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Atmospheric acoustics of Titan, Mars, Venus, and Earth

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Abstract

Planetary atmospheres are complex dynamical systems whose structure, composition, and dynamics intimately affect the propagation of sound. Thus, acoustic waves, being coupled directly to the medium, can effectively probe planetary environments. Here we show how the acoustic absorption and speed of sound in the atmospheres of Venus, Mars, Titan, and Earth (as predicted by a recent molecular acoustics model) mirror the different environments. Starting at the surface, where the sound speed ranges from ∼200 m/s for Titan to ∼410 m/s for Venus, the vertical sound speed profiles reveal differences in the atmospheres' thermal layering and composition. The absorption profiles are relatively smooth for Mars, Titan, and Earth while Venus stands out with a noticeable attenuation dip occurring between 40 and 100 km. We also simulate a descent module sampling the sound field produced by a low-frequency "event" near the surface noting the occurrence of acoustic quiet zones.

Keywords: Atmospheres, composition; Atmospheres, structure; Mars, atmosphere; Titan; Venus, atmosphere

1. Introduction

On January 14, 2005, the *Huygens* lander made planetfall on Titan. The probe carried not only a microphone for recording ambient noise and potential lightning events (Fulchignoni et al., 1997), but also active acoustic sensors for measuring surface topography, average molecular weight, altitude, wind speed, and surface acoustic impedance (Zarnecki et al., 1997). *Huygens*' acoustic devices signal a successful resurgence in using acoustic instrumentation for planetary science after the late 90s' ill-fated *Mars Polar Lander*'s microphone (http://sprg.ssl.berkeley.edu/marsmic), which followed a lull of almost two decades since two Russian *Venera* spacecraft carried microphones in an attempt to detect thunder signatures on Venus (Lorenz, 1999).

The structure of planetary atmospheres is imposed by the atmospheric composition, pressure, density, and temperature profiles. The propagation of acoustic waves is very sensitive to these quantities, a property that was recently exploited during the descent of the *Huygens* Titan probe (Fulchignoni et al., 1997, 2005; Zarnecki et al., 1997). Recent work (Bass and Chambers, 2001; Williams, 2001) on extraterrestrial atmospheric acoustics has been focused on Mars and then only on sound propagation close to the planet's surface. We present a comparative theoretical study of acoustic propagation through the entire extent of the atmospheres of Titan, Venus, Mars, and Earth, as well as at the planets' surfaces using a sophisticated molecular acoustics model.

Titan—the only moon with a significant atmosphere—with its cold (90 K) and thick (1.6 atm) nitrogen–methane atmosphere, interests scientists since it may hold clues to the prebiotic Earth. It is a relatively young body, which may have weather cycles similar to Earth's. As described, Titan's surface may contain liquid hydrocarbon lakes and "cryovolcanoes"—phenomena that can be probed directly by sound waves—while its atmosphere may sustain strong lightning activity (Sotin et al., 2005). The data obtained so far is still being analyzed, and more work is needed to understand Titan's environment. With a surface pressure of 90 atm and a temperature of 730 K, Venus is veiled in mystery despite decades of studies. Observations have revealed electromagnetic radiation in the visible and radio ranges from localized sources, raising the potential for lightning. On Mars, a heavy dust presence conveys heat from the

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surface into the thin atmosphere thus preventing cloud formation. Strong tornado-like dust devils are a common occurrence. Electrically charged dust present in the martian atmosphere may generate wide diffuse electrical discharges (Kolecki and Hillard, 1992). Sensing packages incorporating microphones tailored specifically for each environment can be used to analyze acoustic arrivals and, by comparing these with electromagnetic signatures, determine the occurrence of lightning.

Very little work has been done to quantify sound propagation in planetary atmospheres based on non-empirical models, even though several planetary probes have implemented acoustic sensors. Notable contributions were a study of sound propagation at the martian surface based on a quasi-empirical approach (Bass and Chambers, 2001) and a more general survey of the acoustic environment of Mars (Williams, 2001). However, both studies only address sound propagation in the vicinity of the planet's surface and neither uses a first-principles model to calculate the acoustic properties of the martian atmosphere. Studies of the atmospheric acoustic properties on Venus and Titan appear to be even sparser.

