Infrasonic Acoustic Wave Propagation in Terrestrial Planetary Atmospheres

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Abstract

Through the use of a one-dimensional, nonlinear, compressible planetary atmospheric acoustics model, this study performs investigations of propagating infrasonic acoustic waves through the mesospheres and thermospheres of three terrestrial planets - Earth, Mars, and Venus - in order to quantify the propagation, growth, and dissipation of waves on these planets. Due to their greatly differing ambient conditions and atmospheric compositions, which are here provided by the NASA Global Reference Atmosphere Models (GRAM) [Leslie and Justus, 2011; Justus and Johnson, 2001; Justh et al., 2006], there is significant variation in the behavior of atmospheric acoustic waves, which will be assessed in this study. Furthermore, the effects of propagating infrasonic acoustic waves on neutral atmospheric and D-region ionospheric species layers [Snively, 2013; Marshall and Snively, 2014] are investigated. We assess the observability of naturally-occurring acoustic wave phenomena in the upper-atmospheres of these terrestrial planets. We also assess the potential implications of varied solar and thermospheric conditions on measurable atmospheric acoustic disturbances.

Numerical Model Formulation

This modeling makes use of the nonlinear compressible Euler equations with gravity, which, derived from the Navier-Stokes equation, describe the conservation of mass, momentum, and energy of a system.

One-Dimensional Euler Equations:

$$\frac{\partial \rho}{\partial t} = \frac{\partial (\rho u)}{\partial z} = 0$$

$$\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial z} = -\frac{\partial p}{\partial z} + \rho g$$

$$\frac{\partial E}{\partial t} + \frac{\partial (u(E+p))}{\partial z} = -\rho g u$$

$$E = \frac{p}{(\gamma - 1)} + \frac{1}{2}\rho u^2$$

These equations are solved using a two-step Richtmyer Lax-Wendroff method for advection. This method is an explicit forward-in-time, centered-in-space method that utilizes three time steps to achieve the final result.

Diffusive source terms are also added in order to simulate molecular viscosity and thermal diffusion in the dissipation of propagating atmospheric waves. These are solved using an implicit Euler method for diffusion.

Kinematic Viscosity and Thermal Conduction:

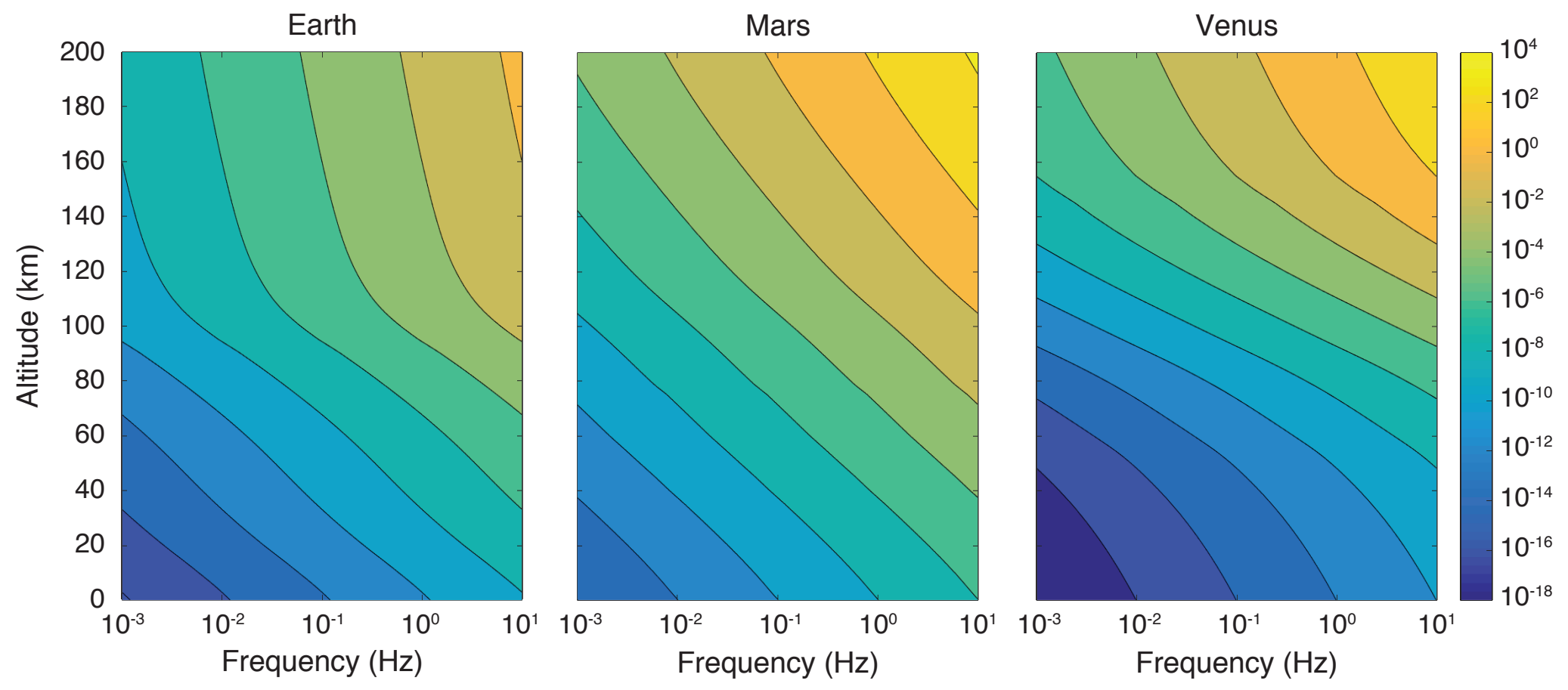
$$\frac{\partial u}{\partial t} = \frac{4\nu}{3}\frac{\partial^2 u}{\partial z^2} \qquad \frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2}$$

