Linking IIP Technology Development to NASA Aura Satellite Calibration: A Case Study of Isotopes

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Abstract-**The recent development of the integrated cavity output spectroscopy (ICOS) technique under IIP support, which improved the *in situ* detection of key trace species in the troposphere and stratosphere by a factor of fifty, is reviewed in the context of field missions designed to test the absolute calibration of key Aura instruments. The new technology development under the IIP program proved critical to two recent Aura Validation Experiment (AVE) campaigns designed as a collaboration between the scientific objectives of the Aura and airborne communities. The most recent results are presented.**

I. Introduction

The NASA Science Mission Directorate (SMD) vision to improve life here with the mission to understand and protect our home planet demands fundamentally new technology that advances economic and societal safety and stability through a decidedly more sophisticated union of *in situ* and remote observations of the Earth system. Investigation of how the living Earth system is changing due to naturally occurring and human induced processes, and investigation of the consequences of these changes for life on Earth, can only be achieved by tactical advances in the technology that more effectively joins the observational and modeling strategy of the SMD.

Predominant issues that underpin the national effort in Earth system science, climate research and human health include:

- The dynamical, chemical and radiative structure of the dominant regional-to-global scale plumes from the rapidly expanding economies of the world that establish an imperative to forecast events that constitute a collision between human health, economic build-up, and international guidelines on the import/export of air and water-borne toxicity.
- The dynamical, chemical and radiative structure of the tropics and subtropics that establish the fundamental structure and function of the Earth's climate system and, in addition, determine how that structure will change in response to a rapidly increasing array of climate forcings by both infrared trapping and short-wave, aerosol induced changes in albedo.
- The predominant, seasonally dependent pathways in the Hadley, Walker, Brewer-Dobson, Monsoon and associated smaller scale systems that are fundamental to the transport structure of the atmospheric system and to changes in those patterns in response to changes in sea surface temperatures, ice and snow cover, and optical properties of the atmosphere, etc.
- Accurate forecasting of ultraviolet dosage levels over heavily populated regions of the Earth in the coming decades as changing boundary conditions in the tropopause region of the tropics alter both the temperature and water vapor mole fraction of the stratosphere, affecting both the free radical catalytic destruction of ozone and the transport patterns that carry ozone from its production region in the tropics to mid and high-latitudes.
- Quantitatively rigorous accounting of national budgets for carbon compounds by comprehensive determination of sources and sinks via sophisticated flux measurements, and for nitrate, sulfate and organic precursors both for photo-oxidant production and for changes in optical properties that control the energy balance of the Earth-Sun system.
- Structure and response to chemical and physical forcing of the cloud/water vapor system of the Earth's atmosphere that dictates the balance between (1) low altitude cloud systems that, through short-wave forcing, potentially cool the planet, and (2) high altitude cirrus systems that constitute powerful infrared trapping.

A key regime in technology innovation to advance the objectives of SMD is the union between advanced laser development, the application of UAVs, and collaboration with the new generation of NASA satellites for Earth observations. The schematic depicting this strategy is displayed in Fig. 1.

In order to realize major advances in achieving NASA SMD objectives, it is important to identify new strategies for uniting the orbital and sub-orbital components of the program that will effectively join *in situ* and remote observations from a combination of platforms to far more rigorously test key hypotheses, establish the veracity of retrievals, expand the spatial and temporal coverage of the overlap between high resolution *in situ* measurements of fluxes and of chemical, dynamical and radiatively important species, and finally join, with a far more comprehensive footprint, sub-orbital *in situ*/remote observations with observations from the NASA

