

Analysis of Integrated Cloud Liquid and Precipitable Water Vapor Retrievals from the ARM Microwave Radiometer During SHEBA

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Introduction

Dual frequency, ground-based, Microwave Radiometers (MWRs) have been used for more than 20 years to derive columnar amounts of both water vapor (WV) and cloud liquid and a large number of studies have been made comparing retrievals of precipitable water vapor by MWRs vs. radiosondes and vs. Raman Lidar. Comparisons of MWR cloud liquid retrievals are much more limited, primarily because cloud liquid is not a quantity routinely measured by radiosondes. However, MWR retrievals of cloud liquid for warm stratocumulus clouds have compared well with both in situ aircraft and adiabatic estimates. Although MWRs have been used extensively for research on super-cooled liquid clouds in winter storms, comparisons with in situ measurements are scarce. However, the recent Surface Heat Budget of the Arctic Ocean (SHEBA) experiment allowed several comparisons with aircraft in situ data (Curry et al. 2000). Data acquired in situ did not always agree with the original MWR liquid retrievals, with MWR estimates at times being too large by perhaps a factor of 2. These differences led us to examine in detail several of the assumptions that go into WV and integrated cloud liquid retrievals. As a preliminary to our analysis, we first outline the steps taken in moisture retrieval. We then examine several contemporary absorption algorithms for both clear and cloudy skies, and then evaluate differences in moisture retrieval using these algorithms. Finally, we apply these algorithms to the SHEBA MWR data.

Retrieval Methods

The MWR operated during SHEBA was one of the operational units from the Atmospheric Radiation Measurement (ARM) Program and a complete description of this instrument is given by Liljegren and Lesht (1996). The MWR measures brightness temperature T_b at two frequencies: 23.8 GHz and

31.4 GHz. Because of the relative sensitivities of the channels to vapor and liquid, the first and second channels may be called ‘vapor’ (V) and ‘liquid’ (L) channels, respectively. Because T_b is not a linear function of V and L over the range of atmospheric variation of these quantities, it is customary to convert the data into a quantity that is linear; i.e., the opacity τ . We derive τ from the two T_b s using the mean radiating temperature T_{mr} and cosmic background temperature $T_c = 2.75$ K.

$$\tau = \ln \left(\frac{T_{mr} - T_c}{T_{mr} - T_b} \right) \quad (1)$$

In Eq. (1), T_b is measured and T_{mr} is estimated from radiosondes, from surface temperature measurements, or from climatology. We express τ in terms of mass absorption coefficients of water vapor κ_V , cloud liquid water κ_L , and dry opacity τ_d :

$$\tau = \tau_d + \kappa_V V + \kappa_L L \quad (2)$$

In reality, the mass absorption coefficients κ_V or κ_L depend on the vertical profiles of temperature T, pressure P and water vapor density ρ_V or cloud liquid density ρ_L . Next, we derive τ from measurements T_b at two frequencies 1 and 2 and solve for V and L:

$$\begin{pmatrix} V \\ L \end{pmatrix} = \begin{pmatrix} \kappa_{V1} & \kappa_{L1} \\ \kappa_{V2} & \kappa_{L2} \end{pmatrix}^{-1} \begin{pmatrix} \tau_1 - \tau_{d1} \\ \tau_2 - \tau_{d2} \end{pmatrix} \quad (3)$$

The resulting equations are of the form

$$\hat{V} = c_0 + c_1 \tau_1 + c_2 \tau_2 \quad (4)$$

and

$$\hat{L} = b_0 + b_1 \tau_1 + b_2 \tau_2 \quad (5)$$

We note that Eqs. (4) and (5), as well as T_{mr} , contain terms that depend on the vertical profiles of T, P, ρ_V , and ρ_L . This information is usually not available on the time scale of the MWR observations, and in the case of L is not available at all. We can estimate these background profiles and couple them with a radiative transfer equation (RTE) to provide estimates of V and L. In addition, Minimum Variance Estimation Techniques over an a priori ensemble of profiles lead to equations of the same form as above. The original ARM MWR retrieval algorithms used Linear Statistical Estimation based on the oxygen and WV absorption coefficient algorithms of Liebe and Layton (1987) and the liquid water dielectric constants given by Grant et al. (1957).

Issues in the Retrieval of V and L

Calibration of the Microwave Radiometer

The calibration of the MWR was accomplished through a set of scanning observations that also use measurements of an internal blackbody target and a noise diode, in the so-called “tip cal method” (Han and Westwater 2000). During SHEBA, the ARM MWR performed a series of symmetrical scans from zenith to an airmass of 1.5 (elevation angle = 41.8 degrees) that provided the basis of calibration. The quality of the tip cal can be judged in a variety of ways. We used the dispersion of equivalent zenith brightness temperatures, standard deviation (STD) (T_b), as a measure of calibration quality (Han and Westwater 2000) and find that, at least during clear days when the tip cal could be performed, the absolute accuracy of the radiometer was excellent: on the order of 0.3 K root mean square (rms). However, as evidenced by negative cloud liquid retrievals on a few occasions, the MWR may have had small calibration drifts. In Figure 1, we present a time series of T_b during both clear and cloudy conditions. We note that during clear conditions, as identified by a lidar/cloud radar, STD (T_b) is generally less than 0.1 K rms, but that during the presence of clouds, which tend to be poorly stratified, there is substantially more variation. To be conservative, we use 0.3 K rms as an estimated noise level in retrieval analysis.

