Sound Speed on Mars measured by the SuperCam microphone on Perseverance.

Baptiste Chide[1], Tanguy Bertrand[2], Ralph Lorenz[3], Ricardo Hueso[4], Don Banfield[5], Agustin Sanchez Lavega[4], Asier Munguira Ruiz[4], Manuel de la Torre Juárez[5], Xavier Jacob[6], Alexander Stott[7], Naomi Murdoch[7], David Mimoun[7], Travis S.J. Gabriel[8], Jose Antonio Rodríguez Manfredi[9], Sylvestre Maurice[10], Roger Wiens[1]. [1]LANL, Los Alamos, NM, USA (bchide@lanl.gov), [2]LESIA, Meudon, France. [3]Johns Hopkins APL, Laurel, MD, USA [4]Universidad del País Vasco, Bilbao, Spain, [5]Cornell University, Ithaca, NY, USA, [5]JPL, Pasadena, CA, USA. [6]IMFT, Toulouse, France, [7]ISAE-SUPAERO, Toulouse, France, [8]USGS, Flagstaff, AZ, USA, [9]Centro de Astrobiologia, INTA, Madrid, Spain, [10]IRAP-CNRS, Toulouse, France.

Introduction: The Planetary Boundary Layer (PBL) of Mars, which represents the lower part of the atmosphere interacting with the surface, is a highly dynamical layer that follows an important diurnal cycle. It is strongly turbulent during the daytime due to convective updrafts induced by the warm surface whereas at night, the atmosphere is more stable and stratified [1]. In-situ measurements provided by Pathfinder [2] and by the Mars Explorations Rovers [3] probed the near-surface and showed that there is a vertical thermal gradient of -20 K/m between the surface and 2 m height during daytime, which translates into a speed of sound variation of 10%. The layer also shows a maximum instability during the afternoon with temperature fluctuations up to 8K over time scales shorter than 30 s [4], e.g. ~2% variation in the speed of sound.

Acoustic anemometry on Mars, through the measurement of the speed of sound, was shown to be a promising technique to determine meteorological quantities, in particular the air temperature but also wind speed at high frequencies [5]. It does not suffer from radiative and conductive contamination as traditional hot film temperature sensors, and the measurement is very fast. However, the sound speed derived air temperature retrieval must take into account seasonal variation of the atmospheric composition, to reach an error lower than 1 K [6].

The Perseverance rover that landed on Feb. 18, 2021, is carrying the two first microphones operating at the surface of Mars. In particular, the SuperCam microphone [7] is located at 2.1m of height, on top of the remote sensing mast of the rover. It was primarily designed to record pressure fluctuations associated with the laser-induced breakdown spectroscopy technique (LIBS) of SuperCam, that creates an acoustic wave when ablating rocks and soils at the Mars surface with a powerful infrared laser [8]. However, it also records the environmental noise induced by the atmospheric turbulence, winds and convective vortices [9].

Sound Speed on Mars: The speed of sound on Mars can be determined using the propagation time of the laser-induced acoustic signal as it travels from the ground up to the microphone height. A scheme of the experiment is proposed in Fig. 1.

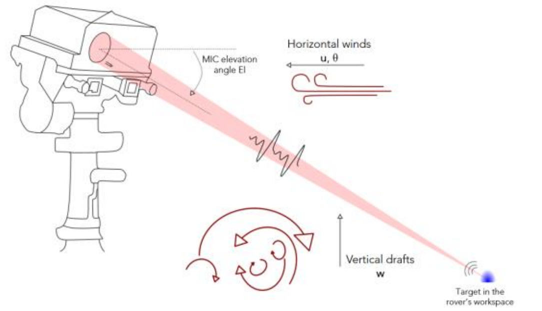

Figure 1 - Sound speed measurement with the SuperCam Microphone

Method. Supercam LIBS typical analysis consists of bursts of 30 laser shots, fired at a cadence of 3Hz (total duration of a burst is 10s), at each target location. It can be extended to bursts of 150 shots for specific targets. For each target, 5 to 10 bursts are repeated on points separated by a few millimeters. In total, a Supercam LIBS analysis of Mars' surface targets lasts for about 20min, including ~50 to 100s of laser shots, and the rest dedicated to Supercam operations.

When firing the LIBS laser on targets at the Mars' surface, the expansion of the laser-induced plasma into the Mars's atmosphere generates a shock wave that relaxes and then propagates up to the microphone as a high frequency acoustic signal (> 2kHz). Thanks to a precise synchronization between the laser and the microphone, the propagation time can be determined with a precision of ±10µs (the propagation time for a target located at 2m is 8.33ms considering a sound speed of 240 m/s). The propagation distance is retrieved within ±0.5% with the autofocus capability of Supercam's telescope. All in all, the sound speed can be determined, for every laser shot with a precision of ±0.51%.

Atmospheric parameters. The speed of sound retrieved by this technique is computed over the entire acoustic propagation path, which goes from the ground to the height of the microphone. Therefore,, at any given wavelength it is convoluted by the variations of temperature and wind speed and direction along this path. The measured sound speed can be expressed as:

$$c_{measured} = c_0 + u\cos(\theta - Az) + w\sin(-El)$$

with c_0 the speed of sound in a static atmosphere, u the horizontal component of the wind speed and w the vertical component. θ the horizontal wind direction and Az and El the azimuth and elevation of the direction pointed by Supercam.

