Enhanced Scattering-Based Speed Sensor

for Space Applications

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Abstract

We design a speed sensor based on current LIDAR technology, with significant improvements to range and sensitivity. The chief measurement technique is performed by scattering atmospheric particles from a laser beam and measuring the wavelength shift induced by their relative motion (Doppler shift). Sensing is done through a micro-resonator assembly, about the size of a grain of salt, utilizing the principle of Whispering-Gallery Modes (WGMs) in a similar fashion to the operating principle of a Fabry-Perot Interferometer. Utilizing this type of sensor allows to eliminate traditional sensing elements like Pitot-tubes and Inertial Units that require significant post-processing and may be saturated. The ultimate goal is to create a light, small, and robust velocimeter setup that may be employed on re-entry landers at supersonic and hypersonic speeds, as well as on other space missions. The improvements over previous designs and data analysis algorithms are presented, in addition to techniques used in the elimination of signal loss sources.

Principle of Operation

- LIDAR-based system collects scattered light (fig.1)

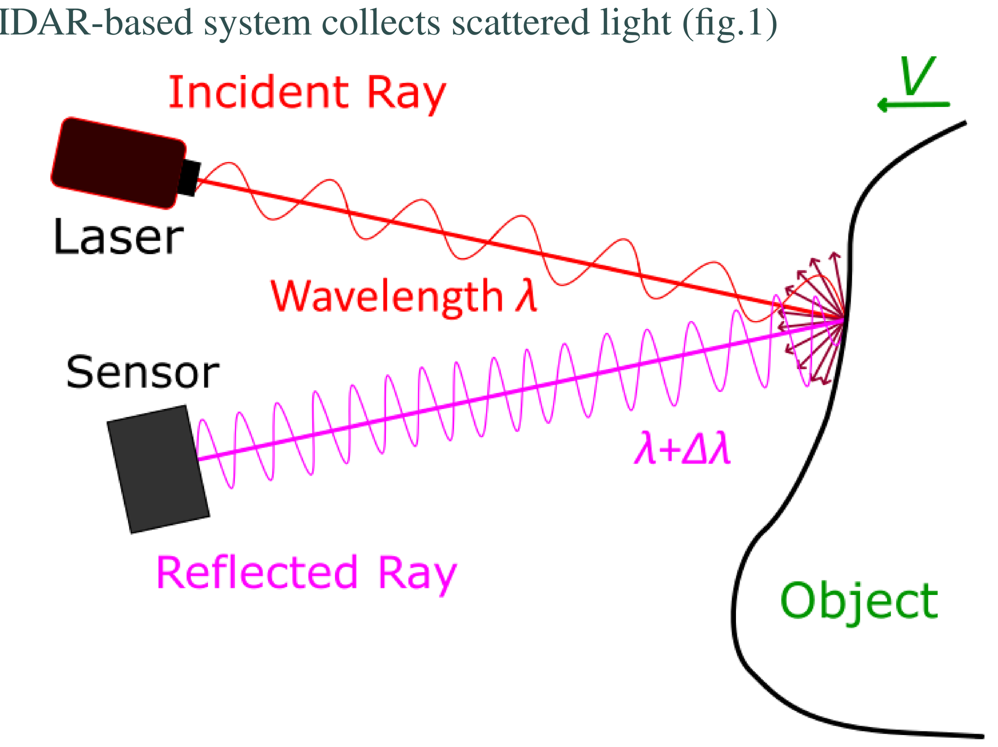

Figure 1: LIDAR Speed-Sensing Operation Principle

- Special Microresonator sensors detect "Doppler shift" using Whispering Gallery Mode (WGM) principle
- Detected shift can represent strain, motion, velocity, induced Electric field,[1] and even vibration intensity[2]

Micro-Resonators and the WGM Principle

Whispering-Gallery Modes (WGM):

- Demonstrated by Lord Raleigh in 1910
- Occur when waves propagate along an enclosed interior surface, allowing wave amplification through total internal reflection[3]
- Condition required governed by Resonance Equation 1:

$$2\pi r n_0 = m\lambda \qquad m = 0, 1, 2, ... \tag{1}$$

Micro-Resonators:

- Based on WGM phenomenon in circular optical cavities
- Mostly composed of Dielectric micro-spheres (Silica, PDMS, PMMA, etc.; fig.2)
- Coupling done through free-space or through fiber-coupling (fig.2)
- Resonance condition detected at receiving end by dips in transmission spectrum or peaks in scattering spectrum (fig.3)

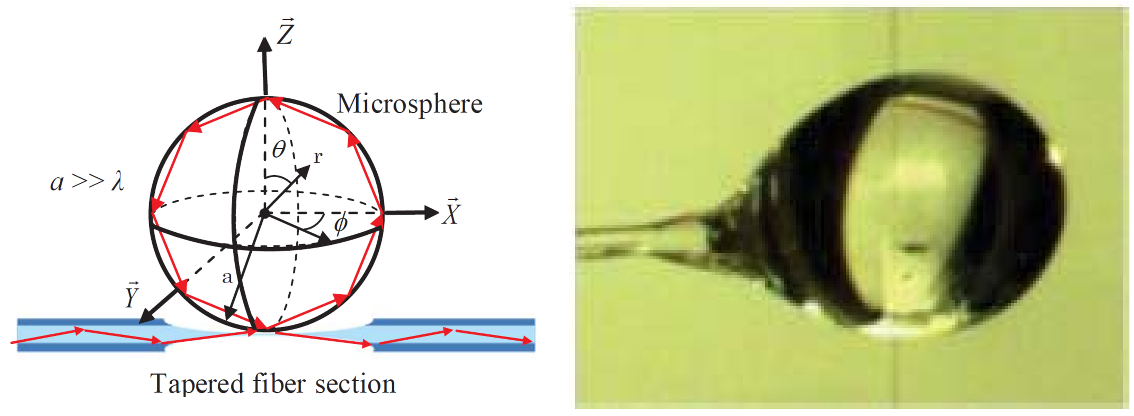

Figure 2: **(Left)** Light-path sketch inside a fiber-coupled WGM resonator;**(Right)** 60:1 600μm PDMS Microsphere coupled to a Single-Mode Fiber

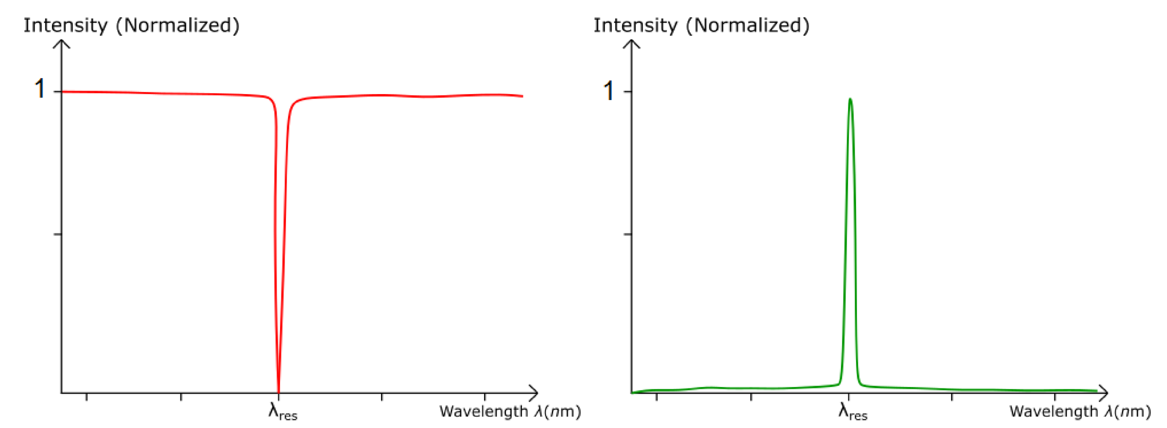

Figure 3: Ideal Spectral Intensity Profiles for **(Left)** Transmission; and **(Right)** Scattering at Receiving End of Fiber/Collection Optics

