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EP 340 Thesis Project Proposal:

DEVELOPMENT AND VALIDATION OF AN ATMOSPHERIC ACOUSTICS MODEL FOR FLEXIBLE PLANETARY ATMOSPHERES

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ABSTRACT

We propose to develop a one-dimensional, nonlinear, atmospheric acoustics model in order to investigate the propagation and dissipation of atmospheric acoustic waves in differing planetary atmospheres. The project will involve the creation and validation of this model with FORTRAN and MATLAB, and validate results using atmospheric characteristics for Earth, Mars, and Venus provided by the MSIS model and NASA's GRAM softwares, in addition to simplified model atmospheres. These planets are selected due to their similarities as terrestrial worlds and extreme atmospheric differences, including temperature, density, composition, etc.

Table of Contents

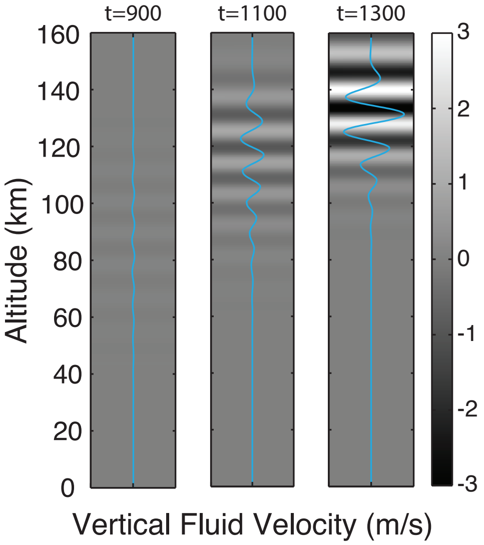

FIGURE 1: One- and two-dimensional model runs of 62.8 second acoustic waves in an infinite horizontal domain, which propagate upward through the Martian atmosphere. [e.g., *Schroeder et al.*, 2013]

1 Introduction

This proposal discusses an undergraduate thesis topic to be completed during the Fall 2014 and Spring 2015 semesters at Embry-Riddle Aeronautical University (ERAU). The proposed research involves the development and validation of a new one-dimensional, nonlinear, atmospheric acoustics model for flexible planetary atmospheres, which will be validated using atmospheric parameters from Earth, Mars, and Venus. Through use of this model, we seek to investigate the propagation and dissipation of nonlinear atmospheric acoustic waves at infrasonic frequencies, and to explore how wave propagation differs within varying ambient conditions. The propagation of atmospheric acoustics on different terrestrial worlds will be modeled, and the relation to planetary atmospheric conditions will be determined.

Previous work has shown that acoustic waves propagating through the Martian atmosphere dissipate much more rapidly, and at lower altitudes, than on Earth [e.g., *Schroeder et al.*, 2013]. This is likely due to the low density and high viscosity of the atmosphere, as well as the lack of thermospheric heating. Martian acoustic waves have also been found to be negligibly weak at lower altitudes before quickly increasing in amplitude at about 100 km. This project seeks to further explore the properties of Martian acoustic waves, as well as investigate propagation and dissipation on Venus, due to the fact that its atmosphere is at the other extreme from Mars - very hot and dense, rather than cold and sparse [e.g., *Petculescu and Lueptow*, 2006].

2 Scientific Background and Rationale

2.1 Comparative Aeronomy

Table 1 lists significant atmospheric surface conditions, specifically temperature, pressure, and atmospheric composition, for the three planets in question, and Table 2 lists relevant planetary parameters: surface gravity, distance from the sun, and planetary radius.

Table 1: Surface Conditions of Planets to be Investigated [e.g., *Petculescu and Lueptow*, 2006]

Planet	Temperature (K)	Pressure (atm)	Prominent Atmospheric Constituents		
Earth	290	1	N2 (77%)	O_2 (21%)	H_2O (1%)
Mars	220	0.007	CO_2 (95%)	N_2 (2.7%)	Ar (1.6%)
Venus	730	90	CO_2 (96%)	N_2 (3.5%)	SO_2 (<0.5%)

Table 2: Planet parameters [e.g., *Bougher et al.*, 2002]

Planet	Gravity at Surface (m/s^2)	Heliocentric Distance (AU)	Radius (km)
Earth	9.82	1.0	6371
Venus	8.88	0.72	6050
Mars	3.73	1.38-1.67	3396

Earth

Earth's atmosphere consists of distinct atmospheric regions in which the temperature and constituents vary with altitude. Surface conditions, as shown in Table 1, are very median for the selected planets, with temperature around 300K and pressure at 1 atm. Below about 100 km (the mesopause), the atmosphere is primarily dominated by nitrogen and oxygen, with these beginning to taper off at higher altitudes to be replaced by atomic oxygen. Furthermore, there is a drop in both density and pressure at the mesopause, as well as a significant change in temperature. Until the mesopause around 100 km, the temperature hovers between 200 and 300 K, with increases and decreases throughout the different regions but remaining more or less consistent. As the atmosphere transitions to the thermosphere at the mesopause, the temperature rapidly increases to upwards of 1000 K at high altitudes [e.g., *Bougher et al.*, 2008]. Quantities of interest, namely temperature, pressure, and atmospheric composition, are plotted in Figure 2.

