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Modeling Infrasound Waveforms in a Windy Environment

Catherine de Groot-Hedlin

Introduction

Acoustic propagation through the atmosphere is controlled primarily by temperature, which governs the static sound speed, and by wind velocity. A common practice in numerical computations of the infrasound wavefield is to add the horizontal wind velocity profile in the direction of propagation to the sound speed profile. That is, the moving medium is transformed to a stationary medium by modifying the sound velocity profiles, thus the fact that wind is a vector quantity is not taken into account. The problem with this approximation is illustrated in Figure 1. If a sound wave is moving with speed c at an initial angle of α *with respect to the horizontal, and a horizontal wind with velocity w is introduced, then only the component of sound velocity in the direction of the wind is altered. In two dimensions, the new velocity is given by* $\mathbf{v}_w = (w + c \cos\alpha)\,\mathbf{i} + (c \sin\alpha)\,\mathbf{j}$. *By contrast, if the sound speed profile is modified by simply adding the wind speed, the modified velocity would be given by* $\mathbf{v}_m = (w + c)\cos\alpha\,\mathbf{i} + (w + c)\sin\alpha)\,\mathbf{j}$.

Inframatics Editorial Board

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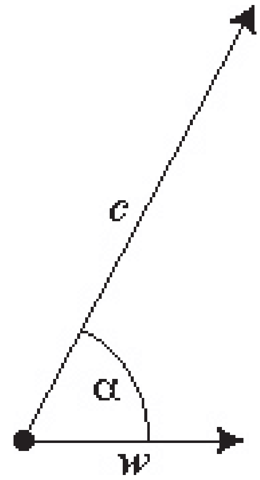

Figure 1. The process by which sound characteristics are affected by the action of wind is called advection. If a wind in the direction **i** acts upon a sound wave moving in the direction α at speed c, then both the sound velocity and direction are altered. In two dimensions, the new velocity is given by $\mathbf{v}_w = (w + c \cos \alpha)\,\mathbf{i} + (c \sin \alpha)\,\mathbf{j}$ and the new direction of motion is given by $\theta = \tan^{-1} (c \sin \alpha / (w + c \cos \alpha))$. Thus the velocity of the sound wave depends on the direction of motion.

As shown in Figure 1, the sound velocity depends on the direction of motion. For nearly horizontal propagation of sound, adding the horizontal wind velocity profile to the static sound speed profile is a pretty good approximation. However, the accuracy decreases as the propagation angle increases from the horizontal. Since sound waves recorded at infrasound stations often propagate at high angles with respect to the horizontal for a significant part of their paths (for example, see Figure 2) a more accurate method of handling winds in numerical solutions of the infrasound wavefield is required.

Although the equations for sound propagation in a moving medium are more complicated than those for a stationary medium, they can be linearized to yield tractable methods of including wind as a vector quantity. Recently, several groups have developed methods for accurate computation of sound fields in a moving fluid, including a PE solution by Lingevitch et.al. (2002), and finite difference time domain (FDTD) methods by Blumrich and Heinmann, (2002), Van Renterghem and Botteldoren (2003), and Ostashev *et.al.*, (2005). In this paper, I follow FDTD method introduced by Ostashev *et.al.* (2005) for computing acoustic waves advected through a windy atmosphere. The FDTD method is based on solving discretized versions of the wave equation. This gives finite difference methods their primary advantage over other propagation algorithms that are based on various approximations to the wave equation. That is, any type of observed wave phenomenon can be modeled using finite difference algorithms, including reflection, transmission, refraction, scattering (including back-scatter), and dispersion. In general, finite difference methods also allow for incorporation of arbitrary sound speed and topography models. However, in this paper the equations are developed in two dimensions for a stratified atmosphere, that is, the sound velocity, density, and wind velocity all vary only with altitude. This is a preliminary treatment of the problem, fully 3-d wind structure is to be accommodated in a future version of the code.

Wave equations for a fluid in motion

The equations governing propagation of sound in the atmosphere are the conservation of momentum, conservation of mass, and the equation of state. If the effects of viscosity, gravity and the earth's rotation and curvature are neglected, these equations may be stated as

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \mathbf{F}, \qquad (1)$$

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{V} = \mathbf{0}, \qquad (2)$$

$$\frac{D\rho}{Dt} = c^2 \frac{D\rho}{Dt}, \qquad (3)$$

(Gill, 1982) which relate the velocity **V**, the pressure p, and the density ρ. The force acting upon the medium is denoted by **F**, and c is the adiabatic sound speed.

