An Improved Compact Atmospheric Speed Sensor
for Mars Missions

Benjamin J.A. Wise, Jaime DaSilva, and Elie R. Salameh

Adviser: M. Volkan Ötügen

Mechanical Engineering, Lyle School of Engineering, Southern Methodist University

Contact Information:
Micro-Sensor Laboratory
Southern Methodist University
3101 Dyer Street, Room 215,
Dallas, TX 75205
Phone: +1 (214) 768 9051
Email: `bwise@smu.edu`

Abstract

We are developing a laser velocimeter which operates by illuminating atmospheric particles, collecting scattered light, and measuring the Doppler shift of the scattered light to determine the airspeed, or relative velocity between the aircraft and particles. This instrument is designed to eliminate pitot-static tube systems, and similar devices, which have severe limitations at high altitude and at super- and hyper-sonic conditions. Improvements include replacing the key Doppler shift measuring devices, a Fabry-Perot Interferometer and a CCD camera imager, which are very sensitive to vibrations, in addition to being physically bulky and heavy (both detrimental to use on spacecraft), with whispering gallery mode micro-resonators, which are smaller, significantly lighter, and more robust, and offer a conservative theoretical measurement sensitivity gain of over one order of magnitude. We present improvements to the signal processing algorithm and the physical design, including the elimination of several significant sources of signal loss.

Operating Principle

- Laser-based velocimetry system is miniaturized to allow use on space vehicles for hypersonic re-entry speed measurements.
- LIDAR-based system collects Rayleigh back-scattered light and analyzes its Doppler shift to determine the relative speed of the entry vehicle.
- Doppler shift is determined using whispering gallery modes of spherical microresonators, rather than the typically used Fabry-Perot interferometer, allowing miniaturization.
- Rayleigh scattered light is either free-space or fiber coupled (using single mode optical fiber) to the micro-resonator.

The Whispering Gallery Mode

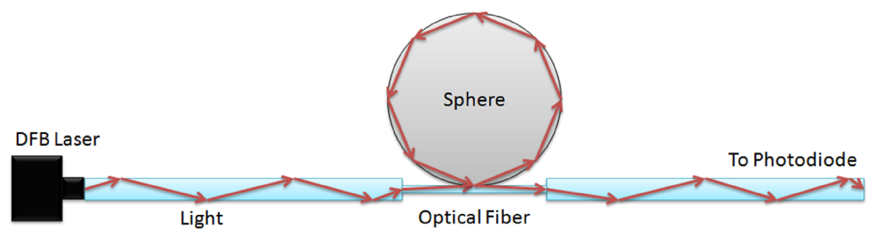

Figure 1: Light-path sketch inside a fiber-coupled WGM resonator.

- Demonstrated by Lord Raleigh in 1910, Whispering Gallery Modes are the phenomena that occurs when sound waves propagate along the interior surface of a sphere, such as a dome, allowing a whisper to be heard a great distance away.
- Similar phenomenon can occur in circular optical cavities, where light from a tunable laser is coupled tangentially into a dielectric micro-sphere (Silica, PDMS, PMMA, etc.).
- The light experiences total internal reflection and travels circumferentially in the sphere when the resonance condition shown in Equation 1 is met.[1]

$$2\pi r n_0 = l\lambda \tag{1}$$

Physical Design Improvements

In previous projects, such as the E-Field Sensors[2] and the seismometer[3] designed in the Micro-Sensor Lab, our optical sensors have always utilized direct fiber coupling, as in Figure 1, which resulted in a coupling signal that was stable in time with respect to the stability of the laser diode that produced the light. However, in subsequent experiments, especially ones where we attempted to measure the tangential velocity of a rotating disk, we began to experience intermittent signal loss. We hypothesized that this signal loss was likely due to beam steering, occurring due to the imperfect motion of the rotating disk and the precise coupling from free space to a single mode fiber. We later confirmed through analysis of the data we had collected that we experienced **intermittent signal dropout**, as shown below in Figure 4a below.

