Unveiling Mars: Sounds of the Red Planet

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A Brief Journey Through Planetary Microphones History

The concept of capturing sounds from Mars has always sparked curiosity and excitement among the general public. The history of these ambitious attempts dates to the groundbreaking Soviet missions in the early 1980s. It was during this period that the Union of Soviet Socialist Republics (USSR) embarked on ambitious endeavors to explore our enigmatic planetary neighbor Venus (Ksanfomaliti et al., 1982; see bit.ly/4bFp5bm). These missions, officially launched in 1981, represented a significant leap forward in planetary exploration.

The spacecraft Venera 13 and 14 were designed to survive the harsh Venusian environment, characterized by crushing pressures (90 bar) and scorching temperatures (480°C). On their successful landing on Venus's surface in March 1982, these spacecraft became the first to transmit color images and valuable data back to Earth from the planet's surface. Integral to these missions was the Groza 2 instrument suite, tasked with characterizing the atmospheric and surface conditions of Venus, notably searching for thunder.

Despite the groundbreaking nature of these missions, the limited data sent back to Earth meant that only plots of sound amplitude, showing the presence of wind noise and sounds of spacecraft operation (notably, camera covers blowing off and operation of a drill) are their only acoustic legacies. They have sparked curiosity and speculation among scientists and space enthusiasts alike.

Sounds from Titan

A significant milestone in space exploration was later achieved with the Huygens probe (see bit.ly/46toZmi), part of the Cassini-Huygens mission when it successfully recorded the sounds of its descent through Titan's atmosphere in 2005. This mission, a collaboration between NASA, the European Space Agency (ESA), and the Italian Space Agency (ASI), marked the first time a probe landed on Titan, Saturn's largest moon.

The Huygens probe, named after the Dutch astronomer Christiaan Huygens, was equipped with a suite of scientific instruments designed to study Titan's atmosphere and surface. On January 14, 2005, the Huygens probe began its descent through Titan's thick (1.5 bar), cold (−180°C), nitrogen-rich atmosphere. As it parachuted down, the probe recorded the changing atmospheric conditions and a crude microphone picked up the noise of the air rushing past. These sounds, later processed and made available to the public, provided an unprecedented sensory experience of another world (see bit.ly/HuygensSounds).

The recordings quickly gained immense popularity, with thousands of downloads from the ESA's website. The Huygens probe also featured an active acoustic instrument, a 15-kHz sonar, intended to measure the depth of Titan's liquid methane seas in case the probe landed in a liquid. The probe landed in a desert, but it did pick up an atmospheric echo from the surface in the last seconds of its historic descent (Towner et al., 2006). Additionally, after 10 min on the surface, a speed-of-sound sensor detected a drop in sound propagation, perhaps due to sound-absorbing gases like ethane or carbon dioxide sweated out of the ground by the warm probe (Lorenz et al., 2014).

Going to Mars

In 1998, a groundbreaking project emerged from the Space Sciences Laboratory (SSL) at the University of California, Berkeley. Working in collaboration with The Planetary Society (see bit.ly/MarsMicrophone), with mostly outreach objectives, the SSL developed the Mars microphone

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for NASA's Mars polar lander (MPL) mission (Delory et al., 2007). This Mars Microphone was a marvel of engineering, designed to be small, robust, and capable of withstanding the harsh Martian environment. It was built to endure extreme conditions, including high levels of radiation and the frigid temperatures of the Martian surface. This microphone was expected to record a range of sounds, from the whisper of Martian winds to the potential crunch of surface material beneath the lander.

However, this innovative project faced a significant setback. On December 3, 1999, the MPL embarked on its descent toward the Martian surface. Tragically, contact with the spacecraft was lost shortly after it entered the Martian atmosphere.

The intense interest in capturing the sounds of Mars led to another promising opportunity for the Mars microphone with the Centre National d'Etudes Spatiales (CNES) on the NetLander mission. Scheduled for a 2007 launch, the NetLander mission was designed to deploy multiple landers on the Martian surface, each equipped with scientific instruments, including a Mars microphone, to study the planet's geology and atmosphere.

