Support for the Harvard University Water Vapor and total Water Instruments For the 2004 NASA WB57 Middle Latitude Cirrus Experiment

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Holyoke Center, Suite 600
1350 Massachusetts Avenue
Cambridge, Massachusetts 02138

James G. Anderson, Principal Investigator
Division of Engineering and Applied Sciences and
Department of Chemistry and Chemical Biology
Harvard University
12 Oxford Street
Cambridge, MA 02138

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B. Prof. James G. Anderson, Harvard University, 12 Oxford Street, Cambridge, MA 02138. Phone: 617-495-5922; Fax: 617-495-4902; E-mail: anderson@huarp.harvard.edu; http://www.arp.harvard.edu/

In order to improve our understanding of the role clouds play in the climate system, NASA is investing considerable effort in characterizing clouds with instruments ranging from passive remote sensors on board the EOS platforms, to the forthcoming active remote sensors on Cloudsat and Calipso. These missions, when taken together, have the capacity to advance our understanding of the coupling between various components of the hydrologic cycle and the atmospheric circulation, and hold the additional potential of leading to significant improvements in the characterization of cloud feedbacks in global models. This is especially true considering that several of these platforms will be flown in an identical orbit within several minutes of one another—a constellation of satellites known as the A-Train. The algorithms that are being implemented and developed to convert these new data streams from radiance and reflectivity measurements into geophysical parameters invariably rely on some set of simplifying assumptions and empirical constants. Uncertainties in these relationships lead to poorly understood random and systematic errors in the retrieved properties. This lack of understanding introduces ambiguity in interpreting the data and in using the global data sets for their intended purposes. In light of this, a series of flights with the WB57F was proposed to address certain specific issues related to the basic properties of mid latitude cirrus clouds: the NASA WB57 Middle Latitude Cirrus Experiment ("MidCiX"). The science questions addressed are:

1) Can cloud property retrieval algorithms developed for A-Train active and passive remote sensing measurements accurately characterize the microphysical properties of synoptic and convectively generated cirrus cloud systems?
2) What are the relationships between the cirrus particle mass, projected area, and particle size spectrum in various genre of cirrus clouds?
3) Does the present compliment of state of the art in situ cloud probes provide the level of precision and accuracy needed to develop and validate algorithms and to contribute to our understanding of the characteristics and microphysical processes operating in cirrus clouds?

The timeframe and location for this flight series was the May to June 2004 period; flights were deployed from Ellington Field at Johnson Space Center in Houston, Texas. In support of the 2004 MidCiX, Harvard University personnel performed the following tasks:

- Ensured that the Harvard University Total Water and Water Vapor instruments were compatible with the WB57 aircraft platform and that the instrument collected data useful for the scientific objectives of the mission experiment.
- Integrated the Total Water and Water Vapor instruments on the WB57 prior to science data collection; personnel remained in the field to maintain the instruments and the duties associated with them.
- Designated a team member to attend morning and afternoon planning meetings.

- Ensured that preliminary flight data were made available as quickly as possible after the conclusion of a flight, in a format that facilitated preliminary comparison of basic results.
- Disseminated data to the scientific community following mission completion.

The Harvard Lyman-α instrument has been previously described in detail (Weinstock *et al.*, 1994). Briefly, as illustrated in Figure 1, 121.6 nm (Lyman-α) radiation from an RF discharge lamp photodissociates water vapor in a 2-inch duct. A fraction of the resulting OH fragments are formed in their first excited electronic state ($A^2\Sigma^+$), and the OH fluorescence at ~ 315 nm is collected at right angles to the L_α beam and the air flow through a filter and detected with a photomultiplier tube (not shown). Because the fluorescence is strongly quenched by collisions with O_2 and N_2 at a rate proportional to the air density, at altitudes of the upper troposphere and lower stratosphere the observed detector signal is proportional to the water vapor mole-fraction. Solar and lamp scatter near 315 nm are measured by using a quartz window to periodically block the L_α beam. Changes in lamp intensity monitored with a vacuum photodiode opposite the lamp are used to normalize the fluorescence signal. A rear-surface MgF_2 mirror adjacent to the diode reflects some of the radiation back across the duct to a second diode, allowing water measurements by direct (Beer's Law) absorption at sufficiently high water vapor (mid to upper troposphere).

