

AN INSTRUMENT TO MEASURE TURBULENT EDDY FLUXES IN THE ATMOSPHERE OF MARS.

S. Rafkin¹, D. Banfield², R. Dissly³, J. Silver⁴, A. Stanton⁴, and E. Wilkinson¹, W. Massman⁵, J. Ham⁶, ¹Southwest Research Institute (rafkin@boulder.swri.edu), ²Cornell University, ³Ball Aerospace Corporation, ⁴Southwest Sciences, Inc., ⁵U.S. Forest Service, ⁶Colorado State University.

Introduction: Turbulent eddies in the planetary boundary layer of the terrestrial planet atmospheres are the primary mechanism by which energy, momentum, gasses, and aerosols are exchanged between the surface and the atmosphere [1]. The importance of eddies has long been recognized by the Earth atmospheric science community, and turbulent theory for Earth has a long history with a massive amount of literature backed by over half a century of detailed field campaigns. Every climate and weather forecasting model in existence relies extensively on turbulent eddy theory supported through observational validation. The importance of eddies in atmospheric dynamics, chemistry, and climate science cannot be overstated.

The atmospheres of the other terrestrial planets are no different than Earth. An understanding of the climate and weather of these other planets rests upon the work and transport of turbulent eddies.

The Mars science community has specifically recognized the importance of turbulent fluxes within the atmosphere of Mars. The MEPAG Science Goals Document has understanding the structure and processes operating in boundary layer as its highest priority Climate Science Goals [2]. It is difficult to conceive of other data within the boundary layer that would be more valuable than the meteorological parameters needed to construct a quantitatively accurate picture of the fluxes due to turbulent eddies [3][4][5]. One way to make a major rather than incremental leap in the understanding of the Mars climate system is to measure eddy fluxes.

Although turbulent eddies are critically important to understanding climate systems, volatile cycles, dust and aerosol cycles, chemical cycles, aeolian activity, and the entire energy and momentum budget within atmospheres, these eddy fluxes have never been directly measured on a planet other than Earth. Additionally, there is a dramatic and glaring paucity of wind, temperature, and volatile gas concentration information from which one might be able to learn at least something about the eddies, even if they are not measured directly.

Models of the Martian atmosphere are used to simulate the climate and provide atmospheric predictions for entry, descent, and landing of spacecraft incorporate parameterizations of eddies, but have yet to be validated [6][7][8][9]. Model estimates of eddy fluxes vary by factors of two or more [10][11], and these differences can result in different predictions

about the safety of landing sites, as well as general scientific results (e.g., convective updrafts and boundary layer heights). In the case of the Mars Exploration Rovers, some of the highest priority landing sites were determined unsafe solely due to the information from unvalidated models. To further compound the lack of data, the measurements needed to quantify the eddy processes cannot be made from orbit. It is inescapable that such measurements must be made in situ, but at present, there is no mature flight instrumentation that can do so.

We are developing an instrument that combines sonic anemometry and tunable laser spectroscopy to obtain the desperately needed eddy flux measurements. We are focusing our attention on Mars as a proof-of-concept, but the resulting instrument can be adapted to Venus, Titan, or the atmospheres of the ice giants (Figure 1).

Science and Traceability: The instrument we are developing is driven by the science goals outlined by the Mars community in the MEPAG Goals Document, as enumerated below:

- 1) Obtain measurements of standard meteorological parameters: Temperature, humidity, and winds.
- 2) Quantify the surface fluxes of momentum and the surface stress required for saltation and dust lifting.
- 3) Quantify the contribution of the sensible heat flux to the global energy budget and provide validation for the highly unconstrained model predictions.
- 4) Determine the power spectra of turbulence in the atmospheric surface layer.
- 5) Quantify the atmosphere-regolith exchange of water.

