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A method is presented to estimate the ratio of the transmittances in the two channels of the AVHRR split window. This method uses only the radiances and requires no a priori information. Precipitable water estimates from the AVHRR are compared with those estimated from radiosondes.

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Thomas J. Kleespies

22b. TELEPHONE (Include Area Code)
(617)377-3136

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# Determination of Precipitable Water with the AVHRR

Thomas J. Kleespies
Air Force Geophysics Laboratory/LYS
Hanscom AFB, Bedford MA 01731

Larry M. McMillin
National Oceanic and Atmospheric Administration
National Environmental Satellite, Data, and Information Service
Washington D.C. 20233

## 1. INTRODUCTION

The "split window" technique was originally derived for the determination of surface skin temperature, specifically sea surface temperature (Anding and Kauth, 1969). The technique makes use of two differentially absorbing channels in the 11- to 12- μm region to remove the contaminating effect of water vapor and thus arrives at an improved estimate of the skin temperature. See McMillin and Crosby (1984) for a detailed discussion of the split window technique and an extensive review of the literature.

More recently the channels used for the split window have been applied to the retrieval of precipitable water (Chesters, et al. 1983, Chesters et al. 1987). Whereas these methods seemed to produce internally consistent fields of "low level water vapor", they required *a priori* knowledge of the mean air temperature and empirical adjustment of the absorption coefficients in order to bring the results in agreement with in situ observations.

In this paper we present the results of an extension to the split window technique such that precipitable water can be retrieved with a minimum of *a priori* information.

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## 2. THEORETICAL DISCUSSION

Kleespies and McMillin (1984,1986) have presented a theoretical discussion of this extension to the split window technique. Summarized briefly, the upwelling longwave infrared radiance emitted from a plane parallel, non scattering atmosphere in local thermodynamic equilibrium and a surface with unit emissivity can be expressed as

$$I = B_s \tau_s + \int_{\tau_s}^{1} B \, d\tau \qquad (1)$$

where I is the radiance measured by the satellite, B is the Planck radiance, $\tau$ is the transmittance from a given level to the top of the atmosphere, the subscript s refers to the surface of the earth, and the integral is the radiance originating from the atmosphere alone. Equation (1) may also be written as

$$I = B_s \tau_s + \bar{B}_a (1-\tau_s) \qquad (2)$$

where $\bar{B}$ is a weighted average given by

$$\bar{B}_a = \frac{\int_{\tau_s}^{1} B \, d\tau}{\int_{\tau_s}^{1} d\tau} \qquad (3)$$

Consider observations of the earth under conditions where the surface contribution to the outgoing infrared radiance varies markedly, but where the atmospheric contribution changes very little. We can now write a set of four equations, one for each of the two channels, and one for each of the different surface observing conditions:

$$I_{11}^{1} = B_{s_{11}}^{1} \tau_{s_{11}} + \bar{B}_{a_{11}} (1-\tau_{s_{11}}) \qquad (4a)$$

$$I_{12}^{1} = B_{s_{12}}^{1} \tau_{s_{12}} + \bar{B}_{a_{12}} (1-\tau_{s_{12}}) \qquad (4b)$$

$$I_{11}^2 = B_{s_{11}}^2 \tau_{s_{11}} + \bar{B}_{a_{11}}(1-\tau_{s_{11}}) \tag{4c}$$

$$I_{12}^2 = B_{s_{12}}^2 \tau_{s_{12}} + B_{a_{12}}(1-\tau_{s_{12}}) \tag{4d}$$

where the superscripts 1 and 2 refer to the viewing conditions and the subscripts 11 and 12 refer to the nominal 11 and 12 micrometer channels in the split window. We can eliminate the atmospheric term $\bar{B}_a$ by differencing to yield two equations

$$\Delta I_{11} = \Delta B_{s_{11}} \tau_{11} \tag{5a}$$

$$\Delta I_{12} = \Delta B_{s_{12}} \tau_{12} \tag{5b}$$

where for compactness we have written the delta quantities as

$$\Delta I_{11} = I_{11}^1 - I_{11}^2 \tag{6a}$$

$$\Delta B_{11} = B_{11}^1 - B_{11}^2 \tag{6b}$$

The ratio of transmittances in the two channels may be formed by dividing Eqs. (5) to yield

$$\frac{\tau_{11}}{\tau_{12}} = \frac{\Delta I_{11}\, \Delta B_{s_{12}}}{\Delta I_{12}\, \Delta B_{s_{11}}} \tag{7}$$

Following the approach of McMillin (1971), Eq. (7) can be linearized by converting from radiances to temperatures, the $\Delta B_s$ become $\Delta T_s$ and cancel, and after expanding the delta quantities we are left with

$$\frac{\tau_{11}}{\tau_{12}} = \frac{T_{11}^1 - T_{11}^2}{T_{12}^1 - T_{12}^2} \; . \tag{8}$$

It has been shown that this ratio can be related to "low level water vapor" i.e., precipitable water (Chesters, et al, 1983).