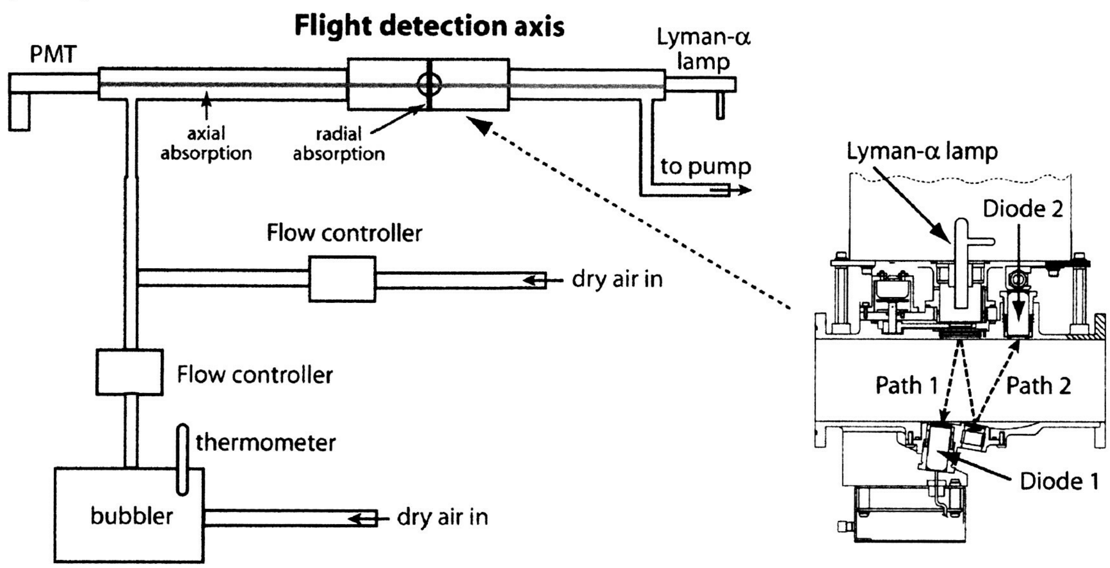

Figure 1. A schematic of the calibration system used in the laboratory and in the field. For calibration the detection axis, with the schematic representation of the components necessary for radial absorption shown on the right, is positioned within the flow tube where axial absorption is carried out.

The instrument is shown on the left in Figure 2 as it is mounted in the WB57 spearpod. We show in the right-hand panel of Figure 2 a schematic representation of the flow through the instrument. An inner duct picks up the laminar core of the ram-fed flow. Flow velocities to the detection axis are controlled by a throttle valve and are varied during flight from 40 to 80 m/sec to verify that there is complete isolation between the sampled air and the wall of the flow system. This double-ducted flow system was developed for our free radical measurements that demand complete isolation of the measurement volume from instrument walls and has been used for all our aircraft-borne water vapor measurements on the ER2 and WB57 since 1992.