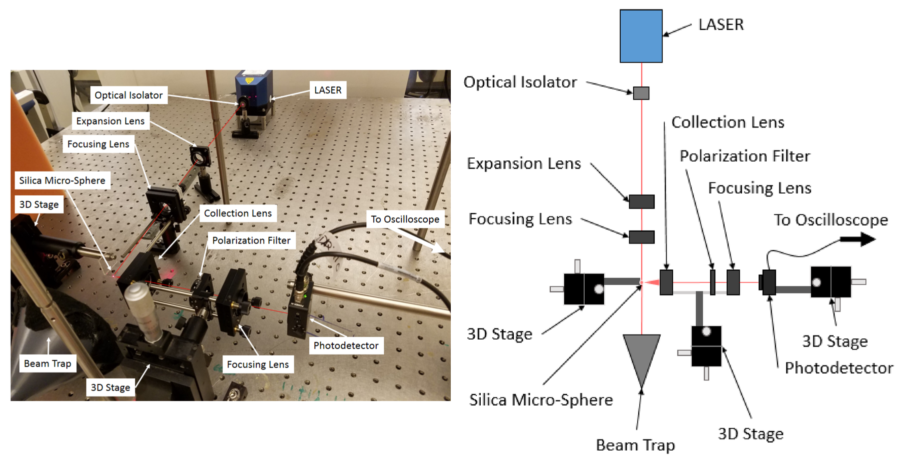

Figure 2: Free Space Coupling Experimental Setup

In order to make our sensor design more robust, we decided to pursue direct free space coupling of the sphere from our laser as shown in Figure 2. Since we have previously demonstrated the ability to measure the velocity of a moving target, our new setup omits the moving target. However, since we can modulate the wavelength of the laser we can easily omit this step, while still demonstrating the efficacy of a free space coupled system. The free space system, given its reduced sensitivity to beam steering (which will undoubtedly occur in a final design that is intended to measure the relative velocity between a spacecraft and atmospheric particles) shows that there are various options which do not depend on coupling into a single mode optical fiber, greatly increasing the robustness of any final system.

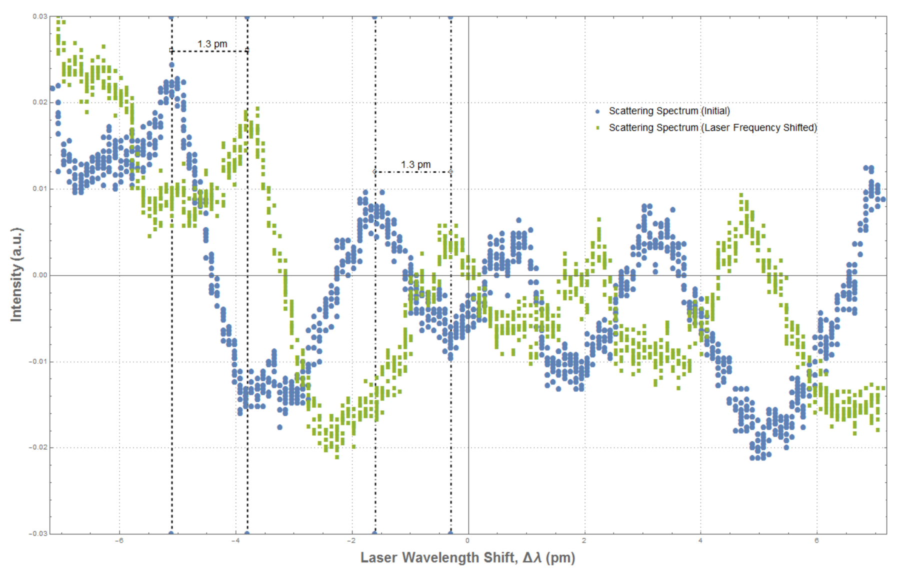

Figure 3: Free Space Coupling Results

Figure 3 demonstrates that using a silica microsphere excited via free space laser light, we can accurately detect a shift in the wavelength of the light irradiating the sphere, such as that caused by a Doppler shift due to the motion of the vehicle, by determining the wavelength shift in the scattering (WGM) spectra. We do this by varying the wavelength of the laser in a triangle waveform (approximated by $\lambda_{Initial}(t) = \lambda_{Center} \pm m \times t$, for any given linear section of a scan) about some central wavelength, λ_{Center}, in this case $639.045nm$. The laser scanning, in combination with the various resonance modes of the micro-sphere, leads to the initial scattering spectrum (blue). In Figure 3 we have also imposed a shift, $\lambda_{Doppler} = 1.3pm$, on the center wavelength such that $\lambda_{Shifted}(t) = (\lambda_{Center} + \lambda_{Doppler}) \pm m \times t$, which is responsible for the laser frequency shifted scattering spectrum (green). Measurement of the wavelength delay between features in the initial and shifted scattering spectra (corresponding to resonance modes of the microsphere) allows us to determine the corresponding wavelength shift of the incoming light due to $\lambda_{Doppler}$. Given the fact that resonance wavelengths are nearly constant in time for a given resonator (assuming it is not undergoing large temperature or morphological changes), we know that the apparent shift in resonance wavelength $\Delta\lambda = \lambda_{Shifted}(t) - \lambda_{Initial}(t) = \lambda_{Doppler}$. We can see from Figure 3 that there is very good agreement between the imposed Doppler shift and the calculated shift from the scattering spectra.

Signal Processing Algorithm

As discussed in the previous section, we experienced signal degradation caused by beam steering and the sensitive nature of free space to single mode fiber coupling. Clearly, a more robust signal processing method (in conjunction with the physical design improvements presented above) is required in order to increase the reliability of our sensor. We were able to quickly confirm that beam steering was the culprit by visualizing various scans we collected throughout the experiment. Shown below, in Figure 4a, are three different scans from the same data set, taken no more than a few seconds apart. In orange we see what a typical WGM spectrum looks like, a fairly complex signal with many distinct peaks and valleys of transmission, in blue we see a scan that potentially has some interesting information, particularly between indices 6000 and 8000, but otherwise appears to be mostly background noise, and in green we see a spectrum that is almost completely background noise. These three scans are indicative of the signal we were getting for each of the over 500 scans we collected for various different target speeds, some scans contain excellent information, some contain intermittent information, and some contain nothing but noise.

