PROGRESS REPORT OF FY 1998 ACTIVITIES: The Application of Kalman Filtering to Derive Water Vapor Profiles from Combined Ground-Based Sensors: Raman Lidar, Microwave Radiometers,GPS, and Radiosondes

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ABSTRACT

Previously, the proposers have delivered to ARM a documented algorithm, that is now applied operationally, and which derives water vapor profiles from combined remote sensor measurements of water vapor radiometers, cloud-base ceilometers, and radio acoustic sounding systems (RASS). With the expanded deployment of a Raman lidar at the CART Central Facility, high quality, high vertical-resolution, water vapor profiles will be provided during nighttime clear conditions, and during clear daytime conditions, to somewhat lower altitudes. The object of this effort is to use Kalman Filtering, previously applied to the combination of nighttime Raman lidar and microwave radiometer data, to derive high-quality water vapor profiles, during non-precipitating conditions, from data routinely available at the CART site. Input data to the algorithm would include: Raman lidar data, highly quality-controlled data of integrated moisture from microwave radiometers and GPS, RASS, and radiosondes. The focus of this years activities has been on the intercomparison of data obtained during the Water Vapor Intensive Operating Period'97 at the SGP CART site in central Oklahoma.

PARTICIPATION IN THE WATER VAPOR INTENSIVE OPERATING PERIOD IN 1997.

To combine data by Kalman filtering, it is necessary to know the error characteristics of each data source and to eliminate, as far as possible, sources of internal inconsistency between the data. The input data for our Kalman algorithm will be mixing ratio profiles from the ARM Raman lidar, precipitable water vapor (PWV) from the ARM microwave radiometer (MWR) and possibly PWV from the Global Positioning System (GPS) that is operated by the National Weather Service at Lamont, Oklahoma, and Vaisalla type radiosondes that are operated on the Balloon Borne Sounding System (BBSS) at the Southern Great Plains CART Central Facility. To gather and analyze data relevant to this combination, we participated in the Water Vapor Intensive Operating Period (WVIOP) at the SGP Central Facility from September 15 -Oct 5, 1997. As an aid to evaluate the performance of the ARM MWR, we brought to the CART site and operated two dual-channel radiometers belonging to the Environmental Technology Laboratory (ETL). The costs of bringing the ETL radiometers to WVIOP'97 were obtained independently of this effort but the analysis of these data was supported by the Kalman filtering project. Previously, we had analyzed data from WVIOP'96 and ETL and Jim Liljegren, the ARM instrument mentor for the MWR, collaborated closely on the 96 analysis. However, in 1997-1998, with Liljegren no longer being a MWR instrument mentor, most of our analysis was independent of instrument mentor input. We found, in contrast to the 1996 experiment, that there was now a significant bias between the ARM MWR, and a variety of other independent instruments,

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including two ETL MWR's, GPS, ARM radiosondes (BBSS), and a Raman lidar that was calibrated by the CART in situ instruments on the 60 -m tower. A time series of selected PWV data gathered from the experiment is shown in Figure 1 and more comprehensive results of these analyses are summarized Figure 2 and in Table 1. We note that there is generally good agreement between all data, and that there was a substantial range in PWV (from 1.0 to 5.0 cm) during this two-week experiment. However, as shown in Figure 2, there was a 0.2 -cm offset between the ARM WVR and other sources of data. To be useful in combined retrievals, it is believed that accuracies of at least 0.1 cm rms in PWV are required. We therefore spent a substantial amount of time comparing data from the ETL and ARM radiometers, the NWS GPS system, and the Balloon Borne Sounding System (Vaisalla) radiosondes. Part of the experimental procedure was to randomly deploy radiosondes from different calibration lots and examine the differences, if any, between the two data lots. In contrast to data from WVIOP'96, there were no significant differences between radiosonde calibration lots. We are now examining in detail the calibration procedure of both the ARM and the ETL radiometers. In particular, since the NASA Raman lidar was occasionally operated in a scanning mode, we are using the scanning data to estimate the effects of departures from horizontal stratification on the "tip cal" calibration procedure used by both ETL and ARM MWR's.

