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# DETERMINATION OF THE TELLURIC WATER VAPOR ABSORPTION CORRECTION FOR ASTRONOMICAL DATA OBTAINED FROM THE KUIPER AIRBORNE OBSERVATORY

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## Summary

This report compares the amount of telluric water vapor along the line of sight of the Kuiper Airborne Observatory telescope as obtained concommitantly on 23 flights with the NASA-Ames Michelson interferometer and with the NOAA-Boulder radiometer. A strong correlation between the two determinations exists, and a method for computing the atmospheric transmission for a given radiometer reading is established.

## Introduction

A problem commonly faced by scientists making astronomical observations from within the Earth's atmosphere is the correction of the measured intensity for telluric absorption. From the operating altitude of the Kuiper Airborne Observatory (KAO), the problem can still be severe, depending on the wavelength range and spectral resolution of the observation. Over most of the infrared portion (1-1000 μm) of the spectrum the major absorbing constituent is water. Two NOAA-Boulder water vapor radiometers (Kuhn *et al.*, 1975; Kuhn *et al.*, 1976) are operated routinely onboard the observatory to provide experimenters a record of the amount of water vapor (1) along the line of sight (LOS) of the telescope, and (2) on a vertical line or zenith (z) above the aircraft.

## Water Radiometer Measurements

The NOAA radiometers measure the absolute energy in a spectral band extending from approximately 19-37 μm. The response of the radiometer in this band is a product of the window and filter transmissions, the detector response function, and the amplifier gain. The shape of the radiometer response function versus wavelength is determined from the response curves of the separate components. The absolute responsivity (V/W) is calibrated in the laboratory using a cooled and purged black body source. In flight, the radiometer sees the sky chopped against a $273^{\circ}$K reference source. The radiant power P from the sky is determined from the radiometer output. A separate radiometer, operating from 14-16 μ on the edge of the $CO_2$ band determines the air temperature T. The amount of precipitable water vapor W is then determined from predictions of P by a multilayer atmospheric model which have been previously calculated using the radiometer response function, for various values of T and W. The water vapor line strengths for the radiometer emission are based on the current Air Force Geophysical Laboratory line strength compilation adapted to a specific transfer computer model. Pressure broadening and temperature corrections to the absorption coefficients are introduced for each layer. Program DEGRADE and NOAA programs KBAR and LINES (NOAA-APCL-R31-1977) are combined to obtain the broad band absorption coefficients employed in the model. A preliminary value of W is available on-line during the observations, and a final record of W versus time during a flight is available within a few days of the flight after processing on the NOAA computer at Boulder. The record of W (both LOS and z) as a function of time is available to each telescope user for the period of his observations.

## Far Infrared Spectral Observations

An independent estimate of the LOS value of W has been obtained a number of times from measurements of the atmospheric transmission made with the NASA-Ames Michelson interferometer. This instrument flies typically a few times per year on the KAO to observe astronomical sources. The wavelength region covered on any one flight is broad, with extreme limits of ∿20μ and 200μ. The exact wavelength range is determined by filters and beamsplitters (Erickson et al., 1977). Over this wavelength range the atmosphere is, on the average, only about 70% transmitting due to absorption by the atmospheric water vapor. The water vapor absorption consists of optically thick broad lines spaced at irregular intervals throughout the spectrum, with relatively clear wavelengths inbetween. Since the Michelson interferometer sees each of these lines (or groups of lines at low resolution), it is possible to determine the amount of atmospheric absorption in each individual spectrum.

Transmission spectra for the Earth's atmosphere can be computed for any amount of water vapor, using program "DEGRADE" on the NASA-Ames CDC 7600. The program assumes a single layer atmosphere and the Curtis-Godson approximation for temperature and pressure (Augason et al., 1975; Augason and Burnes, 1977). The $H_2O$ and $O_3$ line list of McClatchey et al. (1973) is used.