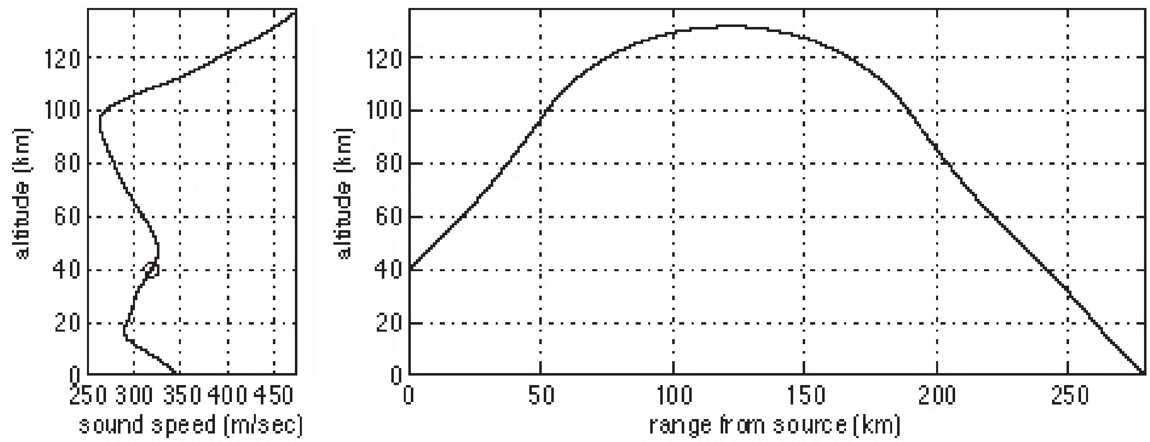

Figure 2. The left panel shows an example of the ray path ray with an initial angle of 45° with respect to the horizontal, for a source at 40km altitude, typical for a bolide explosion. The aspect ratio for this plot is 1:1. Propagation is through a medium having the sound speed profile indicated in the right panel.

The convective derivative (also known as the Lagrangian derivative) D/Dt acting on a quantity G is defined by

$$\frac{DG}{Dt} = \frac{\partial G}{dt} + (\mathbf{V} \cdot \nabla)G \qquad (4)$$

where the derivative on the left represents the change of G with time in a frame moving with the fluid. The first term on the right side of Eq. 4 represents the change of the quantity G at a point fixed in space. The second term represents the change of G as the observer moves with the fluid at the velocity **V**, and is called the advective term. Generally, quantities are expressed in terms of a fixed point in space in order to compare computational results with observations made at stationary sensors.

The propagation of sound waves in the atmosphere introduce fluctuations in the pressure, density, and velocity fields. The standard procedure (*e.g.* Lingevitch *et.al.,* 2002; Ostashev *et.al.*, 2005), in solving equations 1-3 is to consider a solution of the form

$$p = p_o + p_s, \quad \rho = \rho_o + \rho_s, \quad \mathbf{V} = \mathbf{w} + \mathbf{v}, \qquad (5)$$

where p_o, ρ_o, **w** are the ambient solutions in the absence of the perturbations, and p_s, ρ_s, **v** are caused by the passage of a sound wave. In what follows, **w** denotes the wind velocity profile, and **v** denotes the particle velocity associated with the sound wave. Waveforms are derived by computing the pressure perturbations, p_s, as a function of time.

Finite difference modeling of sound waves in a windy environment

Here, an FDTD method is outlined for sound waves in a stratified medium. That is, it is assumed that the wind blows horizontally, and that densities, and sound velocities vary much more gradually in the horizontal direction than vertically.

A two-dimensional FDTD solution method for sound waves in a windy atmosphere has been presented by Ostashev *et.al.,* (2005). They considered propagation of high frequency sound for small scales over which the ambient density does not vary significantly. For problems of interest in infrasound, where propagation paths may sample the upper atmosphere, the density may vary by several orders of magnitude. This may make the solution developed by Ostashev *et.al.,* (2005) unstable. Fortunately, a simple transformation of variables $\rho_o^{-1/2}\, p_s$ may be used to stabilize the solution; this change of variables was suggested by Lingevitch *et.al.,* (1999) for a the solution of acousto-gravity waves using a parabolic equation method.