Mars

The Martian atmosphere is largely composed of Carbon Dioxide (95%), along with Nitrogen (2.7%), Argon (1.6%), and Oxygen (<1%). Unlike Earth, the atmospheric constituents remain relatively consistent in their ratios with increasing altitudes. One of the most significant features of the Martian atmosphere is its lack of a distinguishable thermosphere as

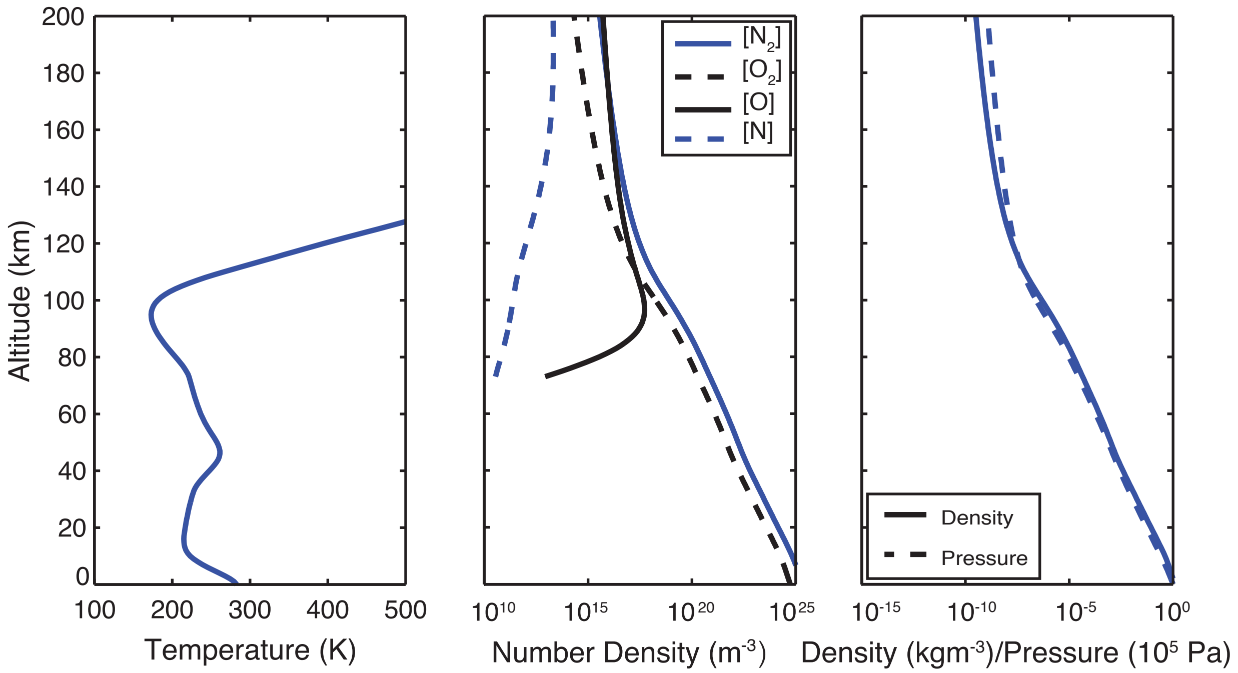

FIGURE 2: Plots of atmospheric temperature, constituents, density, and pressure on Earth. [e.g., *Schroeder et al.*, 2013]