Design Objectives and Parameters

- Suggestion based on the European Space Agency Schiaparelli EDM crash on Mars (fig.4)
- Suitable Sensor Design Parameters:
  - Small/Lightweight
  - Robust, Rugged, and Versatile
  - Highly Sensitive and Accurate
- Design Objective: Measurement of the relative velocity between a spacecraft and atmospheric particles by Rayleigh scattering
- WGM Micro-Resonator suggested as main sensing unit

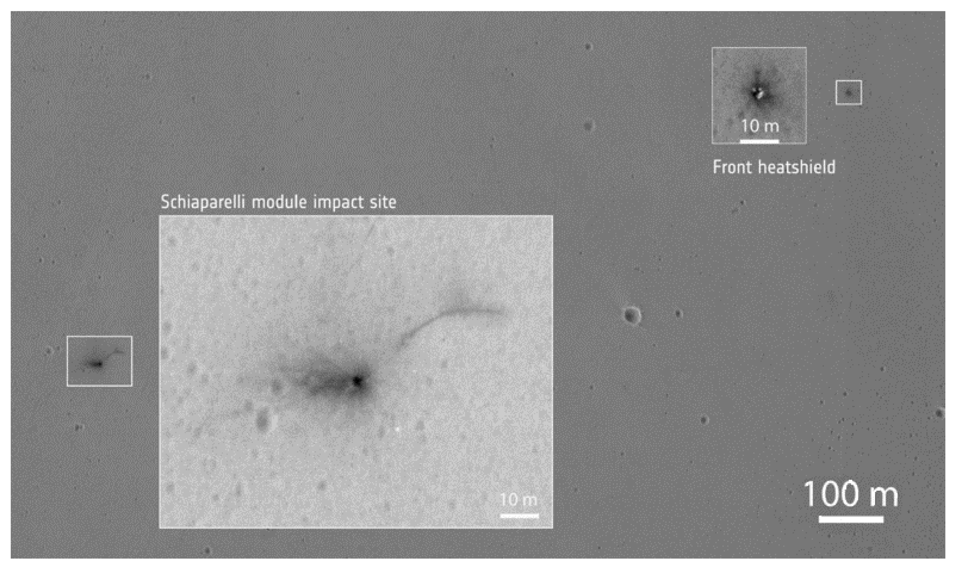

Figure 4: Schiaparelli Mars Crash Site[4]

Previous Work and Experimental Setup

Previous Work:

E-Field Sensors[1] and Seismometers[2] in previous projects utilized fiber-coupling (fig.2), resulting in a stable coupling signal in time in reference to the supply diode laser. However, quality of signal degraded with preliminary velocity-measurement experiments, possibly attributed to beam steering, in addition to the free space to single mode fiber coupling from the measured object. Thus, direct free-space coupling of the sphere from the laser was suggested for velocity-measurement experiments.

Experimental Setup:

- Objective is to measure relative velocity through Rayleigh scattering
- Rayleigh scattering requires more complex analysis, so setup is simplified by starting with Mie scattering as first step and then moving to Rayleigh
- Mie scattering intensity is angle-dependant (fig.5), thus proper angling of laser and collection optics is required ($45°$)
- Mie scattering also depends on particle sizing; thus proper sizing is chosen for both maximum intensity and maximum particle density for laser probe volume (Silver-coated nanoparticles $1 - 50\mu m$)
- Resonator Material is chosen as Silica due to its higher sensitivity and stiffness, based on previous work
- Initial setup with collection optics shown in fig.6