Wave Forcing (at the bottom boundary):

$$u(t) = A e^{-t^2/2\sigma^2} \sin(\omega t)$$

The absorption of acoustic waves due to viscosity and thermal conduction is given by the classical absorption coefficient (in Np/m) [*Bass and Chambers*, 2001]:

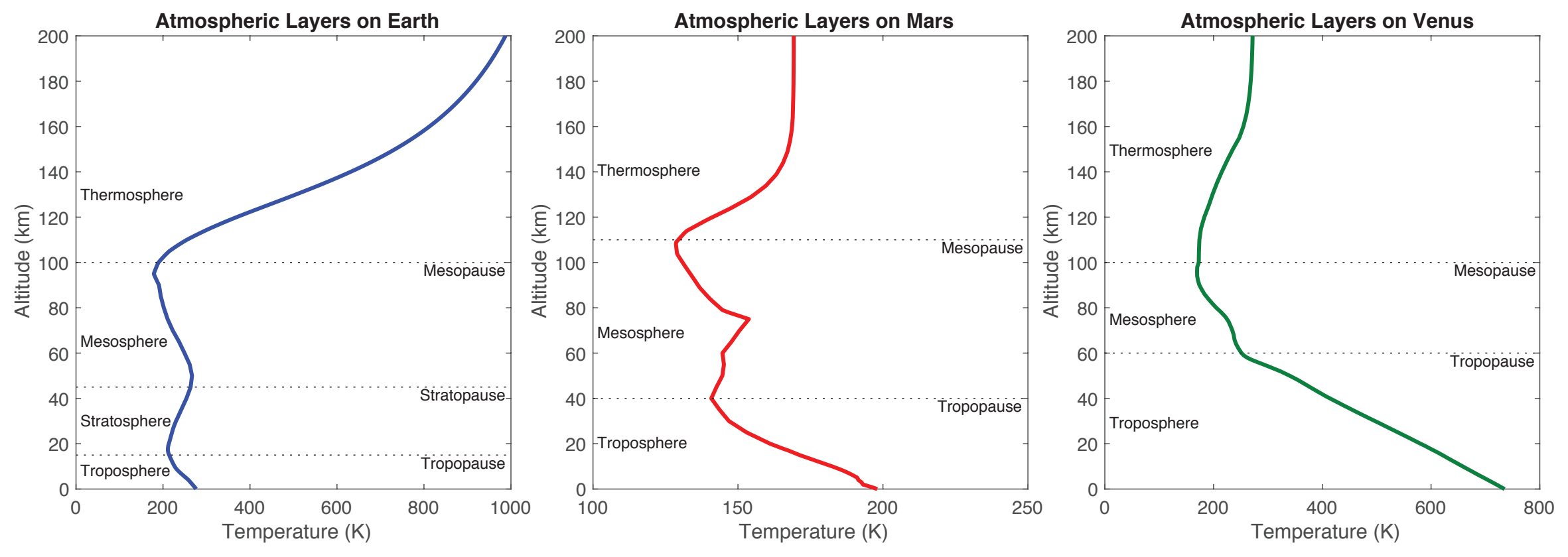
$$\alpha_c = \frac{2\pi^2 f^2 \mu}{\gamma p_0 c_s}\left[\frac{4}{3} + \frac{15(\gamma - 1)}{4\gamma}\left(\frac{4}{15} + \frac{3R^*}{5C_v}\right)\right]$$