However, the ambitious NetLander mission (see bit.ly/NetLander) faced significant financial and logistical challenges. In 2001, the CNES announced the cancellation of NetLander, dashing hopes for the Mars microphone's deployment. This setback was a major disappointment for the scientific community, which remained eager to hear the sounds of Mars.

Undeterred, the team behind the Mars microphone sought another opportunity, this time with NASA's Phoenix Mars mission. The microphone was integrated into the Mars descent imager (MARDI) camera system, designed to capture high-resolution images during the spacecraft's descent and landing. The inclusion of the microphone promised to provide an audio accompaniment to the visual descent, offering a richer sensory experience.

As the Phoenix mission prepared for its 2008 launch, excitement grew once again. Yet, the Mars microphone faced another obstacle. Concerns arose about potential interference issues with other critical systems on the Phoenix lander. To mitigate these risks, mission planners decided not to activate the microphone during the mission. The disappointment was palpable, but the scientific community remained resolute.

Finally, the Mars 2020 Mission Microphones Were a Success

The NASA Mars 2020 Perseverance rover (see bit.ly/MarsLander) marked a significant milestone in the exploration of the Red Planet when it landed on February 18, 2021. Among its advanced suite of instruments, the mission payload included microphones designed to capture the sounds of Mars, contributing to the mission's scientific objectives. The Mars 2020 mission aimed to search for signs of ancient microbial life, study the planet's climate and geology, collect samples of Martian rocks and soil for potential return to Earth, and prepare for future human missions to Mars.

One of the most innovative tools of NASA's Perseverance rover is the SuperCam instrument (Maurice et al., 2021; Wiens et al., 2021). This advanced piece of technology combines several scientific techniques to study the Red Planet's surface in unprecedented detail. Central to SuperCam's capabilities is its use of laser-induced breakdown spectroscopy (LIBS). This sophisticated technique involves firing a powerful laser at Martian rocks and soils. When the laser hits the surface, it creates a small, intense burst of energy that breaks down the material into a glowing plasma. By analyzing the light emitted from this plasma, scientists can determine the chemical composition of the targeted materials. This process allows researchers to identify various elements and minerals present on Mars, offering crucial clues about the planet's geology and history.

The inclusion of a microphone in the SuperCam instrument (Mimoun et al., 2023) enhances its analytical power (e.g., Chide et al., 2019; Murdoch et al., 2019). When the LIBS laser fires, it generates shockwaves that produce sound. By recording these sounds, the microphone captures the acoustic signatures of the laser impacts. These recordings provide scientists with valuable information about the hardness and texture of Martian rocks and soils. For instance, different materials produce distinct sounds when struck by the laser, helping researchers distinguish between various types of geological formations.

The insights gained from SuperCam's analyses are vital for understanding Mars' geological past. By studying the chemical makeup and physical properties of Martian

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materials, scientists can reconstruct the planet's environmental history, including the presence and movement of water. This information is crucial for unraveling the mysteries of Mars's past climate and its potential for supporting life.