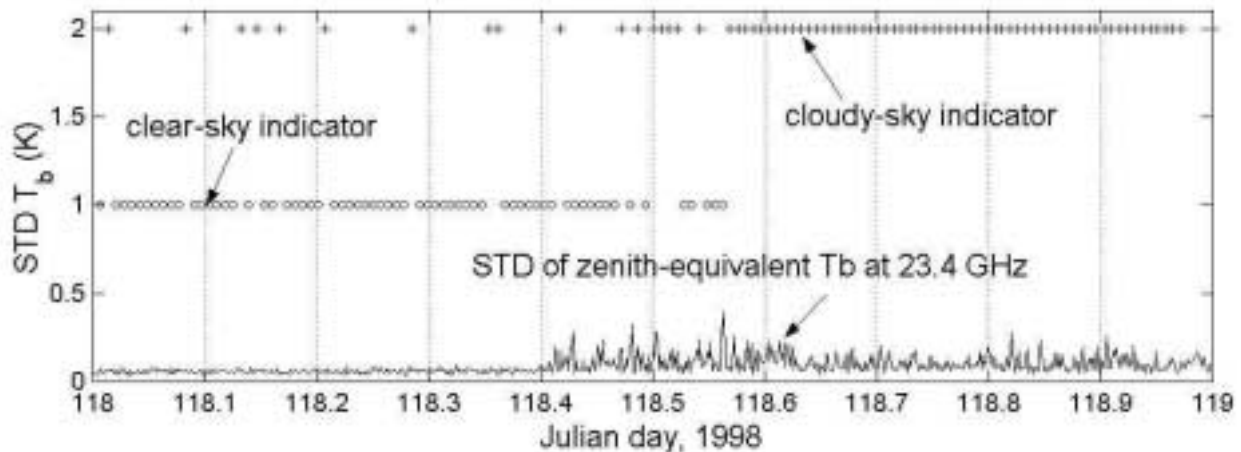


Figure 1. Standard deviation of equivalent zenith T_b at 23.8 GHz for the MWR as a function of Julian Day 1998 during the SHEBA experiment. Cloudy sky indicators derived from a combination of lidar and cloud-radar data.

Dry Opacity

Equations (2) and (3) require the dry opacity τ_d . Although this quantity depends on atmospheric conditions, primarily surface pressure and temperature, the largest part of its uncertainty comes from the molecular absorption model used for its evaluation. In this work, we compare three contemporary absorption models (Liebe and Layton 1987, Liebe et al. 1993, and Rosenkranz 1998). For convenience, we will refer to these models as Rosenkranz98, Liebe87, and Liebe93. Table 1 shows the average and

Table 1. Computed statistical variations of τ_d and T_b for three absorption models. Barrow, Alaska, 1990 to 1996, May to July. T_b calculated for $V = 0.0$ cm. Sample size = 1234.

	$\langle \tau_d \rangle \pm \text{std}$ (nepers) Rosenkranz98	$\langle \tau_d \rangle \pm \text{std}$ (nepers) Liebe87	$\langle \tau_d \rangle \pm \text{std}$ (nepers) Liebe93	$\langle T_b \rangle \pm \text{std}$ (K) Rosenkranz98	$\langle T_b \rangle \pm \text{std}$ (K) Liebe87	$\langle T_b \rangle \pm \text{std}$ (K) Liebe93
23.8 GHz	0.0172 ± 0.0006	0.0155 ± 0.0006	0.0174 ± 0.0006	7.24 ± 0.16	6.80 ± 0.16	7.29 ± 0.16
31.4 GHz	0.0283 ± 0.0011	0.0261 ± 0.0010	0.0285 ± 0.0011	10.02 ± 0.29	9.45 ± 0.26	10.07 ± 0.29

standard deviation of τ_d calculated from an a priori database of Arctic soundings. This database was constructed from 7 years of radiosonde soundings (1990 to 1996) at Barrow, Alaska. We note first that the differences in the averages between the models are much greater than the climatological variations for a given model. We also note that the differential contributions to the brightness temperatures from the dry component of the three models can be as large as 0.5 K. A difference of this magnitude could certainly be a factor in retrievals of V and L , especially during dry Arctic conditions. Using the Rosenkranz98 model would reduce the amount of inferred L or V relative to the original ARM data, which used Liebe87.