The focus in this paper is the prediction of acoustic properties over a range of altitudes based on the local atmospheric conditions (temperature, pressure, and gas composition) using a relatively recent quantitative, first-principles physical model that has been successful in predicting sound absorption in multi-component gas mixtures (Dain and Lueptow, 2001; Petculescu et al., 2006). Using molecular acoustics and atmospheric data, we calculate the vertical profiles of attenuation and sound speed for the four planets. (Although Titan is technically a *moon*, we use the term "planet" cavalierly.) For high-frequency active sensing (e.g. sound and wind speed measurement), we show quantitatively how the different atmospheres would affect the acoustic signal over a 1-m sensing path. Then we consider passive acoustic sensing that can be used to detect low-frequency signatures of natural phenomena (e.g. thunder, turbulence, etc.), with particular attention to the "ground-effect" acoustic interference patterns that would be sampled by a descending atmospheric probe.

2. Theoretical model of sound propagation in polyatomic gases

In a gas, the classical acoustic attenuation due to viscosity, heat conduction, and diffusion is supplemented by the non-classical absorption associated with molecular relaxation. We model the acoustic wave-number (including the sound speed and attenuation) using the linear acoustics equations involving small fluctuations of pressure p, density ρ, temperature T, particle velocity u, and energy ϵ, written as in Eq. (1). (We assume that diffusion effects are negligible.)

$$\frac{p}{p_0}=\frac{T}{T_0}+\frac{\rho}{\rho_0},\qquad \frac{\partial\rho}{\partial t}+\rho_0\frac{\partial u}{\partial x}=0,$$
$$\frac{\partial u}{\partial t}+\frac{1}{\rho_0}\frac{\partial p}{\partial x}=0,\qquad \frac{\partial\epsilon}{\partial t}-\frac{p_0}{\rho_0^2}\frac{\partial\rho}{\partial t}=0. \tag{1}$$

Here, p_0, T_0, ρ_0 are, respectively, the ambient pressure, temperature, and density. The first equation in (1) is the equation of state. The second, third, and fourth equations express the conservation of mass, momentum, and energy, respectively. The energy fluctuation ϵ depends not only on the acoustic temperature T but also on the fluctuations of the internal temperatures of the relaxing vibrational modes, T_j^{vib} ($j=1,2,\ldots$), of the molecular species forming the gas mixture,

$$\epsilon=c_V T+\sum_j \xi_j c_j^{\text{vib}} T_j^{\text{vib}}, \tag{2}$$

where c_V is the translational isochoric specific heat of the mixture, and c_j^{vib} and ξ_j are, respectively, the internal specific heat and the molar fraction of the jth vibrational mode. The internal temperatures of the vibrational modes ν_j participating in the relaxation process are of the form:

$$\frac{\mathrm{d}T_j^{\text{vib}}}{\mathrm{d}t}=\frac{T-T_j^{\text{vib}}}{\tau_j^{\text{tran}}}+\sum_{k=1,k\neq j}\frac{1}{\tau_{j,k}^{\text{vib}}}\frac{1-\exp(-h\nu_j/k_BT_0)}{1-\exp(-h\nu_k/k_BT_0)}\times\left[\left(T-T_j^{\text{vib}}\right)-\frac{\nu_k}{\nu_j}\left(T-T_k^{\text{vib}}\right)\right], \tag{3}$$

based on single-quantum collisions, where $h=6.626\times10^{-34}$ J s is Planck's constant, and $k_B=1.38\times10^{33}$ J/K is Boltzmann's constant. The relaxation times τ are dependent upon the molecular collision rates and the transition probabilities for molecular excitation/relaxation processes. The kinetic theory of gases provides the collision rates while quantum mechanics provides the transition probabilities. The above equations form an eigenvalue problem that can be solved to determine the acoustic attenuation and sound speed as a function of frequency (Dain and Lueptow, 2001), via an *effective* wave-number given by $k^{\text{eff}}(f)=2\pi f\sqrt{\rho_0 p_0^{-1}c_V^{\text{eff}}(f)c_P(f)^{-1}}$ (Petculescu and Lueptow, 2004, 2005), where f is the acoustic frequency and c_V^{eff} and c_P^{eff} are the complex-valued isochoric and isobaric *effective* specific heats, respectively—fundamental footprints of thermal relaxation phenomena (Herzfeld and Litovitz, 1959). The effective wave-number can also be expressed as $k^{\text{eff}}=(2\pi f)/c-i\alpha_{\text{relax}}$, thus providing the frequency-dependent acoustic phase velocity c and relaxational attenuation α_{relax}. Adding the classical attenuation α_{class}, sound propagation in a relaxing gas is described by the *full* acoustic wave-number, $k_{\text{ac}}=(2\pi f)/c-i[\alpha_{\text{relax}}+\alpha_{\text{class}}]$. The classical attenuation coefficient is calculated based on the gas viscosity η and thermal conductivity κ:

$$\alpha_{\text{class}}=\frac{2\pi^2 f^2}{\rho_0 c^3}\left[\frac{4}{3}\eta+(\gamma-1)\frac{\kappa}{c_P}\right], \tag{4}$$

where c_P is the isobaric specific heat and $\gamma=c_P/c_V$. For a single gas component, the coefficients of viscosity η and thermal conductivity κ are available from tables. For a mixture of gases, however, one needs to calculate the composition-dependent values of the two coefficients. We used generalizations of Wilke's expressions for the viscosity and thermal conductivity of mixtures (Wilke, 1950), namely:

$$A_{\text{mixture}} = \sum_{a=1}^{N} \frac{x_a A_a}{\sum_{b=1}^{N} x_b \phi_{ab}}, \tag{5}$$

where

$$\phi_{ab} \equiv \frac{[1 + \sqrt{\eta_a/\eta_b}(M_b/M_a)^{1/4}]^2}{\sqrt{8(1 + M_a/M_b)}}. \tag{6}$$

Here, A is the desired transport quantity (viscosity η or conductivity κ), N is the total number of components in the mixture, and M_a is the molecular weight of molecule species a. Gas non-ideality corrections are important, especially in the high-pressure environments of Titan (Lindal et al., 1983) and Venus (Herzfeld and Litovitz, 1959, p. 192, non-ideal corrections for CO_2).

3. Acoustics at the surface

The surface atmospheric conditions and compositions considered in the model for the four planets are as follows (from the Planetary Society website, http://www.planetary.org):

Venus: 730 K, 90 atm 96% CO_2, 3.5% N_2, 150 ppm SO_2;
Mars: 220 K, 0.007 atm 95% CO_2, 2.7% N_2, 1.6% Ar, 0.13% O_2;
Titan: 95 K, 1.6 atm 95% N_2, 5% CH_4;
Earth: 290 K, 1 atm 77% N_2, 21% O_2, 1% H_2O.

Trace gases were omitted from the analysis. The thermodynamic and molecular properties of the gas species were taken from the National Institute for Standards and Technology (NIST) database (http://webbook.nist.gov).

The model predictions for the frequency-dependent sound speed and acoustic attenuation in the surface atmospheres of Venus, Mars, Titan, and Earth are shown in Fig. 1. Inflection points in both sound speed and attenuation indicate the presence of molecular relaxation processes. Titan's cold nitrogen-rich environment inhibits the collisional exchange of energy between external and internal molecular degrees of freedom. This makes thermal and viscous effects the dominant source of attenuation, imposing a quadratic frequency dependence. Titan's atmosphere absorbs the least acoustic energy at all frequencies. The CO_2-dominated martian environment has the highest absorption coefficient of the four planets at all frequencies except in the 1–10 kHz window where it is comparable to that of Venus' atmosphere. On Venus, due to the elevated temperature, relaxational effects extend well into the MHz range, as indicated by the presence of the two attenuation inflection points. The environment of Venus is acoustically the "fastest," while Titan's atmosphere is the "slowest." Even though Mars and Venus have similar atmospheric compositions, the large difference in their temperatures plays a major role in 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 that are critical in setting the resolution of sound speed measurements.