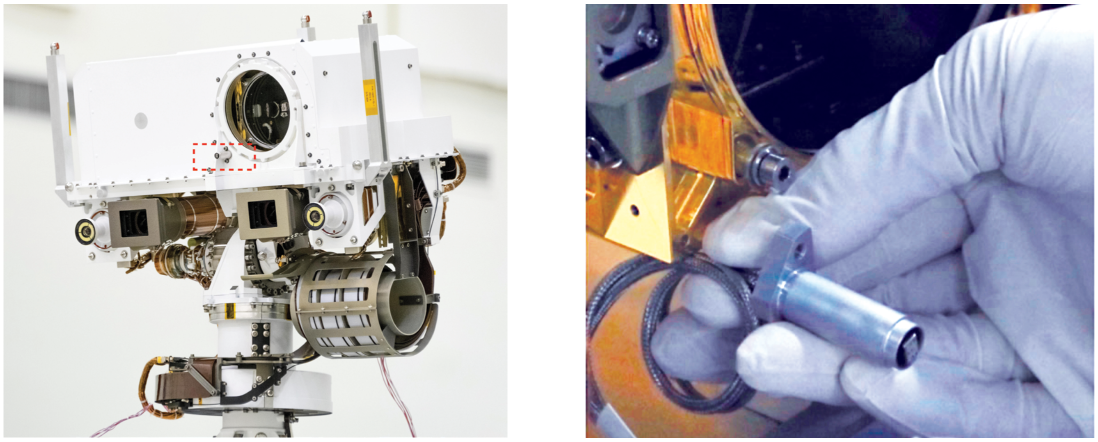
Moreover, the SuperCam plays a critical role in the Mars sample return mission. By identifying the most promising samples, the SuperCam helps scientists select the rocks and soils that hold the greatest scientific value. The audio data from the microphone adds another layer of precision, ensuring that the chosen samples provide a comprehensive snapshot of Mars' diverse geology.

Another microphone has been accommodated on the flank of the Mars 2020 Perseverance rover: the entry, descent, and landing (EDL) microphone. This microphone was specifically installed to record the sounds during the rover's dramatic descent through the Martian atmosphere and its subsequent landing on the planet's surface. The EDL microphone aimed to provide a new sensory perspective on the landing process. As the rover plunged through the thin Martian atmosphere on February 18, 2021, it experienced a series of intense and rapid events known as the "seven minutes of terror" (see bit.ly/4b16Cph). The EDL microphone was designed to capture these moments in real time, recording everything from the deployment of the parachute to the rover's final touchdown on Mars (Maki et al., 2020).

Behind the Scenes of SuperCam's Microphone: Technological Challenges

The decision to integrate a microphone, the move that would bring the sounds of Mars to Earth for the first time, was made in the late stages of developing the SuperCam mast unit (see bit.ly/MastUnit).

Figure 1. ***Left:*** *SuperCam instrument on the Perseverance rover.* ***Dashed red rectangle:*** *microphone location.* ***Right:*** *microphone during its tests. It is 3.4 cm long and weighs a mere 13 g!* ***Left*** *courtesy of NASA/JPL-Caltech;* ***right*** *courtesy of ISAE-SUPAERO.*



Every component of a space mission must meet exacting standards to survive the harsh conditions of space travel and operate reliably on another planet. There were concerns that the microphone might interfere with other critical parts of the SuperCam. Engineers and scientists faced a delicate balancing act. They needed to ensure that the microphone would not compromise the primary objectives of the mission. The decision to include it was continually reassessed, with the understanding that it could be removed if it posed any risk to the mission's success.

The design of the SuperCam microphone (Mimoun et al., 2023) was heavily influenced by this late addition to the unit (**Figure 1**). Instead of having a dedicated data-acquisition system, the microphone "piggybacked" on the existing system of the SuperCam instrument, sharing the same analog to the digital channel as the laser's housekeeping. One of its key features is its ability to operate at two different sampling frequencies: 25 kHz and 100 kHz. These frequencies determine how many times per second the microphone samples sound waves, influencing the quality and detail of the recordings.

This setup introduced minor operational constraints. The SuperCam team could not simultaneously use the laser temperature housekeeping and the microphone and the total acquisition volume, and therefore its duration was limited. Instead, each recording session could not exceed 8 megabytes, which is the same amount of memory required for a single image from the rover's remote micro-imager (RMI), an already existing feature of the instrument.

Depending on the chosen sampling frequency, this memory limit allows for a maximum recording duration of either 41 s at 100 kHz or 167 s at 25 kHz.

To manage this limitation and ensure efficient use of the rover's telemetry, engineers developed a sophisticated filtering algorithm. This algorithm, embedded in the SuperCam body unit's flight software, processes the audio data to optimize its transmission back to Earth, reducing the amount of data without losing essential information.