WV Absorption Coefficients

In both dual-frequency and single-frequency retrievals, the mass absorption coefficient κ_v enters directly. From our a priori database of Arctic soundings, we computed averages and standard deviations of κ_v and show the results in Table 2. We note that Rosenkranz98 and Liebe87 give comparable results for κ_v , and that Liebe93, is 5 to 10 percent larger. Thus, only the use of Liebe93 would result in differences in either V or L from the original ARM retrievals.

Table 2. Computed statistical variations of κ_v for three absorption models. Barrow, Alaska, 1990 to 1996, May to July. Sample size = 1234.

	$\langle \kappa_v \rangle \pm \text{std}$ (nepers/cm) Rosenkranz98	$\langle \kappa_v \rangle \pm \text{std}$ (nepers/cm) Liebe87	$\langle \kappa_v \rangle \pm \text{std}$ (nepers/cm) Liebe93
23.8 GHz	0.0523 ± 0.0005	0.0532 ± 0.0005	0.0562 ± 0.0005
31.4 GHz	0.0178 ± 0.0006	0.0179 ± 0.0007	0.0211 ± 0.0008

Cloud Liquid Water Absorption Coefficients

Again, from Eqs. (2) and (3), we find that κ_L plays an important role. In addition to uncertainties in determining κ_L from different models, an additional uncertainty arises if the effective temperature of a cloud is unknown. The strong temperature dependence of the dielectric constant of liquid water has been known for more than 40 years (Grant et al. 1957). Here, we evaluate the uncertainties in both V

and L retrievals using the dielectric constant equations from three sources (Grant et al. 1957, Rosenberg 1972, and Liebe et al. 1991). We also assumed Rayleigh absorption, for which the liquid absorption depends only on the total liquid amount and does not depend on the drop size distribution. When the dielectric models are coupled with the Rayleigh absorption equations, we refer to the resulting κ_L models as Grant57, Rosenberg72, and Liebe91. The strong temperature dependence of κ_L is present in all three models, but is different. The original ARM retrievals were generated using Grant57 and this model had been widely used for several years. The model has given good agreement with adiabatic assumptions during conditions of warm stratus clouds. However, the laboratory data from which this model was developed were taken at temperatures above 0°C. The Rosenberg72 model had been used for several years by Soviet investigators. Some laboratory data taken at -10°C were used in the development of this model. Finally, Liebe et al. (1991) developed the third model, based on a variety of laboratory data, some of which were taken at temperatures as low as -4°C. Figure 2 shows our calculations of κ_L at 23.8 and 31.4 GHz for each model as a function of cloud temperature. Note the significant departures between the models at temperatures below -10°C.