On Earth, turbulent fluxes are often obtained by combining independent measurements from physically different instruments. With an acoustic anemometer (AA) and tunable laser spectrometer (TLS), 3-D wind information is combined with gas abundance to construct a time series of covariances. With information of atmospheric composition, pressure, and temperature, the density can be calculated and combined with the covariances to determine the eddy flux. The technique of using an AA and TLS should be effective in other planetary atmospheres, but the implementation must be different due to a variety of key issues that make the measurements less straightforward than on Earth. These issues include: 1) Importance of sensor collocation for measuring small eddies and minimizing sensor flow distortion; 2) Compositional changes in the atmosphere over time; 3) Contamination of tempera-

ture and wind measurements due to solar heating of a TLS structure; and 4) Limited resources typically available to instruments. Due to the expected scale of eddies, an instrumentation implementation that integrates AA and TLS sensors is a strict requirement. Because the TLS and AA sensors are relatively mature, technical risk is not from the individual sensors, but in the integration. Thus, the focus of the effort is to better understand mechanical sensor interactions, mitigate those interactions to a level sufficient to achieve measurement objectives, test the mechanical sensor solution, and find a common, integrated solution for the electronics. Conceptually, our integrated instrument is shown in 1.

Anemometer Description: The Martian AA is in its 3rd year of PIDDP development by Co-I Banfield. The instrument has advanced from a proof of concept based on commercially available terrestrial AAs to a breadboard prototype instrument. The AA transducers have been tested in a Mars-like environment in a thermal-vacuum chamber, and the full sensor capabilities will be demonstrated on a stratospheric balloon to further replicate Mars-like atmospheric conditions later this year.

The challenge for adapting a commercial AA for use on Mars was two-fold: the atmospheric density is so low that it is difficult to generate and receive sound, and the CO₂ atmosphere attenuates high-frequency sound waves much more strongly than does the N₂ on Earth. To couple well to the thin Martian atmosphere, we used customized acoustic transducers that are designed with very light electrically driven membranes that can both produce and sense sound waves at Mars with relatively high efficiency. The high attenuation and challenges in coupling to Martian atmospheric density is tackled with sophisticated signal processing techniques (i.e., Pulse Compression borrowed from RADAR techniques).

The AA consists of a computer back-end that controls the initiation of the measurement sequence, as well as the computational processing required to perform the sophisticated digital signal processing needed to extract as much information as possible from the received signals. This computer back-end is now implemented using an FPGA with a clear path to flight. It sends a digital representation of the signal to be emitted (a “chirp”) to a chirp generation board where it is converted to an analog signal, amplified and sent to all six transducers (two opposing transducers for each of the three orthogonal axes). This signal becomes a sonic signal through the sending element of each transducer, transits across the sensing volume (at different rates depending on the temperature and the wind vector) and is received at the other end by the receiving element of the opposing transducer. The six receive signals are then each amplified using very spe-