Given the unknown nature of Mars' acoustic environment, the microphone was designed to operate at four different gain settings. These settings adjust the microphone's sensitivity to capture sounds of varying intensities, from the faint whisper of Martian winds to the sharp crackle of the SuperCam's laser.

Additionally, the microphone includes a "pulsed" mode specifically designed to save data. In this mode, the microphone records only the brief sound bursts generated by the LIBS-induced shots. Although this mode conserves data, it is not suitable for continuous recordings, such as capturing the ambient noise or wind turbulence in the Martian atmosphere.

Physically, the microphone was strategically mounted beside the SuperCam telescope input window holder to optimize the recording of the incoming shockwave. As a result of this, despite the microphone part being omnidirectional at lower frequencies, the surrounding large-scale elements, such as the remote warm electronics box (RWEB), mast unit, and rover body, affected its directional performance once integrated.

Every day, this microphone is exposed to a dramatic range of temperatures, plunging to as low as −80°C at night and rising to around 0°C during the day. Despite these harsh conditions, the microphone is built to endure and operate effectively, even when temperatures fluctuate between −135°C and +60°C.

However, although the microphone itself can tolerate these extremes, its delicate electronics are far more sensitive. To protect these vital components, the electronics are housed inside the optics box, a specially designed enclosure on the rover. This box shields the electronics from the severe cold, keeping them within a safer operational range of −55°C to +60°C. This protective measure ensures that the microphone can continue to function reliably, capturing valuable audio data from the Martian surface.

To guarantee the microphone's resilience to Mars' relentless temperature cycles, engineers subjected a development model to rigorous testing. This model experienced more than 1,000 cycles of temperature variations, simulating the harsh daily changes it would face on Mars. These tests were crucial to verify that the microphone could maintain its performance and durability over time, even when exposed to the planet's extreme and rapidly changing conditions.

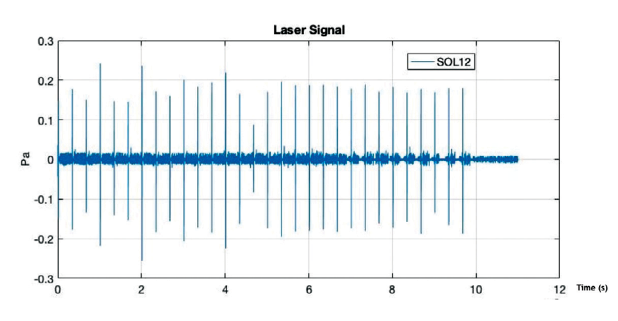


Figure 2. *Recording of the laser signal on Sol (Martian day) 12 of the mission. Reproduced from Mimoun et al. (2023). ©2023 D. Mimoun et al.*

This thorough testing process reflects the meticulous planning and engineering required to prepare instruments for the Martian environment. Each component of the Perseverance rover, including the SuperCam microphone, undergoes extensive validation to ensure it can withstand the rigors of space exploration. The ability to endure such extremes is vital for the success of the mission.

The Sounds of Science

The Mars microphones serve several objectives (Mimoun et al., 2023). The main microphone, part of the SuperCam instrument, supports both scientific and engineering goals. As described, its primary scientific objective is to enhance LIBS by analyzing the sounds produced when the laser vaporizes rock, generating a shockwave (see **Figure 2**). Additionally, the microphones record environmental sounds, such as the Martian wind and potential thunder from storms, providing insights into the Martian weather and atmospheric conditions. Also, engineering objectives include the monitoring of the rover's mechanical operations, such as the sound of wheels turning and the mast swiveling, which helps diagnose and troubleshoot mechanical issues. Finally, microphones also have significant public and educational value by adding an auditory dimension to the Mars exploration experience, making the distant planet more tangible and engaging for the public (see bit.ly/MarSound).