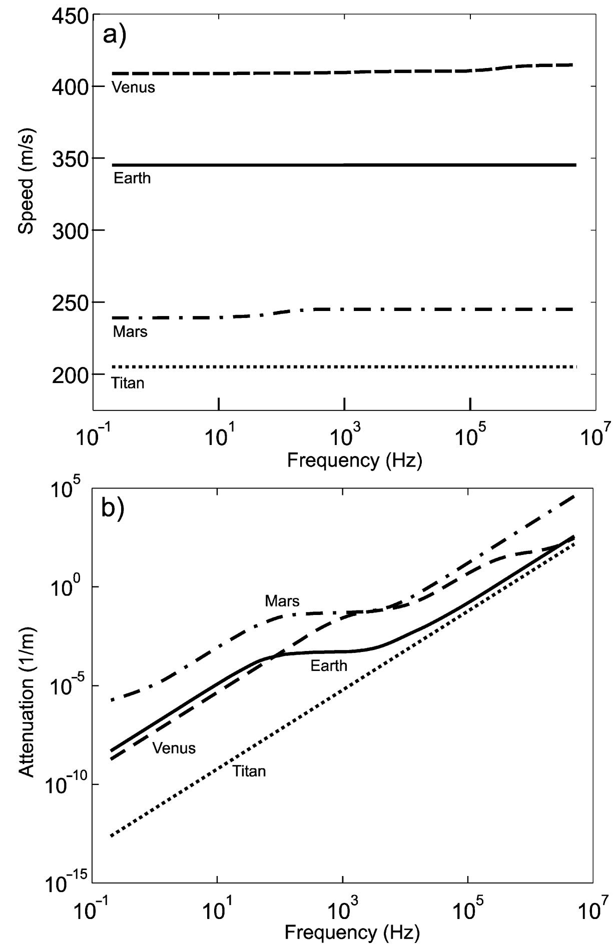

Fig. 1. Frequency dependence of the (a) sound speed and (b) attenuation coefficient at the surfaces of the four planets.

4. Characteristic acoustic impedance

Attenuation and phase velocity characterize the *propagation* of sound waves in a given medium via the wave-number. When developing sensing applications, the capacity of the medium to *sustain* pressure waves must also be considered at the outset, since it is this property that dictates how much acoustic energy can be coupled into and out of the medium. This coupling property is embodied by the fluid's complex-valued *characteristic acoustic impedance*, $Z_{\text{ac}} \equiv p/u$, where p and u are, respectively, the instantaneous pressure and particle speed. For plane waves, p and u are in phase and $Z_{\text{ac}} = \rho_0 c$. The characteristic impedance is important for propagation across the interface between two different media: Z_{ac} is a measure of the reaction force between the two media. Earth and Mars stand out as the least "acoustically responsive," with Z_{ac} of 407 and 4.439 $\text{kg/m}^2\,\text{s}$, respectively, at the surface. The almost two orders of magnitude discrepancy between their acoustic impedances translate into signals on Mars being 20 dB weaker than on Earth, if produced by the same source, not accounting for propagation losses. Titan has $Z_{\text{ac}} = 1186\ \text{kg/m}^2\,\text{s}$, while Venus' high surface pressure makes its characteristic acoustic impedance $Z_{\text{ac}} = 26960\ \text{kg/m}^2\,\text{s}$. Ignoring attenuation, signals on Titan and Venus would be 10 and 20 dB, respec-

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tively, stronger than on Earth, due to the impedance difference. A sense of scale for the impedance can be conveyed by noting that Z_{ac} is $\sim 1.5 \times 10^5$ kg/m^2 s for water and is of order 10^7 kg/m^2 s for piezoelectric crystals or ceramics.

5. Vertical acoustic profiles

Acoustic anemometry, sound speed measurement, and small-scale turbulence characterization rely on active sensors operating at frequencies >10 kHz. The path lengths involved in these applications are short, of the order of 1 m, imposed by space restrictions on the spacecraft. We assume that sound waves of 15 kHz—the operating frequency of the active sensors of the Huygens Surface Science Package (Zarnecki et al., 1997)—are generated by a transducer element whose surface vibration amplitude is 1 nm, typical for piezoelectric emitters. A measure of acoustic intensity is the *sound pressure level* (SPL), defined as $\mathrm{SPL} = 20\log_{10}|p(r)/p_{\mathrm{ref}}|$, where $p(r)$ is the pressure amplitude at distance r, including attenuation, and $p_{\mathrm{ref}} = 20$ μPa. Over the 1-m sensing path, SPL drops imperceptibly for Earth (from 65.686 to 65.634 dB) and Titan (from 88.664 to 88.650 dB), while on Venus the SPL drop is also fairly small (from 101.983 to 100.406 dB). The highly absorptive environment of Mars induces a much larger change (from 26.512 to 22.995 dB).