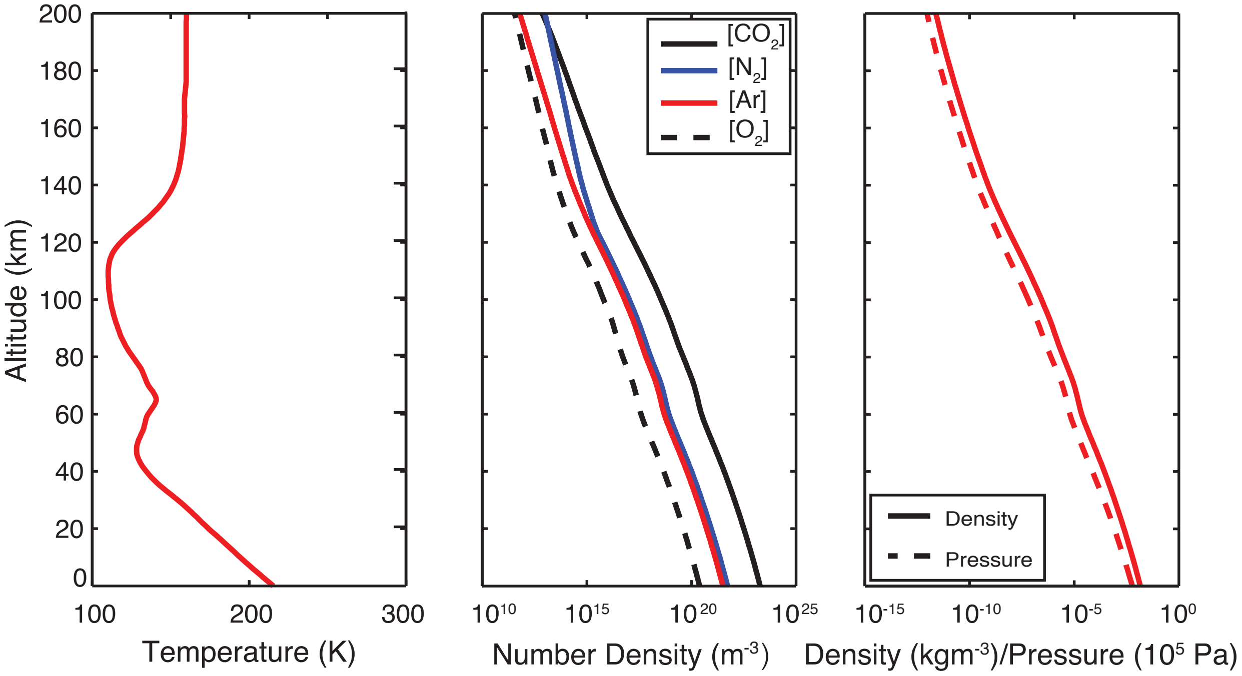

FIGURE 3: Plots of atmospheric temperature, constituents, density, and pressure on Mars. [e.g., *Schroeder et al.*, 2013]

on Earth, with temperatures continuing to remain constant above 120 km. As a result, the scale height and speed of sound remain fairly stagnant with increasing altitude, and are lower than on Earth, with the speed of sound at ground-level only 69% that of Earth. Mars' atmosphere is also significantly more sparse than Earth's (only 12% density), with a lower pressure as a result. As shown in Table 1, the surface temperature is much colder than Earth, and surface pressure is only 0.007 atm (7% that of Earth.) Conversely, the viscosity of the Martian atmosphere is about 770% higher than on Earth, which likely contributes to dampening of atmospheric dynamics events. Quantities of interest, namely temperature, pressure, and atmospheric composition, are plotted in Figure 3.

Venus

Venus' atmosphere has similarities and differences to both Earth and Mars. Its composition is 93-97% Carbon Dioxide and 2-5% Nitrogen and other inert gases [e.g., *Mueller-Wodard et al.*]. Venutian surface conditions are characterized by a temperature of 730 K and a pressure of 90 atm, which makes it an ideal example of a high pressure atmosphere for validation of the model [e.g., *Fjeldbo et al.*, 1971]. Like Mars, Venus also lacks significant thermosphere heating, and actually becomes cooler than Mars at high altitudes (above 150 kilometers) [e.g., *Bougher et al.*, 2002]. It is within reason to consider that Venusian acoustic waves may propagate similarly to those in the Martian upper-atmosphere at these high altitudes, though it is unknown yet whether they will dissipate before reaching these altitudes, due to the extreme density of Venus' low altitude atmosphere.

2.2 Atmospheric Acoustics

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 [e.g., *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 two major parameters (see Figure 4), the first being the speed of sound: the speed at which acoustic waves propagate through the atmosphere, given by [e.g., *Kinsler et al.*, 2000]

$$c^2 = \gamma R_{specific} T_K \tag{1}$$

where γ is the adiabatic index, $R_{specific}$ is the specific gas constant, which is simply the universal gas constant R divided by the molar mass or the Boltzmann constant k_B divided by the molecular mass (both γ and $R_{specific}$ are dependent on the molecular mass, so they vary as atmospheric constituents change. See Figure 2 for an example of composition change with altitude), and T_K is the temperature in Kelvin. These three parameters all vary with increasing altitude, which indicates that acoustic waves move through varying speeds of sound as they propagate upwards, contributing to their speed, refraction or reflection, as well as eventual dissipation. The second significant quantity is the scale height, which essentially measures the "thickness" of the atmosphere by describing the distance over which the