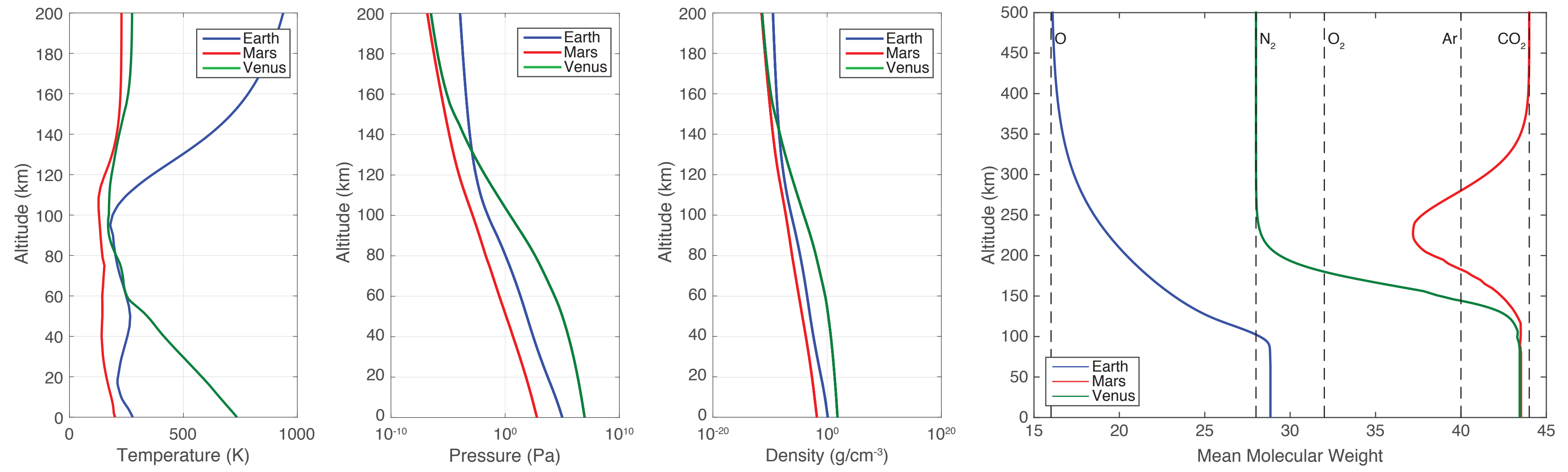


Comparative Aeronomy of Earth, Mars, and Venus

The three major terrestrial planets of our solar system, Earth, Venus, and Mars, will be considered, as they each possess a gravitationally-stratified atmosphere consisting of similar gaseous species and layered thermal structure. Nonetheless, intrinsic characteristics of the atmospheres differ greatly; for example, Venus has an incredibly dense, high-pressure atmosphere, while Mars' is very tenuous, and Earth lies somewhere in between. Due to their similarities, it is reasonable to consider that physical dynamic properties, such as the propagation and attenuation of atmospheric acoustic waves, will behave similarly, however notable contrasts are expected.

Background profiles were specified by the Earth, Mars, and Venus Global Reference Atmospheric Models (EarthGRAM 2010, MarsGRAM 2010, and VenusGRAM 2005) throughout this investigation. These models are provided by NASA Marshall Space Flight Center. [Leslie and Justus, 2011; Justus and Johnson, 2001; Justh et al., 2006]

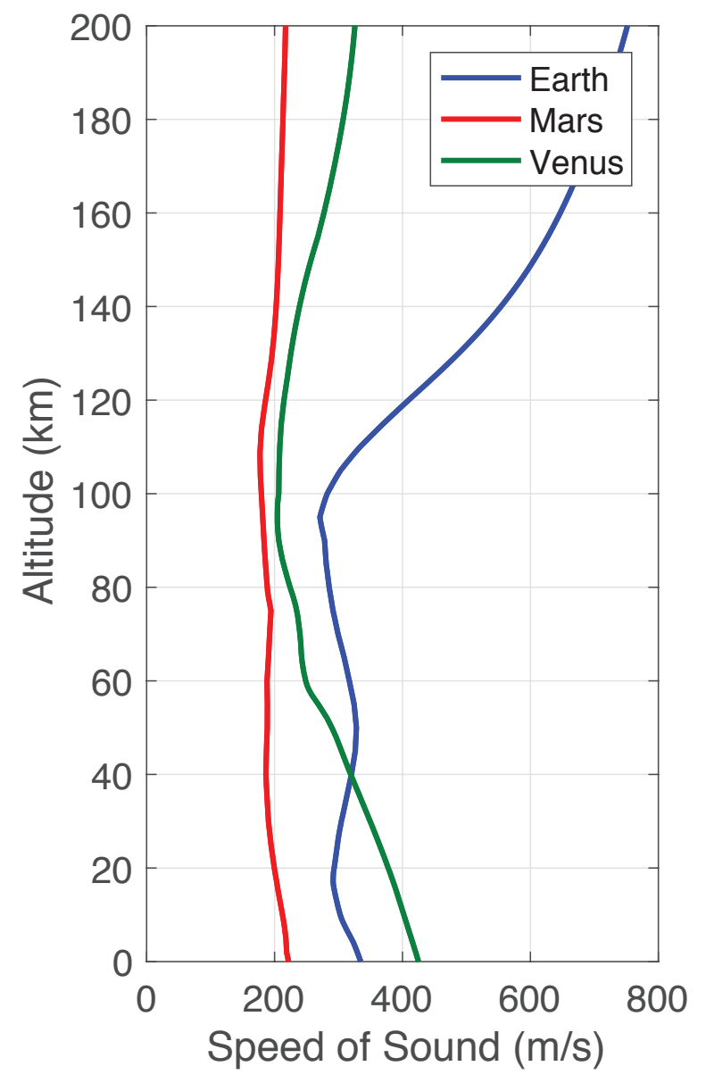




Above: A planet's atmospheric mass is, by definition, vertically stratified due to the compressibility of air [Salby, 1996]. Most stratified atmospheres contain three main layers, as defined by the variation of temperature and density with altitude. These are the troposphere, mesosphere, and thermosphere. Some planets have additional layers due to anomalies in their profiles; for example, Earth possesses a region of heating between about 20 and 40 kilometers, due to its ozone abundance, which not found on other terrestrial planets - this layer is called the stratosphere. Aside from extraneous regions such as Earth's stratosphere, most planetary thermal regions are analogous to one another, allowing for the universal application of the terms originally used to identify regions in our own atmosphere [Mueller-Wodarg et al., 2008].

