ALIEN SOUNDSCAPES: A CONCISE GUIDE TO THE ATMOSPHERIC ACOUSTICS OF VENUS, MARS, TITAN, AND EARTH

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In the winter of 2004, the public was able to listen to the sounds of an alien world for the first time. The world was Titan, a moon of Saturn, and the sounds were audio recordings taken during the descent of the *Huygens* probe.[1] That marked an important step in space exploration, namely the effort to convince the scientific community of the benefits of acoustic sensing in planetary science, given the wealth of information about a planet's environment that acoustics can unlock.

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Despite the potential benefits, there have been but only a handful of planetary science missions that implemented acoustic sensors. In the early 1980s, two Russian *Venera* spacecraft carried passive acoustic sensors in the hope of detecting thunder signatures on Venus. However, the data was inconclusive.[2] It was not until the late 1990s that another attempt to launch a microphone as part of a planetary science mission was made on board the *Mars Polar Lander*.[3] Unfortunately, the spacecraft was lost during descent in the Martian atmosphere in September 1999. On January 14, 2004, as part of the *Cassini-Huygens* mission to Saturn, the *Huygens* lander made a historic descent through Titan's atmosphere, during which it broadcast the sounds of an alien world. The probe carried not only a microphone[4] for recording ambient noise and potential lightning events, but also active acoustic sensors[5] for measuring surface topography, sound speed, altitude, and wind speed, as well as the surface acoustic impedance of the landing zone. The data obtained is still being analyzed, and more work will be needed to understand Titan's acoustic environment.

Planetary atmospheres are intriguing dynamic fluid systems in continuous physical and chemical interaction with solar radiation and the planet's surface. The atmospheres' complexity is linked to the history of the planet and may offer insights into its future. Acoustics has perhaps a unique role in atmospheric sensing, bestowed by the very fact that it is the atmosphere itself in which the sound waves propagate. A small variation in the local equilibrium can change the sound propagation characteristics drastically. It is this sensitivity that can be exploited in acoustic sensing of planetary environments.

Lower and warmer altitudes have high concentrations of condensable molecular species. At higher altitudes and lower temperatures, the concentration of these constituents drops due to their decreasing vapor pressures—the cold-trap zone. Above this region, the condensable molecules have a constant concentration. The sensitivity of sound wave propagation to this variation of temperature and composition can be fully exploited in descent-phase atmospheric sensing. Moreover, since acoustic perturbations are sustained by the gaseous medium itself, they can be used to probe the structure, composition, and dynamics of the atmospheres both passively ("listen" mode only) and actively ("transmit-receive" mode).

We consider here four planetary bodies: Venus, Mars, Titan, and, for comparison, Earth. Sound waves can effectively probe the properties of the four environments.

With a surface pressure of 90 atm and a temperature of 730 K, Venus is veiled in mystery despite decades of studies. For example, it is unknown why, given its closeness to the Sun, the planet's middle atmosphere (60-110 km) can be as cold as 300 K on the day side and even colder (110 K) on the night side. Despite this large temperature difference, no notable winds have been measured at those altitudes. However, at Venus' cloud level, wind speeds reach 360 km/h, while its surface environment is quiescent. Furthermore, observations have revealed electromagnetic radiation in the visible and radio ranges from localized sources, raising the hypothesis of lightning.

Mars is a world of mountains, canyons, channels, and dust storms. The all-pervasive dust conveys heat from the surface to the thin Martian atmosphere thus preventing water vapor from condensing into clouds. Strong tornado-like dust devils are a common occurrence on Mars. The heavy presence of electrically charged dust in the Martian atmosphere may generate wide diffuse electrical phenomena.[6]

Titan—the only moon in the Solar System with a substantial atmosphere—with its cold (90 K) and thick (1.6 atm) nitrogen-methane atmosphere, has been studied with renewed interest lately, since it is believed that its environment may hold clues to the prebiotic Earth. Titan is a relatively young body, with climate dynamics that may be similar to that of our planet. Titan's surface may contain expanses of liquid hydrocarbons and "cryovolcanoes" (geyser-like phenomena spurting liquid methane or other hydrocarbons), while its atmosphere may sustain strong lightning activity.