The Mars idiosyncrasy. Due to the unique properties of the carbon dioxide molecules at low pressure, Mars is the only terrestrial-planet atmosphere in the Solar System experiencing a change in speed of sound right in the middle of the audible bandwidth (20 Hz – 20 kHz) [10]. For an acoustic wave with a frequency higher than ~240 Hz (relaxation frequency), CO_2 vibrational modes activated through collisions do not have time to relax their energy [11]. In that case, it is as if the medium has only 5 degrees of freedom compared to 7 at lower frequencies (3 translational modes, 2 rotational modes and 1 doubly-degenerate vibrational mode). Therefore the adiabatic ratio at high frequency is reduced to $\gamma_\infty = 7/5$ compared to $\gamma_0 = 9/7$ at low frequencies. It turns out that, on Mars, frequencies above 240 Hz travel more than 10 m/s faster than low frequencies. It may induce a unique listening experience on Mars with an early arrival of high-pitched sounds compared to bass.

Acoustic Temperature: Sound speeds measured by SuperCam are subsequently converted into temperatures using the ideal gas:

$$c_{measured}^2 = \frac{\gamma_\infty R T_{atm}}{M}$$

with T_{atm} the associated air temperature, R the universal gas constant and M the molar weight of the atmosphere.

Temperatures derived from sound speeds recorded on target Villette (five points of 150 laser shots, sol 189 of the mission) are displays in Fig. 2 and compared with horizontal winds and temperature retrieved at the same time by the Mars Environmental Dynamic Analyzer (MEDA), the weather station of Perseverance [12]. The acoustic temperatures are very well correlated with MEDA. However, they are higher than MEDA temperatures, which highlights the influence of the negative thermal gradient that biases the acoustic temperatures towards surface's values. The most remarkable points are the higher temperature fluctuations seen with the microphone (±5K/s in average and up to 10K/s), that are not seen on MEDA. Indeed this new measurement method samples faster the atmosphere than MEDA sensors, and catches temperature variations due to small eddies and gusts, thus providing insights and constraints to the turbulent activity in the two first meters above surface and more generally in the PBL.

Perspective of this work: Acoustic data shed light on very high temperature fluctuations of the Mars atmospheric surface layer that were not observed before with traditional sensors. In order to explain this phenomenon, the acoustic temperature will be compared with outputs from Large Eddy Simulation (LES) for Jezero. Diurnal and seasonal variations will also be studied in comparison with other meteorological parameters.

References: [1] Petrosyan, A. et al. (2011), Rev. Geophys, [2] Schofield J. T. et al. (1997) Science, [3] Smith M. D. et al. (2006) JGR:Planets, [4] Spanovich N. et al. (2006) Icarus, [5] Arnold K. et al. (1999) Phys. and Chem. of the Earth B, [6] Rafkin S.C.R. and Banfield D. (2020) Plan. Space. Sci, [7] Mimoun D et al. (submit), SSR, [8] Chide B. et al. (2020) SAB, [9] Chide B. et al. (2021), Icarus, [10] Petculescu A. and Lueptow R. M. (2007) Icarus, [11] Zhang X. et al. (2020) Meas. Sci. And Tech., [12] Rodríguez Manfredi J.A. et al. (2021) SSR.

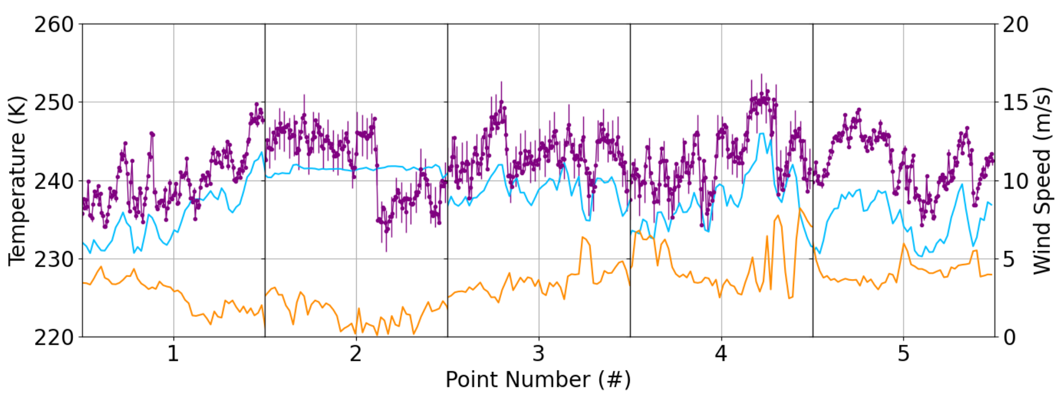

Figure 2 - Evolution of the acoustic temperature (purple points) derived from sound speed measurements on targets Villette (Sol 189, 5 bursts of 150 shots). Each point is separated by 333ms. Each panels (representing the five different burst) are separated in time by about 5min. Error bars take into account the uncertainty of the distance retrieved by Supercam, depending on points where there is an autofocus or not (points #1 and #5 with autofocus, the other without). Acoustic data are compared with air temperature data at 1.45m (blue lines) and with the horizontal wind speed (orange). Both are measured by MEDA.