ARM vs. ETL microwave radiometers for determination of PWV.

It was obvious from the data that the three radiometers (ARM MWR + two ETL MWR's) were highly correlated, even during cloudy conditions. Two ETL radiometers were also internally consistent (bias = 0. 006 and rms = 0.051 cm). Small non-linearities in one radiometer required a modified 'tip cal' method. However, there was a significant bias of about 0.2 cm between the ARM and the ETL radiometers. A bias of this magnitude did not exist in the WVIOP'96 data. A major part of our current activities has been devoted to determining the reason for the discrepancy between the two systems. However, the bias in the ARM MWR was independent of water vapor amount; this suggests that once the bias is corrected, very high quality data can be produced during non-precipitating conditions.

The results demonstrate that ARM MWR data can be used in Kalman filtering algorithms during non-precipitating conditions. However, the bias problem is significant and must be addressed.

ARM and ETL microwave radiometers vs. GPS for determination of PWV.

Two GPS instruments (Lamont, OK, and the SGP CART CF) and two processing algorithms (ERL and SIO) were internally consistent in determining PWV with a bias of 0.056 cm and rms differences of 0.08 cm. The PWV data produced by GPS are 30-min averages, whereas the MWR data are produced roughly every 30 sec. Nevertheless, as seen in Table 1, there was close agreement between all of the GPS products and the ETL radiometers. We also noticed that the GPS was much less effected by precipitation than either the ETL or ARM MWR's.

Thus, at the very least, the GPS could serve as an effective quality control on the ARM MWR, which is subject to problems during and immediately after precipitation.

ARM and ETL microwave radiometers, GPS, vs. BBSS radiosondes

As seen in Table 1, the ETL radiometers, the various GPS products, and the PWV from the BBSS, were all consistent and approaching the 0.1 cm rms level. However, data from the WVIOP'96 showed that there could be calibration differences between different calibration lots of the BBSS radiosondes.

It is thus still recommended that ARM MWR data be used to normalize data between different lots.

PLANS FOR FY 1999

- Using the scanning data from the NASA Raman lidar that were obtained during WVIOP'96, to evaluate the effect of horizontal gradients on "tip cal" calibration procedure used for the ARM MWR. We also are continuing on a comprehensive analysis of the "tip cal" procedure, including antenna beam width effects and the effects of averaging sequential "tip cal" data.

- Using the quality controlled data base obtained during wviop'96 and WVIOP'97 extend the analysis to include the ARM Raman lidar, which was operating throughout most of the IOPS.

- To develop the error covariance matrices and transition matrices that are required for the Kalman filter algorithm from a subset of the WVIOP'96 and WVIOP'97 data and apply the algorithm to independent data taken from SGP instruments.

- Deliver a Kalman filter algorithm to ARM

- To publish the results of WVIOP'96 and WVIOP'97 in an open literature publication

PAPERS PUBLISHED OR SUBMITTED AFTER OCTOBER 1, 1997

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5. E. R. Westwater, Y. Han, S. I. Gutman, and D. E. Wolfe: (1998): “Remote sensing of total precipitable water vapor by microwave radiometers and GPS during the 1997 Water Vapor Intensive Operating Period,” Proc. IGARSS’98, 6-19 July, 1998, Seattle, WA (in press).

6. E. R. Westwater, Y. Han, S. I. Gutman, and D. E. Wolfe: (1998) “Remote sensing of column integrated water vapor by microwave radiometers and GPS during the 1997 Water Vapor Intensive Operating Period,” Proc. Eighth ARM Science Team Meeting, March 23-27th, 1998, Tucson, Arizona, (in press).