There are several ways in which acoustics can be used to probe physical phenomena in the atmospheres of these planetary bodies. Microphones tailored specifically for each environment can be used to analyze acoustic arrivals and, together with the electromagnetic signatures, determine the occurrence of lightning. Of interest is also low-frequency sound, which can propagate over large distances, even in thin atmospheres. Low-frequency sound can be generated aero-acoustically by gas flow around vehicles, meteorological phenomena such as dust devils and lightning, booming sand dunes, bolide impacts, and maybe even as nonlinear interactions at the interface between the atmosphere and liquid bodies such as Titan's hydrocarbon "lakes." Furthermore, long-wavelength ducted acoustic propagation in a planet's atmosphere can be inverted to yield quantitative information on the atmospheric boundary layer.[7]

An application of atmospheric acoustic sensing that shows much promise is acoustic anemometry enabling direct measurements of local velocity fields. Due to the direct coupling of acoustic waves and the medium of propagation, acoustics may provide a very good tool to investigate and quantify three-dimensional turbulence.[8] In broad terms, turbulence creates an effective medium with a complex compressibility that affects the acoustic wave number while turbulent eddies can efficiently scatter acoustic wavelengths commensurate with the turbulence length scales.[9] Therefore, sound waves can effectively be "tuned" to investigate specific turbulent regimes in the atmosphere.

Attenuation and speed of sound on Venus, Mars, Titan, and Earth

A quantitative analysis of a fluid environment can be achieved acoustically if both the sound speed and attenuation are measured. Besides the classical attenuation due to viscosity, heat conduction, and diffusion, non-classical losses arise from molecular relaxation. The non-classical, or molecular, acoustic attenuation provides a direct way to measure the relaxation times, characteristic of the molecular species and atmospheric composition. The frequency dependence of the sound speed can yield the specific heat ratio of the medium under study.

Physical models[10,11] of acoustic wave propagation in the mixtures of gases forming a planetary atmosphere combine the equations of linear acoustics, namely conservation of mass, momentum, and energy, and the equation of state. When the system is solved, the outcome is a complex-valued effective wave number that is a function of the effective specific heats—footprints of molecular relaxation.[12] The real and imaginary parts of the effective wave number contain, respectively, the frequency-dependent acoustic phase velocity (speed of sound) c and relaxational attenuation α_{relax}. By adding the classical absorption component α_{class} to the relaxational component, sound propagation in a relaxing medium is described by the full acoustic wave-number,

$$k_{ac} = \frac{2\pi f}{c} - i\,(\alpha_{relax} + \alpha_{class})\,, \qquad (1)$$

where f is the acoustic frequency.

To understand the dependence of acoustics on a planet's environment better, we compare the acoustic attenuation and sound speed in the atmospheres of Earth and three solar system bodies whose environments are compositionally similar to Earth's—Venus, Mars, and Titan. The average surface conditions (temperature in degrees Kelvin, pressure in Earth atmospheres) and approximate compositions are given below:

Table 1. Surface temperature, pressure, and composition of the atmospheres of Venus, Mars, Titan, and Earth.

Planet	T_0 (K)	p_0 (atm)	Composition *(main constituents)*
Venus	730	90	96 % CO_2, 3.99 % N_2, 150 ppm SO_2
Mars	227	0.007	95 % CO_2, 3.27 % N_2, 1.6 % Ar. 0.13 % O_2
Titan	95	1.6	95 % N_2, 5 % CH_4
Earth	295	1	77.97 % N_2, 21 % O_2, 1 % H_2O

