MARS ACOUSTIC ANEMOMETER - EDDY FLUXES. D. Banfield, *Cornell Astronomy, Ithaca, NY 14853, USA, (banfield@astro.cornell.edu)*, R. Dissly, *Ball Aerospace*, A. D. Toigo, P. J. Gierasch, *Cornell Astronomy*, W. R. Dagle, *Applied Technologies*, D. Schindel, *MicroAcoustic Instruments*, D. A. Hutchins, *University of Warwick*, B. T. Khuri-Yakub, *Stanford University*.

Overview

We are developing an acoustic anemometer for use in the low pressure atmosphere of Mars. Acoustic anemometers have high sensitivity, high temporal resolution, high accuracy, are insensitive to radiative heating and demand little power. In these ways they are superior to the anemometers previously flown to Mars. Accurate, well-calibrated anemometers are crucial for understanding the near-surface atmospheric environment (e.g., slope winds, convective cells, dust devils, and aeolian processes in general). Furthermore, the high time-resolution, sensitivity, 3-D capabilities and well-defined, open sampling volume available from an acoustic anemometer allow it to resolve individual turbulent eddies, a first for Mars. This feature allows it to directly measure eddy fluxes, for example water vapor vertical fluxes between the surface and atmosphere when coupled with a fast hygrometer (e.g. a TDL). This novel ability to measure water vapor fluxes is viewed as a high priority science goal of Mars landers. We expect that the instrument designed in this program will be a prime candidate to fly on either the Mars Science Laboratory Lander, or any of the future planned Mars Scout landers or Mars Surveyor Landers.

Acoustic anemometers are well developed for Earth, but need modifications to function in the vastly different martian pressure environment. The two main hurdles are sound attenuation in Mars air, and transducer coupling inefficiency from density and sound speed mismatches with Mars air. The sound attenuation on Mars is significant, especially at ultrasonic frequencies. We have a simple model of the relevant phenomena to guide our choices to the optimal frequencies for Mars. The coupling between a transducer and the atmosphere is characterized by the match of their densities and sound speeds, or acoustic impedances, similar to index of refraction in optics. The Martian atmosphere has an acoustic impedance of about 1% that of the Earth. The commonly used (on Earth) piezo transducers lose about 110dB coupling with Mars air. Matching plates are unsuitable due to bandwidth limitations. Acoustic horns may aid in matching impedances. Capacitive transducers have an inherently low acoustic impedance, and are now becoming available in the frequency ranges needed for Mars. We are in the process of testing 3 styles of cutting-edge capacitive transducers in a simulated martian atmosphere anechoic chamber. Initial testing looks very favorable for producing a successful instrument for Mars. We will integrate the optimized transducer with Applied Technologies' electronics for Earth acoustic anemometers, with some possible modifications to again optimize performance at Mars. All of these issues are being addressed with respect to mass and power considerations. The goal of this project is to produce a proof-of-concept and functional design of an accurate, robust, versatile Martian anemometer with significantly greater capabilities than its predecessors.

Martian Surface Winds: Crucial to Observe

Future landers on Mars will need to carry anemometers. The atmosphere is currently the most active element of change on Mars, and if we are to understand the changes that are happening and those that have come before, we must understand the atmosphere of Mars. In particular, its interaction with the surface is of critical importance, and can only be adequately studied from a landed perspective.

The safety of future landers, bases and astronauts is an important driver for more fully understanding Mars' surface winds. Mesoscale models have been used to estimate wind shears for descending probes, but without adequate ground truth, the capabilities of the models to accurately predict true conditions is limited. Only additional observations taken within the boundary layer will allow us to properly validate these models, and more safety operate on the surface of Mars.