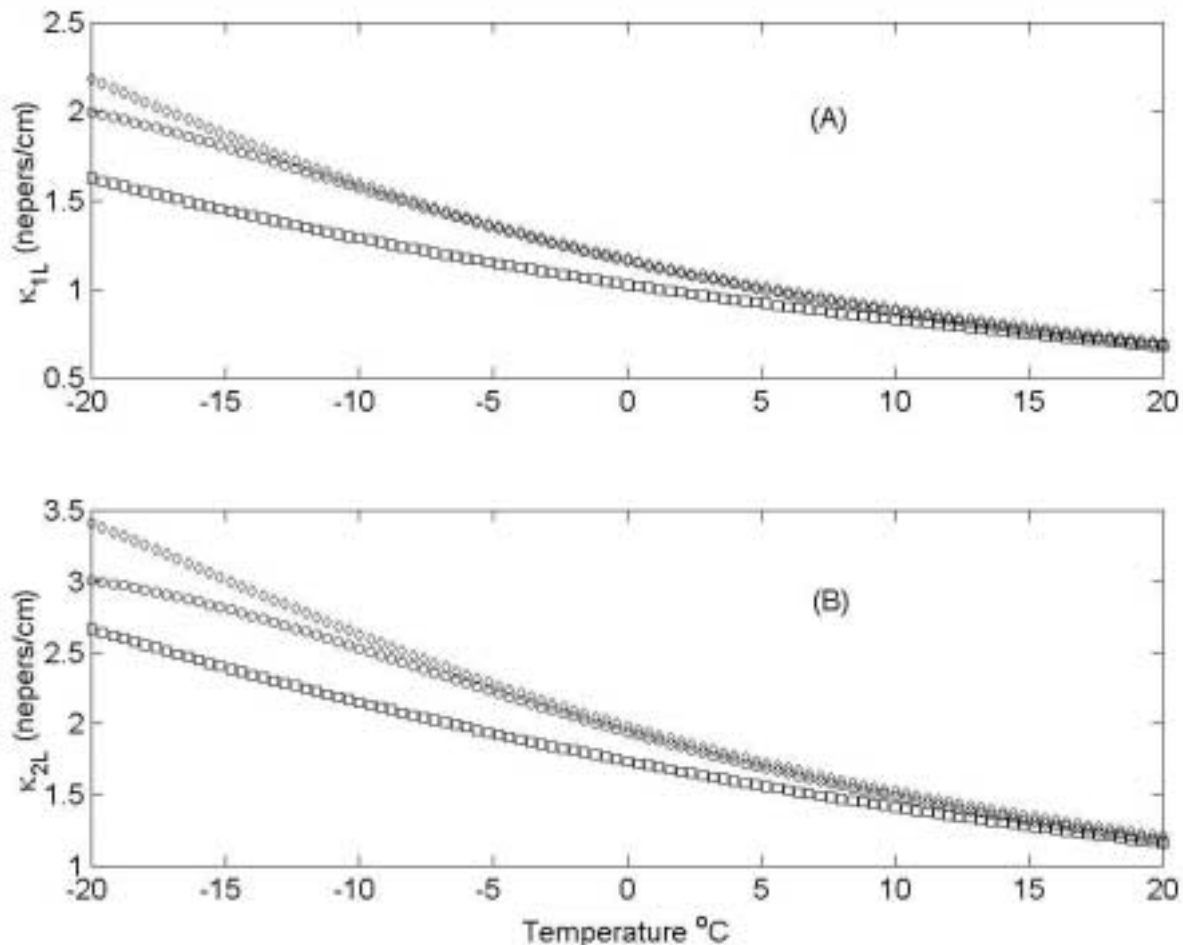


Figure 2. Mass absorption coefficient of liquid water for the models of Rosenberg (1972) - diamonds, Liebe (1991) - circles, and Grant et al. (1957) - squares. (A) 23.8 GHz; (B) 31.4 GHz.

Model Differences in Physical Retrieval Methods

A variety of retrieval methods can be applied to determine V and L from MWR measurements, and the availability of additional information dictates which method is desirable. If, for example, knowledge of the temperature profile, cloud base height, and cloud thickness is available, a physical method that explicitly calculates L is appropriate. If an MWR is operating without the availability of ancillary data, statistical inversion methods can be used. However, since this inversion problem is well posed (two parameters V and L are determined from two measurements of opacity) the retrievals are not greatly sensitive to reasonable applications of either method. However, each method requires an absorption model. Our calculations showed that the liquid absorption model changes result in only a small percentage change in V , but that as much as a 25 percent lowering of L could occur. These theoretical results are consistent with reanalysis of the original data, as we will show.

Physical vs. Statistical Retrieval Methods

The original ARM retrievals were performed using linear statistical retrievals in which the coefficients of Eqs. (4) and (5) were evaluated over an a priori database of Arctic radiosonde profiles. For this determination, the Liebe87 algorithm was used for water vapor and oxygen absorption, while the Grant57 model was used for the liquid absorption. Changing the absorption model will result in changing the coefficients in Eqs. (4) and (5). However, for a given absorption model, there still could be substantial differences in the coefficients in Eqs. (4) and (5) between statistical and physical algorithms for different cloud temperatures. Although statistical retrieval coefficients are constructed to provide minimum variance estimators of V and L over the training set of a priori profiles, the principal difference between the physical and statistical retrieval method is the treatment of variability in cloud temperature. Our statistical inversion method, when applied to the original SHEBA dataset, had a fixed set of coefficients for each month of interest. The method also provides an estimate of the accuracy of V and L retrievals. The physical methods that we apply determine V and L from Eq. (1) T , P , and ρ_v interpolated in time from adjacent radiosonde soundings, Eq. (2) cloud base height as determined from lidar and cloud radar measurements, and Eq. (3) cloud thickness from the adiabatic assumption. The determination of effective cloud temperature T_{cld} is required to determine κ_L and T_{mr} and the principal advantage of the physical method is the use of the additional meteorological information.

Methods Used in SHEBA MWR Data Analysis

As discussed in *Retrieval Methods* Section, before retrieving V and L we need to estimate several parameters that enter into Eq. (3) such as T_{mr} , κ_v , and κ_L . For physical retrievals, these parameters are usually obtained by using the estimates of height profiles of T , P , ρ_v , and ρ_L , and the RTE. The cloud liquid water profiles are mainly used for the computation of κ_L , which is an average of the temperature-dependent cloud liquid absorption coefficient over the cloud layer, weighted by the liquid water content profile. For SHEBA, we obtained T , P , and ρ_v by interpolating radiosonde profiles into the radiometer time grids. During the experiment, radiosondes were launched two to four times a day. The lidar/cloud-radar that was collocated with the radiometer provided cloud base height measurements. The mean cloud liquid absorption coefficient κ_L , along with other parameters, was estimated iteratively when retrieving V and L . We initially assumed a small amount of ρ_v distributed through the cloud and tried both a constant liquid water content profile and an adiabatic profile as distribution functions. We found

that the retrieval results were not sensitive to the distribution profiles for the cloud thickness encountered during SHEBA; these thicknesses for liquid clouds were generally less than 1 km. The initial liquid water and the interpolated radiosonde profiles were input into the RTE model and L and the other parameters are computed and used to retrieve V and an updated L. Then the retrieved ρ_L was used again to derive an updated κ_L with other parameters. The iteration was stopped when the difference between two consecutive L retrievals was insignificant.

