Profiling of Atmospheric Water Vapor With MIR and LASE

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***Abstract*—Concurrent measurements of atmospheric water vapor profiles were conducted over the Atlantic Ocean on September 25, 1995 with both the millimeter-wave imaging radiometer (MIR) and lidar atmospheric sounding experiment (LASE) on board the NASA ER-2 aircraft. LASE provides high precision measurements of both aerosol backscatter and water vapor profiles; aerosol backscatter has a vertical resolution of 60 m while the water vapor profiles have a resolution of 330 m in the low-to-mid troposphere and 550 m in the upper troposphere. Therefore, LASE measurements provide an excellent resource for assessing the capabilities and limitations of MIR as a water vapor profiler. Previously, the water vapor profiles retrieved from the MIR measurements have been compared with those of rawinsonde and Raman lidar observations at point locations. The frequency and extent of the comparisons made in that fashion were largely constrained by the requirement of near coincidence in time and space. The data acquired concurrently by MIR and LASE from this ER-2 aircraft flight enable the comparison of MIR-retrieved and LASE-measured moisture profiles over a long stretch of time and space. In addition, the LASE-measured profiles of aerosol backscatter provide a resource to assess the impact of clouds on the retrieval of water vapor profiles from the MIR measurements.**

It is shown that profiles of water vapor mixing ratio retrieved from the MIR data generally conform to those measured by the LASE; however, differences in the values of mixing ratio at individual altitude levels are quite often not small. The standard deviations of these differences are found to be about $\pm 0.98, \pm 0.84, \pm 0.95, \pm 0.42$, and ± 0.06 g/kg at altitudes of 1.25, 2.75, 4.75, 7.25, and 10.25 km. It is demonstrated that a substantial portion of these differences are due to the poor vertical resolution inherent in the profile retrieval using the MIR radiometric measurements. Additionally, MIR water vapor profiling under cloudy conditions is demonstrated, and it is shown that location and height of the low-altitude clouds estimated from the retrieval process were generally consistent with those observed by the LASE. For study cases where cirrus clouds are present, retrievals from the MIR data over-estimate the mixing ratio; this over-estimate is provoked by brightness temperature decreases that occur at 183–220 GHz within these regions. Undoubtedly, the retrieval method needs an additional procedure to account for the millimeter-wave scattering by cloud ice particles so that water vapor profiling can be improved within regions where cirrus clouds are present.

***Index Terms*—Millimeter-wave radiometry, remote sensing, water vapor.**

I. INTRODUCTION

PROFILING of atmospheric water vapor using the strong absorption line at 183.3 GHz has been studied for nearly two decades [1]–[13]. Theoretically, Schaerer and Wilheit [1] explored the characteristics of this strong water vapor line by performing both forward calculations and profile retrievals over the ocean surface. The approach was extended by Wilheit [7] to retrieve water vapor profiles under both clear and cloudy conditions. Other alternative simulation studies and analyzes have been performed by Rosenkranz *et al.* [2], Kuo *et al.* [11] and Muller *et al.* [12]. Experimentally, water vapor profiles have been retrieved using radiometric measurements by the Airborne Microwave Moisture Sounder (AMMS) in the 1980s [3]–[6]. Because of its limited number of channels and poor temperature sensitivity (ΔT), the AMMS radiometric measurements could not provide robust retrievals of water vapor profiles under cloudy conditions [8]. More recently, a millimeter-wave imaging radiometer (MIR) was built and after a number of field experiments [9], [10] the radiometer was shown to provide more robust radiometric measurements than the AMMS. It contains six channels in the frequency range of 89–220 GHz and, with a comparable integration time to the AMMS, has ΔT's of <1 K at all channels [14]. The radiometric measurements from this sensor have been used to retrieve water vapor profiles under cloudy conditions with reasonable success [10]. Burns *et al.* [13] have also examined the effects of precipitation and cloud ice on these water vapor channels using measurements from the special sensor microwave/temperature-2 (SSM/T-2) on board the defense meteorological satellite program (DMSP) F-11 satellite. These theoretical and experimental efforts provide an effective demonstration of the capabilities and limitations of using the 183.3 GHz line for water vapor profiling.

The experimental results of water vapor profiling derived from the AMMS and MIR measurements were routinely compared with nearly concurrent (within ± 3 hours) rawinsonde observations at some selected locations [3], [6], [9]. Additionally, a comparison of water vapor profiles retrieved from the MIR measurements was made with ground-based Raman lidar observations at NASA's Wallops Flight Facility (WFF), Wallops Island, Virginia during the Convection and Atmospheric Moisture Experiment (CAMEX) of July–August, 1993 [9]. Reasonable agreements were found between the profiles retrieved from these AMMS and MIR measurements and those measured at the ground locations. However, these comparisons were limited to single locations and there has been no validation of the profiles retrieved from the measurements of these sounders over an extended region. During September 1995, MIR and LASE (Lidar Atmospheric Sensing Experiment) were on board the NASA ER-2 aircraft during a number of flights both over land and ocean areas in the eastern U.S. LASE measures both aerosol backscatter and water vapor mixing ratio with high accuracy and vertical resolution [15], [16]. The LASE-measured mixing ratio was compared with that measured concurrently by the ground-base Raman Lidar and rawinsondes at WFF and an excellent agreement was found among the three different approaches [15]. These flights provide the first opportunity to validate the water vapor profiling method derived from the MIR radiometric measurements over an extended region.