Properties of Atmospheric Acoustic Waves

Periodic disturbances in the atmosphere above the Brunt-Väisälä Frequency produce short-period acoustic waves which move through the upper-atmosphere. These waves cause large compressions in the atmosphere at infrasonic frequencies, which propagate upward and dissipate at high altitudes [Blackstock, 2000]. The propagation and dissipation of infrasonic (< 10 Hz) acoustic waves is directly related to atmospheric properties, such as temperature, density, pressure, viscosity, etc. that affect major parameters, such as the speed of sound [Kinsler et al., 2000].

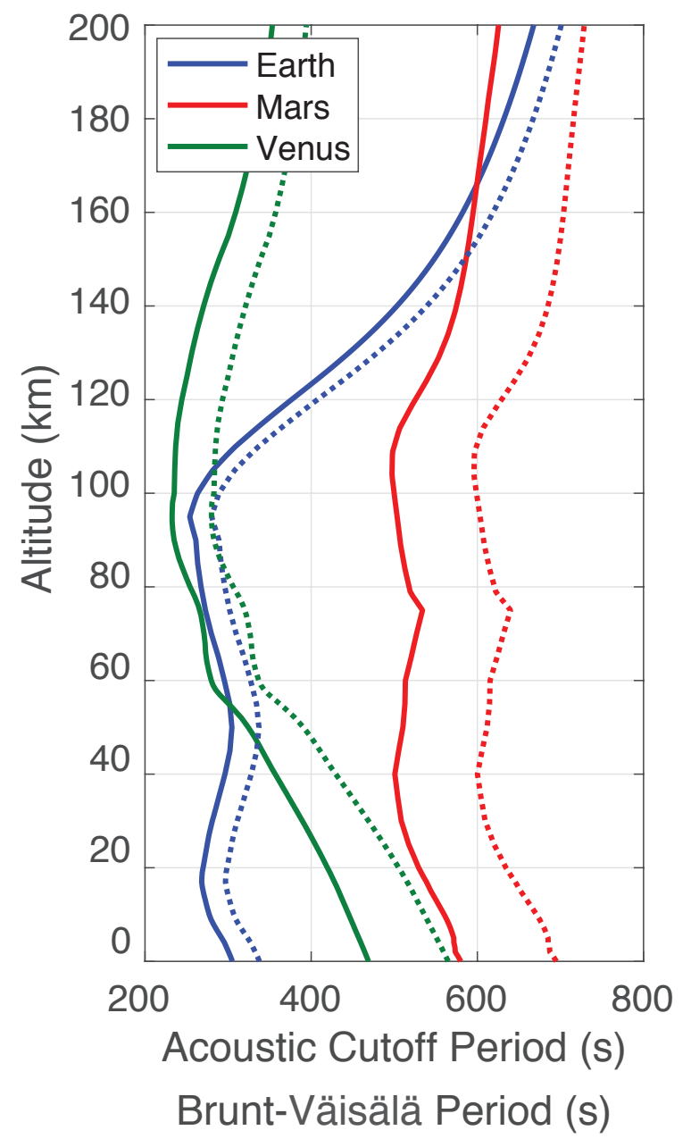


Left: The speed of sound dictates the velocity of propagating acoustic waves in the atmosphere, and is directly related to temperature and chemical composition.

$$c_s = \sqrt{\gamma R T}$$

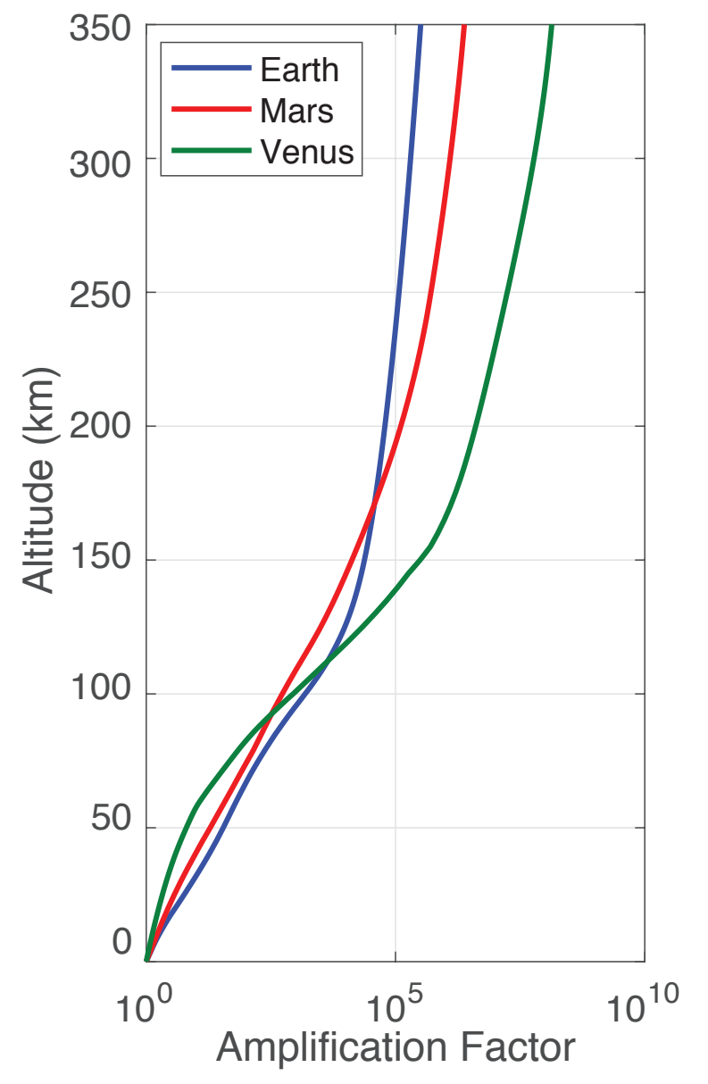
Right: The acoustic cutoff period (solid) represents the largest possible period of a propagating acoustic wave in the atmosphere.
The Brunt-Väisälä period (dotted) is the period at which a parcel displaced vertically in a stratified atmosphere will naturally oscillate.