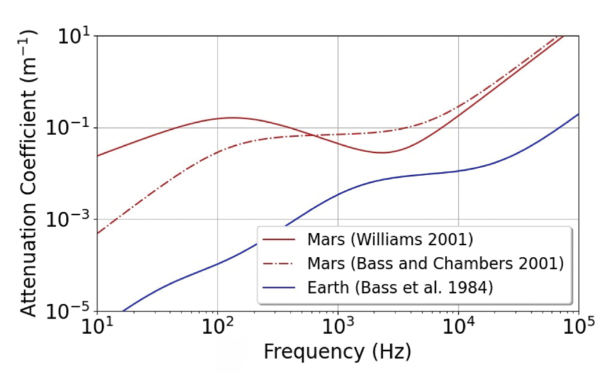
Propagation of the Sound in the Martian Atmosphere

One of the primary reasons for the relatively late integration of Mars microphones as part of the science payloads of Mars missions was the skepticism about whether there is enough sound to record due to the planet's low atmospheric pressure. Many scientists believed the thin atmosphere might render audio recordings impossible.

Sound on Mars behaves similarly to how it does in the Earth's stratosphere, where atmospheric pressure averages between 6 and 8 mbar (at 35 km altitude), and the mean temperature hovers around 240K. Attenuation on Mars was expected to result from both classical and molecular absorption processes. Studies on acoustic modeling of multicomponent gas mixtures predict a frequency-dependent sound speed and attenuation. Given Mars' cold, CO_2-rich atmosphere, significant attenuation is expected. Most sounds within the human hearing range may not be audible beyond a few tens of meters from the source.

However, the situation is different for lower frequencies. Infrasound, frequencies below the human hearing range, potentially caused by dust devils, meteor impacts, or other sources, can travel over kilometer ranges. For instance, the attenuation of a 50 dB sound at various frequencies demonstrates that high frequencies are more strongly attenuated, whereas infrasounds propagate well on both Mars and Earth (Gillier, 2024).

Figure 3. *Sound attenuation coefficient for an atmosphere of CO_2 at 240K and 740 Pa. The sound attenuation coefficient is a measure of how much sound decreases in intensity as it travels through a medium. Based on the models from Williams (2001)* (***solid red line***), *and Bass and Chambers (2001)* (***dashed red line***). ***Solid blue line:*** *frequency-dependent attenuation coefficient for the Earth. Reproduced from Mimoun et al. (2023). ©2023 D. Mimoun et al.*



In the quest to explore Mars, understanding how sound travels across its surface is crucial. A model of sound propagation on Mars is therefore essential for several reasons. First, to accurately interpret the acoustic properties of a sound source based on the received signal, the effects of sound propagation through the Martian atmosphere must be considered. Conversely, if the sound source is known, analyzing the received signal can reveal properties of the atmosphere. This dual approach necessitates a thorough understanding of how acoustic waves travel through Mars' atmosphere.

A sound propagation model is also pivotal for designing future acoustic instruments and experiments. The characteristics of the sound source intended for recording dictate the specifications needed for these instruments.

The SuperCam microphone, for example, was designed using existing models of sound propagation in the Martian atmosphere. These models (**Figure 3**) allowed scientists to calculate the attenuation coefficient and speed of sound for both a general Martian atmosphere and specific atmospheric profiles from the surface to the upper atmosphere. In the instrument design, the choice of the relevant model was crucial because it governs the level of sound expected at the microphone level and therefore the required gain tuning.

Capturing the Sounds of the Red Planet

Since the Perseverance rover's arrival on Mars, the SuperCam microphone has recorded approximately 27 h 20 min of audio (**Figure 4**) by Sol 1200 (a sol is the Martian equivalent of a day on Earth, slightly longer by about 40 min). Despite the generally quiet environment of Mars, the microphone has successfully documented notable events. These include the flight of the Ingenuity helicopter and the passing of a Martian dust devil. These recordings offer valuable insights into the Martian atmosphere and contribute to our understanding of the acoustic landscape on Mars.