The boundary layer is the medium through which the bulk of the atmosphere affects its impact on the surface. Aeolian processes are currently the strongest factor in shaping the surface, yet we do not fully understand them. The drag that the atmosphere puts on the surface is poorly specified at best. No *direct* study of the transfer of momentum between the atmosphere and surface has been performed at Mars, yet this is the chief agent of change on Mars' surface. Additionally, no direct study of the transport of heat from the surface to the atmosphere has been done on Mars. This has significant impacts on the thermal stability of materials (e.g., H_2O, CO_2 frost) at or near the surface on Mars. The flux of heat between the surface and atmosphere on Mars is critically important for understanding Mars' climate. Measuring the transport of water itself between the surface and atmosphere has not been attempted. The flux of water between the surface and the atmosphere may tell us about the regions in which it is stable or sequestered below the surface. Combining a thermometer or hygrometer with a fast sensing anemometer allows all of these transports to be measured. By examining the correlation between the vertical wind variations and horizontal wind, temperature or (e.g.) water abundance variations, the net flux of these parameters away from the surface due to the turbulent eddies in the boundary layer can be directly measured. However, it requires an anemometer that can resolve the eddies in both space and time. This is routinely done on Earth in scientific studies, and could be done on Mars as well if the appropriate anemometer were flown.

The importance of dust storms of all scales and dust devils in the climate cycle of the planet is unquestionable, and yet we still don't fully understand why they start where or when they do. We don't fully understand how they grow, or precisely what causes them to stop. Clearly wind observations will help us to understand both of these phenomena that are scientific keystones to Mars' climate.

Our first understanding of the synoptic scale weather systems that Mars experiences were from the Viking Landers wind (and temperature and pressure) sensors. In fact it is only through the *combination* of these different observations that the global scale nature of the weather systems were first inferred (Barnes, 1980). Recent work with orbiting thermal sounders has revealed synoptic weather systems from a global perspective (Wilson *et al.* 2002) but recognize that orbital sounders have little access to the conditions in the lowest half scale height of the atmosphere. Significantly, the weather systems that are dominant near the surface are only marginally observable using orbital thermal sounders. Furthermore, the thermal sounders only can infer the vertical gradient of winds via the thermal wind equation. With a meteorological station measuring wind at the surface, more appropriate wind profiles could be estimated, at least in the location of the lander. The landed observations would also provide ground truth to general circulation models (GCMs). These complex models need as much validation as possible for them to be truly useful. Clearly to fully understand the weather of Mars, we need full landed meteorological suites, including anemometers.

Need For Something Better

Anemometers have been flown on the Viking Landers, Mars Pathfinder, and the ill-fated Mars Polar Lander. All of these missions used variations on the concept of hot-wire anemometry, where the power required to maintain a probe at a constant temperature was measured. The advantage of this approach is simply that it is simple and light. Its drawbacks are numerous.

Its response time is relatively slow, too slow to measure turbulent fluctuations (Hess *et al.*, 1972). Seiff*et al.* (1997) compared turbulent power spectra from Mars Pathfinder and Earth, noting that much of the differences may arise from the Pathfinder instrument's time constant. Without actually measuring the eddy structures with fast response instruments (fast enough to sample the inertial subrange, i.e. about 1Hz (e.g., Seiff *et al.* 1997, Tillman *et al.* 1994)) we can't even estimate how well our slower instruments did at characterizing the turbulent behavior. With such slow response anemometers, *direct* sensing of heat, momentum or volatile fluxes from the surface to the atmosphere is only marginally feasible. A significant fraction of the turbulent eddies are averaged together over time. Assumptions about the boundary layer structure must be made, without the possibility of checking them.

Measuring the heat loss from a probe due to the wind is an indirect measurement. It is prone to confusion from other heating or cooling sources. For example, direct solar heating on the heated probe could seriously bias inferred wind speeds if the solar heating were not properly accounted for. A better instrument would more directly measure the wind itself. Additionally, heating from the lander itself can skew the results. Wind measurements made in the lee of the lander were not only influenced by the wind shadow of the lander, but also its thermal state as well. All of this makes hot-wire techniques difficult to calibrate and interpret.