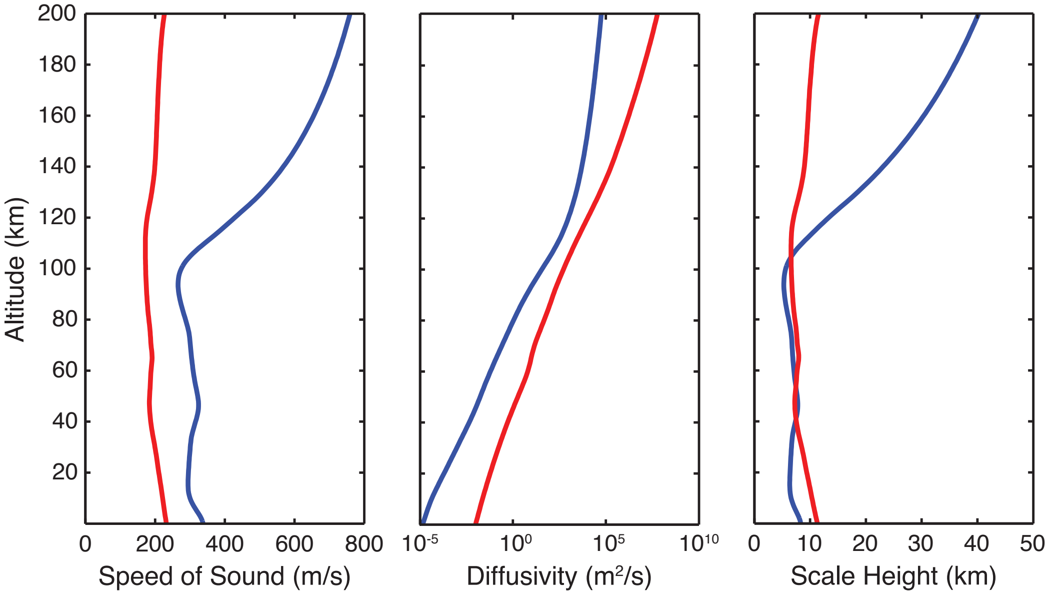

FIGURE 4: Speed of sound, diffusivity, and scale height on Earth (blue) and Mars (red). [e.g., *Schroeder et al.*, 2013]

pressure/density of the atmosphere changes by a factor of e (as a function of temperature), which is given by [e.g., *Kalkofen et al.*, 1994]

$$H = \frac{c^2}{\gamma g} \tag{2}$$

for previously defined quantities, with g being the acceleration due to gravity, which varies slightly with altitude like all other parameters.

The equation for acoustic waves within a gravitationally stratified, isothermal atmosphere is given by [e.g., *Kalkofen et al.*, 1994]:

$$\frac{\partial^2 v}{\partial t^2} = c^2 v \left(\frac{\partial^2}{\partial z^2} - \frac{1}{H} \frac{\partial}{\partial z} \right) \tag{3}$$

for previously defined quantities, with v being the velocity of the perturbation and z being the distance measured positive in the outward direction.

Because the three terrestrial planets in question have such different atmospheres in terms of aforementioned quantities, it is known that atmospheric dynamics, such as acoustic waves, will propagate and behave differently. Figure 5 shows upward propagation of an acoustic wave in the Martian atmosphere, at both linear and non-linear amplitudes. These waves behaves much differently than it would have on Earth with the same forcing parameters.