Natural Sounds

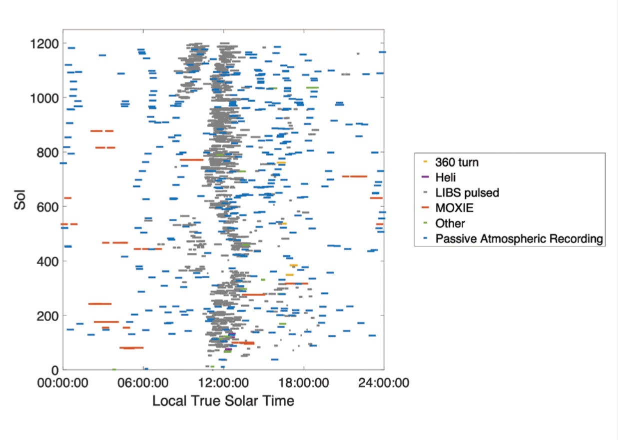


Figure 4. *A summary of the 1,200 first sols (about 2 years) of microphone recording. The various colors represent the types of recording identified. Heli, helicopter; LIBS (laser-induced breakdown spectroscopy), SuperCam; MOXIE (Mars oxygen in situ resource utilization experiment), oxygen production. Various sound descriptions are detailed in the text. Figure courtesy of Martin Giller, private communication.*

Many of the "natural" recordings made by the SuperCam microphone are due to interactions between the Martian wind and the microphone itself. The microphone records pressure fluctuations generated by the instrument blocking the wind flow, known as the stagnation pressure, rather than by sound waves traveling through the Martian atmosphere (Chide et al., 2021).

A remarkable milestone was achieved when the SuperCam microphone captured the sound of a Martian dust devil (Murdoch et al., 2022). This unique event was simultaneously documented by the Mars environmental dynamics analyzer (MEDA) instrument and the rover's navigation camera, which recorded meteorological data and images during the encounter. The sound of a Martian dust devil is available at bit.ly/dustsound.

Analysis combining the captured data with models revealed that the dust devil was approximately 25 m in diameter and at least 118 m tall. It passed directly over the rover, traveling at about 5 m/s. Additionally, valuable information about the density of dust grains within the vortex was collected.

This shows that microphones as atmospheric sensors complement traditional wind sensors with high-frequency measurements, addressing the dedicated sensors' slower response times that typically span several seconds. Moreover, the detection of grain impacts via the microphone offers an unprecedented opportunity to directly measure wind-blown grain fluxes on Mars. This capability provides new data on Martian surface dynamics and aeolian processes.

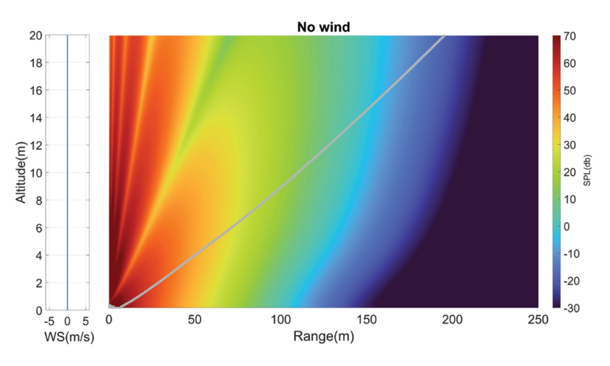
Anthropogenic Sounds

Anthropogenic sounds, or human-made noises, are the most common sources of noise on Mars. The microphone on Perseverance predominantly picks up human-made, or anthropogenic, sounds, a testament to its design. These sounds fall into two categories. First are internal rover sounds that include the hums and whirs from internal systems such as MOXIE (Mars oxygen in situ resource utilization experiment; see bit.ly/4dGyIYA), the remote sensing mast (RSM), and possibly the cooling system motors. The second set of sounds are from environment interaction. These include the sounds born from the rover's actions like the zaps from the LIBSshots, the crunch of its wheels against the Martian surface, and the buzz of the Ingenuity helicopter (see bit.ly/4cgMK2y).

