# Planetary Descent Probes: Polarization Nephelometer and Hydrogen Ortho/Para Instruments

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*Abstract*—While much has been gleaned about the details of the atmospheres of the giant planets, Venus and Titan via remote sensing, it will never replace the direct reality of an in situ instrument. There remain many questions about the structure and dynamics of the other planetary atmospheres in our solar system that need to be addressed by in situ instrumentation, and thus the development of a new breed of descent probe instruments in well warranted. We are developing two instruments that would be excellent additions to the payloads of planetary atmosphere descent probes into the Giant planets, Venus, or Titan. Our first instrument, a polarization nephelometer, uses polarization modulation to determine the intensity and polarization ratio phase functions of ambient aerosols. Measuring both of these phase functions allows much more discriminating conclusions to be drawn about the molecular composition and microphysical parameters of the aerosols. Atmospheric aerosols are key determinants of the global heat balances and atmospheric circulations on all of the above planets. They are as yet still poorly understood. There is a distinct need for polarization nephelometers on descent probes into these planetary atmospheres. Our second instrument, a hydrogen ortho/para instrument, will use acoustic techniques to measure the vertical distribution of this thermodynamically important quantity on the giant planets. The hydrogen ortho/para fraction influences the dynamics of these planet's atmospheres, as well as acting as a tracer of these motions.[1][2]

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## 1. INTRODUCTION

For our contribution to in situ descent probe instruments, we have focused on the questions of aerosol structure (nephelometer) and hydrogen ortho/para structure (acoustic composition experiment) of the large planetary atmospheres. We envision that these instruments will be crucial additions to planetary descent probes that are being planned for the large atmospheres in our solar system. Both of these instruments ingest the ambient atmosphere and perform their measurements on the sampled air within the body of the instruments, so these are in situ instruments as opposed to remote sensing instruments. We will briefly discuss these two instrument development projects in turn.

## 2. POLARIZATION NEPHELOMETER

### Observational Significance

The aerosols that reside in the atmospheres of Venus, the giant planets and Titan are the visible faces of these planets, and yet we have quite limited knowledge of them. The impact of this lack of knowledge is significant on our understanding of the composition, structure and dynamics of these planetary atmospheres. We directly address this with our proposed polarizing nephelometer.

#### *Venus*

For Venus, we have some detailed knowledge of the cloud layers from remote sensing and also from earlier nephelometers placed in Venus' atmosphere on Russian and American probes. These studies, crudely summarized, have told us that the Venus atmosphere has 3 main cloud decks, extending from about 45km to 70km, with hazes both above, below and between these layers. The optical thickness of the top-most cloud is dominated by 1 um spherical aerosols of concentrated sulfuric acid. There are large opacity variations in the middle and lower cloud decks. But in spite of this detailed knowledge of the clouds on Venus, there are still significant questions that can be answered with a polarization nephelometer at Venus.

As a basis for this discussion, we take the goals outlined in the NRC Solar System Exploration Decadal Survey's chapter, ``The Case for Venus Exploration." The first topic

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identified there for which a polarization nephelometer is crucial is the trace gases in Venus' atmosphere. These include sulfur, which plays a key role both in the clouds (via $H_2SO_4$), and the surface-atmosphere interactions (via volcanic injection and/or surface chemical weathering). If a probe only measured the gas phase abundances of sulfur bearing molecules it would exclude a significant reservoir, namely the aerosols. In the clouds, roughly 1/3 of the sulfur may be in aerosols. Our proposed polarization nephelometer could yield these abundances, completing the trace gas inventories produced by a Venus probe. Furthermore, the debate still continues whether a crystalline "mode 3" family of particles exists in the middle and lower clouds. If these are a distinct material from $H_2SO_4$, then they represent a significant reservoir of unknown material, and must be accounted for in chemical/aerosol models of the atmosphere. Our proposed instrument could do a good job of determining the size, shape and index of refraction of the aerosols in Venus' atmosphere with little ambiguity, clarifying these outstanding questions.

The second topic concerns the greenhouse effect on Venus. Current greenhouse models still leave open debates about the relative importance of various contributors to the observed temperature on Venus. The clouds represent a substantial absorber of solar and thermal energy on Venus, and defining their microphysical properties and vertical structure is critical in fully understanding the mechanisms that control the greenhouse. A prime example is that the upper cloud has a still unknown blue absorber which is responsible for about 1/4 of all solar energy absorbed by Venus. Identifying this absorber is a task that our proposed polarizing nephelometer would be ideally suited to.