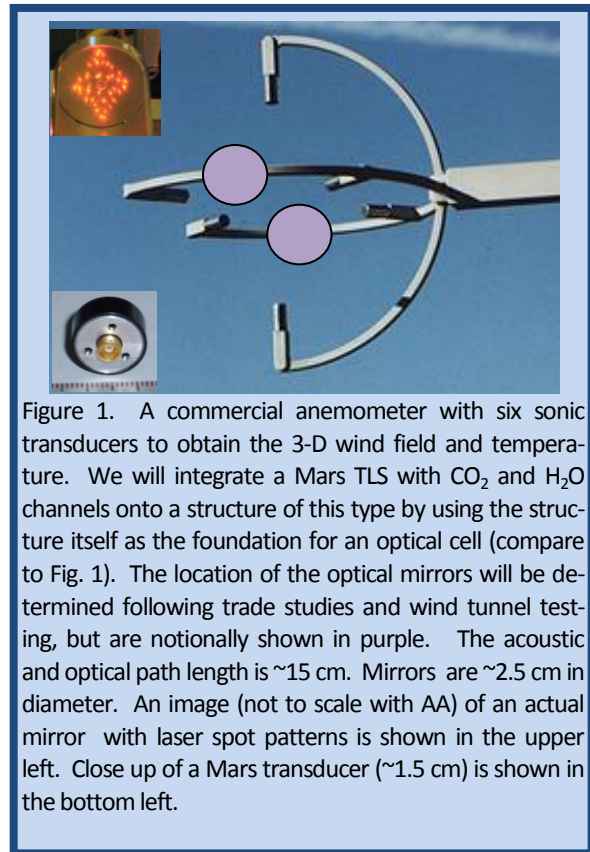


Figure 1. A commercial anemometer with six sonic transducers to obtain the 3-D wind field and temperature. We will integrate a Mars TLS with CO₂ and H₂O channels onto a structure of this type by using the structure itself as the foundation for an optical cell (compare to Fig. 1). The location of the optical mirrors will be determined following trade studies and wind tunnel testing, but are notionally shown in purple. The acoustic and optical path length is ~15 cm. Mirrors are ~2.5 cm in diameter. An image (not to scale with AA) of an actual mirror with laser spot patterns is shown in the upper left. Close up of a Mars transducer (~1.5 cm) is shown in the bottom left.

cialized pre-amplifiers and the signals are passed on to a receiver board where a final amplification and A-D conversion is performed. These digital signals are stored in a FIFO until they are transferred to the FPGA on request. The FPGA then performs a convolution of the received signals with the send signal in Fourier Space (for speed). The convolution peak identifies the travel time for each signal, and then some simple algebra of these travel times yields the wind speed vector and C_s that become the instrument’s fundamental data stream.

The AA has transducers near the final design that they will likely attain for use on Mars. The sensitivity is a factor of eight over any commercially available transducer under Martian conditions, and the form factor of the transducers is as small as possible while still yielding sufficient signal strength to perform the measurements with the repetition rate (>20 Hz) and accuracy (<5 mm/s) desired. The transducers have been tested for 90 cycles oscillating from 0C to -60C, and for 3 cycles from 153-273 K, with a single dip to 138K (below the CO₂ condensation temperature on Mars). Performance was unaffected throughout these temperature swings. The current FPGA draws about 4W of power and is the main power usage on the instrument at this stage. Under the final year of Co-I Banfield’s PIDDP effort, the AA will be tested under realistic Martian conditions (CO₂, pressure, and temperature)