The observing conditions under which the surface contribution to the upwelling radiances can change markedly but the atmospheric contribution can change very little fall into two general categories; that of variation in time, and that of variation in space. Consecutive observations of a land surface from a geosynchronous satellite during the heating cycle of the day would be one example. Another would be observations from either a geosynchronous or polar orbiting satellite of immediately adjacent land and water surfaces with contrasting skin temperatures.

Kleespies and McMillin (1984) discuss the theoretical application of this extension to the Visible Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS), and in their 1986 paper describe, again in theoretical terms, its application to Advanced Very High Resolution Radiometer (AVHRR) split window data. In ensuing sections, application of this technique to the AVHRR instruments is demonstrated with real data.

## 3. APPLICATION TO SATELLITE RADIOMETER DATA

The test of a retrieval algorithm is to apply it to real data and to somehow verify it with ground truth. However this is fraught with difficulties, including cloud contamination, aerosol problems, collocation inaccuracies, and errors in the satellite instrument and the in situ measurements. In the following sections we apply this technique to measurements made with the AVHRR. In all cases where atmospheric transmittance was computed or radiative transfer was performed, the wide-band radiative transfer model described by Weinreb and Hill (1980) was used.

Global Area Coverage (GAC) data from the AVHRR were collected from NOAA-7 for 11 June 1982. GAC data has a nominal resolution of 4 km and is distinguished from the nominal AVHRR sensor 1 km resolution by the fact that four pixels are averaged along scan and four scans are skipped to make a GAC scan line. Bands 4 and 5 have the nominal wavelength of 10.7- and 11.8- μm respectively. Nighttime data over North America was used in order to be as close as possible to radiosonde launch time and in order to avoid convective cloudiness. The orbits were from four hours to one hour prior to synoptic time. Cloud free areas were selected at the AFGL Interactive Meteorological System (AIMS) (Gustafson et al, 1987) workstation by examining 24-bit multispectral imagery created from AVHRR bands 3, 4 and 5 (d'Entremont and Thomason, 1987). In this imagery opaque clouds appear white, low clouds and fog appear bright red against a brown background, and thin cirrus appears cyan, yielding a fairly unambiguous rendition of clear/cloudy regions. Contrasting surface temperatures were determined by selecting a body of water (lake, river, coastline) which at nighttime in the late spring was relatively warm compared to the surrounding countryside. A 3×3 array of GAC spots were selected for both the warm water surface and the cooler countryside surrounding it. Since many of these water surfaces did not fill the 3×3 array of GAC pixels, a method was developed to determine the "best" combination of warm and cold brightness temperatures. A comparison of two ensembles of 3×3 arrays yields 81 possible combinations. The brightness temperature differences between these 81 combinations were sorted in descending order for each of the two channels. The sum of the rank order of the pixel pairs between the two scenes and the two channels was used as a "quality measure", the idea being to maximize the brightness temperature difference between the warm and the cold scenes for both channels. A truncated normal type of filter was applied to the pixel pairs with the top ten "quality measures". The mean and standard deviation of the transmittance ratio as determined by Eq. 8 was computed. Any transmission ratio outside of one standard deviation was discarded and the mean recomputed from the remaining ratios. The effect of this procedure was to objectively eliminate outliers. The next step is to computes precipitable water from the transmission ratio. This was done by synthetic regression. Two hundred and ninety six North American radiosondes were collected from three consecutive synoptic times beginning at 12Z 8 June 1982. Transmittances were computed for these radiosondes and regressed against the radiosonde precipitable water. The line of best fit and error statistics are given in Figure 1.

Next the precipitable water determined with the AVHRR was compared with the 12Z radiosondes. Collocation distance was 300km and collocation time depended upon the orbit, and varied from one to four hours. This comparison is given in Figure 2. Given the large collocation window these results are quite good, with a correlation of .7077, mean difference of 0.11 cm and standard difference of 0.552 cm. However the large collocation window can certainly be improved upon. For example, one of these "collocations" was between an AVHRR observation near Pittsburgh, PA and a radiosonde near Washington DC, which was on the other side of the Appalachian mountains and on the opposite side of a cold front.

