Harvard Water Vapor

The Harvard Water Vapor (HWV) instrument combines two independent measurement methods for the simultaneous in situ detection of ambient water vapor mixing ratios in a single duct. This dual axis instrument combines the heritage of the Harvard Lyman-α photo-fragment fluorescence instrument (LyA) with the newly designed tunable diode laser direct absorption instrument (HHH). The Lyman-α detection axis functions as a benchmark measurement, and provides a requisite link to the long measurement history of Harvard Lyman-α aboard NASA's WB-57 and ER-2 aircraft [*Weinstock et al.*, 1994; *Hintsa et al.*, 1999; *Weinstock et al.*, 2009]. The inclusion of HHH provides a second high precision measurement that is more robust than LyA to changes in its measurement sensitivity [*Sargent et al.*, *in preparation*]. The simultaneous utilization of radically different measurement techniques facilitates the identification, diagnosis, and constraint of systematic errors both in the laboratory and in flight. As such, it constitutes a significant step toward resolving the controversy surrounding water vapor measurements in the upper troposphere and lower stratosphere.

Measurement Methods

LyA: The Lyman-α photo-fragment fluorescence detection method was developed for the in situ measurement of stratospheric water vapor because of its molecular specificity and high sensitivity. Lyman-α radiation, generated by a small amount of hydrogen gas in a radiofrequency plasma discharge lamp, photo-dissociates water vapor in the sample duct. A fraction of the resulting OH fragments are formed in their first excited electronic state ($A^2\Sigma^+$) denoted OH*. These excited state fragments either fluoresce, or are quenched by collisions with nitrogen and oxygen. At the altitudes of the upper troposphere and lower stratosphere the observed fluorescence signal is proportional to the water vapor volume mixing ratio. Empirically determined proportionality constants, established during laboratory calibrations, are used to convert the raw signal to measured mixing ratio. The final output is water vapor mixing ratio (ppmv) recorded at 1 Hz.

HHH: HHH measures water vapor via direct absorption in the near infrared utilizing a fiber-coupled tunable diode laser and a multi-pass Herriott cell. The Beer-Lambert law relates the transmitted light intensity to the concentration of water vapor within the cell. The use of direct absorption distinguishes HHH from other airborne laser absorption instruments, which rely on second harmonic detection to achieve the desired precision. State of the art signal processing and data acquisition systems allow us to achieve both high precision and accuracy with the direct absorption technique.

HHH uses a fiber coupled 1.4 µm DFB laser to scan over a strong water vapor absorption feature, in this case a single rotational-vibrational transition at 7178.75 cm^{-1}. The Herriott cell is comprised of two 3-inch mirrors, which are embedded in the walls (~4 inches apart) of the primary duct of the HWV instrument. The cell supports a 92 pass pattern, generating a total absorption path of 10.05 m. The light intensity from each laser scan is detected by an InGaAS photodetector. The scans are recorded, and the data are processed using fitting algorithms designed at Harvard. The algorithms utilize a Voigt lineshape, and spectral parameters from the HITRAN database to calculate water vapor number density. The final output is water vapor mixing ratio (ppmv) recorded at 1 Hz.

Instrument Performance

The performance characteristics of HHH and LyA are summarized in Table 1. We expect to obtain 1 Hz measurements of the ambient water vapor mixing ratio from ~1 to ~1000 ppmv with

an accuracy of 5% and a precision of ~0.1 ppmv for mixing ratios <10 ppmv, and ~1% for mixing ratios >10 ppmv. Our measurement accuracy of ~5% (1σ) is determined through a combination of careful laboratory calibrations and in-flight diagnostic tests [*Weinstock et al.*, 1994; *Smith, J. B.*, 2012]. At mixing ratios ~<10 ppmv, our precision, which is at or better than 0.1 ppmv in 1 second, also contributes to our measurement uncertainty. Laboratory tests constrain biases in the HHH and LyA detection axes to less than +0.2 ppmv. The requisite agreement between the two measurements in the laboratory and in flight provides a stringent test of the achieved accuracy.