Unexpected Acoustic Findings: Ingenuity Helicopter Sounds on Mars

In the first year of the Perseverance mission, one of the most puzzling surprises was the SuperCam microphone's ability to record the sound of the Ingenuity helicopter from distances exceeding 200 m. Simple propagation models, which consider ray-tracing methods, geometric attenuation, and empirical absorption, suggested that sounds should not be detectable beyond 80-100 m (see **Figure 5**).

Figure 5. *Amplitude of a Martian sound as a function of the distance to a sound source located at the (0,0) point.* ***Dark blue zone:*** *shadow zone where the sound is strongly attenuated. This is an effect due to the temperature gradient. Reproduced from Gillier et al. (2024); licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) license (creativecommons.org/licenses/by/4.0).*



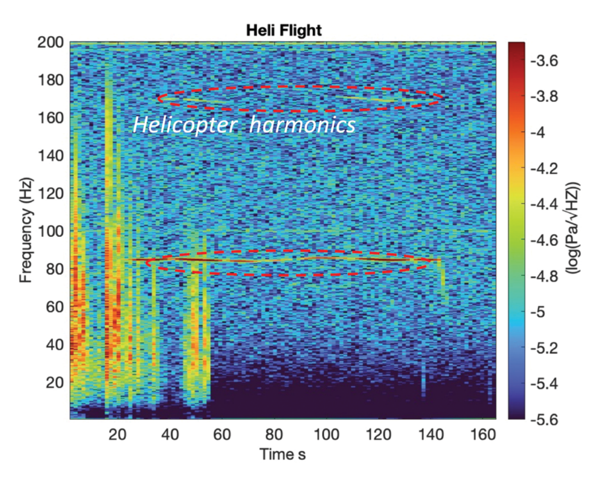


Figure 6. *This spectrogram recording of the Mars helicopter is like a visual map of the helicopter's sounds over time. There was a loud wind gust noise at the start (**vertical lines**), followed by specific sound patterns made by the helicopter at certain pitches (80 Hz and 160 Hz) that continue over time.* ***Colors:*** *sound intensity, with **red** and **yellow** representing the louder sounds. Vertical axis: SPL, sound pressure level. Reproduced from Lorenz et al., 2023; licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) license (creativecommons.org/licenses/by/4.0).*

However, the recordings defied these expectations. The sound of the helicopter was distinctly audible. Two harmonics were captured, one at 84 Hz and a second at 168 Hz. Although the 168-Hz tone is barely audible, the 84-Hz tone is distinct enough to measure the Doppler effect along with other acoustic phenomena (see **Figure 6** for the spectrogram). Higher harmonics are seen in tests on Earth, but those higher frequencies are inaudible after about 100 meters of propagation on Mars. A detailed analysis of the helicopter recordings (Lorenz et al., 2023) discusses the Doppler and attenuation effects and also discusses a modulation of the tones due to an unexpected small difference in the spin of the two coaxial rotors. These findings provide new insights into sound propagation in the Martian atmosphere, challenging existing models and enhancing our understanding of acoustic behavior on Mars.

Unveiling Martian Turbulence

By capturing the sounds of wind turbulence dust devils, and other atmospheric phenomen, the microphone provides valuable data on Mars' surface environment. One aspect that is worth stressing here is the fact that acoustic recordings have proven to be exceptionally effective for characterizing turbulence and resolving the wind structures of vortices. The wind sensors so far sent to Mars have a sample frequency of about 1 or 2 samples/s and can easily miss high-frequency effects. This is not the case with the microphones. This tool allows scientists to explore Martian turbulence on scales that were previously inaccessible.

With the microphone, we have been able to investigate how the spectral slope and regime transitions vary with different factors such as wind speed, wind direction, local time, and season (**Figure 7**). As more data are collected, these investigations will provide deeper insights into the complex atmospheric dynamics of Mars.