Other factors to consider that are not specifically called out in the decadal survey include aerosol-dynamic feedbacks and their influence on local trace gas abundances. Nightside near-IR contrast variations suggest that small scale convection patterns occur in the lower cloud while the middle cloud has a global scale (m=1) pattern of cloud opacity variation. The heating caused by these opacity variations is enough to locally influence the buoyancy and circulation, perhaps suggesting a feedback between flow and aerosol opacity. The possibility exists that such feedbacks may be important in controlling the local profiles of trace gases, especially those that have significant vertical variations in the vicinity of the clouds. Obtaining gas phase abundance measurements without placing them in the context of the local heating environment (and thus the local vertical flow) could lead to inaccurate assessments of atmospheric chemical cycles. Thermal structure and accelerometer measurements alone will not reveal the vertical winds that the probe moves through. Measuring the aerosol density is one approach to infer these effects on the rest of the descent probe's observations. Another practical matter involves identifying precisely when an observation from (e.g.) a mass spectrometer may have ingested an aerosol drop, skewing its results. Without a direct measure of the aerosol density, this will leave an ambiguity in the interpretation of gas phase measurements.

## *Jupiter*

For Jupiter, we know even less about the clouds than for Venus. The one descent probe that entered Jupiter's atmosphere, Galileo's probe, entered into an anomalous hotspot location. It is generally not believed that the Galileo probe's findings are representative of the cloud structure of a generic region on Jupiter. Remote sensing has revealed significant facts about Jupiter's clouds, but important ambiguities still remain. An example of this is that we do not know the vertical structure of the clouds on Jupiter. For instance, the contrast-bearing cloud deck may be composed of either ammonia or ammonium hydrosulfide aerosols. Remote sensing studies have been unable to agree on this point, with visible wavelengths tending to support ammonia clouds bearing the contrast, and near-infrared wavelengths indicating ammonium hydrosulfide. A side effect of this remote sensing ambiguity is that when we measure cloud-tracked winds on Jupiter, we do not know what level (or levels) they represent. This significant hole in our understanding has propagating effects into dynamical models, limiting their ability to fully understand the driving circulations of Jupiter. A nephelometer on a Jupiter descent probe, entering a representative region of the planet would easily clarify the vertical structure of Jupiter's clouds.

It may turn out that Jupiter's clouds are a more complex mixture of aerosols of water, ammonia and ammonium hydrosulfide than our simple models have suggested. There are several indicators that water vapor is advected up above the top cloud deck. This certainly raises the issue of how mixed the cloud species are on Jupiter. In situ measurement of the optical properties of the aerosols with our proposed polarization nephelometer can yield not only the vertical structure and thicknesses of the clouds, but also some leverage into identifying their chemical makeup.

Another example where a polarization nephelometer would have significant value addresses the fact that we don't understand what provides the colors of Jupiter. Studies suggest it is blue absorbers located in the upper troposphere, and that there are probably at least 2 different coloring agents. Beyond this, little is known about these absorbers. Our proposed instrument should be able to identify the real and imaginary parts of the index of refraction of the aerosols at two different wavelengths. This should give significant leverage in identifying these chromophores. Presumably identifying the chromophores will also have impacts on the photochemical/aerosol models of Jupiter's stratosphere and upper troposphere.

Finally, documenting the aerosol size distributions more carefully, as we could do with our proposed polarization nephelometer, would allow a more accurate assessment of the thermal and radiative balance at varying levels in the giant planet atmospheres to be determined. The thermal infrared flux that is capable of escaping the atmosphere from the layers below the visible cloud deck is poorly constrained, and important for understanding the dynamics in the layers just below the visible cloud deck. There are hints from the water vapor cumulus towers that the dynamics in this region (1-6 bars) might be pivotal in controlling the ``weather'' on Jupiter. For us to fully understand the role that radiation and convection play in transporting heat through this region, the aerosols need to be well quantified, not only in number density versus pressure level, but also size distribution, shape and albedo. Our proposed polarization nephelometer is the ideal instrument to characterize the aerosols in all these dimensions. It should be noted that many of the arguments listed above for a polarization nephelometer at Jupiter apply equally well to the other giant planets and some also apply to Titan.