For linear statistical retrievals, the parameters in Eq. (3) were not directly estimated. Instead, retrieval coefficients (three for V and three for L) were derived through a linear regression. In the regression the dependent variables, V and L were obtained from a historical set of radiosondes (for temperature and WV profiles) plus a cloud model to determine cloud liquid profiles. Simulated T_b and T_{mr} were calculated from the modeled profiles using the RTE model. Gaussian noise with zero mean and 0.3 K standard deviation was added to the simulated brightness temperatures, which were then converted to τ using Eq. (1). Our 7-year radiosonde dataset collected at Barrow, Alaska, was used to derive the retrieval coefficients.

Experimental Results

All comparisons, either between retrieval methods or between retrievals and in situ measurements, were conducted at the times when in situ measurements were available. The term “ETL retrievals,” refers to physical retrievals when the Rosenkranz98 clear air absorption model and the Liebe91 cloud liquid absorption model were used. The term “original” refers to the original SHEBA archived retrievals that were derived using the statistical method with Liebe87 clear air absorption models and the Grant57 cloud liquid model. In situ measurements of cloud liquid density were taken by the King Hot-wire probe and the Gerber PVM-100A mounted in the National Center for Atmospheric Radiation (NCAR) C-130 research aircraft that flew over the SHEA site during May 8 to May 27, and July 8 to July 30, 1998 (Curry et al. 2000).

Original vs. ETL Dual-Channel Liquid Retrievals

Comparisons of the original and ETL dual-channel technique (Figure 3) shows that the original retrievals of L are higher by 13 g/m^2 than the ETL retrievals. The rms difference is 20 g/m^2 . If we limit the data range to $L < 100 \text{ g/m}^2$, the mean difference is again 13 g/m^2 and the rms difference is reduced slightly to 16 g/m^2 . Assuming a nominal average value of 50 g/m^2 , this rms value is 32 percent. As discussed in previous sections, these differences are due to the differences in the dry absorption and cloud liquid absorption models used in the original and ETL retrieval methods as well as to the difference between the physical and statistical retrieval methods.

Original Liquid Retrievals vs. In Situ Aircraft Data

We computed the mean and rms differences between original L retrievals and the aircraft in situ data from the King and Gerber liquid probes. The averages of the original retrievals are higher than either the King or Gerber measurements by 69 g/m^2 and 73 g/m^2 , respectively. The corresponding rms differences are 138 g/m^2 and 166 g/m^2 , respectively. However, the large differences are dominated by points with large L values. If we limit the data range to $L < 100 \text{ g/m}^2$, as shown in Figure 4, the mean

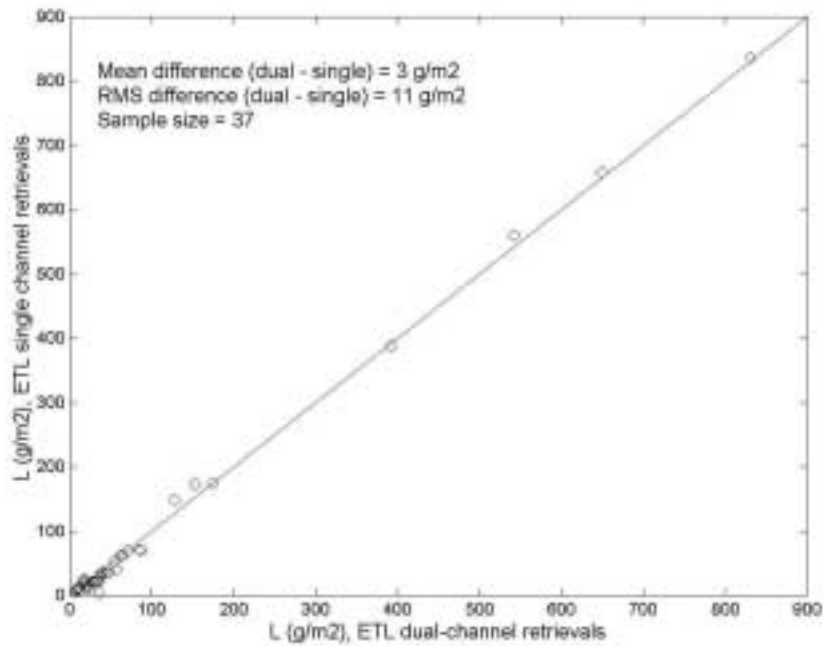


Figure 3. Scatter plot of ETL dual-channel L retrievals vs. the original ARM retrievals. The clear air absorption models of Rosenkranz (1998) and the liquid absorption of Liebe (1991) were used in the ETL retrievals, while the clear air absorption models of Liebe and Layton (1987) and the liquid absorption of Grant et al. (1957) were used in the ARM retrievals.