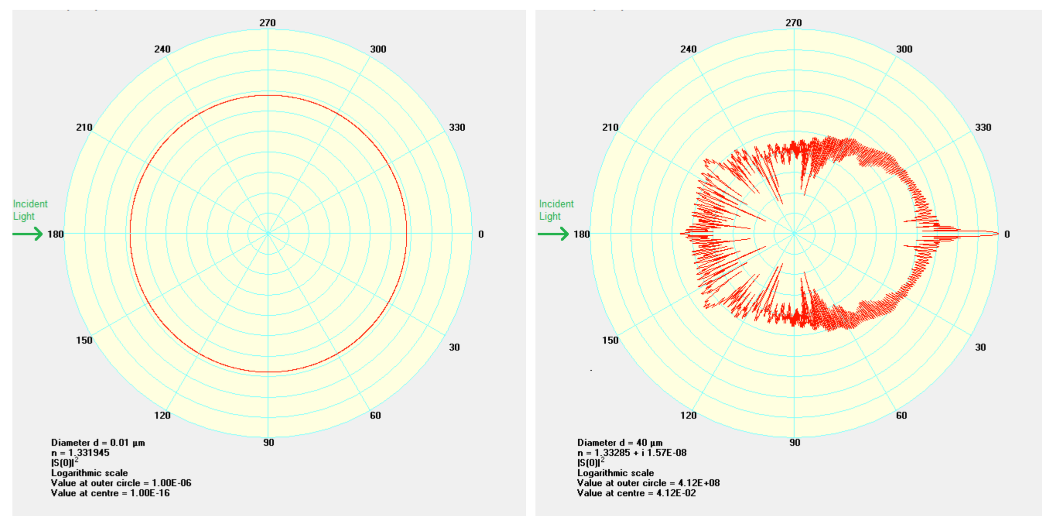

Figure 5: Polar Plot of Rayleigh Scattering (left) vs Mie Scattering Spectrum (right) as function of collection angle

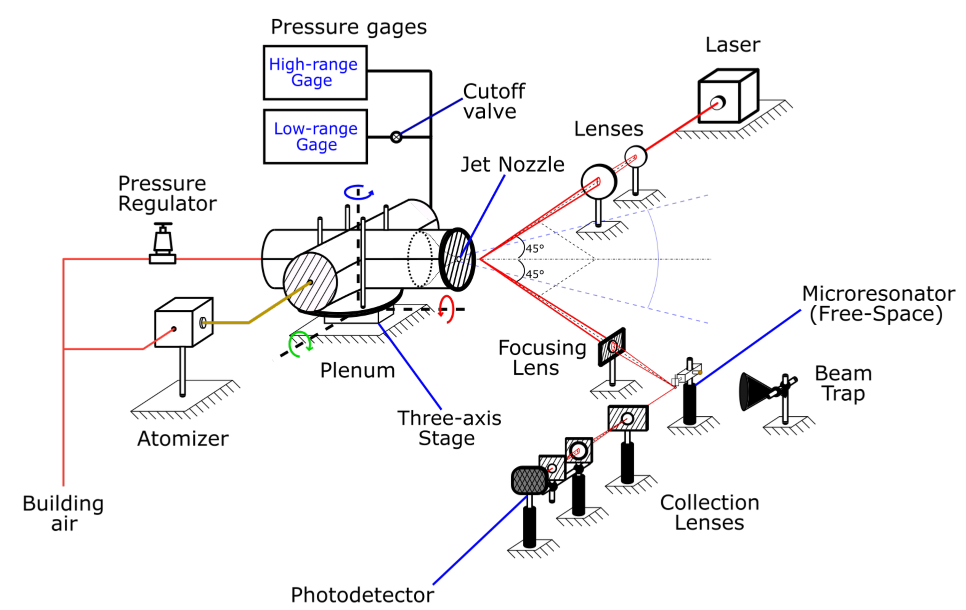

Figure 6: Mie-Scattering Jet Velocity-Measurement Experimental Setup

Experimental Run and Initial Results

From the Resonance condition (eq. 1), a shift can be induced by changing one or more of the following:

- The Resonator Radius r (by applying a strain or displacement on the resonating sphere)
- The Refractive Index n_0 (by changing the resonator temperature)
- The Wavelength λ (by either applying a change in the evanescent field or in the receiving signal wavelength, such as scanning the supplying laser over a frequency range)

For the preliminary experiments, shifts are achieved by varying the wavelength of the laser in a triangle waveform (i.e. scanning the laser), which can be 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, the central wavelength is taken as $\lambda = 639.045nm$.