VI. Conclusion

Measurements of water vapor profiles were made concurrently with LASE and MIR on board the NASA ER-2 aircraft over the Atlantic ocean on September 25, 1995. The LASE measured profiles have a vertical resolution of 330 to 550 m, depending on altitude, and, therefore, serve as an excellent standard for comparison with the lower-resolution profiles retrieved from the MIR measurements. Previously, the water vapor profiles obtained from the MIR measurements were compared only with those measured by dropsondes released from a different aircraft or by the ground-based Raman lidar and rawinsondes [9], [10]. The requirement of the approximate coincidence in time and location of these measurements essentially limited the comparison to a few selected cases. The 3-h flight of LASE and MIR described above, on the other hand, provides about 180 independent and concurrent measurements over an ocean area that includes both clear and cloudy conditions. This combined LASE and MIR data set serves as an extremely valuable resource that can be utilized to analyze and evaluate the capabilities and limitations of millimeter-wave remote sensing to profile water vapor. However, there is a deficiency related to this data set: it is obtained within a short time period over a small geographic region and, as a consequence, the range of observed variation in the moisture field of the atmosphere is rather limited.

The comparison of the MIR-retrieved profiles of water vapor mixing ratio with those measured by LASE leads to the following conclusions. First, in general the MIR-retrieved profiles correspond well with those measured by the LASE, although they could not provide the fine vertical structure reflecting the rapid changes of moisture with altitude that was observed by LASE. At individual altitude levels, the differences in the mixing ratios retrieved by the MIR and measured by LASE are not small. A substantial portion of these differences is undoubtedly caused by the poor vertical resolution of the retrieved profiles that is inherent to the inversion process. For instance, column 3 of Table I shows that, using LASE measurements as a standard, the inversion process could cause standard deviations of $\pm 0.95, \pm 0.57, \pm 0.16$, and ± 0.02 g/kg at the altitudes of 2.75, 4.75, 7.25, and 10.25 km. The retrieval results from the MIR measurements give corresponding numbers of $\pm 0.84, \pm 0.95, \pm 0.42$, and ± 0.06 g/kg at those respective altitudes; the larger numerical values at higher altitudes could be attributed to the measurement differences between the two sensors. The standard deviations were significantly smaller than those of climatological variations. Therefore, radiometric measurements at the MIR frequencies can provide water vapor profiles that are useful for studying the large-scale changes in the water vapor fields of the atmosphere.

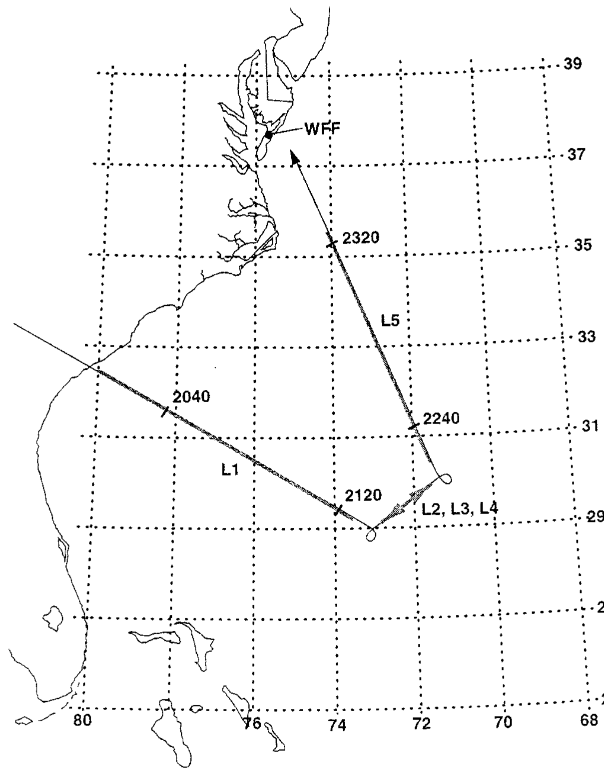

Fig. 1. Sketch showing the path of the ER-2 aircraft flight over the Atlantic Ocean on September 25, 1995. Five straight line segments are denoted by L1, L2, L3, L4, and L5. L2, L3, and L4 are repeated passes over the same region.

Next, it was shown that MIR could profile atmospheric water vapor over a region with moderate, low-altitude cloud cover. There is a close association between the locations where low-level clouds are detected by LASE and the locations where the cloud liquid water were also required as input to the MIR retrieval algorithm to reach a convergent retrieval of water vapor profiles from the MIR measurements. The cloud tops predicted by the retrieval algorithm are closely related to those observed by the LASE; however, the retrieval does experience some difficulty in areas of dense clouds where the measured 89 GHz brightness temperatures are >270 K (Fig. 3). The retrievals for these areas result in low values of mixing ratio at altitudes below the cloud tops, require cloud liquid water in excess of 0.4 kg/m^2, and are associated with poor convergent criteria ($\Delta T_b \simeq 2$–3 K) (see Fig. 4).

Finally, in the region of dense cirrus clouds where the depressions in 220 GHz brightness temperatures are clearly observed, the effect of millimeter-wave scattering by ice particles must be considered to improve retrievals of water vapor profiles. The algorithm used to retrieve water vapor profiles from the MIR measurements, as discussed above, does not currently incorporate such a procedure.