In order to determine the water vapor absorption from the observed spectrum of any given astronomical source, one must have a good idea of the true source spectrum and the instrument response. For the lunar spectrum we assume a gray body at a temperature appropriate to the location of our beam on the lunar surface relative to the subsolar point (Linsky, 1973). For Mars, Jupiter, and Saturn, brightness temperatures as a function of wavelength described by Erickson et al. (1978) were used to compute the source spectra. The instrument function is determined by iteration from the comparison of the measured spectrum with a synthetic spectrum. The initial instrument function is determined from laboratory measurements made with a blackbody in vacuum. The instrument response function is then revised for those wavelengths where the synthetic spectrum disagrees with the observed spectrum and the transmission is good enough that water absorption is not the cause of the disagreement.

To determine the amount of water vapor in the line of sight, synthetic spectra are computed for various values of W. Each synthetic spectrum is compared to the observed spectrum and the sum of the squares of the residuals is computed for wavelengths where the instrument response function times the source spectrum is greater than a certain amount. The finite spectral range is chosen to minimize the effects of noise where the signal is very low, but otherwise, the widest possible spectral range is used. The "best fit" value of W corresponds to the minimum in the sum of the squares of the residuals. The accuracy of this procedure depends upon the resolution of the spectra. For 5 $cm^{-1}$ resolution W can be obtained to about 1.0 precipitable microns. For 2.5 $cm^{-1}$ resolution the water vapor can be determined to about 0.25 $\mu$. For 10 $cm^{-1}$ resolution, the procedure does not give reliable results. These numbers are for the range 2 to ∿8μ of $H_2O$. For larger amounts of water the accuracy decrease. In fact, the accuracy seems to be proportional to the log of the water vapor column density.

Some examples are plotted in Figures 1 and 2. Both figures show a measured spectrum of the Moon and the best fit synthetic spectrum at 5 $cm^{-1}$ resolution. The small deviations throughout the spectra may be due to noise and to the fact that the instrument response function is tabulated only every 10 $cm^{-1}$. The RMS average deviation for each point is 2.2% for scan 9 from 28 June, 1977 and 1.8% for scan 49 from 1 July, 1977, relative to the measured peak intensity.

## Comparison of the Two Experiments

Determinations of the water vapor column density in the line of sight for 36 scans from 5 different days are plotted in Figure 3. The abscissa is the value of W determined by the Ames Michelson interferometer ($W_M$) and the ordinate is the value determined by the NOAA radiometer ($W_R$) for the same times during the flights. The astronomical sources were the Moon, Jupiter, and Mars for Nov. 17, 1977 and Nov. 21, 1977, the Moon for April 21, 1978, and Mars, Jupiter, and Saturn for January 21, 1976 and January 26, 1976.

There is seen to be a strong correlation (0.90 for all 36 points) in the data, with the radiometer values ($W_R$) consistently (with one exception) higher than the Michelson values ($W_M$). A quadratic equation fitted by the method of least squares to the data gives

$$W_M = 0.526\ W_R\ (1 + 0.016\ W_R) \qquad (1)$$

Submillimeter spectroscopy has also shown a good correlation with the radiometer measurements (Nolt *et al.*, 1979).

## Correction of Astronomical Data for Telluric Absorption

The differences between the values of W determined by the two methods could arise from a number of causes. However, the important question for an astronomer using the telescope is how to calculate an atmospheric absorption correction to his data given a value of $W_R$. From Figures 1 and 2 it appears that the atmospheric transmission is modeled to ∿1% by the computer program DEGRADE using the value $W_M$.

The following simple procedure then provides a reasonable correction: using equation 1, calculate a value of $W_M$ from the measured $W_R$. Then use this value of $W_M$ in program DEGRADE---or its ADAMS equivalent, CDG21 (Augason and Burnes, 1977)--to compute the transmission over the wavelength range and at the spectral resolution of interest. The error in the correction may be obtained by estimating the limits on $W_M$ from Figure 3, and using the program to recompute the transmission for these values of $W_M$.

Programs DEGRADE and CDG21 use a number of parameters, in addition to W, to computer the transmission. The following parameters should be used when applying this correction technique:

V1 and V2, the wavenumber limits of the spectrum to be calculated.

Type of slit function and full width at half max for triangular (CDG21 only) or equivalent interferometer mirror travel for a Michelson (DEGRADE only).

Pressure = 0.126 atmospheres and temperature = 216.6°K (These are for the Curtis-Godson approximation (see Augason and Burnes, 1977).