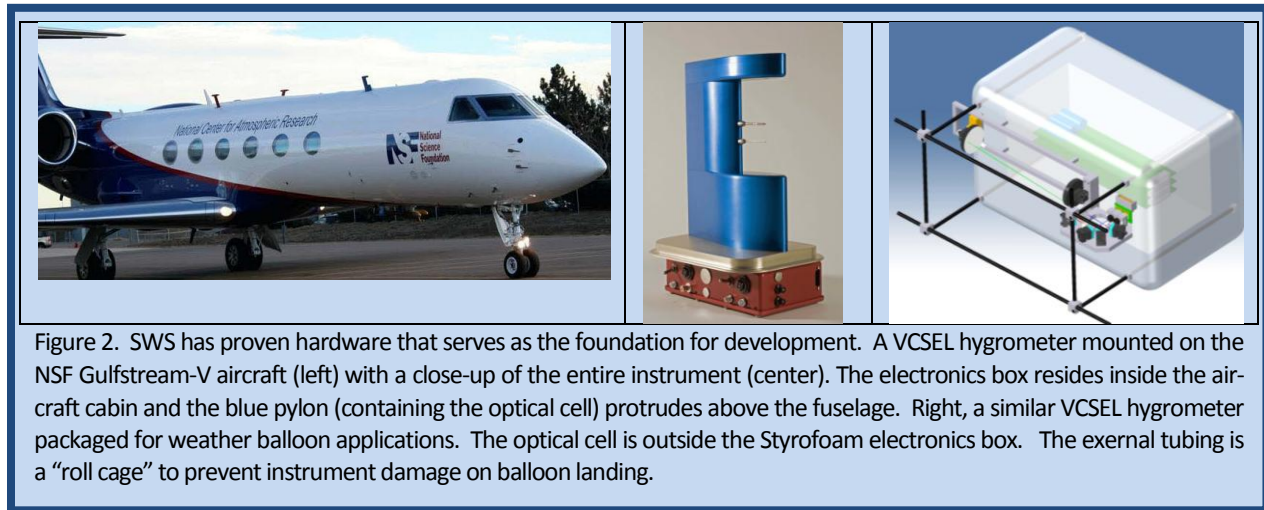


Figure 2. SWS has proven hardware that serves as the foundation for development. A VCSEL hygrometer mounted on the NSF Gulfstream-V aircraft (left) with a close-up of the entire instrument (center). The electronics box resides inside the aircraft cabin and the blue pylon (containing the optical cell) protrudes above the fuselage. Right, a similar VCSEL hygrometer packaged for weather balloon applications. The optical cell is outside the Styrofoam electronics box. The external tubing is a “roll cage” to prevent instrument damage on balloon landing.

at the Mars Simulation Laboratory wind tunnel in Aarhus, Denmark and on a stratospheric balloon flight.

TLS Description: Laser-based instrumentation is becoming increasingly common in planetary exploration. The Phoenix Scout Mission manifested a vertical pointing LIDAR, which successfully measured aerosol and cloud properties [12]. The Mars Science Laboratory has a TLS to measure methane as part of the SAM suite of instruments [13][14], and the ill-fated Mars Polar Lander had a water TLS [15]. TLSs have also been proposed in numerous mission proposals. In short, the TLS concept and instrumentation is mature and presents a low-risk solution for measuring a variety of trace gases in planetary atmospheres.

Our TLS used as a starting point a compact and low-power field-quality TLS hygrometer developed and manufactured by Southwest Sciences, Inc. (SWS). Versions of this instrument function in the laboratory and field environment on Earth [16][17], and have been flown on high-altitude balloons, sounding rockets and on aircraft (Figure 2). The SWS instrument consists of a vertical cavity emitting laser (VCSEL) source and photodetector, a multi-pass optical cell to provide a long absorption path in a compact design, and laser driving and digital signal processing electronics. The sensor takes advantage of two key technological developments: 1) a patented multiple-pass optical cell design that uses small mirrors and dense spot patterns to give a long optical path with a small footprint; and 2) a low power and compact electronics system. For most gases, wavelength modulated spectroscopy (WMS) is used to increase sensitivity [18] and reduce $1/f$ noise in particular. Absorption accuracies to better than 10^{-5} are now routinely made in the lab and with commercial TLS systems using WMS. The WMS signal is analyzed with multi-linear least squares fitting to find the concentration.

Over the last year, efforts were made to produce a new mechanical design of the optical cell sufficient to withstand the rigors of spaceflight and the Martian environment, as well as a redesign of the electronics with space-qualified components (Figure 3). Importantly, we also added capabilities for four simultaneous laser channels using a single optical cell, which satisfies the requirement for both a CO_2 and H_2O channel on Mars. The new design provides the same functionality as the original SWS design, but uses flight qualified electronics. The new flight electronics are expected to draw less than 500 mW. SwRI's Control Electronics Box (CEB) design provides for complete instrument command, control, health and status monitoring and science data processing. The core of the CEB is a radiation tolerant Actel RT ProASIC FPGA. The FPGA provides complete spectra line data acquisition, real-time processing, and control. Incorporated within the FPGA is an 8051 microcontroller for overall instrument commanding, health and status collection, and science data formatting prior to transmission. Supporting the FPGA are a set of four high performance (16 bit) Digital-to-Analog (D/A) converters, Analog-to-Digital (A/D) converters for laser control and tuning. Power distribution, temperature monitoring, and active control of the lasers are incorporated within the CEB.

The light source for the TLS is a fiber-pigtailed VCSEL $2\text{ }\mu\text{m}$ thick and $5\text{ }\mu\text{m}$ in diameter. VCSELs are available over a continuous range of wavelengths from $\sim 1.3\text{ }\mu\text{m}$ to $2.6\text{ }\mu\text{m}$. The manufacturing process and performance of the lasers are effectively identical in this wavelength region and the lasers are functionally interchangeable. We have nominally selected a VCSEL wavelength of $1.877\text{ }\mu\text{m}$ for water, which provides sufficient line strength to meet measurement requirements under Mars conditions. The CO_2 channel has not been selected, but there are numerous absorp-

tion lines in the VCSEL range from which to choose. We will perform a study to identify the best line(s).