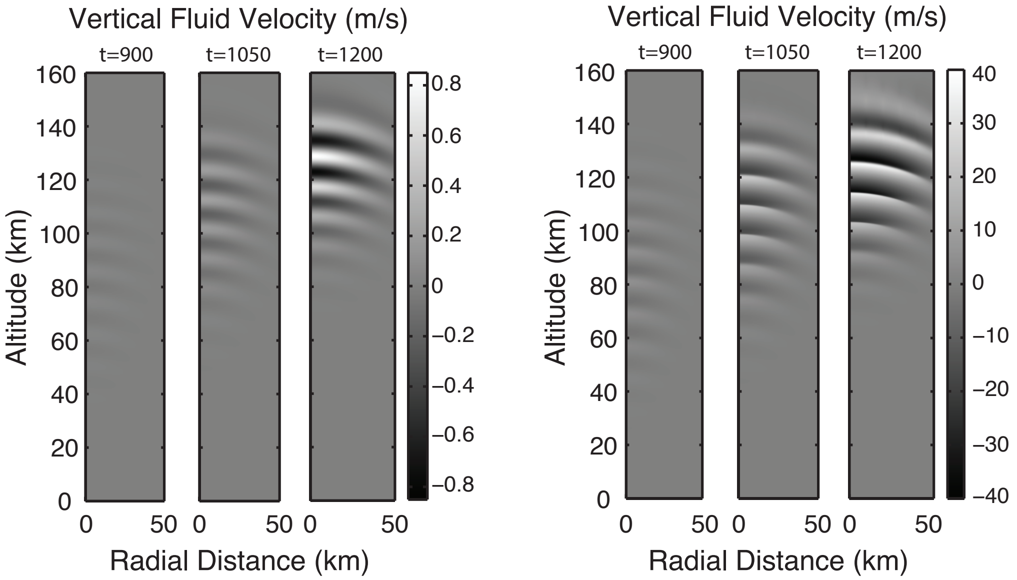

FIGURE 5: Upward propagation of an acoustic wave modeled in a 50 km cylindrical domain through the Martian atmosphere. **Left:** Linear acoustic wave forced by a 10 km radial source. **Right:** Amplitude increased by factor of 100 to simulate non-linear wave steepening. [e.g., *Schroeder et al.*, 2013]

3 Scientific Questions and Approach

Two outstanding science questions will be addressed in the proposed research program:

- **Question 1:** How do atmospheric conditions vary between terrestrial planets, and how does this variation affect the propagation of atmospheric acoustic waves?
- **Question 2:** How can the propagation of atmospheric acoustic waves be modeled within differing planetary atmospheres?

Approach: We will address these two related Science Questions using...

Science Question 1 will be addressed through the development of a one-dimensional model, which will be used to simulate the propagation of acoustic waves within varying ambient conditions. These conditions will be provided by the MSISE90 model [e.g., *Hedin*, 1991] for Earth conditions, and the Global Reference Atmospheric Model software packages [e.g., *Justh et al.*, 2006], developed and provided by NASA's Marshall Spaceflight Center, for Venusian and Martian conditions.

Science Question 2 will be addressed through the non-linear, compressible solution to the conservation equations, which will be solved numerically using a flux-limited Lax-Wendroff Two Step Method in FORTRAN.

These questions have been briefly addressed in past work, which explored how atmospheric acoustic waves propagate through the Martian atmosphere (see Figures 1 and 5.) [e.g., *Schroeder et al.*, 2013] This project intends to expand on previous techniques through the development of a new model, as well as broaden exploration to a greater array of acoustic parameters and planetary atmospheres.

4 Plan of Work

1. This project will begin with a literature investigation into previous planetary acoustics studies, such as discussed in [e.g., *Petculescu and Lueptow*, 2006].
2. Simple molecular models will be developed based on basic atmospheric assumptions. These models will be compared to and used in conjunction with the more powerful models described below.
3. Ambient conditions for Earth will be provided to the model by MSISE90 [e.g., *Hedin*, 1991], and NASA's GRAM software packages, Mars-GRAM 2010 [e.g., *Justus and Johnson*, 2001; *Justh and Burns*, 2013], and Venus-GRAM 2005 [e.g., *Justh et al.*, 2006], will provide for Mars and Venus respectively. These atmospheric conditions will be investigated, and a study of comparative aeronomy will be performed.
4. Near the end of the Fall 2014 semester, development will begin on a new one-dimensional, compressible, nonlinear atmospheric acoustics model, which will solve conservation equations numerically in FORTRAN using a flux-limited Lax-Wendroff two step method.
5. The model will feature a MATLAB interface to examine and display FORTRAN output through plotting.
6. Once the model has been developed, several acoustic waves will be forced on all three planets, results will be explored, and conclusions will be drawn.
7. This project will be completed by the end of the Spring 2015 semester, no later than May 1, 2015.
8. This model will be used and developed in the future to further investigate the propagation and dissipation of planetary acoustic waves for a Master's thesis.

5 Outcomes and Impacts

As part of this project, we will develop and validate a numerical model for simulating the propagation of atmospheric acoustic waves in various planetary atmospheres. The model will be developed to allow for ambient conditions to be varied. The basic propagation and dissipation of infrasonic acoustic waves will be explored using this model on three terrestrial planets: Earth, Venus, and Mars.

Future plans for this research involve a detailed, comparative exploration into the generation and propagation of infrasonic atmospheric acoustic waves on Venus, Earth, and Mars, which seeks to investigate how the propagation of these waves may affect atmospheric dynamics on other planets. This research will ultimately culminate in a Master's Thesis to be completed in Spring 2016.

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