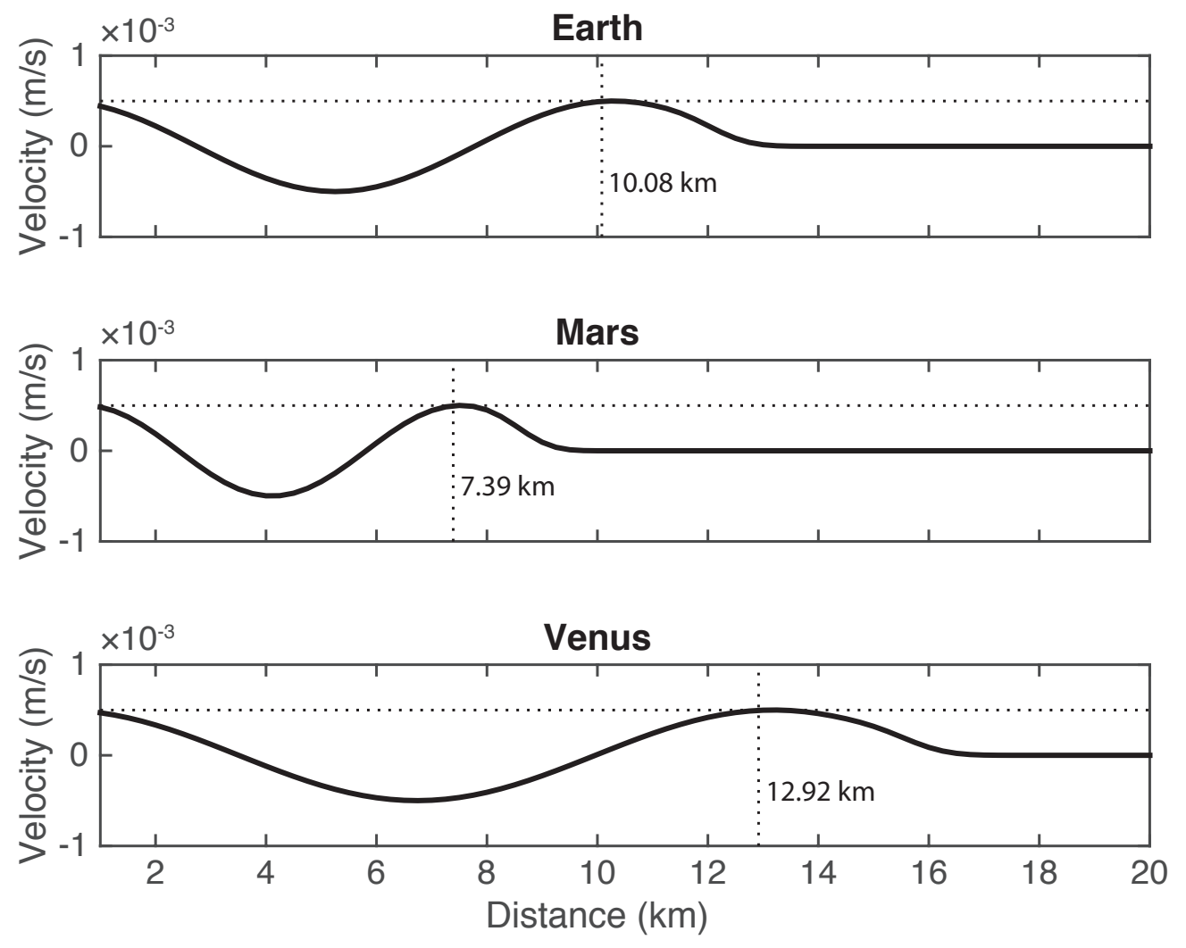
$$\tau_0 = \frac{4\pi c_s}{g\gamma} \qquad \tau_N \simeq \sqrt{\frac{2\pi c_s}{g^2(\gamma - 1)}}$$



Below: The largest contributor to the growth of acoustic waves with increasing altitude is decreasing density in the atmosphere [Garcia et al., 2005]