A folded optical path provides a compact design to achieve high sensitivity. Conventional multiple-pass cells use spherical mirrors in a Herriott cell [13]. Most of the mirror surface is unused. A patented SWS optical cell [18] replaces the more traditional spherical Herriot Cell mirrors, providing a greater percentage of mirror utilized, and a path length-to-volume ratio is about three times greater than that of the Herriott cell. The beam enters the cell at the mirror center and the beam exits back through the entrance hole to strike an InGaAs photodetector. The laser resides in the protected electronics housing.

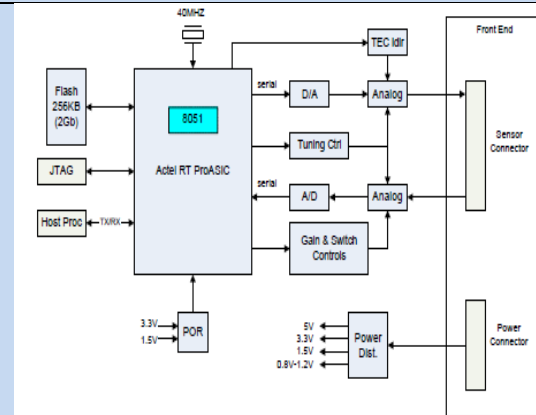
Atmospheric Composition Changes: The major constituents of Earth's atmosphere are to a very good approximation constant in time. The result is that turbulent fluxes can be calculated without great concern about variations of composition, and small corrections can be added for variable water vapor, if desired. This is not the case for Mars, where the dominant gas, CO₂, varies seasonally by up to 25%. As CO₂ mass decreases, the mass of nonvolatile gases such as N₂ and Ar increase in concentration. Water vapor also varies, but the overall abundance is so small that its variations are negligible. To calculate eddy fluxes on Mars, knowledge of composition is absolutely necessary. As we demonstrated from our error analysis, our instrument can determine composition if total pressure is also measured. Of all meteorological sensors, barometers have the most heritage and the same basic design has been successfully deployed in numerous planetary atmospheres including Earth, Mars, Titan, Jupiter, Venus. We will require a measurement of pressure to achieve our stated science goals, but we do not expend effort for this sensor since it is TRL-9 and requires trivial resources. We do require CO₂ measurements, and this can be achieved with our TLS design that allows for up to four separate channels using the same optical sensor cell. By adding a H₂O channel to the

TLS, we further gain the ability to determine the latent heat flux.

Resource Limitations: Resource limitations are almost always a major driver of instrument requirements and accommodation. Integration of sensors to use common mechanical assemblies and common electrical components is a natural way to reduce overall resources. If not for the collocation requirement driven by measurements, resource utilization alone would be a very strong driver for an integrated instrument. We will perform trade studies to balance TLS and anemometer capabilities against integration solutions. For example, larger TLS mirrors may cause more wind interference, but provide for a longer pathlength to improve TLS sensitivity. At the same time, shorter pathlengths give more signal for the AA, but can degrade wind and TLS measurements. We are targeting a total integrated mass of 2 kg=0.25 kg for TLS sensor + 1.0 kg AA sensor and assembly + 0.75 kg for electronics. We are targeting 2 W total power. Currently, the TLS is relatively mature at <1 Kg and 500 mW. The weight includes the entire optical cell that will now become part of the integrated instrument assembly. The AA is less mature. The current sensor head is based entirely on terrestrial design (2 kg), and has undergone very little electronic design for flight (4 W). By integrating sensors and scrutinizing mechanical and electrical design of the AA, we feel confident that we can achieve the resource goal.