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. Fig. 2 shows the vertical atmospheric profiles for sound speed (a) and acoustic attenuation (b) at 15 kHz. The profiles were calculated based on altitude-dependent pressure, temperature, and density values extracted from general circulation models for Titan (Rannou et al., 2005) (online database at http://www.lmd.jussieu.fr/titanDbase), Mars (Forget et al., 1999; Lewis et al., 1999) (online database at http://www-mars.lmd.jussieu.fr), and Earth (online database at http://www.spenvis.oma.be). For Venus, radio occultation data above 35 km (Jenkins et al., 1994) were used. For all planets, the local sound speed values were used. For Mars, Titan, and Earth the profiles at the Equator and the North pole are shown. No coordinate-dependent data could be found for Venus. The martian profiles correspond to a scenario based on the presence of atmospheric dust as observed by Mars Global Surveyor. In a no-dust "cold" scenario at the equator (not shown), the inversion point at ∼55 km is shifted to ∼38 km. On Venus, the small-scale sound speed fluctuations occurring above 60 km are likely caused by gravity waves. The sound speed profiles are a mirror of and therefore can be used to probe the atmospheric structure. For example, inversion layers are evident for Earth (∼18 km at the equator and ∼25 km at the North pole), Titan (∼55 km), and Mars (∼55 km at the equator and ∼30 km at the North pole). Very close to the martian surface, the non-adiabatic temperature lapse rate, manifested by the sharp increase in the sound speed over the first few hundred meters, is probably linked to the atmospheric boundary layer (Christensen et al., 2001). Unlike sound speed profiles, attenuation profiles are fairly smooth functions of altitude except Venus, where the attenuation drops substantially above 40 km before increasing at higher altitudes.

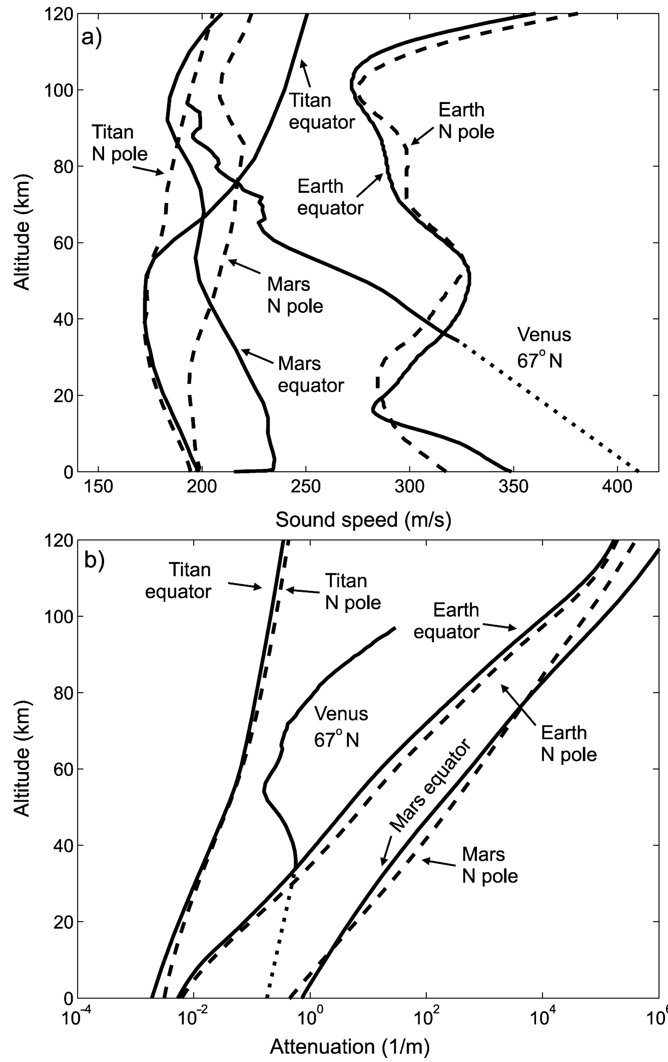

Fig. 2. Vertical acoustic profiles at $f = 15$ kHz. (a) Sound speed profiles. The large sound speed swings, brought about largely by the temperature variability, mirror the atmospheric structure. (b) Attenuation profiles.