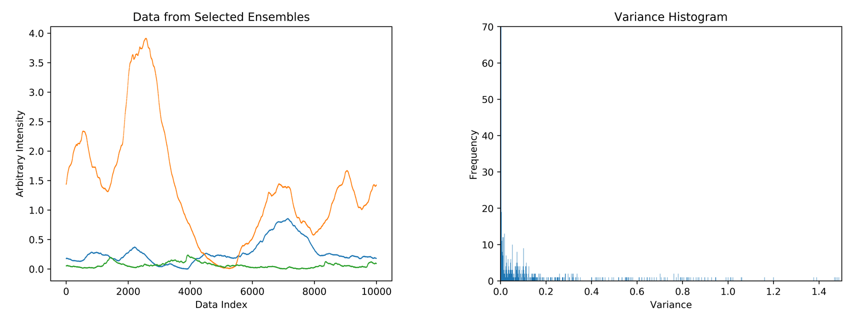

Figure 4: Signal Processing Motivation

In general, we use a fairly simple signal processing algorithm to make a measurement with our sensors: first, we take a "scan" or ensemble of data points corresponding to various times in one cycle of the laser (either triangle or sinusoidal variation of the wavelength), we then compare this ensemble (either manually or via crosscorrelation) to a previous measurement to determine the shift in wavelength of the resonances, and finally, via calibration of the laser we can relate this shift to some change in the quantity we want to measure. Clearly, however, with an intermittent signal such as this one, our standard algorithm is not robust enough to ensure accurate results. We therefore needed a robust method (which is not computationally taxing, due to constraints on the final sensor design) to determine whether a scan had enough interesting information (with a high enough signal to noise ratio) to warrant analysis. What immediately became clear, was that the signals of interest (e.g. the orange line in Figure 4a) had a much broader range about their mean than the noisy or intermittent signals. Analysis of the variances of all 500+ scans in one data set indicated, as shown above in Figure 4b, that a large number of scans showed very low variance, so much so that the first bin in Figure 4b has over 5 times more scans than any other bin. In addition to the filter described above, which was set by introducing a cut-off variance, below which a scan was discarded, we were able to reduce stochastic error by taking a large number of scans and ensemble-average them in order to cancel out a portion of the random noise in the signal.

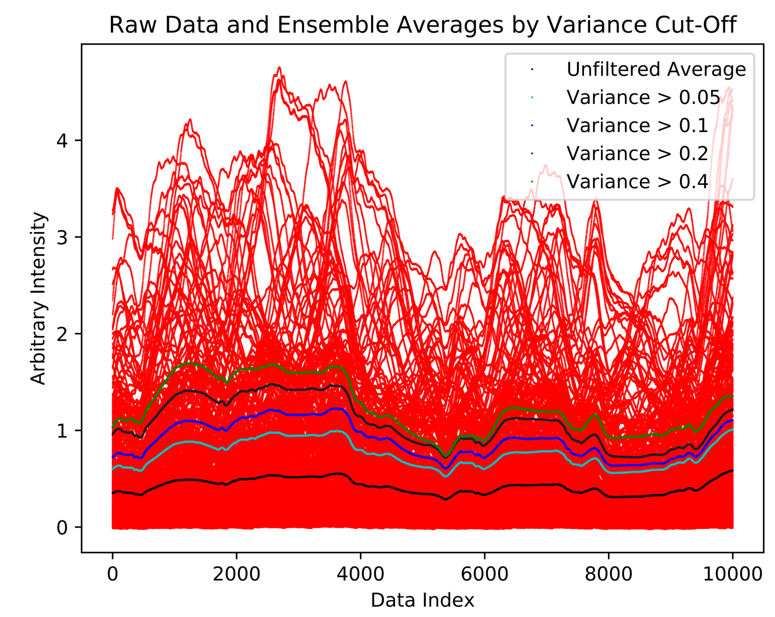

Figure 5: Signal Processing Results

The end results are shown in Figure 5, which shows an entire data set in red, the unfiltered average in black, and various filtered ensemble averages in different colors. A few interesting results are plainly visible: firstly, features are increasingly crisp and more distinct as the cut-off variance is increased, as we would expect given that averaging in fewer flat samples will improve WGM features. Additionally, we can see the signals begin to converge on certain points in the spectrum, e.g. around index 5500, which indicates that a cut-off variance of around that level allows good signal agreement, while smoothing out noise in the individual ensembles.

Forthcoming Research

Future iterations of this project will include microfabrication of resonators and waveguides to increase measurement precision and optimize signal utilization, combination of the free space system with a moving target (such as a rotating disk), as well as direct measurement of Doppler shifted light that has been Rayleigh/Mie scattered from a fast moving jet of particles.

References

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