Predictions based on a physical model[11,13] for the frequency-dependent attenuation coefficient α and sound speed c in the surface atmospheres of Venus, Mars, Titan, and Earth are shown in Fig. 1. At acoustic frequencies corresponding to periods comparable to molecular relaxation times, both sound speed and attenuation go through inflection points. This effect on the two acoustic quantities is different depending on the relaxation characteristics of the particular gas environments. The acoustic attenuation coefficient α is shown in Fig. 1(a), along with the normalized attenuation $\alpha\lambda$, where λ is the acoustic wavelength. Representing $\alpha\lambda$ as a function of frequency has the advantage of emphasizing the molecular relaxation times, which are proportional to the inverses of the frequencies where the $\alpha\lambda$ maxima occur. Mars and Earth have maxima at about 80 Hz due largely to the relaxation of the vibrational degrees of freedom of CO_2 and N_2 molecules, respectively. Venus' two maxima (~ 1 kHz and 320 kHz) also arise from the vibrational relaxation of CO_2. In the 1–10 kHz window, the attenuation on Mars is comparable to that on Venus. The high values of pressure and temperature of Venus' atmosphere lead to increased molecular collision rates that shift the relaxational effects to higher frequencies.[14] Titan's very cold nitrogen-rich environment inhibits the collisional exchange of translational energy with internal energy among molecules. This makes classical effects dominant on the attenuation, imposing virtually quadratic frequency dependence. Over the entire frequency range considered, Titan's atmosphere absorbs the least amount of acoustic energy.

When signal loss is a major concern (as is the case on Mars), acoustic modeling can identify frequency windows of relatively low attenuation that can be explored for measurements. For example, in the Martian atmosphere the approximate range between 1 kHz and 50 kHz would be a good choice for applications that require higher frequencies such as Doppler wind speed measurements or analysis of small- to medium-scale turbulence. Propagation in the low-frequency and infrasonic ranges (<10 Hz) occurs with small losses in all four atmospheres, so these frequencies can be monitored over long distances.

Figure 1(b) shows the frequency dependence of the sound speeds. Due to the scale of the graph, chosen to show the sound speed values in all four environments, the inflection points associated with molecular relaxation are only apparent for Venus and Mars, where relaxational effects are several orders of magnitude stronger than on Earth and Titan, as can be seen from the $\alpha\lambda$ peaks. Owing to its high

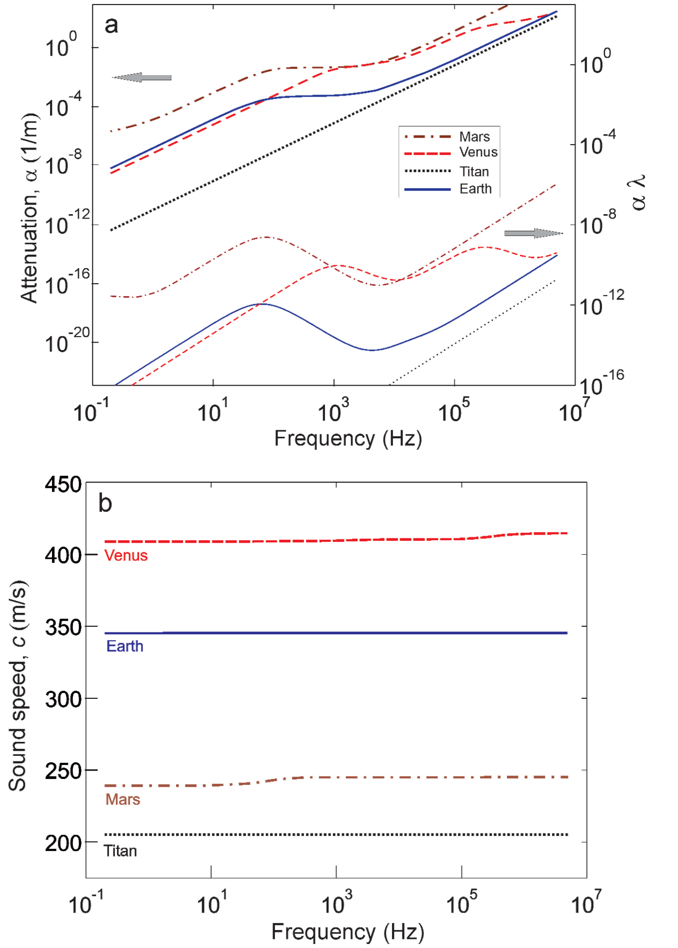

Fig. 1. (a) Frequency dependence of the acoustic attenuation coefficient α and normalized attenuation αλ. The peaks in αλ indicate more readily the effective relaxation frequencies, which are directly related to the molecular relaxation times. (b) Frequency dependence of sound speed c on the planets' surfaces. Over the frequency range considered, the attenuation on CO_2–dominated Mars is the largest while Titan's is the smallest. Due to the extremely hot Venusian environment, relaxational effects extend into the MHz range, as indicated by the two inflection points in both the attenuation and (less visible) sound speed. Even though the main constituents of Mars and Venus are the same (and in comparable concentrations), Venus' high temperature makes its environment acoustically the "fastest," while Titan's cold atmosphere is the "slowest."