6. Low-frequency passive sensing

Microphones can be used as passive sensors to detect low-frequency sound produced by natural phenomena. Close to the ground, the propagation of low-frequency waves is affected by interference between the direct and specularly reflected waves (Attenborough, 2002). Consider a probe during final descent, whose passive sensors monitor a 100 Hz "acoustic event" produced by a unit-amplitude point source at $z_s = 50$ m above ground and at distance r from the probe. (This is not a far-fetched scenario for thunder, since most acoustic energy released by cloud-to-ground lightning is assumed to originate less than 100 m above the surface at frequencies below 200 Hz (Ribner and Roy, 1982). Nevertheless, such low-frequency "events" may very well be generated by other factors such as atmospheric turbulence or meteorites.) To illustrate, the long-range ($r \gg z_s$) acoustic pressure amplitude is, assuming propagation above a locally reacting porous surface (Attenborough, 2002),

$$p(r) = \frac{e^{ik(z)R_1}}{R_1} + \left[R_p + (1 - R_p)F\right]\frac{e^{ik(z)R_2}}{R_2}. \tag{7}$$

The source is located at $(x = 0, y = 0, z = z_s)$. $R_1 = \sqrt{r_{\mathrm{horz}}^2 + (z - z_s)^2}$ and $R_2 = \sqrt{r_{\mathrm{horz}}^2 + (z + z_s)^2}$ are, respectively, the distances from the source and its mirror image to the "field" point (i.e. spacecraft location) $\mathbf{r} = (x, y, z)$, $r_{\mathrm{horz}} = (x, y)$ being the horizontal range; $R_p = (\cos\theta_i - \beta)/(\cos\theta_i + \beta)$ is the plane-wave pressure reflection coefficient, θ_i is the local incidence angle (varying with altitude), and β is the complex normalized acoustic admittance of the surface, $\beta = Z_{\mathrm{air}}/Z_{\mathrm{surface}}$. Taking the surface impedance equal to that of coarse ("gravelly") sand, $Z_{\mathrm{surface}} = 3.647 \times 10^6\ \mathrm{kg/m^2\,s}$ (Hamilton, 1972), one has: $\beta_{\mathrm{Earth}} = 1.1164 \times 10^{-4}$, $\beta_{\mathrm{Mars}} = 1.2171 \times 10^{-6}$, $\beta_{\mathrm{Titan}} = 3.2527 \times 10^{-4}$, $\beta_{\mathrm{Venus}} = 0.0074$. F is the "boundary loss factor," given by $F = 1 + i\sqrt{\pi}\,w \exp(-w^2)\,\mathrm{erfc}(-iw)$ where $w = 0.5(1 + i)\sqrt{kR_2(\cos\theta_i + \beta)}$ (Attenborough, 2002). The bracketed factor in Eq (7) is the spherical-wave reflection coefficient.

To obtain the acoustic pressure at a particular location, the sound is propagated through the vertically non-homogeneous atmosphere using the local conditions of temperature, pressure, and gas composition based on the atmospheric circulation models, which provide local conditions in altitude increments δz on the order of a few hundred meters (as set by the databases providing the temperature, pressure, and density profiles). The horizontal variations in temperature, pressure and composition are assumed to be negligible. The sound starts at the source and propagates through the atmosphere at the local atmospheric conditions near the source, reflected in the initial value of the complex wavenumber $k(z_i)$, until it reaches the boundary between those atmospheric conditions and the conditions at the next step in altitude. Then sound continues to propagate through the next atmospheric layer using the appropriate local complex wavenumber $k(z_i + \delta z)$ and so on until the sound reaches the final elevation z_f. In this way, the integrated effect of the vertically varying local atmospheric conditions on the sound propagation are included in the model. Fig. 3 shows the long-range SPL distribution, produced by the simple source described above, for the four planets as a function of altitude (z) and range (r_{horz}). A probe descending in the atmospheres of Titan, Venus, or Earth would traverse narrow low-signal "strips" that would affect the potential for detecting low-frequency acoustic phenomena. This is not simply an interference pattern. Instead, it represents the effect of the local atmospheric conditions (including the local changes in temperature, pressure, and