Heating a probe is a power hungry approach. In fact, the Pathfinder instrument was power limited, its performance would have been better with a greater overheat for the probe, but this was not available (Seiff *et al.* 1997). Pathfinder's anemometer drew 0.38W while operating, while a standard commercial Earth acoustic anemometer, with 6 (inefficient) piezo transducers firing at 20 Hz will spend only 0.06W. This power usage is also likely to be significantly reduced with the use of more efficient transducers.

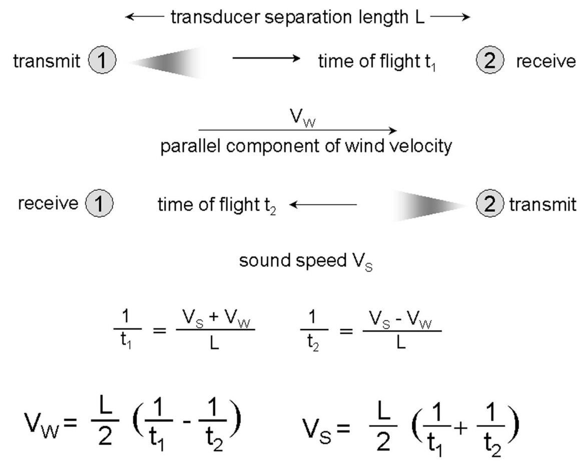

Figure 1: Schematic description of acoustic anemometry.

Previous anemometers have only attempted to infer the horizontal wind vector. This is likely due to two factors. First, the geometry of a heated probe is easier in a 2-D configuration. Trying to array thermocouples around a heated sphere in 3-D would be difficult, and the device's own wind shadow perturbations would be considerable, especially on the generally much lighter vertical winds. Secondly, the magnitude of the vertical winds themselves make them difficult to measure. The smaller vertical wind speeds would require notably more sensitivity than was available for the horizontal measurements of the previous anemometers.

Even if 3-D, fast response configurations of hot-wire style anemometers could be built, they would not allow the simultaneous measurement of other parameters (e.g., humidity) to directly infer the fluxes through the boundary layer. The heated probe itself occupies the volume where the wind speed is sensed, precluding the possibility of using other techniques to measure (e.g.) humidity in that volume. This practical limitation can be overcome with another technique, acoustic anemometry.

Acoustic Anemometer Principles

In concept, an acoustic anemometer is very simple, in part because it is a direct measurement of the motion of the air. The key concept is that sound, being a longitudinal oscillation of the air molecules, is advected with winds. It is easiest to understand the principle in a 1-D scenario (see Fig. 1). Imagine 2 opposing transducers (both emitters and receivers) with a known separation. Pulses are emitted by one transducer and received by the other in an alternating fashion. The pulse travel times are both measured. The average of the two travel times is proportional to the sound speed in the air, which is only a function of the temperature. So the acoustic anemometer is also an accurate, fast-reponse thermometer. The difference of the two travel times is proportional to the wind speed along the direction separating the two transducers. The travel time *with* the wind will be less than that *against* the wind. Beyond this, if two more axes are added, the full 3-D wind vector can be determined (see e.g., Cuerva and Sanz-Andres, 2000).

Benefits of Sonic Anemometry

This is the premier technique for use in research studies of winds in the boundary layer on Earth. It is a well understood technique, with commercial instruments being available since before 1975 (e.g., Applied Technologies Inc., or Kaijo Denki Inc.). It is inherently a low power technique, only demanding significant power for the pulse emission itself, essentially an instant-on/instant-off technique. The quantity being measured is a direct measure of the phenomena of wind, the advection of the sound as the air moves. This removes from the technique many of the potential pitfalls of other techniques, such as the solar heating perturbations of a hot-wire approach. It is generally a very accurate measurement technique, limited by the ability to measure the path length between transducers and the pulse travel times, both of which can be done with high precision. On Earth, it is frequently used to measure not only the horizontal wind vector, but also the vertical winds, which are often smaller by several orders of magnitude, i.e., it measures the full 3-D wind vector. Another result of the simplicity of the technique is that it is very easy and accurate to calibrate. It is also a fast-response thermometer, not easily biased by effects like radiative heating. Finally, and perhaps the most significant advantage is that it is a very fast response technique, typically limited by the pulse repetition rate which often exceeds 20Hz. Because of this, it is the premier approach to directly measure eddy fluxes where the eddies themselves are resolved and correlated with either wind, temperature, or constituent perturbations to yield fluxes. The open and well defined sensing volume is ideally suited to measure other parameters (e.g., humidity with a TDL) which can then be used to compute eddy fluxes of that parameter. As mentioned above, this is not possible with hot-wire techniques, and doppler lidar approaches generally have a poorly defined sensing volume, adding ambiguity in eddy measurements.