As an attempt to bring some of the gradient information from the radiosondes into the comparison, the radiosonde precipitable water observations were analysed to a 2x2 degree grid using a Cressman analysis. The analysed precipitable water was bilinearily interpolated to the AVHRR location. The comparison between the AVHRR observations and the analysed radiosonde precipitable water is given in Figure 3. There are more comparisons in Figure 3 than in Figure 2 because Figure 2 had a maximum separation of 300 km. The comparison here is quite good, yielding a correlation of .8253, effectively no bias and a standard difference of 0.397 cm. The comparison appears even better when the analysis error is examined in Figure 4. Here it is seen that the radiosondes compared with their own analysis have a mean difference of -0.02 cm, a standard difference of 0.463 cm, and a correlation of .8906. These statistics are similar to those given in Figure 3.

## 4. DISCUSSION

The comparison between precipitable water deduced from the AVHRR and analysed radiosondes is quite good, especially considering the fact that there is a difference in observing time of up to four hours, and that the analysis error is only slightly less than the difference between the AVHRR and the analysed radiosonde. It is clear that this technique has potential for determining precipitable water from radiometric observations using *a priori* information only in setting up synthetic regression. However, this particular method of obtaining the contrasting skin temperatures is unwieldy and requires considerable manual effort. While this method may be useful for limited area work of case studies, it's usefulness for large scale applications will probably be limited.

Recently, Jedlovec (1987) has proposed an extension to this technique, where he determines the transmission ratio to be the ratio of the spatial variance of the channel brightness temperatures, and demonstrated it's usefulness with the Multispectral Atmospheric Mapping Sensor (MAMS), an airborne instrument with a resolution of 100m. The Jedlovec technique may be useful in large scale applications, but it remains to be demonstrated if it will work with an instrument such as the AVHRR.

Potentially the most useful platform for this technique is the geosynchronous satellite. Kleespies and McMillin (1988) presented preliminary results from the VISSR Atmospheric Sounder (VAS) on the GOES satellites which indicate that it may be possible to deduce precipitable water in clear air by observing the earth's surface heat up and cool down during the diurnal heating cycle. The geometric considerations of geosynchronous orbit are very amenable to automated techniques. If the difficulties in using the more noisy VAS instrument can be resolved, then truly useful precipitable water measurements can be made from split window observations.

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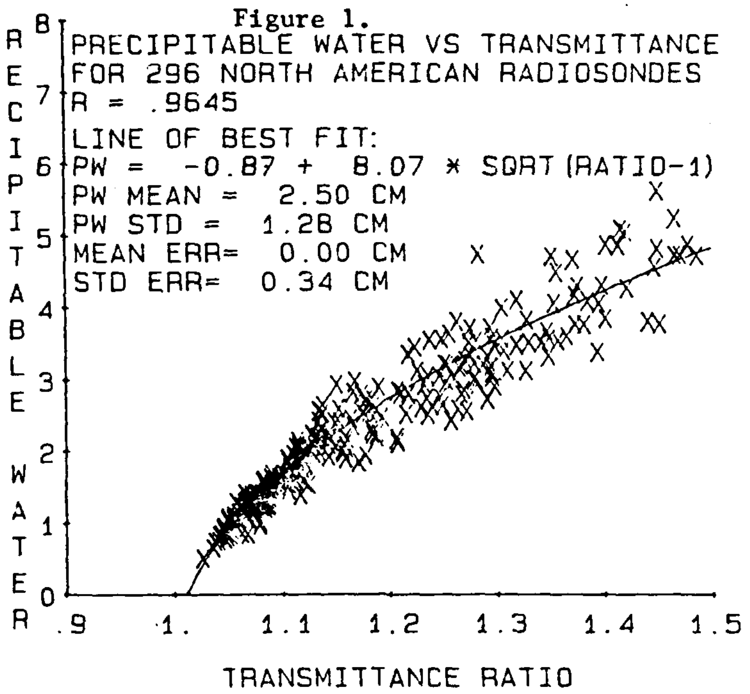

Figure 1.

