THE SOUND OF MUSIC AND VOICES IN SPACE PART 2: MODELING AND SIMULATION

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As is shown in the paper, atmospheres affect both the generation and the propagation of sound. The effect on sound generation, depending on the actual source mechanisms that we exemplify by organ music and speech is two-pronged—the acoustic characteristics are altered not only by the nature of the gas but also by mass loading of the source. For the propagation of sound, the atmospheres act as frequency-dependent "filters," characteristic of the composition and ambient conditions of each planet.

Acoustic generation and fluid loading

The influence of an atmosphere on a sound source was studied based on two considerations. Firstly, both an organ pipe and the vocal cavity can be regarded as resonators. The resonance frequencies depend linearly on the sound speed in the gas in which they vibrate. Thus, at the outset (i.e., before propagating the waveforms), we adjusted the frequencies of the relevant features according to the predicted sound speeds for the atmospheres of Venus, Mars, and Titan (the pitch of the flue organ pipe scales with the sound speed, but for the voice only the frequencies associated with the vocal tract resonances are scaled, leaving the voice pitch unaltered at this stage). Then, secondly, one considers the mass loading of the resonator by the surrounding atmosphere, which introduces an additional relative frequency shift calculated[1,2] as

$$\frac{\Delta f}{f_0} = \sqrt{\frac{m}{m + m_{rad}}} - 1 \qquad (1)$$

Here Δf is the actual frequency change, f_0 is the resonance frequency in the absence of fluid loading, m is the inertial mass of the vibrating structure, and m_{rad} is the correction due to fluid loading, called the radiation mass. The results for the vocal tract of a child,[2] show that a D (f = 293.66 Hz) at Earth's surface is still an approximate D (f = 301.08 Hz) on Mars, but is shifted down close to a D# (f = 158.75 Hz) on Venus and close to a C # (f = 272.70 Hz) on Titan. Fluid loading influences speech much more than it does organ pipes. To emphasize the effect that mass loading has on the generation of sound by sources similar to the vocal cavity, we show speech samples before and after fluid loading was accounted for.

Acoustic propagation

The "filtering" effects of the different environments studied (Earth, Mars, Titan, and Venus) on sound propagation were simulated using a physical model of acoustic wave motion in multi-component gas mixtures. Combining thermo-viscous coupling and vibrational relaxation, the model predicts[3] a frequency-dependent effective wave-number

$$k^{eff}(f) = 2\pi f \sqrt{\frac{\rho_0}{p_0} \frac{C_V^{eff}(f)}{C_P^{eff}(f)}}, \qquad (2)$$

from which the attenuation, α, and speed of sound, c, can be computed at each frequency, respectively, as $\alpha = \text{Im}(k^{eff}) + \alpha_{class}$ and $c = 2\pi f\ /\text{Re}(k^{eff})$, where α_{class} is the classical attenuation coefficient due to thermal, viscous, and diffusional transport, ρ_0 and p_0 are, respectively, the ambient density and pressure, and C_P^{eff} and C_V^{eff} are the effective isobaric and isochoric specific heats. The thermophysical quantities (e.g., specific heats, viscosity, and thermal conductivity) were interpolated at the ambient conditions (composition, pressure, and temperature) of the surface of each planet.[4] The atmospheric effect on sound propagation is to introduce selective attenuation and, to a smaller degree, dispersion, to the frequency content of the initial waveform. As the waveform propagates, it is progressively altered by the atmospheric "filter." These effects can be heard in the music files, which simulate how the Bach fragment behaves at various distances from the source.

Organization of the media files

The media files associated with the article are organized as follows. Table 1 sets the stage. Table 1 contains a calibration tone at 97 dB re 2 μPa. A short clip of the organ solo (played on the organ in St. Margaret's Church, East Wellow, Hampshire, United Kingdom), the words, *Earth, Mars, Titan* and *Venus* are then spoken and are used in the next three tables to illustrate how each might sound at the distances indicated and on each of the locations. The last example in Table 2 illustrates how all the organ clips would sound if played together. Note: If the sound becomes inaudible, it is due to the attenuation of the particular atmosphere. Do not continually adjust the volume to hear the sound.