## Need for Updated Approach

### Modernization and Enhancement

The most recently built planetary descent probe nephelometer was that for the Galileo Probe, designed in the late 1970's. It weighed 4.4kg and used 11W (Ragent et al., 1992). Modern opto-electronics have advanced considerably since then, with better detectors, solid-state lasers, and high temperature fiber optics as well as all the advances in electronics miniaturization. Mass, volume and power are all precious commodities on an entry probe, and these can certainly be trimmed using modern electro-optic approaches to a nephelometer.

Nephelometers designed for use in the Earth's atmosphere have taken advantage of the optoelectronic advances since the Galileo design. Our approach is similar to that of Gayet et al. (1997), and especially that of Barkey and Liou (2001). In both of these cases, semiconductor lasers are used as the light sources, fiber optics are used to collect the scattered light, and photodiodes are used as detectors. We will employ all of these techniques in our design. However, because mass and volume and reliability are given such a premium on planetary instruments, our instrument will differ from those used in the earth's atmosphere. Additionally, the nature of the aerosols encountered on the other planets is much less well known (as fundamental as molecular composition), demanding more information content from our instrument than that which is sufficient for Earth aerosol studies.

### Augmented Capabilities

Our proposed polarization nephelometer will measure both the scattered intensity and polarization ratio at many angles from near backscatter to near forward scatter from aerosols it encounters on descending through a planetary atmosphere. It will perform these measurements at two wavelengths separated by about an octave, with one laser at 1.032um and the other at 516nm.

Traditionally, a simple nephelometer measures at least the backscatter intensity as an indicator of the backscatter coefficient (roughly speaking, the cloud density) of the aerosols in its vicinity. Some nephelometers (e.g., the Galileo Probe nephelometer) also measure the intensity of the scattered radiation with varying scattering angle. Adding this intensity phase function information gives some information on the particle size, shape and indices of refraction. However, typically these parameters can not uniquely be extracted from the intensity phase function alone, and results are quite model dependent. Frequently on Earth, the aerosols are assumed to be water or water ice, and thus the intensity phase function information alone allows reasonably good inferences to be made about particle size and shape. For aerosols encountered on the other planets, we don't have this luxury of knowing the composition a priori, indeed it is an important unknown to constrain. By also measuring the polarization phase function, we can have a drastically improved metric with which to infer the particle microphysical properties as well as its molecular composition (via the index of refraction).

To further augment the information content returned by our instrument, we intend to measure the intensity and polarization phase functions at two wavelengths separated by about an octave. These functions at only one wavelength allow a good inference of the particle properties under assumptions about the simplicity of their size distribution. Adding information at a second wavelength, which samples the aerosols with a size parameter different by about a factor of two, introduces more robustness into the retrievals in the presence of broader aerosol size distributions. We have chosen 1.032um and its frequency doubled wavelength, 516nm, for the range in particle size parameter and the ready availability of flight qualified lasers at these wavelengths.

## Design Concept

As mentioned above, our proposed instrument is similar in design to that of Barkey and Liou (2001), using a semiconductor laser (4 in our case) for the source, fiber optics to collect the scattered light, and photodiodes to detect to light. In our case, the fiber optics not only allow sampling the scattering with fine angular resolution, but also the placement of the detectors within the body of the probe, where the thermal environment can be much more carefully controlled. In fact, the source lasers, the photodiodes and the blocking filters will all be kept within the probe body and temperature controlled using peltier junctions. Given the thermal sensitivity of the detector and source elements in our design, it makes sense to design a system that is robust to the expected thermal environment from the outset. The thermal environment experienced by planetary probes can be extreme. This design places only lens and fiber elements in the ambient environment of the probe, and commercial versions of these elements that can withstand high temperatures are readily available.

Our device will sample the scattered light at many angles along one half of the azimuths (180 degrees) of the scattering plane, from forward to side to backscattered light. It will also have a beam trap in the foward scattering direction, but differing from the configuration of Barkey and Liou's instrument, it will not have beam traps above and below the scattering plane. Rather, to minimize the weight of the device, we intend to design it to function fully open to the ambient environment, both with aerosols and light throughout. To avoid contamination from the ambient light, we will use narrow band filters to block most of the ambient light, yet match that of the source lasers, and also employ chopping to further remove the ambient light effects as was done by Barkey et al. (1999). If we find that neither of these approaches are sufficient, we can fall back to the shrouded design concepts of Barkey and Liou (2001) and Gayet et al. (1997).