surface temperature, the environment of Venus is acoustically the "fastest" while Titan's atmosphere is the "slowest." Even though the overall atmospheric compositions of Mars and Venus are similar, the large difference in temperatures plays a crucial role for the sound speeds. From the point of view of instrument development, the different wave propagation speeds dictate not only the lengths of transmitter-receiver paths in sound speed sensors, but also the data acquisition timing requirements, which are critical in setting the resolution of sound speed measurements.

Acoustic impedance and transducer choice

Perhaps the most important quantity to consider at the outset when developing acoustic sensors is the medium's *characteristic acoustic impedance,* Z_{ac}, defined as the ratio of the instantaneous (acoustic) pressure p and particle velocity u, $Z_{ac} \equiv p/u$, with units of 1 kg/m²s or 1 Rayl. The characteristic acoustic impedance is generally complex-valued due to a phase difference between the instantaneous pressure and

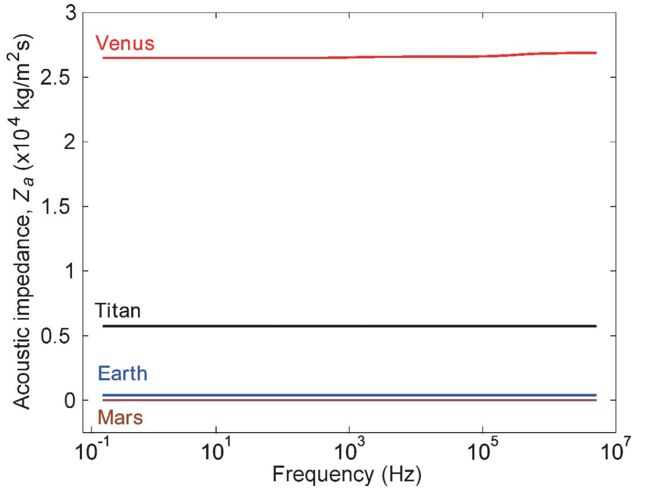

Fig. 2. Frequency dependence of the characteristic acoustic impedances of the atmospheres considered. The choice of acoustic emitters and receivers for the different environments must be such that the impedance of the transducer is matched to that of the respective medium. Thus, piezoelectric materials would be good candidates for Venus and possibly Titan, while for Earth but most critically for Mars, electrostatic capacitive transducers should be used to ensure the best coupling.

particle velocity. For the ideal case of plane waves, a pressure fluctuation produces an in-phase particle velocity, which makes the acoustic impedance real and equal to the product between the ambient density ρ_0 and the sound speed in the medium c. The plane-wave Z_a for the four planets is shown in Fig. 2. The impedance appears flat over the frequency range for Mars, Earth, and Titan due to the vertical scale chosen in the graph (the frequency dependence of Z_a is imposed by that of the sound speed c). A slight inflexion point in Z_a is apparent for Venus at ~ 1 MHz. Earth and Mars are the least "acoustically responsive," with Z_{ac} of 407 and 4.4 kg/m²s, respectively. Considerably higher acoustic impedances characterize the high-pressure environments of Titan and Venus: on Titan, Z_{ac} = 5738 kg/m²s and on Venus, Z_{ac} = 26,687 kg/m²s. Compared to Earth, the intensity of a sound wave would be 20 dB weaker on Mars, and 12 dB and 18 dB *stronger* on Titan and Venus, respectively (if produced by the same source and not accounting for absorption).

