Sound waves traveling at frequencies between 0.05 and 20 Hertz are called infrasound waves. Ocean waves, meteorites (Evers et al., 2001), large earthquakes, and volcanic eruptions (Johnson, 2003) are among the natural phenomena that produce infrasound waves. Nuclear and chemical explosions can also generate infrasound waves. Infrasound waves tend to travel long horizontal distances in the atmosphere due their low absorption (Diamond, 1963).

The study of the propagation of the sound field in the atmosphere requires a detailed knowledge of the current atmospheric conditions. Temperature and wind fields are the most important atmospheric parameters for this propagation. This paper provides some of the approaches that have been done to quantify the influences these atmospheric parameters on the propagation of infrasonic waves. This paper also shows an application where high precision traveltime calculations are done using enhanced atmospheric profiles.

MATHEMATICAL CHARACTERIZATION OF INFRASOUND WAVES

Pressure perturbations, which are small enough to be considered infinitesimal with respect to ambient atmospheric pressure, can be modeled using a linear approximation. The propagation of this pressure perturbation ($\Delta p$), assuming linear approximation, is described by the wave equation:
\[
\frac{1}{c^2} \frac{\partial^2 \Delta p}{\partial t^2} = \nabla(\Delta p),
\]

where \( c \) is the wave velocity. By the use of thermodynamically considerations and assuming an adiabatic propagation, the velocity of the wave is expressed as:

\[
c^2 = \frac{\gamma RT_K}{M},
\]

where \( \gamma = \frac{C_p}{C_v} \), \( C_p \) is the ratio of specific heat at a constant pressure, \( C_v \) is the ratio of specific heat at a constant volume, \( R \) is the universal gas constant, \( T_K \) is the absolute temperature and \( M \) is the mean molecular mass (Bass et al., 2007). An approximation for dry motionless air has been propose by Diamond (1963)

\[
\gamma \frac{R}{M} = 402.8,
\]

this approximation has been used at various levels for general infrasonic studies (Garces et al., 1998, Johnson, 2003).

Infrasonic waves in the atmosphere experience variations in their speeds due to the highly temporal and spatial thermal variability of the atmosphere. The following section shows the thermal layers of the atmosphere and the implications of these layers in infrasound wave propagation.

**STRUCTURE OF THE ATMOSPHERE**

The atmosphere is commonly divided into four vertical thermal layers. These layers are characterized by a uniform change in temperature with respect to altitude (increase or decrease) and include: (1) Troposphere, (2) Stratosphere, (3) Mesosphere, and
(4) Thermosphere. Figure 1 shows a typical vertical temperature profile and the different thermal layers. In the Troposphere, the temperatures decrease with altitude due to adiabatic cooling. Absorption of ultraviolet radiation by ozone makes the temperature increase with altitude in the Stratosphere. A decrease in temperature with height is the characteristic of the Mesosphere. The temperature of the last layer, called Thermosphere, increases again with altitude and can reach as high as 2000 K. The atmosphere has a thermal horizontal distribution at a global scale. This horizontal distribution is the result of different levels of solar radiation that at global scales are significant. The thermal distribution of the atmosphere varies at different time scales (days, months, and seasons). The monitoring of the atmosphere at a global scale is possible due to the efforts of numerous governments and agencies that maintain ground-based and satellite-based weather stations around the Earth (Drob et al., 2003).

Figure 1. Temperature profile and atmospheric layers. Taken from Garces et al., (2002)
A detailed description of the thermal distribution of the atmosphere is vital for studying the propagation of infrasonic waves. This information can be obtained online by several weather databases, e.g.: The British Atmospheric Data Center (BADC). Figure 2 displays the thermal distribution of the northern hemisphere for winter and summer months. In this figure it is possible to identify the different thermal spheres and their horizontal distribution. The influence of the latitude is also noticeable in this distribution. Using the available data of atmospheric temperatures a velocity profile for sound waves can be developed for travel time estimations. This estimation would account for an intrinsic velocity. However, the other main component of the atmosphere, the wind field, plays an important role for infrasound propagation. The following section will develop some of the mathematical results to model the influence of wind on travel-time calculations.

Figure 2. Temperature profiles for the Northern Hemisphere. (A) January and (B) June.
INFLUENCE OF WIND FIELDS ON THE PROPAGATION OF INFRASONIC WAVES

A sound wave traveling in a moving medium will be affected by the velocity of the moving medium. Assuming a horizontal wind velocity that only depends on elevation, it can be shown that a modified ray parameter $p$ is conserved (Garces et al., 1998):

$$p = \frac{\sin(i_o)}{v(z)} \left(1 + \frac{u(z)\sin(i_o)}{v(z)}\right)^{-1}$$

where $i_o$ is the incident angle, $v(z)$ is the intrinsic sound speed and $u(z)$ is the horizontal wind speed. A detailed vertical velocity profile is needed to compute travel times using the ray parameter described above. This information can also be obtained from weather databases. Figure 3 (taken from Drob et al. (2003)) shows a velocity profile for a specific set of atmospheric conditions, the figure also shows the different behavior of zonal (blowing from West to East) and meridional (blowing from South to North) winds. The wind field shows temporal and spatial variability, thus the continuous monitoring of the atmosphere is an essential requirement for travel time wave calculations. The following section will tie both wind field and temperature to develop ray-tracing plots for infrasonic propagation.
Ray-tracing simulations for infrasonic waves can be performed for specific atmospheric conditions. Figure 4 (taken from Drob et al.(2003)) uses the wind and temperature profiles from Figure 3 to perform a ray-tracing simulation. In this simulation the 1000-second interval shows 760 individual ray elements separated 0.25°. This figure shows ray-tracing affected by Zonal winds. The decrease of the velocity with altitude bends the rays initially upward. The strong influence of low-medium atmosphere winds (blowing at 80 m/s W-E) bends the rays back to surface at around 200 Km, this effect creates a 200-Km shadow zone. Multiple arrivals at fixed points in the surface are the result of complex atmospheric conditions.
Figure 4. Ray-tracing simulation.

The mathematical results of the influence of thermal and wind fields in the propagation of infrasonic waves are extensible used. If a detailed characterization of the atmosphere is known high precision locations are suitable. Evers et al.,(2003) show that an accurate knowledge of the atmospheric conditions is required for precise source calculation using infrasonic techniques. Figure 5 shows the atmospheric profiles used by Evers et al.,(2003) to determine the source of infrasonic waves. The calculated locations were found later to be meteorites entering the stratosphere, which was later confirmed by visual reports.

Figure 5. Example of specific atmospheric conditions.
CONCLUSIONS

Temperature and wind velocity are the key parameters that determine the behavior of infrasonic ray paths. The temperature of the atmosphere determines the intrinsic velocity of the wave in first order approximation. The thermal layers in the atmosphere allow very long trajectories for infrasonic waves. A modified ray parameter, that includes the influence of wind and remains constant during the travel time, can be used to study ray-paths. These mathematical ideas along with a detailed knowledge of the atmospheric conditions can be used to precisely locate the source of infrasonic waves.

Other parameters, that would potentially affect the propagation of infrasound waves, have not been covered in this paper such as: chemical compositional variations of the atmosphere as a function of altitude, and electromagnetic gradients. These other parameters have a second order effect on propagation. However, a more detailed study of the propagation of waves in the atmosphere requires considering all possible physical and chemical factors.
REFERENCES