Adaptation to Mars

While acoustic anemometry is a well understood technique for Earth, its adaptation to Mars is not trivial. The most significant differences in the martian environment are the atmospheric attenuation and the acoustic impedance of the air. Beyond these two issues, the standard techniques that are used on Earth will carry over very well to application on Mars. Once we overcome the design hurdles outlined below, we will use the standard electronics and algorithms that Applied Technologies packages with their research-grade Earth acoustic anemometers, greatly simplifying the overall instrument design adaptation to Mars.

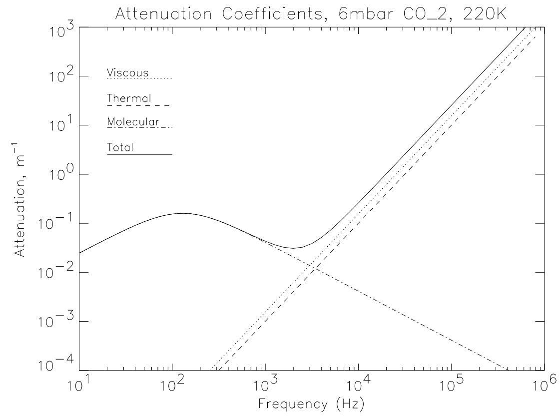

Figure 2: Attenuation on Mars. Attenuation is very strong above about 100kHz. Adapted from Williams (2001).

The attenuation of sound in Mars' atmosphere is quite significant. A good review of the issues involved is in Williams (2001). He presents expressions for the viscous, thermal and molecular attenuation. Fig. 2 shows these effects as a function of acoustic frequency.

The viscous and thermal attenuations are each about 2 orders of magnitude stronger on Mars than on Earth, and for the higher frequencies we'll be considering are the dominant attenuation. Because the attenuation increases so rapidly with frequency, clearly ultrasound beyond about 100kHz will not travel far in the martian atmosphere. As many of the commercially available acoustic anemometers built for Earth use 100kHz (mainly to avoid acoustic interference from human activity), clearly some redesign is necessary. However, lowering the operating frequency too low would reduce the precision possible in determining pulse arrival times, and hence the sensitivity of the instrument.

The most significant issue facing the adaptation of acoustic anemometry to Mars conditions is the acoustic impedance of the air. This parameter, defined as the ratio of a given acoustic pressure perturbation to the resultant velocity of the medium, is extremely low for Mars: $\sim$ 3kg/m^2/s. Earth air has an acoustic impedance of about 400kg/m^2/s, while water has a value of 1.5×10^6kg/m^2/s. Piezo transducers have about the same acoustic impedance as solid granite, about 1.2×10^7kg/m^2/s. Cutting-edge capacitive transducers have acoustic impedances in the range of 1000kg/m^2/s, much closer to those of Earth or Mars air. The reason this is of critical interest is that when a sound wave passes between two media, the power transmitted or reflected depends strongly on the ratio of the two acoustic impedances. It is very analogous to the index of refraction in optics, where for two identical indices of refraction, light is transmitted completely between the two media. For very different indices of refraction, the power is