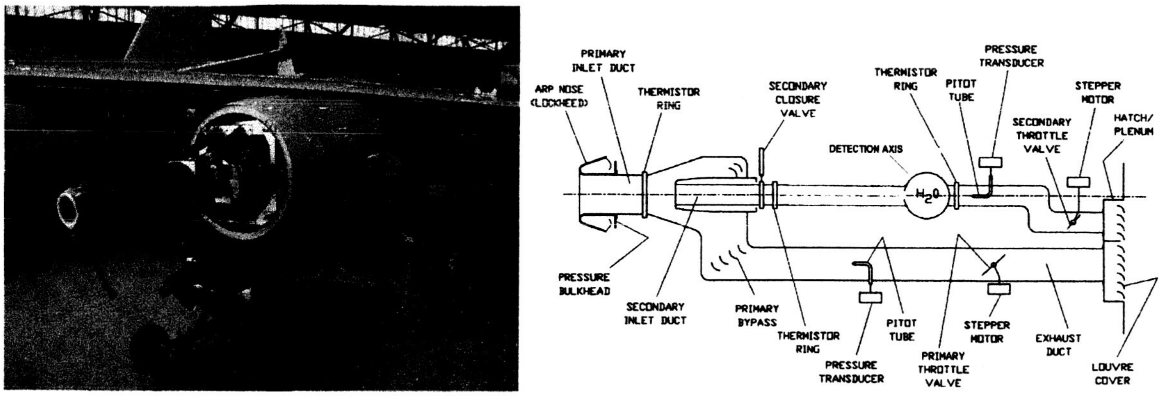

Figure 2. The water vapor instrument as it is mounted in the WB57 spearpod (left). On the right is a schematic of the instrument, illustrating the subsystems that control the flow of air through the instrument as well as measurement of temperature, pressure, and velocity in the ducts.

Starting with the CRYSTAL-FACE mission and continuing through MidCiX, laboratory calibrations are carried out for water vapor and total water in the laboratory and in the field during the deployment. The calibrations establish the sensitivity of the photofragment fluorescence detection axis to varying water vapor mixing ratios over a range of pressures and flow rates, tied to the vapor pressure of water at room temperature and corroborated with simultaneous axial and radial absorption at 121.6 nm at the detection axis as well. The convergence of these simultaneous determinations of the water vapor mixing ratio sets our confidence level for each calibration. A schematic of the calibration system used in the laboratory and in the field (for both the water vapor and total water instruments) is included in Figure 1. The water vapor mixing ratio that is derived from the vapor pressure of water at room temperature is cross-checked by axial absorption along the flow tube. A schematic of the detection axis is included, illustrating the Lyman-α lamp, dual-path absorption axes used in flight, but without the photomultiplier and associated optics that is perpendicular to the Lyman-α excitation and air flow.

The Total Water Photofragment Fluorescence Hygrometer

The Harvard aircraft-borne total water instrument has been flying on the NASA WB57 aircraft since 2001. It has successfully flown during the Clouds, Water Vapor and the Climate System mission in Costa Rica in August 2001; in CRYSTAL FACE in July 2002 out of Key West, FL; with the Pre-AVE mission in January 2004 out of Costa Rica; and the MidCiX campaign out of Houston, TX, (April 15–May 5, 2004). During some of these missions, measurements of the ice water content of thin cirrus clouds near the subtropical or tropical tropopause was a high priority. Such measurements are useful for distinguishing between outflow cirrus and cirrus formed *in situ*; thereby identifying regions where troposphere-to-stratosphere transport may be occurring, for intercomparison with measurements from satellite instruments; and for radiative calculations. Sensitivity requirements for the total water (and water vapor) instrument for measurements in the tropopause region must be better than 0.5 ppmv for detection of clouds that may have significant radiative impact. On the other hand, during most of CRYSTAL FACE and all of MidCiX, the focus was on thicker cirrus with ice water mixing ratios in the hundreds of ppmv or more, and water vapor mixing ratios in the tens to hundreds of ppmv. Accordingly, the instruments must not only achieve a high accuracy level but must also maintain their accuracy over a few orders of magnitude in water and at pressures from 50 to 500 mbar.

Total Water Instrument Details

The total water instrument was designed to fit into a 1-meter wide pallet that is hoisted in place to become part of the underbelly of the WB57 fuselage. Figure 3 shows the instrument as it is mounted in the pallet. The picture illustrates the location of the inlet, extending almost a meter out from the edge of the pallet that is roughly 1.8 meters wide. The inlet is firmly supported by weldments that are bolted to struts at the bottom of the pallet. An aerodynamically designed fiberglass clamshell is bolted to the inlet and the entire assembly is sealed with low temperature RTV silicone sealant. Once assembled in the pallet, the instrument can remain there for the entire mission, because the pallet system is designed to allow easy access to all of the instrument components therein.