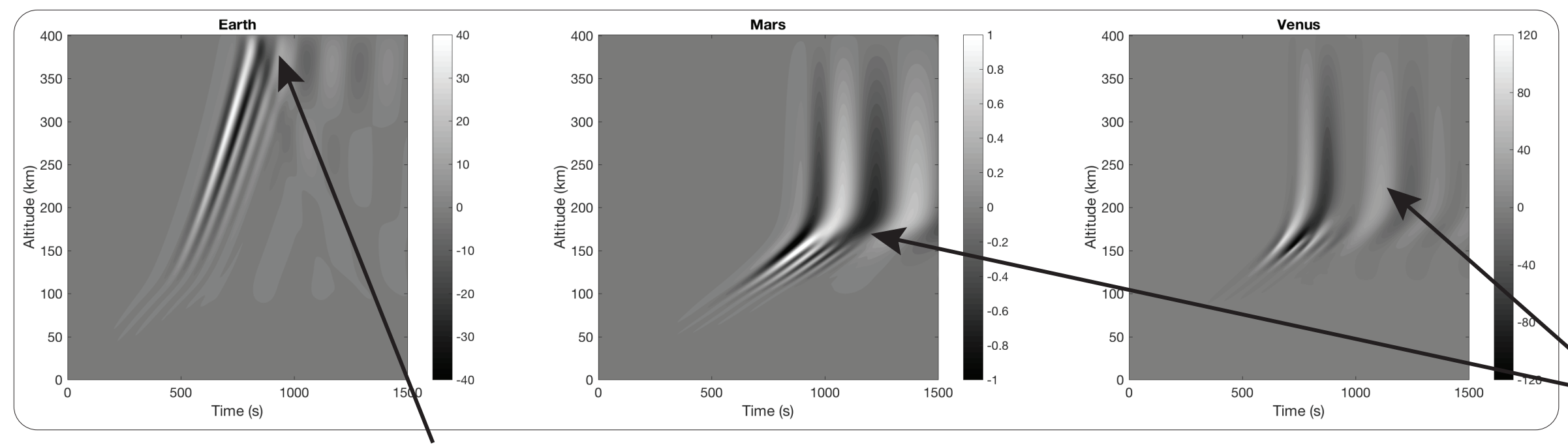
$$\sqrt{\frac{\rho_0}{\rho}}$$





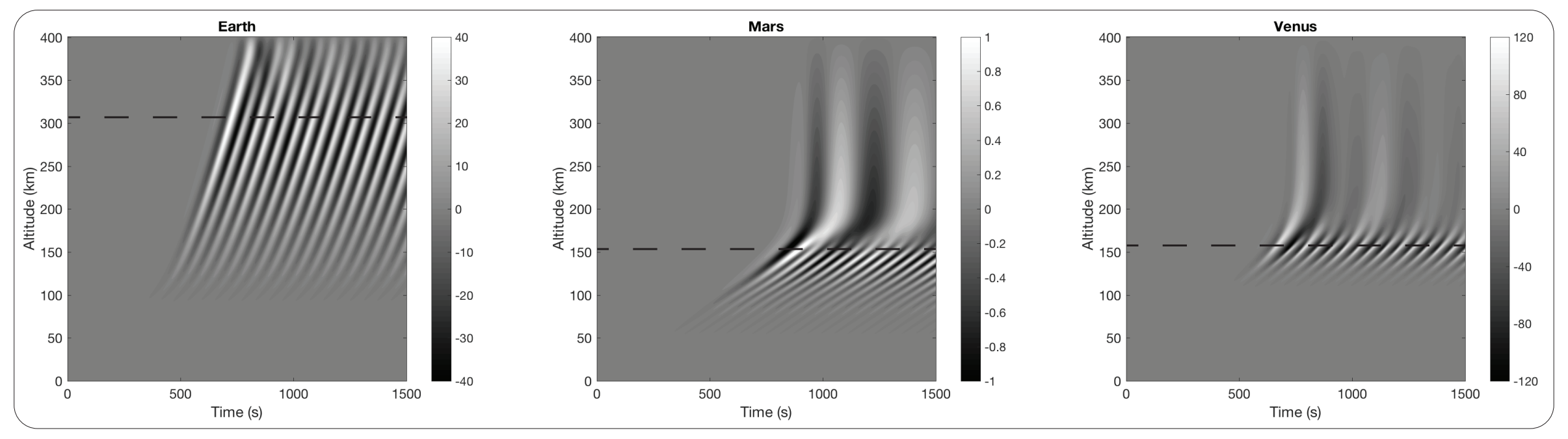
Above: In order to validate that the model produces waves of the correct scale, a thirty-second acoustic wave is propagated horizontally through each atmosphere at surface altitude. For the Earth we anticipate a wavelength of ~ 10 km, ~ 7.5 km for Mars, and ~ 13 km for Venus. Results agree with expectations, therefore the model is validated.