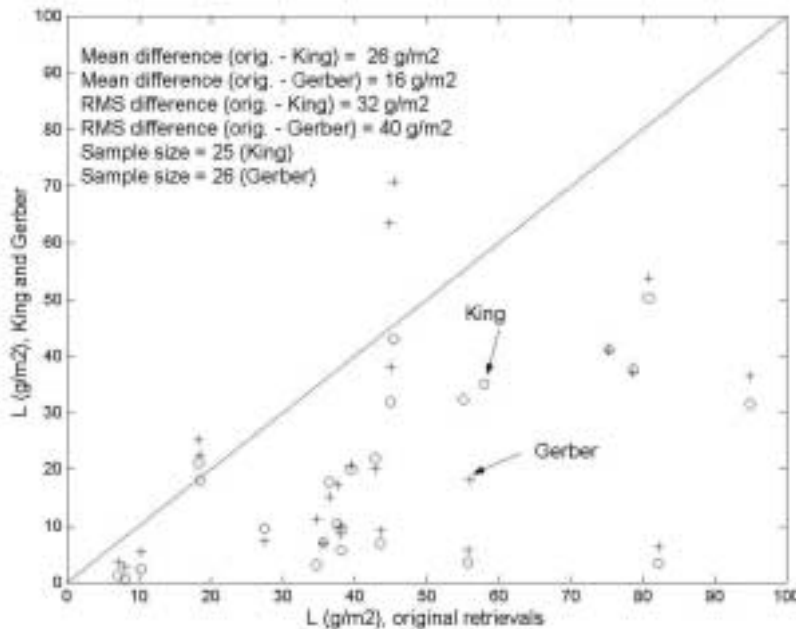


Figure 4. Scatter plot of original L retrievals vs. in situ data taken on the NCAR C-130Q aircraft. The liquid density measurements were made by the King Hot-wire Probe and the Gerber PVM-100A (Curry et al. 2000).

and rms differences between the original retrievals and the King data are 26 g/m^2 and 32 g/m^2 , respectively, and those between the original retrievals and Gerber data are 16 g/m^2 and 40 g/m^2 , respectively.

ETL Dual-Channel Liquid Retrievals vs. In Situ Aircraft Data

As shown in Figure 5, for $L < 100 \text{ g/m}^2$, the mean and rms differences between the ETL dual-channel retrievals and the King data are 14 g/m^2 and 20 g/m^2 (28 percent and 40 percent), respectively, and those between the ETL retrievals and Gerber data are 6 g/m^2 and 30 g/m^2 (12 percent and 60 percent), respectively. If all the data points are included the mean and rms differences between the ETL retrievals and the King data are 54 g/m^2 and 126 g/m^2 , respectively, and those between the ETL retrievals and the Gerber data are 61 g/m^2 and 161 g/m^2 , respectively. Comparing these results in the *Original Liquid Retrievals vs. In Situ Aircraft Data* Section, we see that the ETL retrievals reduced the differences between the original retrievals and in situ measurements by about 10 g/m^2 (20 percent). The reduction is due primarily to the differences in dry absorption and cloud liquid models used in the original and ETL retrieval algorithms and the differences of the two retrieval algorithms.