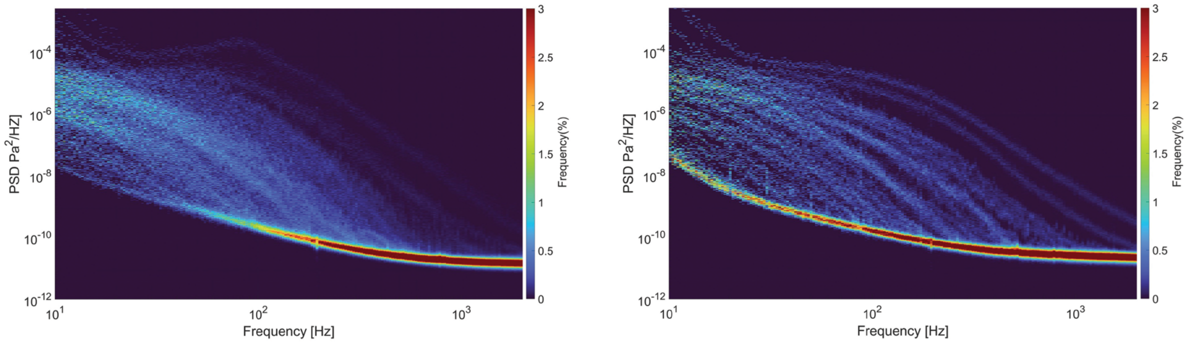
This advancement not only enhances our knowledge of the Martian environment but also paves the way for future explorations and potential habitability studies on the Red Planet. The SuperCam microphone stands as a testament to the innovative spirit driving space exploration, transforming abstract scientific inquiries into tangible discoveries.

The Future of Planetary Acoustics

The Mars microphone represents a significant technological and scientific advancement in planetary exploration. Initially thought of as an add-on to a SuperCam dedicated to rock hardness properties, its most significant applications have been in atmospheric science. Acoustic signatures also provide an important situational awareness tool, recording interaction of vehicle systems with planetary environments that may be diagnostic of the health of the equipment such as pumps or wheels. The Chinese Zhurong rover that landed on Mars just a few weeks after Perseverance also carried a microphone that recorded the clanking sound of the rover driving down a ramp onto the surface (e.g., see bit.ly/3Y6EXke). From an acoustic perspective, Mars is probably one of the most challenging planetary surface environment. Due to both the low pressure and the attenuation of carbon dioxide in the audible range, Martian sounds are faint.

However, other locations in the solar system may be much more promising. Scientists are already considering the prospects for using balloon-borne infrasound observations on Venus to detect seismic events. Looking even further afield and into future decades, several moons of the outer planets (like Jupiter's Europa or Saturn's Enceladus) may have internal water oceans beneath their icy surfaces, and acoustic methods have considerable appeal for geophysical and astrobiological studies (Dziak et al., 2020) should it one day be possible to access those environments. As well as an internal water ocean, Titan has surface liquid (methane) forming lakes and seas, rivers and rain, bringing additional interesting possibilities (Leighton and White, 2004).

Figure 7. *Spectral distribution of the Martian environment sound in the 11th- to 16th-h local time period (**left**) versus the 21st- to 6th-h period (**right**). It shows all the different frequencies of a sound and how intense each one is. Nights are generally quieter than days. Reproduced from Gillier et al. (2024); licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) license (creativecommons.org/licenses/by/4.0).*



Concrete new steps in planetary acoustics are already being taken. The NASA Dragonfly mission (see dragonfly.jhuapl.edu), under development for launch in 2028 with arrival at Titan in 2034, will include a microphone suite (Wray et al., 2024). Its designers benefit from the experience of Perseverance (e.g., using three microphones to enable better determination of sound sources and characterization of sound propagation and the use of more flexible sampling and data-compression schemes). The mission's long cruise in space subjects the instrumentation to a higher radiation dose than Perseverance, and the bitterly cold Titan environment (−180°C) has demanded careful part selection. However, Dragonfly, an octocopter lander (e.g., Lorenz, 2022) using rotor flight to visit dozens of sites with a sampling drill, promises a rich spectrum of both artificial and natural sound sources. The pioneering Perseverance experience suggests the soundscape will be full of surprises. Listen up!

Acknowledgments

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