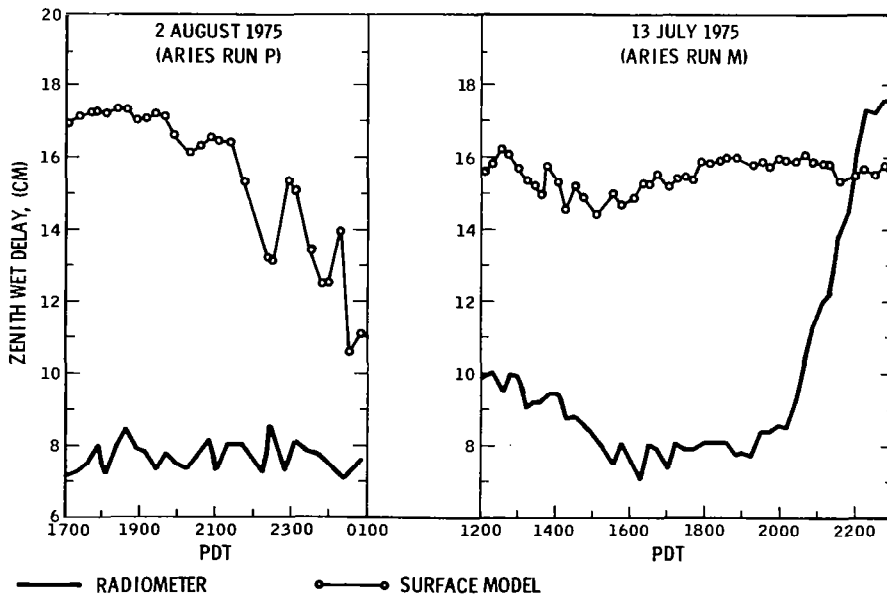


Figure 4. Zenith path delay during ARIES experiments as predicted by radiometer and a surface model.

## RADIO INTERFEROMETRY

- 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 } - EXPENSIVE ~ \$1600 PER DAY.  
AIRCRAFT } OPERATIONALLY INCONVENIENT.  
FLIGHTS RESTRICTED IN OVERCAST CONDITIONS.  
POTENTIAL CALIBRATION ACCURACY ~ 1 CM.
  
- INSTRUMENTED } - \$65 K CAPITAL INVESTMENT (RADIOSONDE RECEIVING EQUIPMENT).  
DRONE } 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 } - VERY EXPENSIVE.  
TRANSMITTER } ELECTROMAGNETIC POLLUTION.  
ONLY OPERATES IN DIRECTION OF SATELLITE.  
POOR ACCURACY POTENTIAL.
  
- OPTICAL/MICROWAVE } - DIRECT MEASURE OF WATER VAPOR DELAY.  
TRANSMITTER } EXPENSIVE OPERATIONALLY.  
NEEDS REPACKAGING FOR USE IN AERIAL PLATFORM.  
OPERATES DAY/NIGHT, BUT NOT UNDER CLOUDS.  
VERY HIGH POTENTIAL ACCURACY  $\sim 0.3$  CM.

Figure 7. Water vapor measurement techniques.

PART III. REMOTE SENSING

- LIDAR (LASER RADAR) - EQUIPMENT INVESTMENT  $\sim$  \$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 } - OPACITY TOO HIGH.  
RADIOMETER (WVR) }
  
- MICROWAVE WATER VAPOR } - COST  $\sim$  \$85K.  
RADIOMETER (WVR) } COMPACT PACKAGE CAN BE AUTOMATED.  
OPERATES DAY OR NIGHT, NOT DURING RAINFALL.  
POTENTIAL ACCURACY  $\sim$  1 CM LINE-OF-SIGHT.

Figure 8. Water vapor measurement techniques.