## 3. ACOUSTIC COMPOSITION EXPERIMENT

### *Scientific Motivation*

A probe mission to Jupiter was recently identified in the Planetary Sciences Decadal Survey as one of 5 medium class missions that should be considered in the following decade. Further, it recommended a Neptune orbiter with multiple probes as a longer term high priority objective. Probe missions to all of the Jovian planets (Jupiter, Saturn, Uranus, and Neptune) had previously been identified by the NASA Outer Planets Science Working Group (OPSWG) as high priority missions for outer solar system exploration.

Recent giant planet probe studies have all included a sound velocity instrument to measure the ortho-para ratio of H2 in these atmospheres. This simply recognizes the fact that knowledge of the ortho-para ratio is important for understanding the thermal balance and dynamics of the atmospheres of the Jovian planets, in particular for Uranus and Neptune. However, no such instrument that can achieve these goals yet exists. Instead, the idea of using sound velocity measurements to measure the ortho-para H2 ratio had been proposed, without extensive scientific studies or engineering tests, on the basis of a 30 year old proposal by Hanel and Strange (1966) to use sound velocity to measure the major gas composition of the atmospheres of Venus and Mars.

Fegley initiated a project in 2000 to demonstrate the feasibility of building such an instrument. His effort went far enough to show that such an instrument is certainly feasible, at least for certain pressure ranges in the giant planet atmospheres. But it did not tackle the tougher problems of demonstrating functionality in the low pressure (and hence low acoustic impedance) regions of the upper tropospheres of the giant planets, where knowledge of H2's ortho-para ratio is probably most interesting. We are continuing the work that Fegley started, pushing the envelope of functionality from just 1 bar to a range of about 0.05 bar to 20 bars. We also plan to introduce cutting edge capacitive transducers to the problem that promise better acoustic impedance matching, tremendous bandwidth (allowing miniaturization), and the ability to account for flow effects. We first describe the physical properties of ortho and para H2 and discuss why knowledge of the ortho to para ratio on Jupiter, Saturn, Uranus, and Neptune is important. We then describe the scientific basis of the sound velocity measurement method. Next we give a basic engineering description of a breadboard instrument to measure sound velocity in H2 and H2-He mixtures. Finally we describe our proposed approach to making the necessary measurements. Because we will be using acoustic measurements to determine chemical composition, the instrument is called ACE for Acoustic Composition Experiment.

### *Scientific Background*

Ortho and para H2 are the two different nuclear spin modifications of H2. Ortho hydrogen (o-H2) has parallel nuclear spins and odd rotational quantum numbers (J = 1,3,5...) and para hydrogen (p-H2) has antiparallel nuclear spins and even rotational quantum numbers (J = 0,2,4...). The ortho to para (o-p) ratio of hydrogen is temperature dependent and is determined by the chemical equilibrium between the two nuclear spin modifications. At high temperatures (~270 K and above), the o-p molar ratio is 3:1 (i.e., 75% o-H2 and 25% p-H2). Hydrogen with a 3:1 o-p ratio is referred to as normal hydrogen. At lower temperatures the proportion of p-H2 increases until it reaches 100% at 0 K. Hydrogen with an equilibrated o-p ratio is known as equilibrium hydrogen.

The physical properties of ortho and para H2, including their vapor pressure, boiling points, triple points, thermal conductivity, heat capacity (Cp), entropy (S), and spectra, are measurably different at low temperatures because the rotational energy level separation is greater than kT due to the low moment of inertia of the H2 molecule. In fact, the different heat capacity of the two spin modifications is the basis for the acoustic composition experiment being pursued. The different entropies of ortho and para H2 also lead to a latent heat of reaction of several hundred J /mole for their conversion. The rate of the conversion between ortho and para hydrogen depends upon the conversion mechanism. The recognized conversion mechanisms are: *Radiative* - very slow due to quantum mechanics restrictions; *Collisional* - Half life ~3 years at one atmosphere; *Homogeneous gas phase reaction*: H + p-H2 = o-H2 + H --- Temperature dependent with an activation energy of a few kJ/ mole; *Heterogeneous surface catalyzed reaction* - Activated charcoal, platinum surfaces are good catalysts; *Homogeneous gas phase catalyzed reaction* - Paramagnetic gases such as NO and O2 are good catalysts.