Propagation of Acoustic Waves: Growth and Dissipation



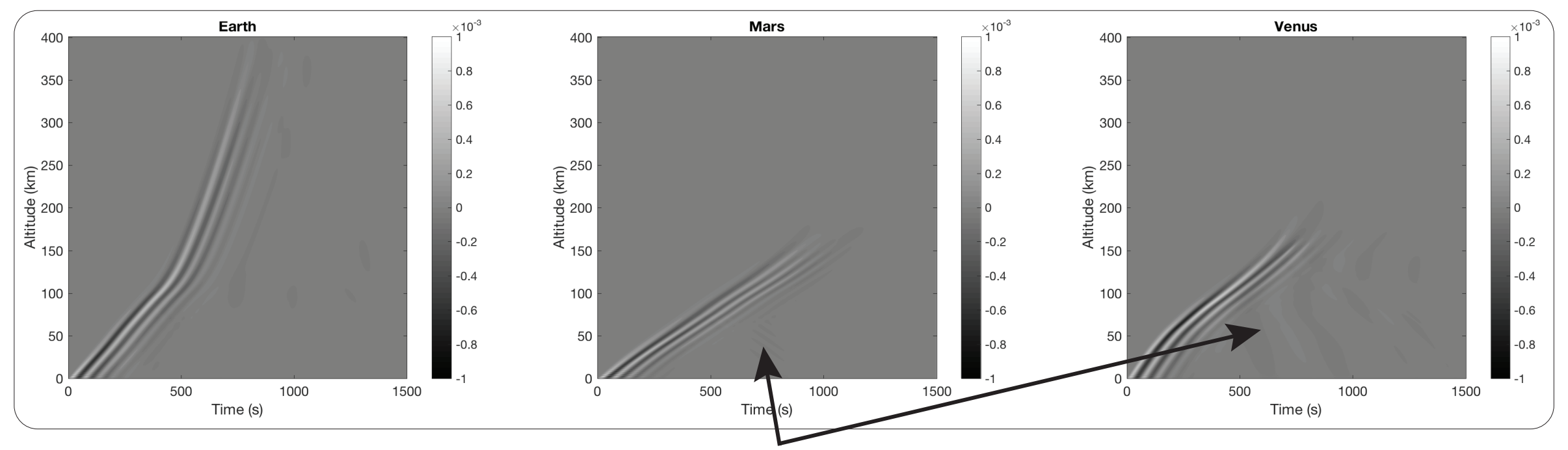
Reflection of undissipated waves

Longer-period oscillations emerge after dissipation



Left-Top: A one-minute period wave packet is forced through the atmospheres of Earth, Mars, and Venus and shown with respect to time and altitude. Several interesting phenomena arise as the wave propagates upward.

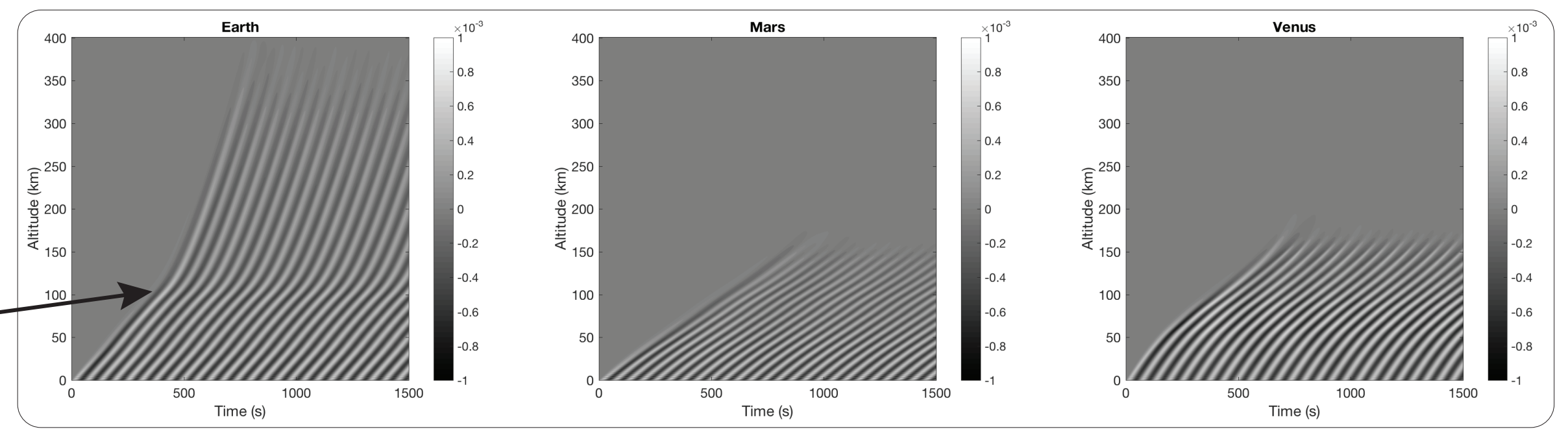
Left-Bottom: A one-minute wave is continuously forced and shown with respect to time and altitude. Amplitude is found to peak near 310 km on Earth, 150 km on Mars, and 155 km on Venus (indicated by the dashed line.)