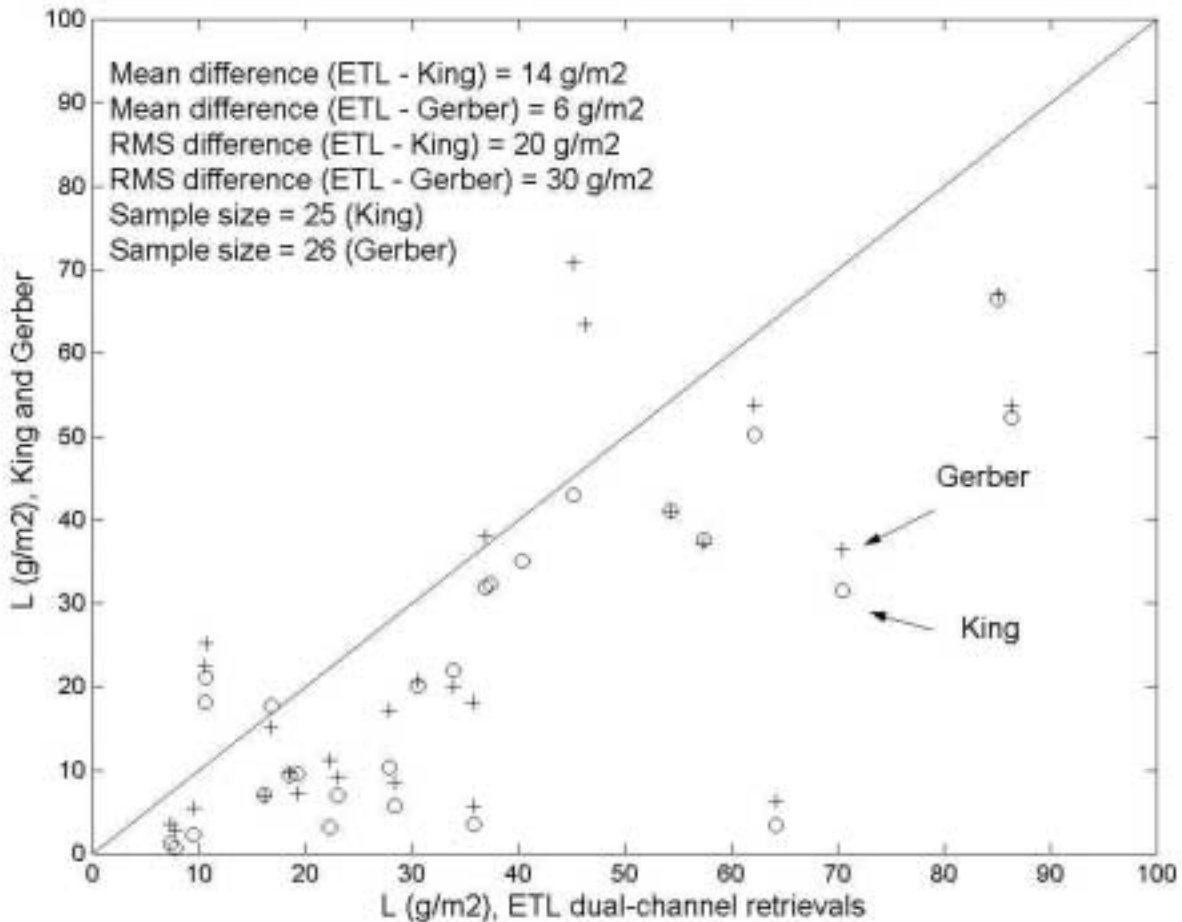


Figure 5. Scatter plot of ETL L retrievals vs. in situ aircraft data (see Figure 6 caption). The clear air absorption models of Rosenkranz (1998) and the liquid absorption of Liebe (1991) were used in the ETL retrievals.

Retrievals of Cloud Liquid Water During Clear-Sky Conditions

Due to various error sources in the retrieval process, the linear L retrievals during clear-sky conditions are usually not exactly zero. One such error source may be the uncertainty in the clear-sky absorption modeling. However, as follows directly from Eqs. (2) and (3), if there are no errors in τ_d or κ_V , L must be zero for a two-channel clear-sky retrieval even when imperfect cloud liquid absorption coefficients κ_L are used. Thus, even with imperfect measurements and estimated parameters, the comparisons of L retrievals under clear-sky conditions may guide us to select the clear-sky absorption models used in the retrieval processes. In Table 3, we listed the mean and rms differences between the MWR L retrievals and the value of $L = 0$ under clear-sky conditions for the period from April 1 to July 31 during SHEBA. The cloud liquid absorption model for these physical retrievals was Liebe91 and the lidar/cloud-radar data were used to obtain times of clear-sky conditions. The table shows that the use of the Rosenkranz98 clear-sky absorption model yields the smallest values of clear-sky liquid retrievals. A similar result was obtained from another experiment conducted in March 1999 at Barrow, Alaska. These results suggest confidence in using the Rosenkranz98 clear-sky model.

Table 3. Mean and rms differences between clear-sky L retrievals and zero for SHEBA, April 1 to July 31, 1998. Sample size = 13128.			
	Rosenkranz98	Liebe87	Liebe93
Mean (g/m ²)	3	14	-6.6
rms (g/m ²)	9	16	10

Original vs. ETL Vapor Retrievals

We found no significant changes in V retrievals when the original retrieval algorithm (statistical, Liebe87, Grant57) was replaced by the ETL retrieval algorithm (physical, Rosenkranz98, Liebe91). However, for small amounts of V (<0.5 cm), as shown in Figure 6, the difference in the dry absorption models used in the retrieval algorithms may result in V differences of over 10 percent. The ETL retrievals are generally lower than the original retrievals by an absolute amount of 0.01 cm.