The initial experimental runs are performed with the laser directly focusing into the resonator and the collection optics. Frequency-scanning is performed, and a shift $\lambda_{Doppler}$ is induced, such that:

$$\lambda_{Shifted}(t) = (\lambda_{Center} + \lambda_{Doppler}) \pm m \times t \tag{2}$$

Light collection is done through a Si-Photodiode and a corresponding FPGA feeding into the National Instruments SignalExpress software. The signal is then noise-filtered and direct correlation is applied as a preliminary shift-detection step. The signal along with its shifted counterpart are shown in fig.7.

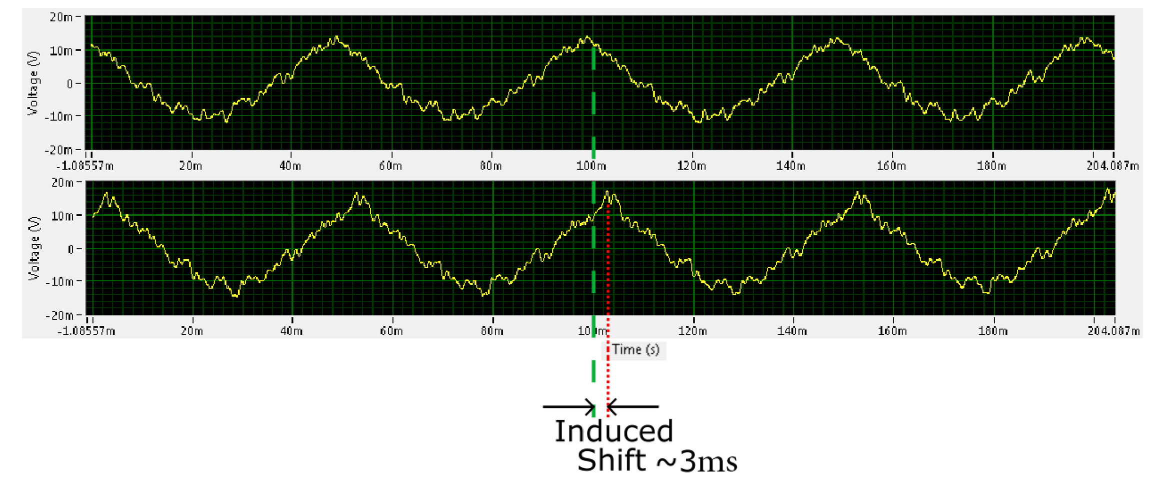

Figure 7: Obtained Waveforms with corresponding shift of $\Delta t = 3ms(\Delta\lambda = 1.06pm)$

Forthcoming Research

Future additions to this project include:

- Enhance shift accuracy with corresponding Real-Time Data Acquisition software
- Obtain an accurate shift from the jet by Mie Scattering along with corresponding Real-Time cross-correlation algorithm
- Enhance setup and adapt for Rayleigh scattering (Custom short-wavelength Laser and Collection Optics Required)
- Design and Build Telescope prototype for advanced light collection

References

[1] Tindaro Ioppolo, Ulas Ayaz, and M. Volkan Otugen. Tuning of whispering gallery modes of spherical resonators using an external electric field. *Optics Express*, 17(19):16465, Jan 2009.

[2] D.C. FOURGUETTE, M.V. OTUGEN, L.M. LAROCQUE, G.A. Ritter, J.J. MEEUSEN, and T. Ioppolo. Whispering-gallery-mode-based seismometer, June 3 2014. US Patent 8,743,372.

[3] T. Ioppolo, U. K. Ayaz, and M. V. Otugen. High-resolution force sensor based on morphology dependent optical resonances of polymeric spheres. *Journal of Applied Physics*, 105(1):013535, 2009.

[4] NASA. Pia21131: Closer look at schiaparelli impact site on mars, 2016.

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