Wavenumber intervals (bin sizes) for calculating and for plotting.

The DEGRADE data cards require a number of other parameters that are the same for every run involving $H_2O$.

It should also be mentioned that an appropriate instrument response function can and should be used with DEGRADE or CDG21 to compute the average transmission.

Assistance in running programs DEGRADE or CDG21 will be provided by the Ames Astronomy Facilities Scientist.

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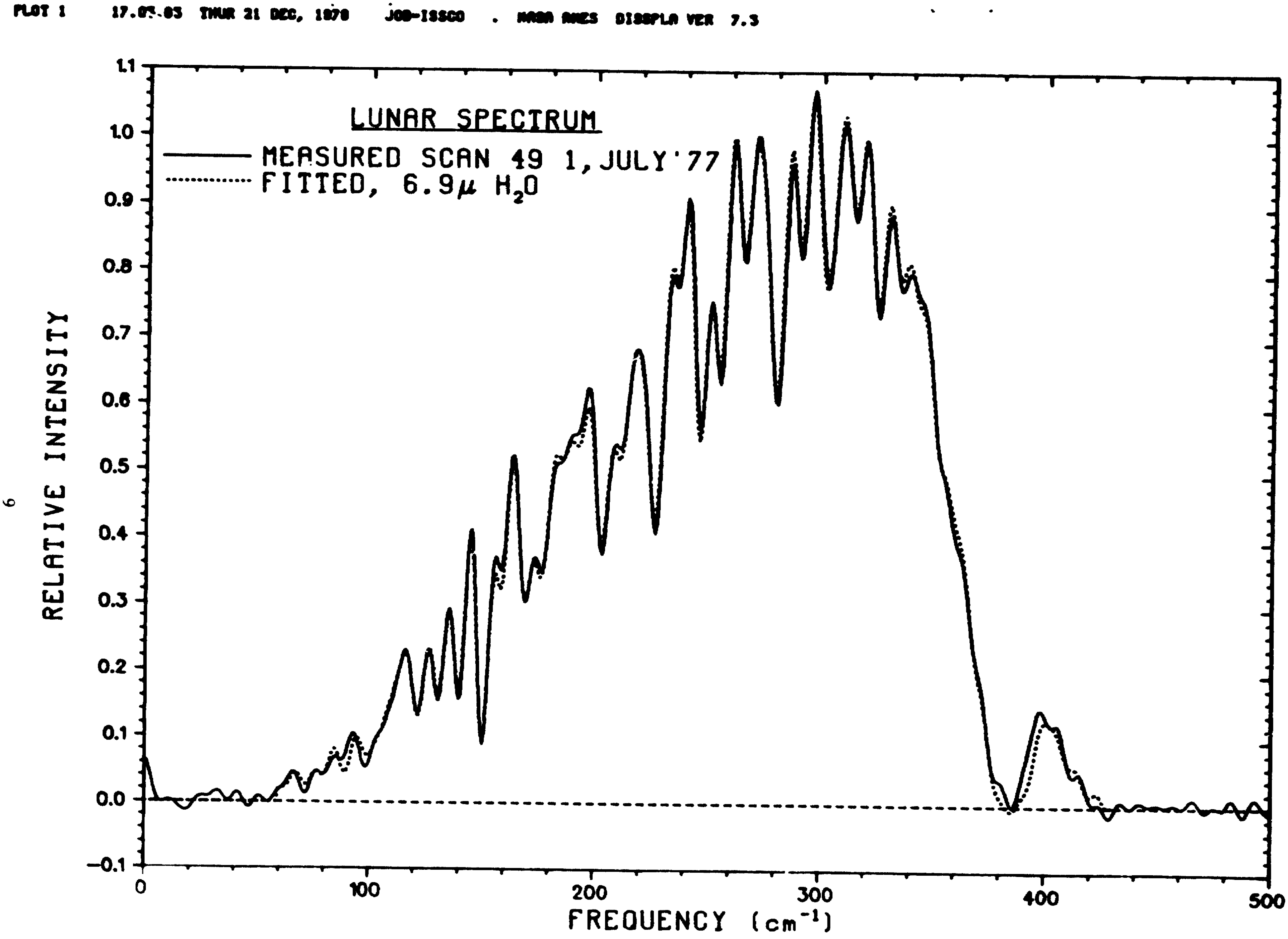

Figure 1. Comparison of measured lunar spectrum with synthetic spectrum using $W$ = 6.9 microns.