The importance of measuring the hydrogen ortho/para ratio for the atmospheres of the Jovian planets arises for several reasons. First, ortho and para H2 are the two most abundant gases in the atmospheres of the Jovian planets. Thus it is important to measure both their abundances and the temporal and spatial variability of their abundances to understand the chemistry and physics of these atmospheres. Some information on the abundances of ortho and para H2 is already available from Voyager and Cassini spectra but the available observations are of poor vertical resolution (>half scale height) and only extend over just more than 1 scale height. Thus, the remote sensing observations alone are insufficient to address many first order questions about atmospheric dynamics and thermal structure. **Measuring hydrogen ortho/para ratios with the greater vertical range and resolution afforded by entry probes will open many of these questions.**

Second, over the 50-250K temperature range, kinetic inhibition of the o-p H2 conversion can have large effects on the thermal structure of the atmospheres of the Jovian planets. After a gas parcel containing ortho and para hydrogen is convectively mixed upward, the high temperature o-p ratio (i.e., the normal H2) begins to approach the low temperature o-p equilibrium ratio (i.e., e-H2). In so doing, the latent heat release drives the atmosphere towards stability. The effect of the latent heat release on atmospheric thermal structure is small on Jupiter but is large on Neptune, where convection can be shut off temporarily. **Thus measuring profiles of the hydrogen ortho/para ratio will help us understand the convective overturning of the tropospheres of these planets.**

Third, the rate of the conversion between ortho and para hydrogen is very slow (years) at the low temperatures found in the upper atmospheres of the Jovian planets unless an efficient catalyst is present. The paramagnetic gases NO and O2 are not present in Jovian planetary atmospheres so the only plausible catalysts are aerosol and cloud particles. Although the efficiency of heterogeneous catalysts by the aerosol and cloud particles in Jovian planetary atmospheres is unknown, it is plausibly less efficient than platinum metal. As a consequence the conversion timescales are probably several years. **Therefore, and perhaps most importantly, we can use the hydrogen ortho/para ratio in these planets upper tropospheres as tracers of vertical motions, a quantity which is otherwise very difficult to constrain.**

## *Chemical Composition from Sound Speed*

The relationship between the sound velocity U and the composition of a three component gas mixture is conveniently expressed as a triangle on a plot of mean molecular weight M versus Cp/Cv. If the temperature and mean molecular mass are known, then adding a sound speed measurement alone provides enough to infer the hydrogen ortho-para ratio. In practice, for Jupiter and Saturn, the tropospheric helium abundance can be measured accurately either by a mass spectrometer or a refractive index experiment (as was done on the Galileo entry probe). So their mean molecular masses can be well constrained. But for Uranus and Neptune, where the mean molecular mass may vary spatially due to methane condensation, we need a means of inferring that as well. Fortunately, there is also an acoustic means for this using the same equipment we'll use to infer the hydrogen ortho/para ratio.

A material's acoustic impedance is defined to be its response in terms of particle velocity to an applied pressure perturbation. If in addition to measuring the atmosphere's sound speed, we can also measure its acoustic impedance, we can then infer the density, which with pressure and temperature, gives us the mean molecular mass. At the interface between two materials, if there is a significant discontinuity in the acoustic impedance, then little acoustic energy will be transmitted across the interface. This is completely analogous with the phenomena of reflection of light at an interface (e.g., from a pane of glass), or with the notion of impedance matching in electrical circuits to maximize throughput. In addition to measuring the travel time of sonic pulses, if we also measure the amplitude with which they arrive, we can infer the losses that occur on either end of the transmitter-atmosphere-receiver system. This so-called two-way insertion loss is simply a measure of the acoustic impedance mismatch between the transducers and the atmosphere. Thus, with the appropriate calibration, we can retrieve the atmospheric acoustic impedance (and its density and mean molecular mass to an accuracy which has yet to be determined) from the received signal strength in our acoustic experiments. We will test the sensitivity of signal strength to mean molecular mass in the course of our experiments.

## *Previous Work*

Fegley and Lodders completed the very first phase of the proof of concept for the ACE: Acoustic Composition Experiment. They used a simple carbon fiber tube filled with ambient air down which to propagate the acoustic waves, and thus perform the measurements. They settled on a tube 1.4cm in diameter and 73cm long. They couldn't reduce the 73cm length of the tube without significantly sacrificing accuracy on the travel time estimate, and thus ultimately the sound speed accuracy as well. This is one area in which we expect to make considerable improvement in the current effort. Fegley and Lodders used simple Bruel and Kjaer condenser microphones to both generate and detect the acoustic signals. While these transducers are the standard in acoustics, they have significant shortcomings (particularly compared to cutting-edge ultrasonic transducers) that we will aim to overcome.