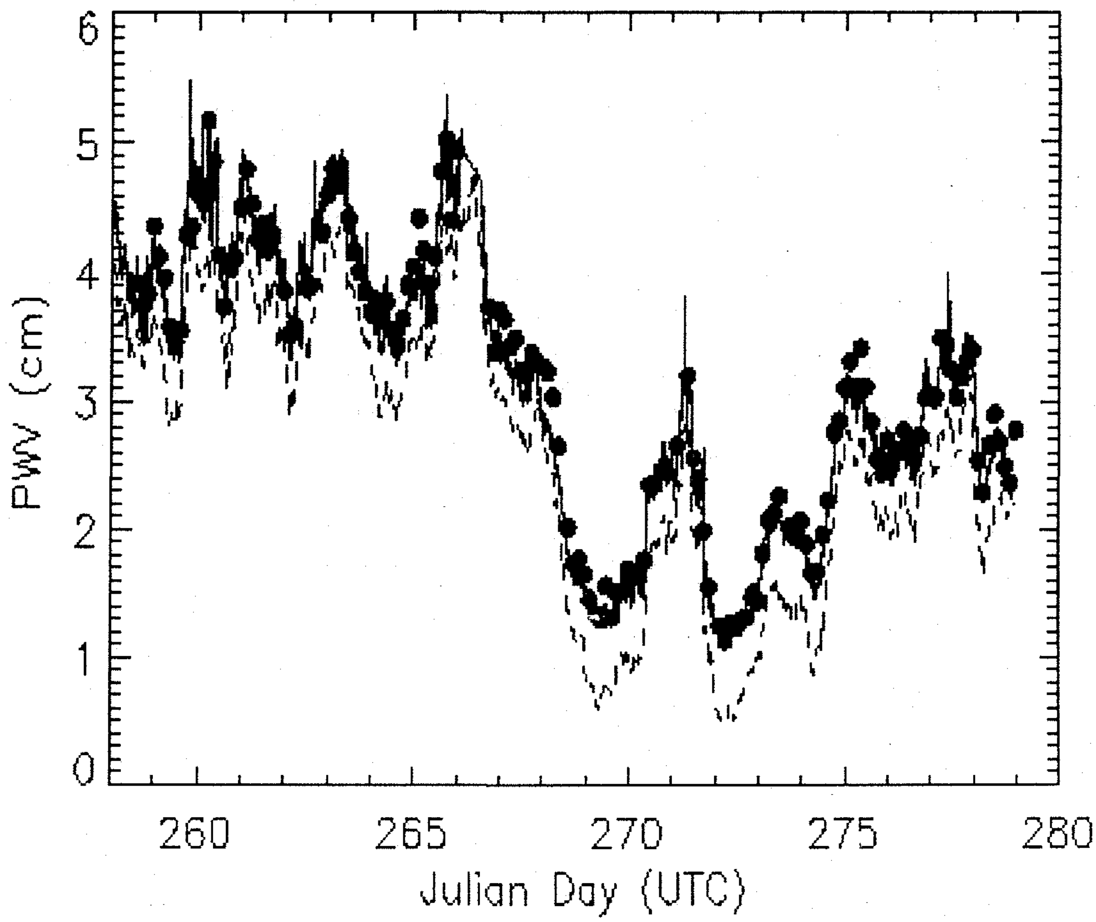

Figure 1. Time series of PWV measurements by MWR ETL1 (solid line), the NPN GPS (with NOAA/ERL processing) near Lamont, OK (dashed line), and radiosondes (BBSS) (circles). For clarity, the GPS soundings have been displaced by 0.5 cm.