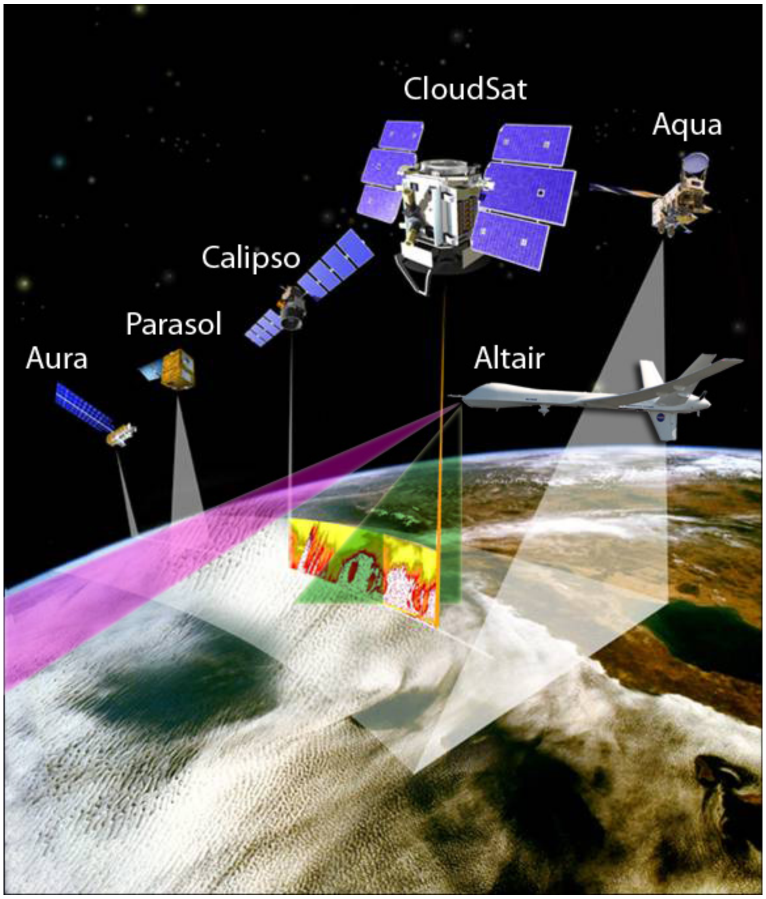

Fig. 1. A key technological strategy is the effective union of the NASA A-Train satellite constellation and the development of powerful *in situ* and remote measurement arrays from UAVs such as the Altair that, with state-of-the-art miniaturized laser systems developed under the IIP program, can provide fundamentally improved tests of satellite measurement accuracy and compelling new collaborative strategies for scientific inquiry and societal benefit.

A-Train constellation of Earth observing satellites. Emphasis focuses on the union of scientific objectives among Aura, Parasol, Calipso, CloudSat, Aqua and the technology innovation for UAV deployment.

We report here the results of an IIP development effort that culminated in the successful deployment of two new instruments to measure water vapor isotopes *in situ* on the WB-57 aircraft that was used in a series of missions to establish a strong collaboration with the NASA Aura satellite community. Two aircraft deployments were carried out: The first, the Aura Validation Experiment-Water Isotope Intercomparison Flights (AVE-WIIF) in summer 2005; the second, the Costa Rica-Aura Validation Experiment (CR-AVE) in winter 2006.

A. The ICOS Technique

The IIP development effort resulted in the design, development, calibration and airborne deployment of two new techniques. The first was the mid-IR Integrated Cavity Output Spectroscopy (ICOS) technique, shown schematically in Fig. 2.

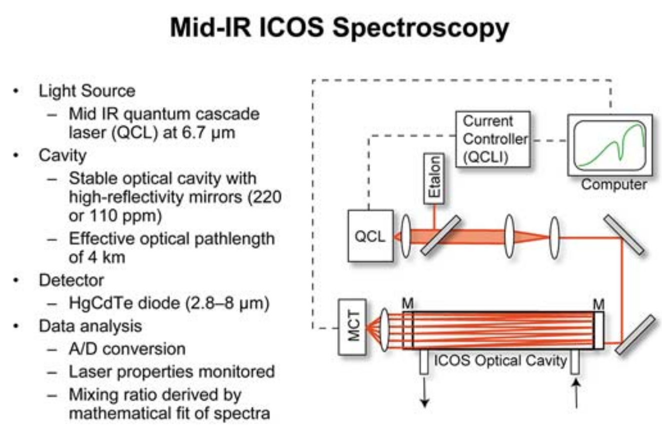

Fig. 2. Schematic of the ICOS technique.

This method employs the coupling of the quantum cascade laser (QCL) with a non-resonant, high finesse cavity to obtain optical pathlengths approaching 10 km in a 1 meter cell with very low optical noise. The result is that a range of critically important species such as HDO, $H_2^{18}O$, NO, NO_2, $HONO_3$, HCl, CH_2O, etc., can be detected *in situ* with a factor of fifty greater sensitivity than was possible with multipass TDL systems. Detection thresholds obtained in the laboratory are undiminished under flight conditions on the WB-57 aircraft.

The instrument prepared for flight is shown in the hangar facility at NASA Johnson Space Center in Fig. 3a, and the upload of the instrument is shown in Fig. 3b.

Fig. 3a.

Fig. 3b.

B. Photolysis-Fluorescence for Detection of Water Isotopes

The second instrument developed under the IIP for the detection of water isotopes uses the novel approach of Photolysis-Fluorescence detection wherein the parent H_2O and HDO molecules are photodissociated in a fast flow system onboard the aircraft and the product OH and OD radicals are detected by Laser Induced Fluorescence (LIF) using a solid state laser pumped dye laser at 287 nm. Fig. 4a shows the schematic approach used in this method, and Fig. 4b displays the key advantage of the method: That the interaction of the radical with the wall prevents the exchange of isotopes with the wall such that the isotopic ratio cannot be altered by the presence of the wall of the instrument. This is particularly important for observation of isotopic rates in the condensed phase.