Implementation in Other Planetary Atmospheres: Although focused on Mars, we fully intend for this instrument to be applicable to various other atmospheres after only very minor modifications. Beyond Earth and Mars, three additional issues must be considered: 1) TLS wavelength selection to match gases of interest; 2) AA transducers matched to the acoustic environment; and 3) the specific environmental conditions in different atmospheres. Importantly, besides a trivial change in TLS wavelength and appropriate selection of a transducer, the rest of the instru-

Figure 3. Functional block diagram and CAD of the Mars TLS. Up to four laser channels are possible in the sensor front end. Total power is <500 mW. Total weight is < 1 Kg. CAD model (below) shows an all-aluminum optical cell with patented mirrors. Fiber is used to direct the signal from a separate laser electronics box. Total length is ~15 cm.



ment system remains unchanged.

CH₄ is a primary gas of interest on Titan. There are strong absorption lines in the VCSEL range that permit this measurement. This can also be accomplished on Mars as well with sensitivities down to ~1 ppbV with a laser at 2350 nm. There is also a whole range of gases that could be detected with meaningful sensitivity with this instrument for Venus. Thermal variations are greatly reduced in the thick atmosphere of Venus, but highly corrosive sulfuric acid becomes an issue in and near the cloud layers. Teflon coating of the mechanical structure and sapphire coatings on the mirrors easily solve the acid problem with no subsystem design changes. Similar, ultrathin coatings would also be suitable to protect the transducers. Pressures and temperature are Earth-like so that commercial transducers are likely to function adequately. Since the instrument electronics (including the laser) can be placed in a thermally controlled and sealed environment, the impact of the external environment on these subsystems is inconsequential. Titan has a benign chemical environment, but is cold. For the TLS, the cold temperatures can be advantageous as it reduces thermal noise. With a dominant N₂ environment, terrestrial transducers could be used, although they would need to be qualified for the cold temperatures. The instrument would also be ideal on probes dropped into the Gas Giants. In short, all these applications require only minimal modifications and none of the solutions affect major subsystem designs.

References: [1] Stull, R. B. (1988). [2] MEPAG (2010). [3] Lenoir, B., D. Banfield, and D. A. Caughey (2010), *Journal of Atmospheric and Oceanic Technology*, 28(2). [4] Mischna, M. A. (2009), *White paper submitted to the National Research Council Space Studies Board*. [5] Rafkin, S. C. R. (2009), *White paper submitted to the National Research Council Space Studies Board*. [6] Michaels, T. I., and S. C. R. Rafkin (2008), *J. Geophys. Res.-Planets*, 113. [7] Rafkin, S. C. R., and T. I. Michaels (2003), *J. Geophys. Res.*, 108(E12). [8] Rafkin, S. C. R., R. M. Haberle, and T. I. Michaels (2001), *Icarus*, 151(2). [9] Tyler, D., J. R. Barnes, and E. D. Skillingstad (2008), *J. Geophys. Res.-Planets*, 113(E8). [10] Michaels, T. I., and S. C. R. Rafkin (2004), *Quarterly Journal of the Royal Meteorological Society*, 130(599). [11] Toigo, A. D., M. I. Richardson, S. P. Ewald, and P. J. Gierasch (2003), *J. Geophys. Res.*, 108(E6). [12] Whiteway, J. A., et al. (2009), *Science*, 325(5936). [13] Tarsitano, C. G., and C. R. Webster (2007), *Appl. Opt.*, 46(28). [14] Webster,

C. R., and P. R. Mahaffy (2011), *Planet Space Sci.*, 59(2-3). [15] May, R. D., S. Forouhar, D. Crisp, W. S. Woodward, D. A. Paige, A. Pathare, and W. V. Boynton (2001), *J. Geophys. Res.*, 106(E8). [16] Paige, M. E. (2005), *Journal of Atmospheric and Oceanic Technology*. [17] Zondlo, M. A., M. E. Paige, S. M. Massick, and J. A. Silver (2010), *J. Geophys. Res.*, 115(D20), D20309. [18] Silver, Joel A. (2005), *Appl. Opt.*, 44(31), 6545-6556.