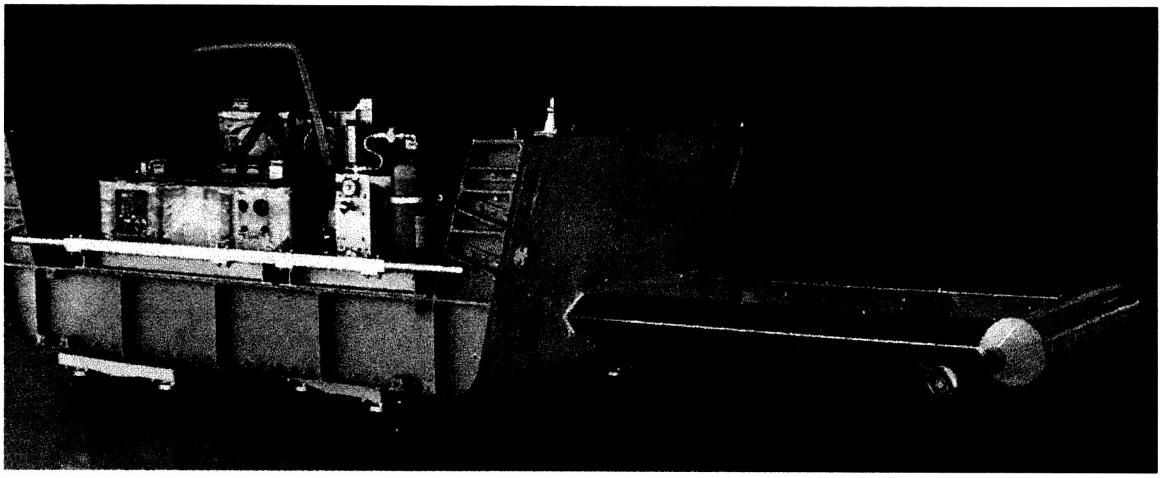

Figure 3. The total water instrument in flight configuration mounted in a WB57 pallet in preparation for a flight at NASA Johnson Space Flight Center.

The detection scheme for the total water instrument is based on the same principles as the water vapor instrument, and is intended to fly in conjunction with it. As illustrated schematically in Figure 4, the total water instrument can be divided into four subsystems:

1. A carefully designed and positioned inlet through which solid water particles are brought into the instrument duct such that the quantitative relationship between ambient ice water content and sampled ice water content of air is determined to better than 10% for particle sizes up to 150 μm in diameter. A shroud is used to straighten the air streamlines as they approach the inlet. The shroud helps compensate for the WB57 angle of attack that is approximately three degrees at cruise, but increases slightly during ascent and descent.
2. A heater that efficiently and completely evaporates the solid/liquid water before it reaches the detection axis.
3. Ducting through which the air flows to the detection axis without perturbing the water vapor mixing ratio.
4. A detection axis that accurately and precisely measures the total water content of the ambient air.

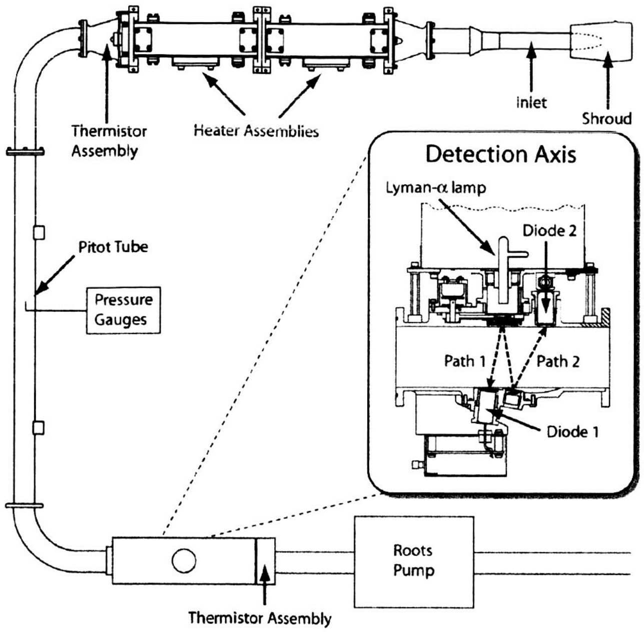

Figure 4. A schematic representation for measuring total water by photofragment fluorescence. The detection axis illustrates the Lyman-α lamp, absorption paths, and photodiodes. The photomultiplier and associated optics for fluorescence detection sit at right angles to the exciting light and air flow and are not shown here.

The accuracy of the instrument depends on how well the instrument performs each of the four functions described above. Instrument uncertainty, discussed below, can be determined by properly combining the uncertainties in the performance of each of those functions.