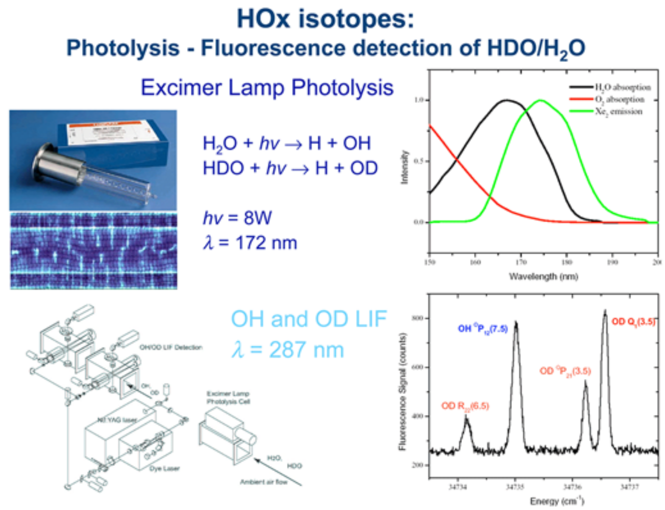

Fig. 4a.

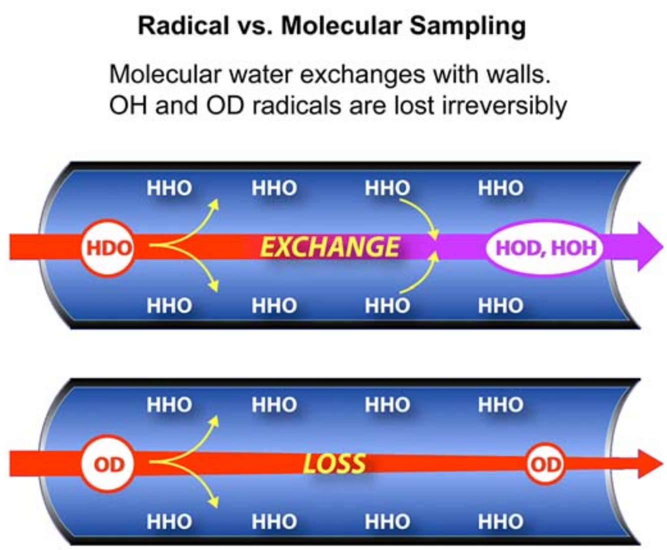

Fig. 4b.

II. CONCLUSIONS

As a result of these flights, the following conclusions were established:

- Accurate and precise measurement of water isotopes are an effective tracer of convective transport.
- Water isotopes follow Rayleigh thermodynamic equilibrium.
- Stratospheric water is isotopically heavy; δD = 460%.
- Evidence for direct injection of water into the overworld stratosphere: The mechanism is independent of tropopause temperature

The development of these new instruments under IIP support not only provided new insight into the mechanism of convective coupling between the troposphere and stratosphere, they also provided new and independent methods for the *in situ* detection of water vapor in the upper troposphere and lower stratosphere. This development has turned out to be critical to the calibration of the Aura satellite instruments and, in fact, for all satellite observations of water vapor.

Fig. 5 presents the flight data intercomparing five *in situ* water vapor instruments on the WB-57:

1. The new IIP ICOS instrument
2. The new IIP HOxotope instrument
3. The Jet Propulsion Laboratory diode laser absorption experiment
4. The Harvard University total water experiment
5. The Harvard University Lyman-α fragment fluorescence experiment.

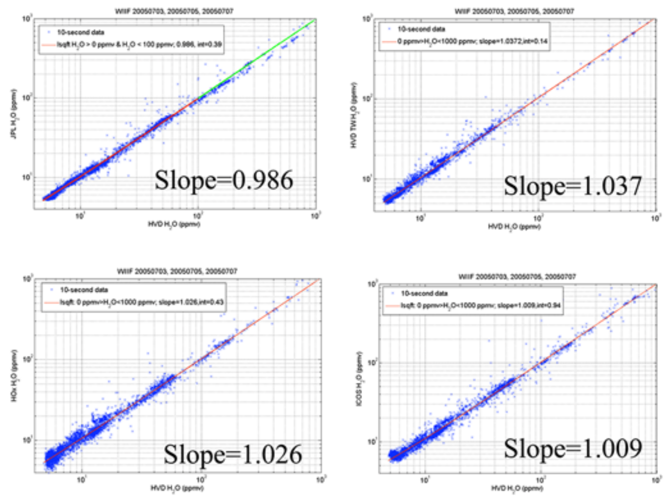

Fig. 5. Flight data intercomparison.

In Fig. 5, the first four instruments are regressed against the Harvard Lyman-α instrument, wherein each of the instruments are independently calibrated against an absolute scale in the laboratory prior to flight.

A critical conclusion emerged from this intercomparison: The *in situ* water vapor measurements onboard the NASA WB-57 are accurate (absolute) to ± 5% in flight. Because there are large systematic errors between the satellite retrievals of water vapor and the *in situ* results, it is now a matter of determining the cause for these large (~ 30%) biases between the satellite and *in situ* observations.

This represents a clear example of how IIP development has directly aided the scientific objectives of the NASA program.