Overall, the accuracy of the measurements they obtained at 1 bar was good enough to be quite convincing of the feasibility of this technique. They were able to measure the sound speed in various H2-He mixtures to within <1% of the theoretical values. This is certainly accurate enough to quantify expected ortho-para variations of interest in the upper tropospheres of the giant planets.

# Conceptual Instrument Improvements

## Improved Acoustic Impedance Matching

The most fundamental difference that we will introduce to the design of the instrument is the use of cutting-edge capacitive transducers. These transducers have come to our attention while designing an acoustic anemometer for Mars. That project has a similar set of challenges in that the acoustic impedance of Mars' atmosphere is also low. Coupling to these low acoustic impedance atmospheres is the trick to ensure that sufficient signal is transmitted between emitter and receiver to accurately define the acoustic travel time. The capacitive transducers that we have identified for use on Mars should function equally as well on the giant planets.

As discussed above, coupling to a medium requires good matching between the acoustic impedances of the medium and the transducers. Most transducers (piezos, speakers) have acoustic impedances greater than earth air by factors ranging from several to $3X10^4$. This means that they just barely couple well to Earth's air. The acoustic impedance at 100 mbar on Jupiter is about 100 times less than that of Earth air. Increasing the acoustic impedance mismatch by this amount would mean a signal loss of about 30dB, and possibly the failure of the instrument to return any usable data. Instead, the capacitive transducers have an acoustic impedance very similar to that of Earth air (which is about in the middle of the range of acoustic impedances we want to span), and have already been shown by us to perform well in acoustic impedances as low as that at 100 mbar on Jupiter.

## Increased Bandwidth

The capacitive transducers have a tremendous bandwidth compared to most acoustic transducers. Typical Bruel and Kjaer transducers have response no higher than about 100kHz (5X higher than the top of the audio range), while the MBAT-1 has a flat response out to about 800kHz. We can exploit this to miniaturize the instrument. The sound speed measurement accuracy is determined by our ability to define a pulse arrival time accurately relative to its total travel time. For low frequency waves, the arrival time can't be very precisely defined, and so the path length must be lengthened to retain accuracy in the sound speed measurement. Using the capacitive transducers, we should be able to use much higher frequencies in our acoustic pulse to more precisely define the travel time. Since the sound speed accuracy is already adequate in the Fegley and Lodders design, this means we can shrink the instrument and still retain the same sound speed accuracy. A rough estimate is that the total length of the instrument can be reduced by the ratio of the peak frequencies of the two types of transducers. Therefore, instead of 73cm long, we might be able to make the device only about 10 cm long. Clearly this is an attractive change to enhance the likelihood of flight for this instrument.

## Better Signal Processing

Another technique that we intend to bring to the breadboard instrument will enhance its capability to precisely define the acoustic travel time, and also to do it more capably at lower S/N. This is the technique of pulse compression, which we are adopting from the field of radar where it is used to best define the range to an object with a very faint return signal. A coded signal is sent, and the received signal is convolved with a copy of the sent signal. For the lag that matches the true travel time, the convolution is a maximum. The width of that maximum is proportional to the inverse of the product of the bandwidth of the pulse used times the duration of the pulse. We will use chirps as the coded signal, as they are nearly the optimal signal for pulse compression, and are easy to produce.

## Correction for Gas Flow

The final upgrade we intend to test on the ACE breadboard instrument takes care of the reality of gas flow in the acoustic tube. Sound waves are advected with flows, and if not accounted for, could significantly bias our results. The simplest manner to account for flow is to measure acoustic travel time in opposite directions. The average is the true sound speed, while the difference is indicative of the flow speed. We have no use for the flow speed measurement in this application, but the average of the two opposing travel times should easily correct for flow. The MBAT-1 capacitive transducers are dual element transducers that can simultaneously emit and receive acoustic signals. The central portion of the membrane will be used as a transmitter, while the annular region surrounding it makes an efficient receiver. So we can simultaneously emit an identical pulse from both ends of the sonic tube, and then without having to quickly switch a single transducer from send to receive, we simply listen at both ends with the dedicated receiver portion of the transducer.

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