Conclusions

We investigated a variety of factors that enter into the determination of precipitable WV and integrated cloud liquid by the ARM dual-channel MWR operated during SHEBA. We first carefully examined the radiometer calibration and concluded it was well calibrated with a 0.3 K rms error. Our main finding is the degree to which both clear air and cloud liquid models have an effect on the retrievals, especially on L retrievals. The most significant changes we saw were due to the dry opacity and the cloud liquid absorption coefficient. The dry opacity is best modeled by Rosenkranz98, since the use of the model resulted the smallest L retrievals during clear-sky conditions. The cloud liquid absorption is best modeled either by the Liebe91 or the Rosenberg72 models since these two

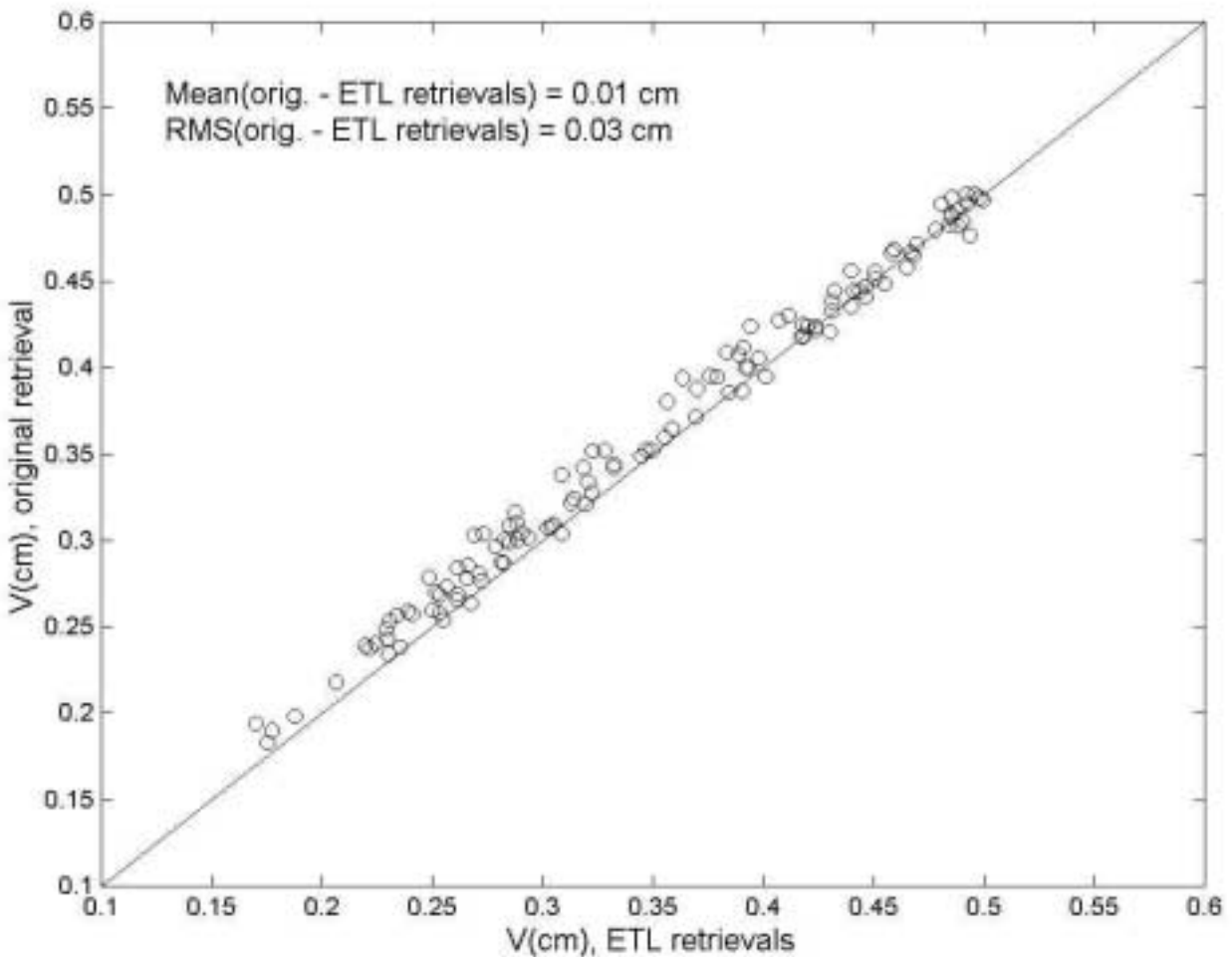


Figure 6. Scatter plot of original vs. ETL V retrievals. The clear air absorption models of Rosenkranz (1998) and the liquid absorption model of Liebe et al. (1991) were used in the ETL retrievals, while the clear air absorption models of Liebe and Layton (1987) and the liquid absorption of Grant et al. (1957) were used in the ARM retrievals.

models used experimental data at temperatures below 0.0°C, while the Grant57 model used data above 0.0°C. Although we found nothing in the original ARM data that was grossly incorrect, application of these more recent models reduced the original ARM retrievals of L by roughly 15 to 20 percent. The predicted accuracy in the L retrievals, for a 0.3 K rms radiometric error, was 10-g/m² rms. The change of clear-air absorption models from Liebe87 models to Rosenkranz98 models has little impact on V retrievals except when V is low. For V < 0.5 cm, the V retrievals using the Rosenkranz98 model may be more than 10 percent lower than those retrieved using the Liebe91 model.

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