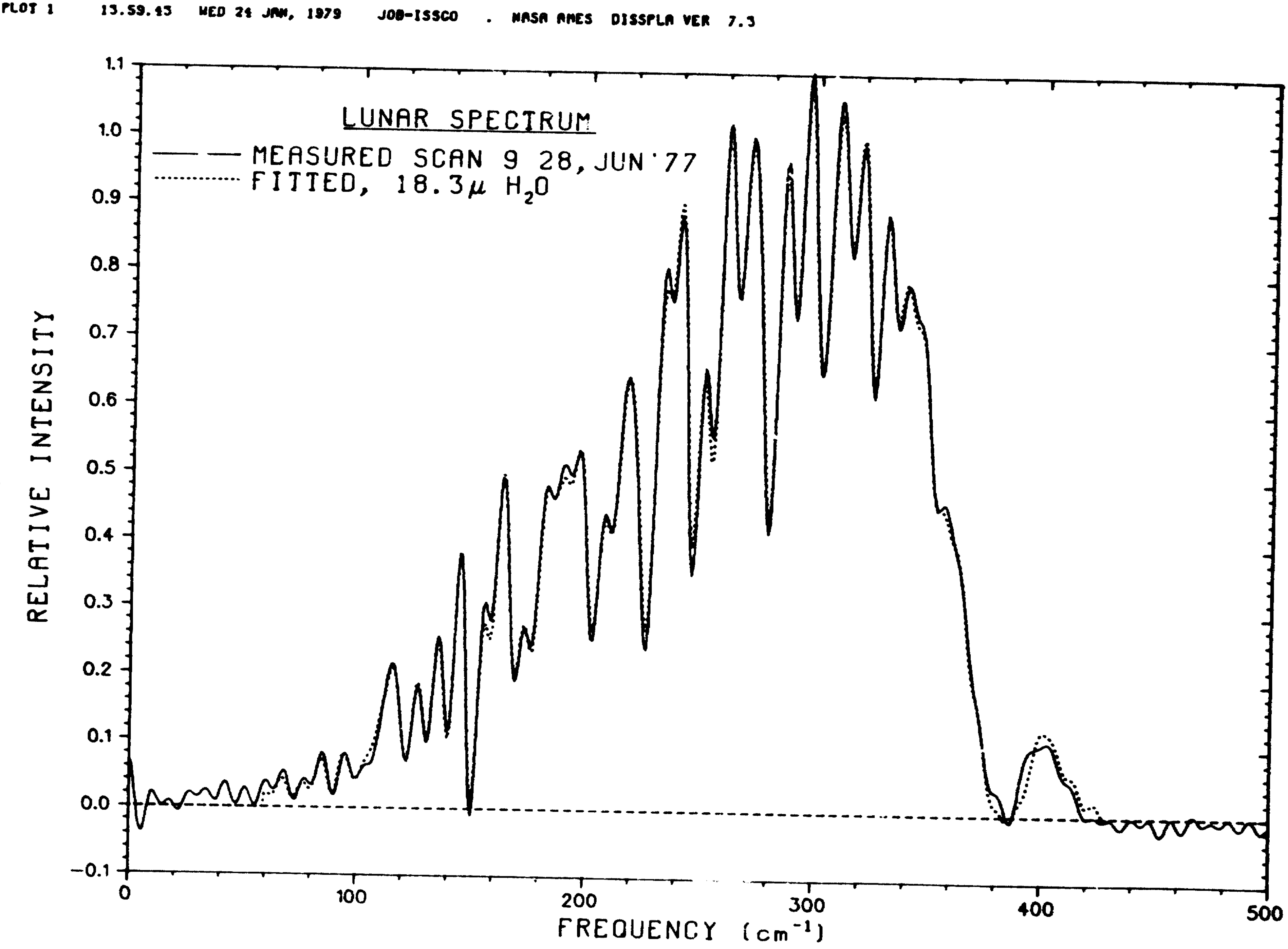

Figure 2.- Comparison of measured lunar spectrum with synthetic spectrum using W = 18.3 microns.