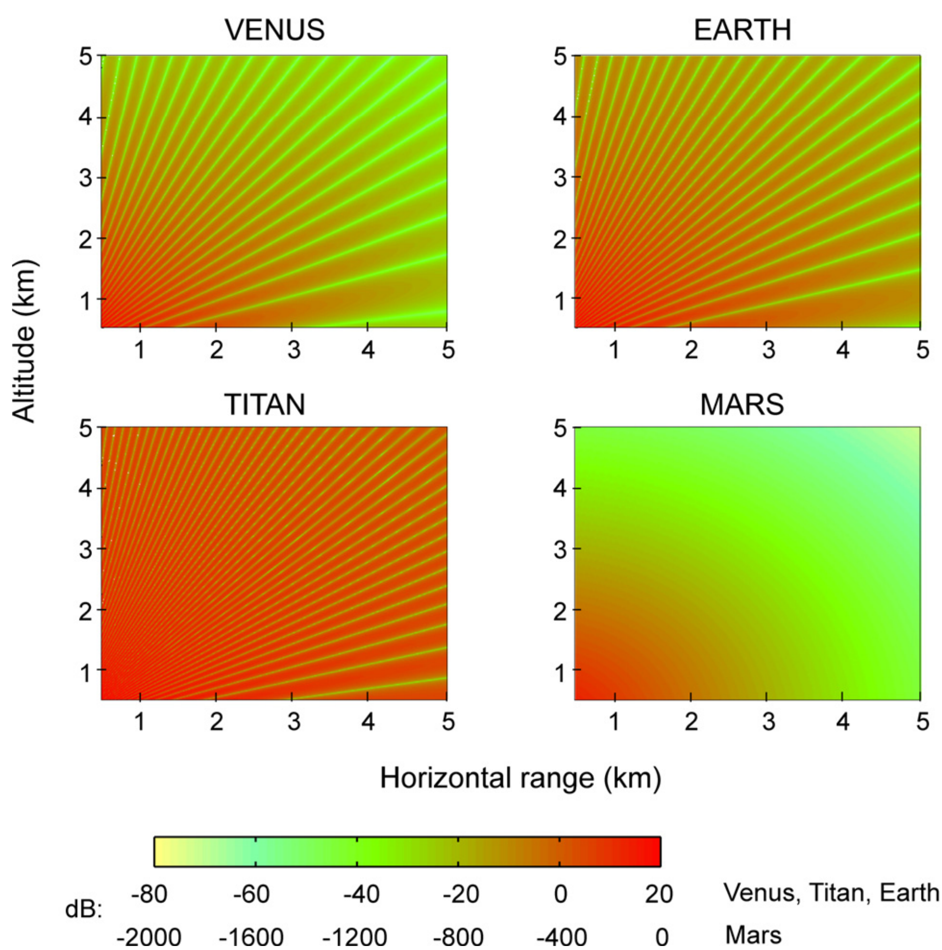

Fig. 3. Sound pressure level distribution for the long-range propagation of a 100 Hz signal produced by a simple acoustic source 50 m above the surface, on the four planets (note the different dB scale for Mars, due to the high attenuation). The "ground effect" wave interference leads to the low-intensity "strips."