Typically, the acoustic impedance of an elastic solid and that of a gas differ by several orders of magnitude. For example, Z_{ac} for piezoelectric crystals or ceramics is about 10^7 kg/m²s, compared to water with Z_{ac} ~1.5 x 10^5 kg/m²s and air at normal conditions with Z_{ac} ~ 400 kg/m²s. Therefore, a stress wave generated in the piezoelectric solid is only partially transmitted as a pressure wave in the fluid. Thus, in active acoustic sensors (i.e. incorporating an emitter-receiver path) this impedance mismatch can drastically reduce the sensing efficiency as acoustic waves are launched in the gas by piezoelectric emitters. For applications such as acoustic anemometry requiring frequencies of tens of kHz, a promising transducer choice for the tenuous Martian environment is low-impedance (Z_{ac} on the order of 1000 kg/m²s), microfabricated, air-gap, capacitive devices that can provide much better acoustic coupling to a tenuous environment and are capable of dynamic ranges in excess of 100 dB.[15] An alternative may be the recently reported optically diffractive capacitive ultrasonic transducers with improved detection sensitivity.[16] The considerably denser atmospheres of Titan and Venus make their acoustic impedances one and two orders of magnitude higher than Earth's, respectively. This makes piezoelectric materials good candidates for acoustic sensing applications on both Titan and Venus. However, for measurements in the extremely hot environment of Venus (730 K), one must consider that past the *Curie temperature*, a piezoelectric material undergoes a phase transition and loses its spontaneous polarization and thereby its piezoelectric characteristics. Lithium niobate and bismuth titanate have very high Curie points (> 1000 K), which makes them viable choices for transduction in Venus atmosphere all the while keeping in mind that the sensor must be able to withstand the extremely high pressure.

Vertical atmospheric profiles of attenuation and sound speed

The descent phase of a planetary science mission is central to collecting data on the planet's atmosphere. This is when a descending probe can obtain first-hand information on the physical properties of the atmosphere that surrounds it. The development of active acoustic sensors designed to extract information as the probe descends into the atmosphere requires a good prediction of sound propagation characteristics as a function of altitude. Figure 3 shows the vertical atmospheric profiles for acoustic attenuation (a) and sound speed (b) at 15 kHz—the active sensing frequency used on board *Huygens*. The profiles are based on pressure, temperature, and density profiles obtained from general circulation models for Titan,[17] Mars,[18] and Earth,[19] and from radio occultation measurements taken above 35 km for Venus.[20] For Mars, Titan, and Earth the profiles at 45° latitude are shown. For Venus, data was only available at 67° latitude and above an altitude of 35 km.

For illustrative purposes, let us consider the descent of a spacecraft (say the *Huygens* probe) through Titan's atmosphere. Starting at an altitude of 120 km, an acoustic sensor would record a smoothly decreasing attenuation with three apparent regimes: a slight decrease down to about 50 km, a more pronounced rate of decrease to about 20 km, and finally, a slow rate of decrease with altitude down to Titan's surface. Simultaneous sound speed measurements would show a marked decrease in sound speed as altitude decreases followed by a plateau and a distinct increase down to the surface.

Over the altitude range considered, the vertical profile of the acoustic attenuation for Mars and Earth is also smooth, monotonically decreasing with altitude as the atmospheric pressure and temperature increase. The attenuation profile for Venus is quite different. It decreases as the probe descends through the higher atmospheric layers, but then plateaus from 70 km down to 50 km before increasing again from 50 km to 35 km. Sound speed profiles, on the other hand, show considerable structure, mirroring the layering of Earth's and Mars' atmospheres. For example, the vertical sound speed profiles reveal inversion layers for Earth (~15 to 35 km), Titan (~30 to 60 km), and Mars (~25 km), brought about largely by variations in temperature. The sound speed for Venus increases as a probe descends in the atmosphere, to regions of higher temperature. The small-scale sound speed fluctuations occurring above 60 km are likely caused by internal gravity waves.

Summary

The characteristics of acoustic wave propagation in a planet's atmosphere mirror the dynamics, structure, and composition of the respective environment. Despite their potential, acoustic sensing techniques have been overlooked in planetary science missions. Recently, the *Cassini-Huygens* mission marked a successful re-emergence of acoustic sensing, bringing to the forefront its potential ability to map out the ambient "soundscape" of planetary atmospheres and to monitor the conditions of descent and landing environments. Acoustic sensors can be passive in the form of microphones to record ambient sounds, or active such as would be implemented in wind velocity sensing (sonic anemometry) or measurements of sound speeds and turbulence fields. Acoustic sensors need not work alone: they can be combined with electromagnetic sensors to provide more information.