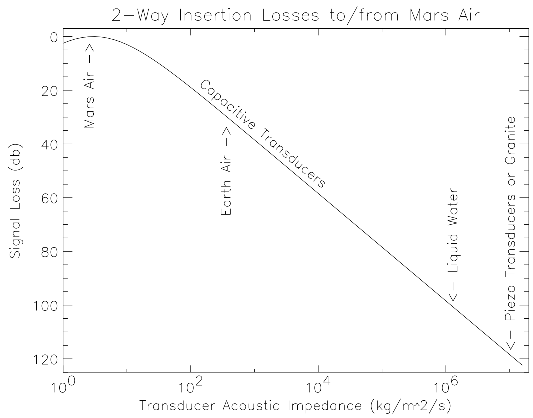

Figure 3: 2-Way insertion losses for sound going between Mars air and a transducer of given acoustic impedance. The acoustic impedances of various materials are indicated. Capacitive transducers are the only feasible match to Mars air.

almost completely reflected at the boundary. The same holds for acoustic impedances and sound waves passing between two media. In the case of acoustic transducers, this loss due to poor coupling between the transducer and the medium is known as an insertion loss. The problem is doubly serious, in that the signal must couple both ways between the transducer and the medium, resulting in twice the losses, i.e., a 2-way insertion loss (see Fig. 3). A transducer that works adequately coupling to Earth air will work much more poorly trying to couple to the tenuous air of Mars. All other things being equal, the two orders of magnitude in acoustic impedance between Earth and Mars air will result in a further loss of signal strength of about 30dB, or a factor of 1000. This is the main hurdle in adapting acoustic anemometry for use on Mars. **Coping with this difficulty is the emphasis of our work.**

Preliminary Design Parameters

To demonstrate that an acoustic anemometer is feasible for Mars, we have developed a simple model accounting for the effects of attenuation in Mars air as well as losses due to beam spreading. Beam spreading losses are simply the losses due to some transmitted acoustic power not striking the opposite transducer, a result of the beam width. This in turn is determined by the size of the transducer head relative to the wavelength of the sound. Combining these two effects, and assuming reasonable values for the transducer head size and spacing, we find a favored frequency of about 30 kHz. The spacing (25 cm) and transducer head sizes ($\sim$ 2.5cm) were chosen as representative values that minimize wind shadowing, and eddy averaging. Furthermore, they are values that are consistent with available space on typical landers. Additionally, with these parameters, the transmission and beam losses total about 23dB, or about a factor of 200 in power.

Our nominal design suggests an instrument roughly 25cm in each dimension. For mass estimates, we can assume that similar commercial Earth instruments (which aren't optimized for low mass) are upper limits. The Applied Technologies commercial instrument is about 0.8kg. We anticipate that this could be reduced by a factor of several. Similarly with power usage, the Applied Technologies instrument uses less than 1W, but it fires all 6 inefficient piezo transducers at 200Hz. We could be quite comfortable with 20Hz repetition rate, and we expect an efficiency increase of at least an order of magnitude using better transducers. This could make the power usage something like a few percent of a Watt.

Finally, the most serious design consideration involves the transducer itself. As mentioned above, the acoustic impedance of the transducer will have an enormous impact on its ability to couple with the tenuous Mars air. Fig. 3 shows how using a piezo transducer (as is typically done on Earth) will result in two-way insertion losses of about 118dB. Combining this with the $\sim$ 23dB from the attenuation and beam effects gives a total loss of about 141dB, or a factor of $\sim 10^{-14}$. This leaves essentially no signal for analysis (typically reported dynamic ranges are only of order 110dB). However, there are two promising approaches for better coupling transducers to very low acoustic impedances, acoustic horns and capacitive transducers. We are already engaged in testing 3 different styles of cutting-edge capacitive transducers, which have shown great promise in initial tests. We will present quantitative results of the first round of testing, and suggest some of the redesign concepts that are being explored going into the second round of testing. We are also starting fabrication of a set of acoustic horns for similar testing. **The focus of the majority of the research in this project is evaluating and perfecting these approaches for use in Mars atmosphere in an acoustic anemometer. We are quite confident that this will result in a successful prototype instrument.**