Partial reflection

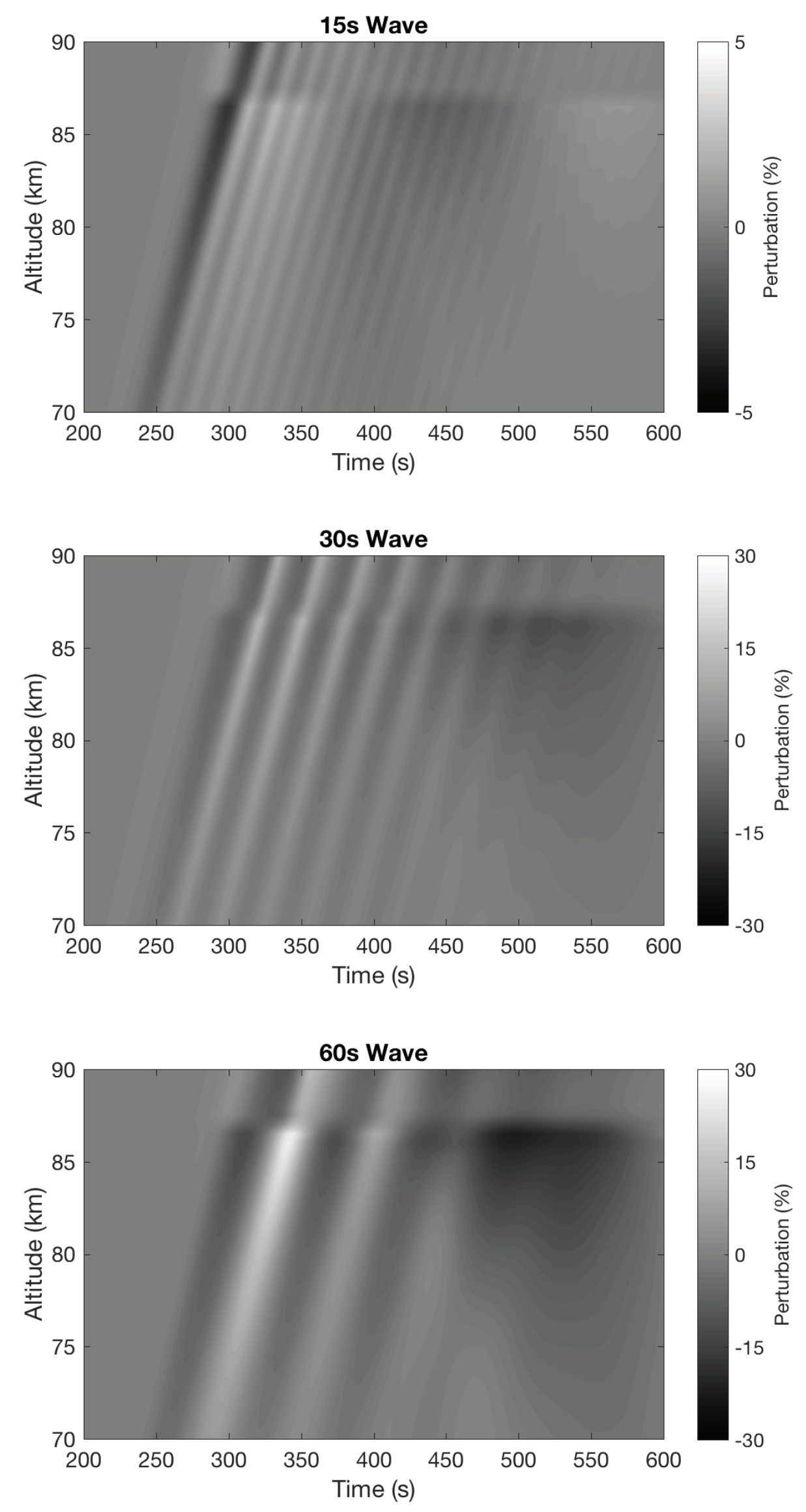
Right-Top: A one-minute period wave packet is forced through the atmospheres of Earth, Mars, and Venus and shown with velocity scaled by the density amplification factor to better trace the path of the wave as it refracts due to changing speed of sound.

Right-Bottom: A one-minute wave is continuously forced and shown with velocity scaled by the same density amplification factor to clearly see dissipation at high altitudes.



Refraction at the base of the thermosphere

Acoustic Disturbance of D-Region Electron Density



Low-frequency disturbances, with periods on the order of tens of seconds to minutes, are seen to propagate and significantly perturb the D-region [Marshall and Snively, 2014] electron densities. D-region perturbations lead to modulation of the propagation of very low frequency electromagnetic waves. As a simple example, we demonstrate electron density perturbations to an initial electron density layer defined by:

$$n_e(z) = (1.43 \times 10^7)\exp\left[(\beta - 0.15)(z - h) - 0.15\right]$$

which is advected by the neutrals using the same two-step Lax-Wendroff method.

At longer periods, larger wavelengths, and stronger amplitudes, acoustic waves effectively modulate the base of this layer over scales that may impact VLF propagation [Marshall and Snively, 2014]. Waves also can modulate the airglow layers at the same height [Snively, 2013] and, on Earth, are even stronger in the F-region [Zettergren and Snively, 2013]. Note that on Venus the ionospheric layer peaks at ~150 km [Peter et al., 2014], similar to where acoustic wave amplitudes are maximized. The possibility that waves generated by volcanic or seismic activity below may be able to produce disturbances at these altitudes with periods on the order of minutes can be investigated in the future with more comprehensive modeling.

Discussion and Conclusions

An atmospheric acoustics model has been developed and validated, and investigations were performed that allow several conclusions to be drawn:
(1) As expected, Martian acoustic waves are found to propagate more slowly, dissipate more quickly, and gain much less amplitude than those on Earth. Conversely, Venusian acoustic waves grow rapidly and propagate quickly, particularly in the troposphere and mesosphere, however they are significantly dampened at high altitudes due to low thermospheric temperatures.
(2) Long period acoustic waves are able to cause noticeable disturbances to the D-region electron layer on the order of tens of percent deviation from the initial condition. This may impact VLF radio wave propagation on Earth.
There are many potential investigations that may be performed in the future:
(1) Implement realistic wave forcing spectra due to seismic, volcanic, and/or lower atmospheric dynamic activity (thunderstorms, dust storms, etc.)
(2) Expand the investigation of electron density perturbations to Mars and Venus (particularly the latter), as well as apply these numerical techniques to study additional neutral species or ionospheric layers.
(3) Incorporate a broader range of dissipation processes to expand the breadth of the spectrum that may be investigated with this model.

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