Directions to download the *interactive* Tables and play the media files

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Table 1. Audio/video sound-source files

97dB Calibration	"Organ"	"Mars"	"Titan"	"Venus"

Unaltered sound-source files that illustrate the recorded music and speech that were processed to simulate the off-world sounds. The announcers are Ms. Rhiannon Leighton and Mr. Rhys Leighton. The organist is Timothy Leighton. These audio/video clips were recorded in QuickTime's .MOV format. If you have difficulty in playing them, you might download the PC or MAC version of *VLC Media Player* from www.videolan.org. This is a non-profit organization that has created a very powerful, cross-platform, free and open source player that works with almost all video and audio formats. To appreciate the effects simulated, it is best not to change the sound level between examples. (For example, Mars has very high attenuation. If you don't hear anything beyond a given distance, it is actually there, but very, very soft.) The audio clips in Tables 2, 3, and 4 were recorded in .MP3 format. Again, you might use the *VLC Media Player* if you are having problems.

Table 2. Organ music, as heard on the location indicated, at the distances indicated.

@1 meter	@10 meters	@20 meters	@50 meters	@100 meters
Earth_Organ_1	Earth_Organ_10	Earth_Organ_20	Earth_Organ_50	Earth_Organ_100
Mars_Organ_1	Mars_Organ_10	Mars_Organ_20	Mars_Organ_50	Mars_Organ_100
Titan_Organ_1	Titan_Organ_10	Titan_Organ_20	Titan_Organ_50	Titan_Organ_100
Venus_Organ_1	Venus_Organ_10	Venus_Organ_20	Venus_Organ_50	Venus_Organ_100
All_Organs_1				

Table 3. Speech files without fluid loading or size effects.

@1 meter	@10 meters	@20 meters	@50 meters	@100 meters
Earth_Speech_1	Earth_Speech_10	Earth_Speech_20	Earth_Speech_50	Earth_Speech_100
Mars_Speech_1	Mars_Speech_10	Mars_Speech_20	Mars_Speech_50	Mars_Speech_100
Titan_Speech_1	Titan_Speech_10	Titan_Speech_20	Titan_Speech_50	Titan_Speech_100
Venus_Speech_1	Venus_Speech_10	Venus_Speech_20	Venus_Speech_50	Venus_Speech_100

Table 4. Speech files with fluid loading and size effects

1 meter	@10 meters	@20 meters	@50 meters	@100 meters
Mars_SpchL_1	Mars_SpchL_10	Mars_SpchL_20	Mars_SpchL_50	Mars_SpchL_100
Titan_SpchL_1	Titan_SpchL_10	Titan_SpchL_20	Titan_SpchL_50	Titan_SpchL_100
Venus_SpchL_1	Venus_SpchL_10	Venus_SpchL_20	Venus_SpchL_50	Venus_SpchL_100

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"00_OpenMe" It is an interactive pdf file that should look exactly like the tables in the article. Leave it as a pdf file in the LeightonData folder and by clicking on any of the files in the tables they should open. Table 1 contains audio/visual clips (except for the calibration that is audio only), while Tables 2-4 are simulated audio clips. Questions? Email the Scitation Help Desk at help@scitation.org or call 1-800-874-6383.

References to Part 2

1 T. G. Leighton, "Fluid loading effects for acoustical sensors in the atmospheres of Mars, Venus, Titan and Jupiter," JASA Express Letters **125**, EL214–EL219 (2009).

2 T. G. Leighton, "The effect of fluid loading on the generation of extraterrestrial sound," ISVR Technical Report No. 325 University of Southampton (2008).

3 A. Petculescu and R. M. Lueptow, "Synthesizing primary molecular relaxation processes in excitable gases using a two-frequency reconstructive algorithm," Physical Rev. Letters **94**, 238301 (2005).

4 A. Petculescu and R. M. Lueptow, "Atmospheric acoustics of Titan, Mars, Venus, and Earth," Icarus **186**, 413–419 (2007).