Acoustics as a new tool to investigate surface-atmosphere interactions. Baptiste Chide[1], Ralph Lorenz[2],Tanguy Bertrand[3], Nina Lanza[1], Don Banfield[4], Jérémie Lasue[5], Sam Clegg[1], Sylvestre Maurice[5], Roger C. Wiens[6], [1]LANL, Los Alamos, NM, United States (bchide@lanl.gov), [2]Johns Hopkins APL, Laurel, MD, USA, [3]LESIA, Meudon, France, [4]NASA Ames, Mountain View, CA, USA, [5]IRAP, Toulouse, France, [6]Purdue University, West Lafayette, IN, USA.

Introduction: On Earth, quantitative analysis of acoustic waves is often used to characterize atmospheric environment. Most notable applications are (i) to characterize various phenomena that are sources of pressure fluctuations: lightning, volcanism [1] atmospheric and fluid circulations (rivers, precipitations, among others), surface movements, aeroacoustic interactions, etc… (ii) to study the acoustic properties of the propagation medium, the atmosphere itself: speed of sound, dispersion, attenuation with distance, and (iii) to infer characteristics of the atmosphere dynamics: wind, turbulence, temperature gradients. Although the Solar System is mostly a quiet place, like the Earth, Venus, Mars and Titan harbor atmospheres that are dense enough for acoustic waves to propagate in the audible range from 20 Hz to 20 kHz, as well as infrasounds below 20 Hz or ultrasounds beyond 20 kHz. Hence, acoustics could be used a new tool in planetary science to understand surface/atmosphere interactions in situ.

Sound propagation in the Solar System: The distance an acoustic signal can propagate depends heavily on the atmospheric physical and chemical properties. Therefore, Venus, the Earth, Mars and Titan show very diverse sound propagation characteristics (see Table 1, [2]). The amplitude of an acoustic signal and therefore, its detectability, is controlled by the efficiency of the coupling between a sound source and the propagation medium, and between the atmosphere and a sound receiver instrument, i.e. the acoustic impedance, that mostly depends on the density of the atmosphere. From this perspective, Venus and Titan have acoustically sensitive atmospheres (respectively +20 dB and +10 dB compared to a reference sound produced on Earth), whereas Mars might be seen as a quiet planet given its thin atmosphere (-20 dB).

As they propagate, acoustic waves decay geometrically, but are also attenuated with the distance due to energy exchanges with molecules composing the atmosphere: the high frequency content of sounds tend to be more strongly absorbed [3]. CO_2 dominated atmospheres like those on Mars and Venus suffer from a large intrinsic attenuation due to vibrational modes of CO_2 so that only infrasounds can propagate over long distances [4,5]. Nevertheless, the planetary boundary layer (PBL) dynamics for these two bodies [6, 7] are a source of aeroacoustic signal, their properties can be recorded by acoustic devices. On the other hand, Titan shows the lowest acoustic attenuation among the terrestrial atmospheres due to its N_2-CH_4 atmospheric composition, allowing audible sounds to propagate much farther than in any other atmosphere. Furthermore, the wealth of the sound sources that might compose the Titan soundscape, including rain falls, dust devils, liquid methane circulations [8], make Titan a very favorable place for acoustic studies. Giant planets and sub-surface outer Solar System oceans are also exotic media where acoustic waves propagate [9].

Acoustics has been scarcely used to explore these extraterrestrial atmospheres [10, 11] because the science rational is only just developing. However, although it appears to be the least favorable planet for sound propagation, the very first sounds from Mars recorded recently by the Perseverance's microphones opened a new sense of investigation.

	Atmosphere	**Pressure (bar)**	**Temp. (K)**	**Sound Speed (m/s)**	**Impedance $Z_{ac} = \rho_0 c_{sound}$ (Pa.s/m)**	**Sound Volume**	**Attenuation (dB/m^{-1})**
Earth	78% N_2, 21% O_2	1	300	347	407	Ref.	$3x10^{-3}$
Mars	95% CO_2	0.007	220	240	4	-20 dB	0.26
Venus	96% CO_2	93	730	410	26960	+20 dB	$4x10^{-3}$
Titan	95% N_2, 5% CH4	1.47	94	195	1186	+10 dB	$4.3x10^{-7}$

Tableau 1 - Sound propagation characteristic for the terrestrial planets harboring a dense atmosphere. Data are extracted from [2]. Sound attenuation are for 100Hz acoustic waves.

First sounds from Mars: On February 18, 2021, NASA's Perseverance rover landed in Jezero Crater carrying the first two microphones operating on the surface of Mars: the SuperCam microphone, positioned on top of the rover's articulating mast and the EDL microphone fixed on the body of the rover. After one year, the Perseverance playlist features more than 5 hours of Martian sounds [12].

Passive sensing of the Mars atmosphere, revealed previously unobserved pressure variations down to 1,000 times smaller scales than ever observed before, highlighting the transition to the turbulent dissipative regime where eddy energy is transferred to small scales and later dissipated. Wind-induced acoustic signals can be used to infer the wind speed and direction [13] and it exhibits rapid fluctuations highlighting very short wind gusts that could not be observed with hot-film anemometers.

Active sensing, relying on the audible sound point sources created by the SuperCam laser vaporizing rock at the surface, is used to extract sound propagation properties of the martian atmosphere. In particular, the measurement of the speed of sound provides a new method on another planet to retrieve the atmospheric temperature independently from traditional thermocouple sensors. In particular, it sheds light on large temperature fluctuations over a very short timescale, ±5K/s in average and up to 10K/s [14]. Altogether, these acoustic measurements on Mars represent a new asset to probe the PBL, a key layer in the surface-atmosphere exchanges on Mars [7].

Perspective for planetary acoustics: Although not very favorable to sound propagation, Mars acoustics opens a new field of investigation to study the small-scale dynamics of the near surface atmosphere. These promising results show the potential of this new technique and confirm the need to send acoustic devices to explore the atmospheres of Venus and Titan. Passive acoustic recordings with microphones can help characterize physical phenomena whose causes result from an interaction between the surface and the atmosphere (turbulence, wind, grain motions [15], rainfalls…). Low-resource arrays of microphones already show good performance in retrieving the high-frequency wind properties [16]. Active sensing provides a new method to measure winds and temperature (through acoustic anemometry [17] or acoustic tomography [18]) with a faster response time. Sound attenuation, which depends on the atmospheric composition, might also be used to infer the atmospheric composition [19, 20] Acoustics is a new, but rising discipline in planetary science: there are currently 3 microphones operating on Mars (2 on NASA Perseverance, 1 on the CNSA Zhurong rover [21]) and there are plans to include microphone instrumentation on the Dragonfly mission. a rotorcraft lander for the exploration of Titan to be launched in 2027.

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