Ultimately, an intercomparison with another well-calibrated total water instrument is desirable. In this case, the MidCiX campaign, during which the Counterflow Virtual Impactor (CVI) instrument that directly measures cloud ice water content (Twohy *et al.,* 1997) flew along with the Harvard water vapor and total water instruments, has provided the first opportunity to compare two independent high quality cloud ice water content measurements. Comparison of our ice water content measurement and that of the CVI instrument ultimately tests two independent instrument requirements. The first is the efficiency of Harvard total water and the CVI instrument to accurately deliver ambient ice water content in the vapor phase to their respective detection axes. The second is the accurate measurement of water vapor as determined by laboratory calibrations. We have already established that the Harvard instruments satisfy the second requirement in previous publications. The sample intercomparison we show in Figure 10 between our ice measurement and the CVI probe provides information on how well the product of the efficiency factor and the calibration factor agrees for the two instruments. The agreement of better than 10% is typical of that seen throughout the mission. Measurement differences between the two instruments may be the result of differences in the inlet efficiencies of the two instruments, our instrument having an isokinetic inlet, while the CVI requires an anisokinetic flow correction, and/or from differences in detection axis sensitivity to water vapor. Because the CVI does not measure water vapor in clear air, laboratory intercomparisons are needed to shed light on this question.