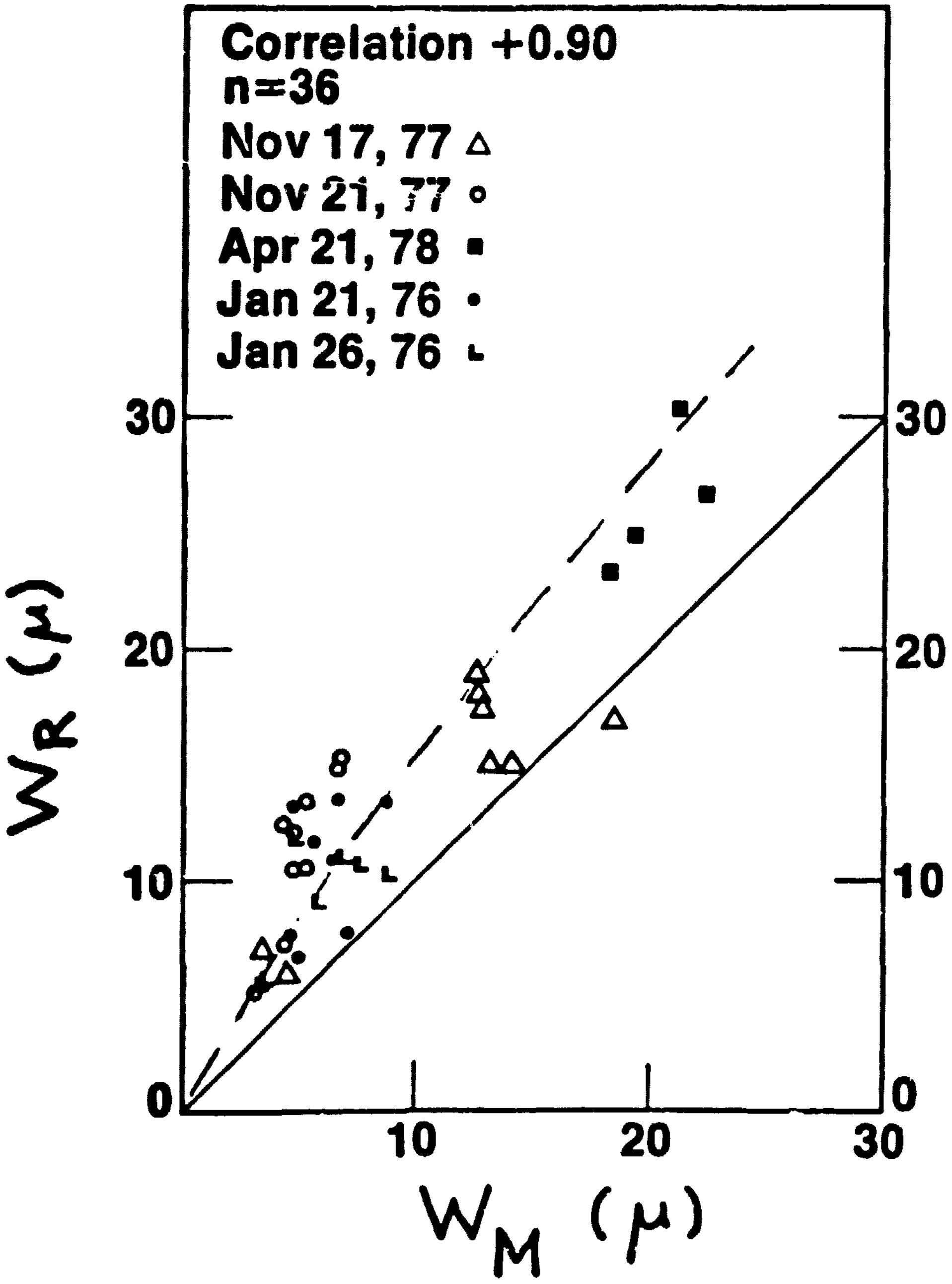

Figure 3.- Comparison of water vapor column densities measured with the radiometer ($W_R$) and the Michelson interferometer ($W_M$). The quadratic fit of equation (1) is shown as a dashed line.