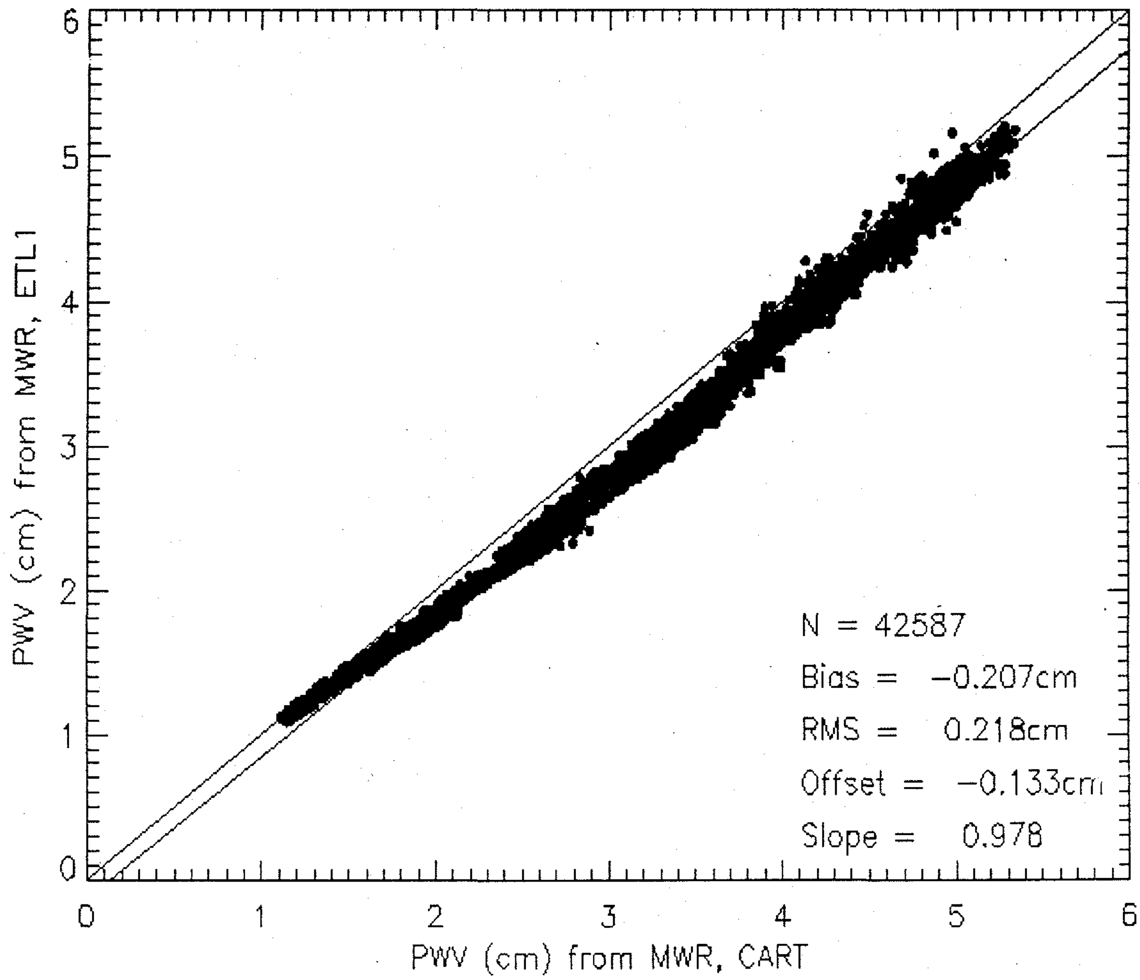

Figure 2. Scatter plot of MWR ARM vs. MWR ETL data taken during WVIOP'97.

Table 1. Statistical summary of PWV (cm) determinations during WVIOP'97. GPS notation: (LM_E)-Lamont, ERL processing; (LM_S)-Lamont, SIO processing;(CF_S)-SGP Central Facility, SIO processing. Data are ranked in increasing order of rms difference.

	OFFSET	SLOPE	BIAS	RMS	N
ETL1-ETL2	0.189	0.954	0.006	0.051	20129
GPS:(LM_S)-(LM_E)	0.050	0.966	0.056	0.080	1056
GPS(LM_E)-ETL1	-0.043	1.018	0.012	0.123	939
GPS(LM_S)-ETL1	0.006	0.985	-0.040	0.125	968
BBSS-ETL1	0.145	0.970	0.052	0.145	146
GPS(CF_S)-ETL1	0.001	0.976	-0.074	0.154	968
BBSS-GPS(LM_E)	0.172	0.957	0.042	0.160	145
ETL1-ARM	-0.133	0.978	-0.207	0.218	42587
GPS(LM_E)-ARM	-0.141	0.983	-0.198	0.225	788