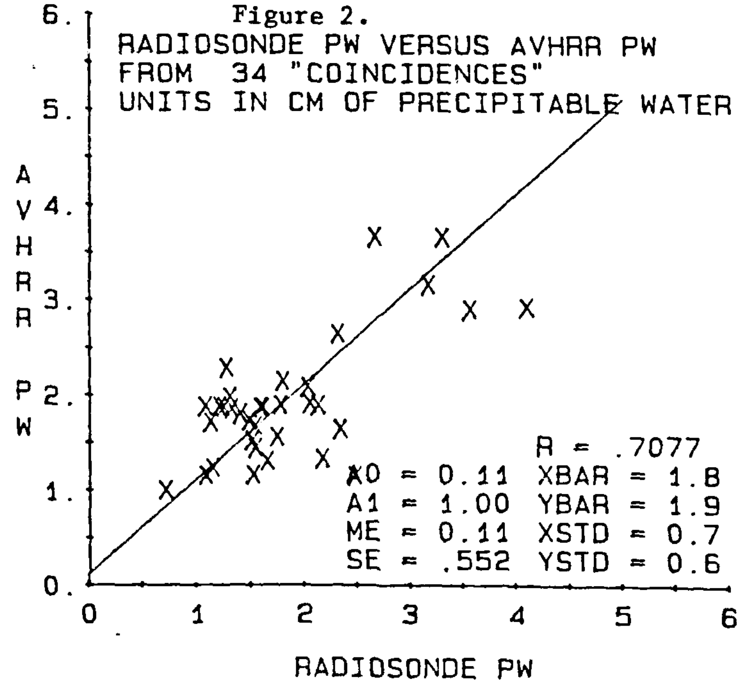

Figure 2.

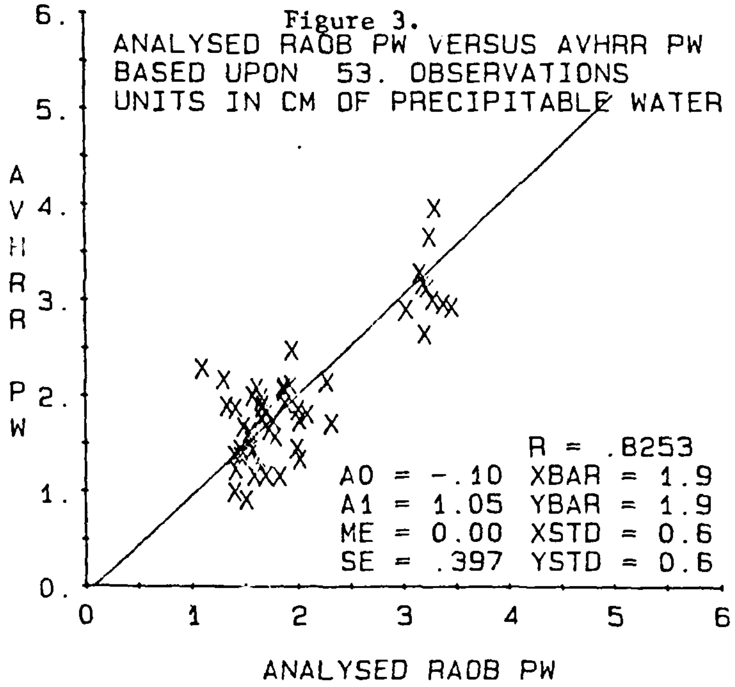

Figure 3.

ANALYSED RAOB PW VERSUS AVHRR PW
BASED UPON 53. OBSERVATIONS
UNITS IN CM OF PRECIPITABLE WATER

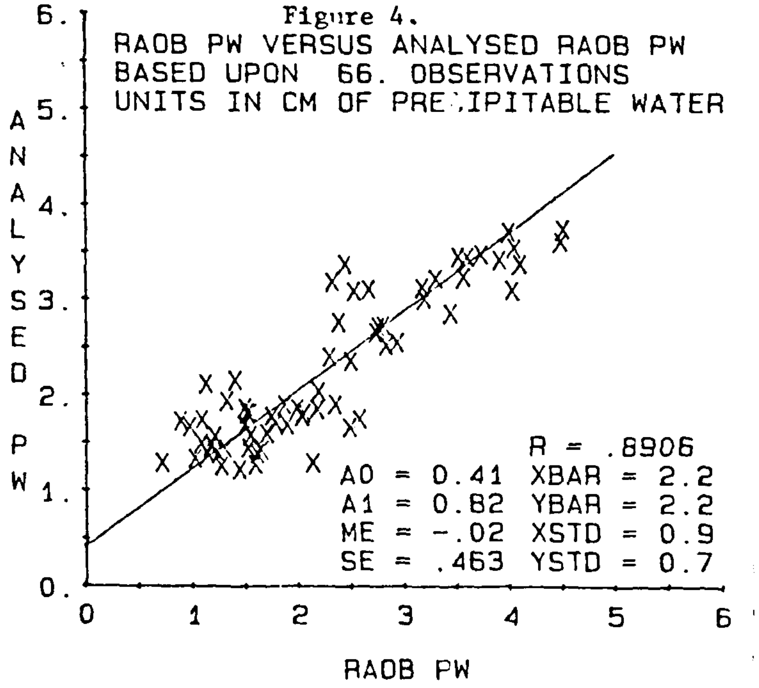

Figure 4.

RAOB PW VERSUS ANALYSED RAOB PW
BASED UPON 66. OBSERVATIONS
UNITS IN CM OF PRECIPITABLE WATER