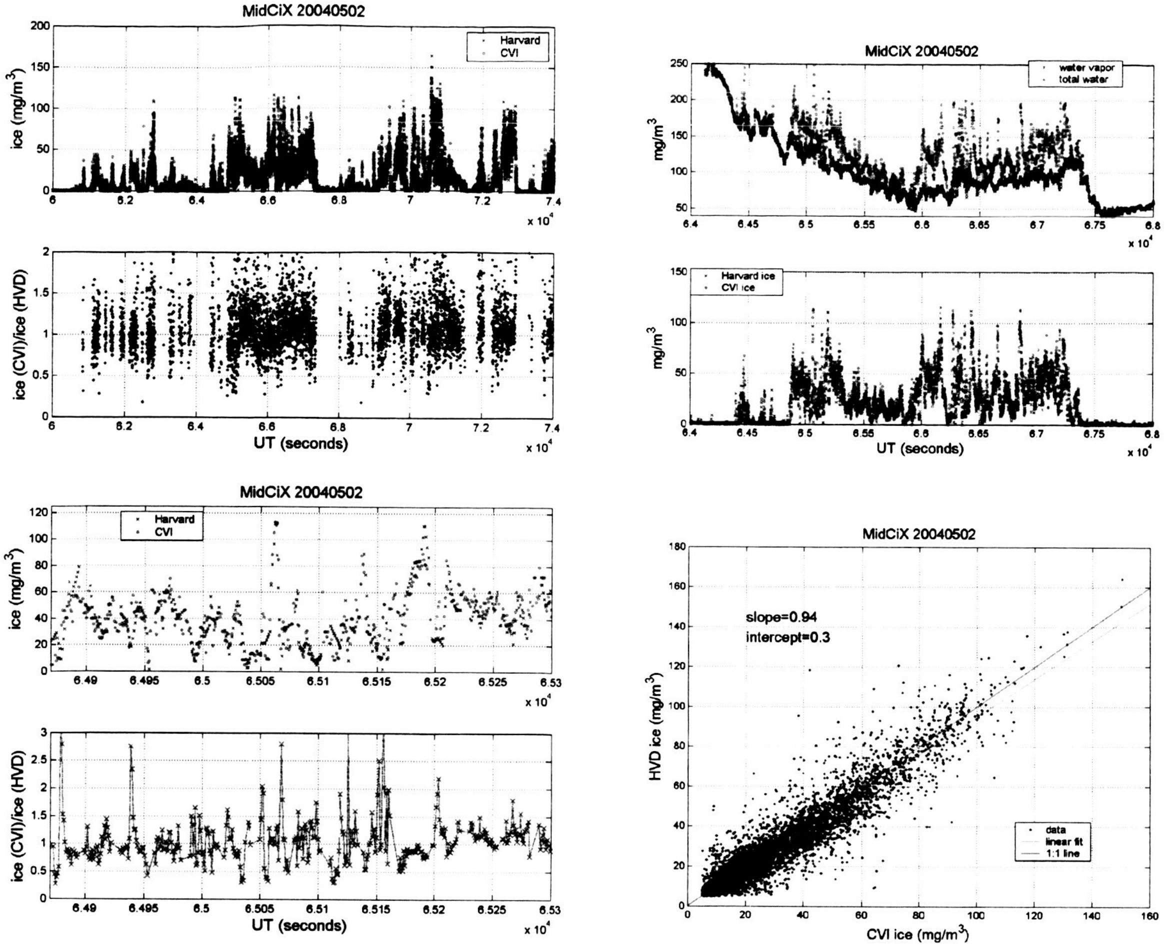

Figure 5. Intercomparison of preliminary 1-second data during MidCiX. The top left panels compare Harvard ice with CVI ice, in mg/m^3, with the ratio of the two plotted as well. The top right panels expand the scale and focus on a central portion of the flight. Here we plot Harvard total water and Harvard water vapor on the top and the two ice measurements below. In the bottom left panels we expand the scale further to similarly show a section of the data under higher temporal resolution. The bottom right panel shows the Harvard ice water content plotted against CVI ice water content for the full flight illustrating the agreement typical throughout the MidCiX mission.

In Figure 6 we show a short section of the May 3 flight, during which the WB57 spiraled up and down over the Department of Energy Atmospheric Radiation Monitoring site located in Billings, OK. In this plot, there is a 2.5% adjustment in the water vapor data to bring the clear air measurements into agreement, thus providing the ice water content measurement plotted in green. These data are representative of the Harvard instruments capability of measuring small amounts of ice in regions with high background water vapor mixing ratios.

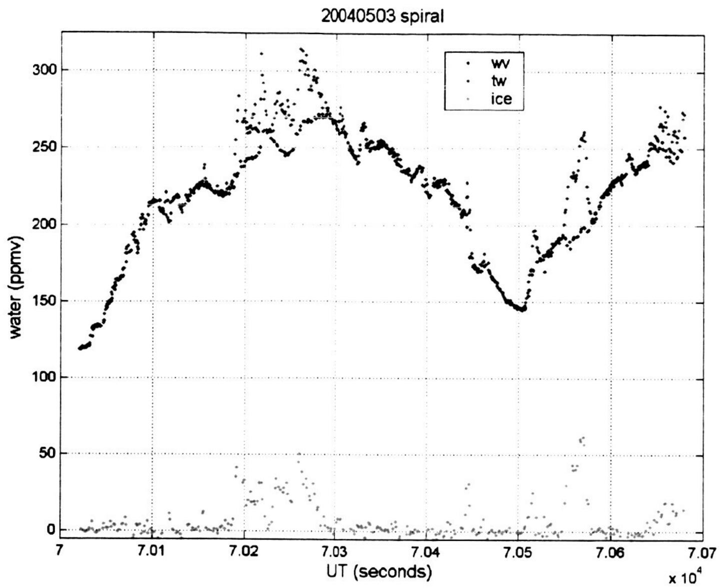

Figure 6. Plots of water vapor, total water, and ice water content during a spiral near the Oklahoma ARM site.

Figures 5 and 6 illustrate the dynamic range capability of our total water and water vapor instruments in the troposphere where water vapor mixing ratios range from tens to hundreds or more ppmv. Furthermore, these plots demonstrate the relatively high sensitivity that both of our instruments achieve. Such signal-to-noise results are required for quantitative measurement of thin cirrus in the tropopause region.

In summary, the Harvard water vapor and total water instruments performed flawlessly during the mission and illustrated excellent agreement with the CVI instrument flown by Cynthia Twohy of the University of Oregon. One of the key outcomes of this mission is that the observed agreement between the two independent ice water measurements of 10% or better provides strong evidence that these instruments have exhibited the accuracy necessary for validating remote sensors on Cloudsat and Calipso.

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Publications

Spackman, J. R, D. S. Sayres, J. V. Pittman, J. B. Smith, E. M. Weinstock, J. G. Anderson, C. H. Twohy and G. Kok, *In Situ* Measurements of Ice Water Content on the NASA WB-57F during MidCiX: Implications for MLS and CloudSat Validation, in preparation.

There are no inventions resulting from this funding.