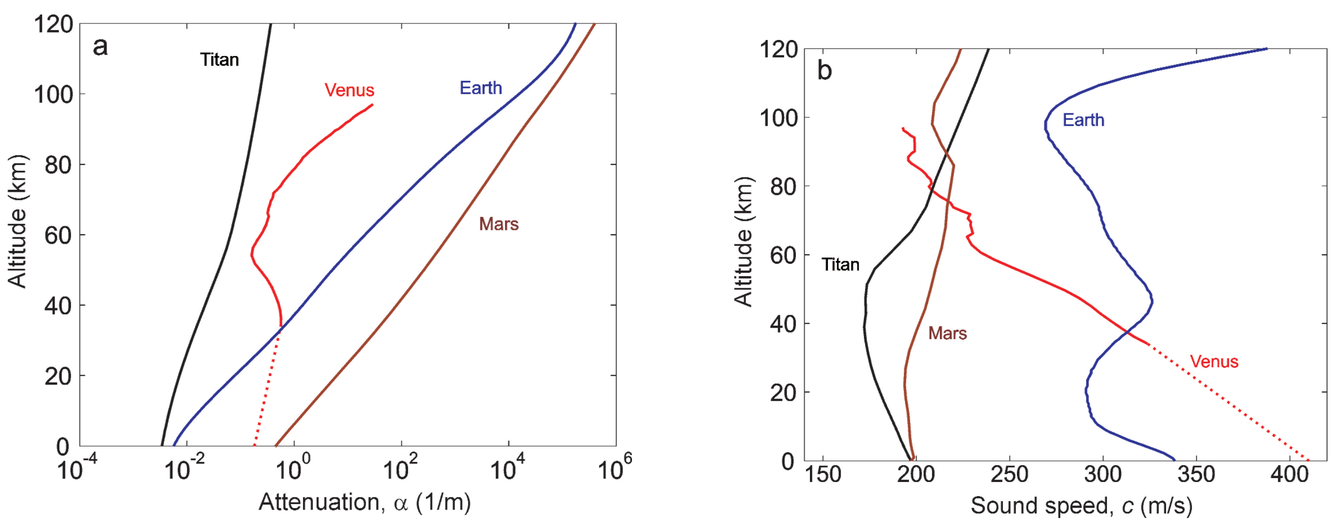

Fig. 3. Vertical atmospheric profiles for the acoustic attenuation coefficient (a) and speed of sound (b), calculated at 45° latitude for Titan, Mars, and Earth, and at 67° latitude for Venus. The attenuation profiles are relatively smooth, with the exception of Venus where α dips noticeably over an altitude range of ~ 40–80 km corresponding roughly to the small-scale sound speed fluctuations that could be generated by internal gravity waves. The large sound speed swings, brought about largely by variations in temperature, mirror the structures of the four atmospheres.

As an example, electromagnetic and acoustic signatures can be compared in order to accurately monitor lightning events.

Nevertheless, considering the continuous advances in acoustic sensing on both the experimental and theoretical fronts, and given that it was only a few years ago that acoustic sensing was successfully implemented in a planetary science mission, one can say that the field of "planetary acoustic sensing" is just now emerging from infancy into early childhood. Modeling sound propagation in various atmospheres can work hand-in-hand with the continuous improvement of general circulation models for planetary atmospheres. The refinement of novel sensing concepts in the laboratory in parallel with telemetry optimization and miniaturization efforts can lead to the development of even better acoustic sensors.

As recently shown by the *Huygens* data, acoustics can have its own well-defined niche in the quantitative characterization of planetary environments, alongside other techniques. The successes of recent planetary exploration missions such as *Cassini-Huygens*, *Venus Express*, and the *Mars Exploration Rovers* herald a new era in the exploration of our solar system. As the data relayed back to Earth by *Huygens* is bound to show, acoustics can play an ever-increasing role in gathering information about alien environments. [This work was funded by NASA.] **AT**

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