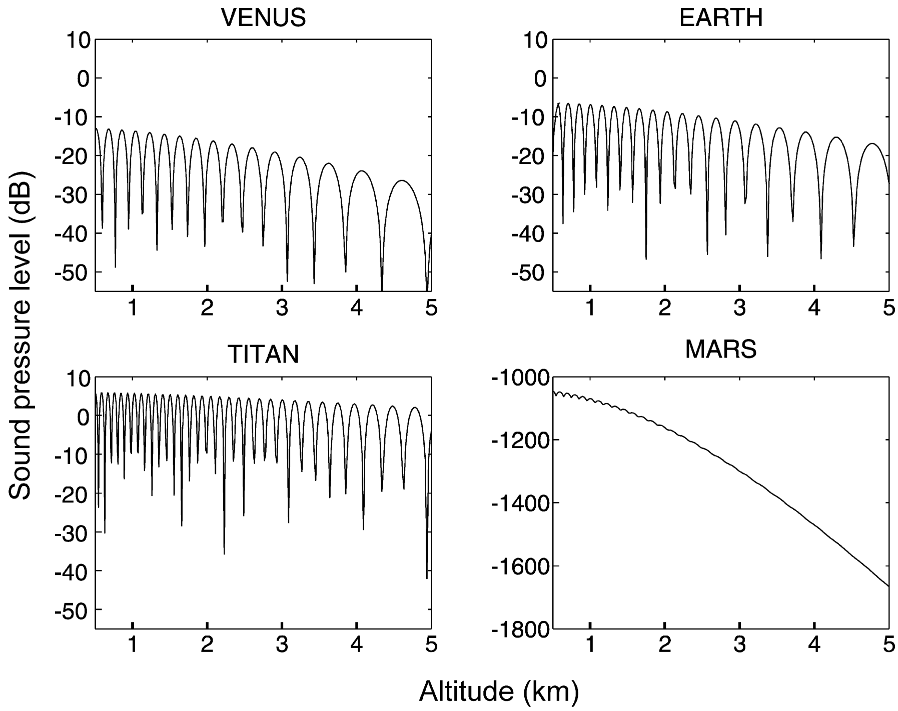

Fig. 4. Vertical slices from Fig. 3 showing the sound pressure level as a function of altitude at $r_{\text{horz}} = 4$ km. Acoustically, the environment of Mars is the "coldest," while Titan's is the "hottest."

density with altitude) in addition to interference on the propagation of sound from a source to any "field" point. A vertical slice through each plot ($r_{\text{horz}} = \text{const}$) corresponds to the descent probe sampling the acoustic field at a particular horizontal range away from the source. Fig. 4 shows the SPL at $r_{\text{horz}} = 4000$ m. The interplay between the different 100-Hz surface attenuation coefficients ($\alpha_{\text{Mars}} = 0.030\ \text{m}^{-1}$, $\alpha_{\text{Titan}} = 4.878 \times 10^{-8}\ \text{m}^{-1}$, $\alpha_{\text{Venus}} = 4.645 \times 10^{-4}\ \text{m}^{-1}$, $\alpha_{\text{Earth}} = 3.478 \times 10^{-4}\ \text{m}^{-1}$) and acoustic impedances ($Z_{\text{Mars}} = 4.439\ \text{kg/m}^2\,\text{s}$, $Z_{\text{Titan}} = 1.186 \times 10^3\ \text{kg/m}^2\,\text{s}$, $Z_{\text{Venus}} = 26.96 \times 10^3\ \text{kg/m}^2\,\text{s}$, $Z_{\text{Earth}} = 407\ \text{kg/m}^2\,\text{s}$) makes the atmosphere of Mars acoustically the "coldest" and that of Titan the "hottest." The number of intensity minima encountered by the descending probe varies depending on the atmospheres considered. This is caused by the different sound speeds (Fig. 1) translating into different acoustic wavelengths (Venus: 4.09 m; Earth: 3.45 m; Mars: 2.43 m, Titan: 2.05 m) at 100 Hz. Assuming that the duration of the 100 Hz "event" is on the order of seconds, the probe, during its descent, will pass through narrow areas of very low signal—"quiet" zones—as it crosses the intensity minima. The probe's descent speed and the vertical spacing between minima in Fig. 3 would dictate the time available to sample the sound field without significant signal losses. For very short events, Fig. 3 shows that the probe could find itself in a quiet zone and thus unable to detect the event.

7. Summary

Sound propagation in a planet's atmosphere is a mirror of atmospheric dynamics, structure, and composition. Despite their potential, acoustic techniques for sensing planetary environments have been relatively overlooked by the scientific community. As demonstrated by the *Cassini–Huygens* mission, acoustic sensors have their own niche in quantifying and monitoring the descent and landing environments. Such sensors can be passive in the form of microphones that record ambient sounds, or active such as would be implemented in wind velocity sensing (sonic anemometry) or sound speed measurement. We show, through several examples based on a physical model of acoustic relaxation in polyatomic gases, the benefits and implications of incorporating acoustic sensors in future planetary missions. The techniques described here were applied at specific planetary latitudes (North pole and equator). However, these methods can be readily used to predict the physical acoustic properties at any location for which the atmospheric pressure, temperature, and composition are known.

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