	1 - 10 ppmv	10 - 100 ppmv	100 - 1000 ppmv
Sampling Period	1 second	1 second	1 second
Pressure Range	<500 hPa	<500 hPa	<500 hPa
Precision (typical)	<±0.1 ppmv	±1%	±1%
Accuracy	±5%	±5%	±5%
Artifacts/Offset	<+0.2 ppmv	<+0.2 ppmv	<+0.2 ppmv

Table 1. Performance characteristics for the HWV instrument.

Aircraft Integration
The instrument package is designed to mount in a spearpod forebody for use with NASA's ER-2 or WB-57 aircraft. A schematic of the instrument is shown in Figure 1. The integration of the HHH axis and redesign of the HWV inlet was achieved without any addition of weight, and an overall improvement in the location of the CG. The total payload weight including the instrument rack is 138 pounds. The CG is at 42" ± 2".
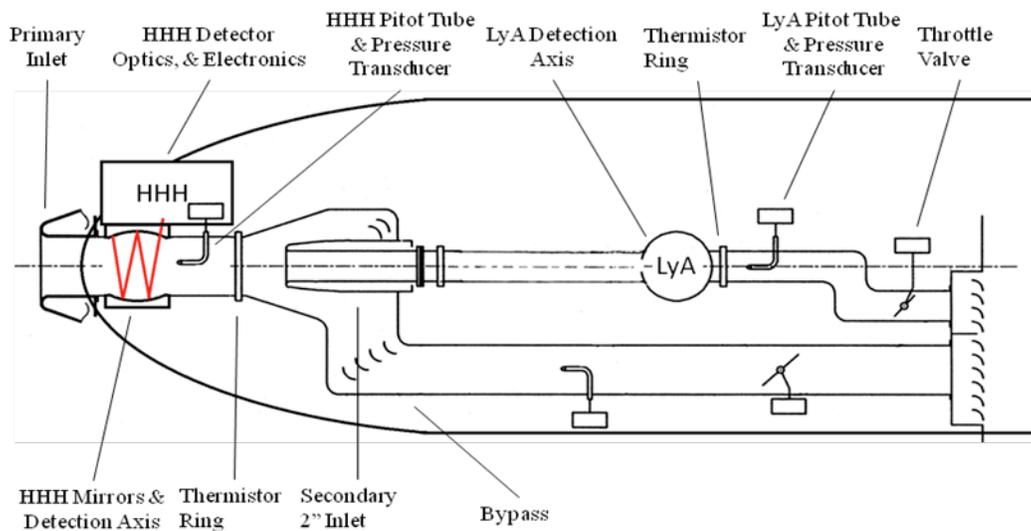

Figure 1. A schematic of the dual axis HHH/LyA Harvard Water Vapor instrument. The two detection axes, and the subsystems that measure temperature and pressure and control the velocity through the instrument duct, are labeled.

A 4" square duct serves as the primary ram air inlet to the instrument. The HHH laser absorption cell, comprised of two 3" diameter mirrors embedded in the walls of the primary duct, is positioned close to the intake to minimize the impact of upstream surface area, but far enough

downstream to ensure stable flow characteristics and to minimize pressure and temperature gradients across the detection region. The ducting downstream of the modified inlet is unchanged from the earlier version of the WB-57 LyA instrument. A 2" square secondary duct samples the laminar core of the primary flow. The air then passes through an aerodynamically designed light trap to exclude solar scatter, and on to the Lyman-α detection axis. Flow velocities in the secondary duct are ~50 m/s, which corresponds to a standard mass flow through LyA of ~1000 slm. (Flows in the primary duct are significantly greater.) The high flow rate allows for fast time response and effectively eliminates any contribution from the instrument walls. Flow through the full duct design was modeled using 3-D CFD simulations.

Data Product
Data are archived using the standard ICAART format. Our data include time, water vapor mixing ratio (ppmv), and an estimate of the uncertainty associated with each data point. The raw data from our sensors are recorded on a flight computer. We analyze the raw data using processing algorithms that have been developed at Harvard. The algorithms and analysis are supported by the MATLAB technical programming language and computing environment built by MathWorks. All data processing software is open source and available upon request.

References
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