Equations 1-5 are combined to derive the solutions for the perturbations in the sound pressure and sound velocity. In a stratified atmosphere, in the presence a wind with velocity w_x, the derivations yield

$$\frac{\partial p}{\partial t} = -w_z \frac{\partial p}{\partial x} - \rho_0 c^2 (\frac{\partial v_z}{\partial x} + \frac{\partial v_y}{\partial y}) \quad (6)$$

$$\frac{\partial v_x}{\partial t} = -w_z \frac{\partial v_z}{\partial x} - v_y \frac{\partial w_z}{\partial y} - \rho_0^{-1} (\frac{\partial p}{\partial x} - F_x) \quad (7)$$

$$\frac{\partial v_y}{\partial t} = -w_z \frac{\partial v_y}{\partial x} - \rho_0^{-1} (\frac{\partial p}{\partial y} - F_y). \quad (8)$$

Equations 6-8 are first-order partial differential equations in both space and time, which make them suitable to computation by finite difference time-domain (FDTD) techniques. Note that for $w_x = 0$, *i.e.,* zero wind velocity, they reduce to the usual equations for acoustic propagation in a static medium (*e.g.* Botteldoren, 1994). The equations differ from those for a standard atmosphere by the inclusion of the advection terms, as well as by the introduction of a wind shear term in Equation 7.

Various numerical implementations have been suggested for the computation of the FDTD equations for sound propagation in windy environments (Blumrich and Heinmann, 2002; Van Renterghem and Botteldoren, 2003; Ostashev *et.al.*, 2005). In particular, it is noted that inclusion of advection terms in the first order equations complicates the standard method of staggering the velocities and pressures in both space and time. Typically, in a stationary medium, the acoustic velocities and pressures are computed in a leap-frog manner (Yee, 1966), thus the velocities and pressures are computed at alternating time-steps, and the fields from the previous time step are over-written. Including wind in the FDTD equations requires modifications to the update equations since first order derivatives in space and time must be computed simultaneously. Here, the method of Ostashev *et.al.*, (2005) is followed, that is pressure and velocity fields over saved over two time steps so that time derivatives may be computed using central differences. Refer to Ostashev *et.al.*, (2005) for further detail.

An example of the FDTD scheme on a very simple model clearly illustrates the effect of wind on sound waves. The effect of wind with a Mach number of 0.2 on an infrasound wavefield is shown in Figure 3. This value is unrealistically high for tropospheric winds, but is reasonable for the upper atmosphere. A high Mach value was used to better illustrate the effects of wind on the acoustic wavefield. Acoustic propagation is fastest in the direction of the wind (to the right in this figure) and slowest in the opposite direction. Sounds speeds for propagation at very steep angles with respect to the horizontal are minimally affected by horizontal winds. Amplitude effects are also evident; wavefronts are stretched out along the propagation direction of the wind thus amplitudes are lower than in the opposite direction.

An example showing the sound field for more realistic sound, wind, and density profiles profiles (Figure 4) is shown in Figure 5, for a source at 100 km altitude, with a center frequency of 0.1Hz.

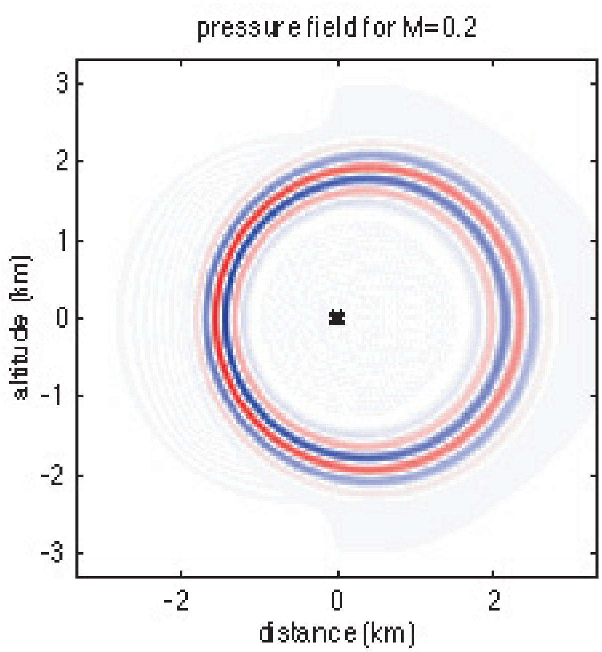

Figure 3. The effect of wind with a Mach number of 0.2 on an infrasound wavefield. The source has a center frequency of 1Hz and is located at the axes origin, marked by the x. Acoustic propagation is fastest in the direction of the wind (the positive x-axis in this case) and slowest in the opposite direction. Amplitude effects are also evident.

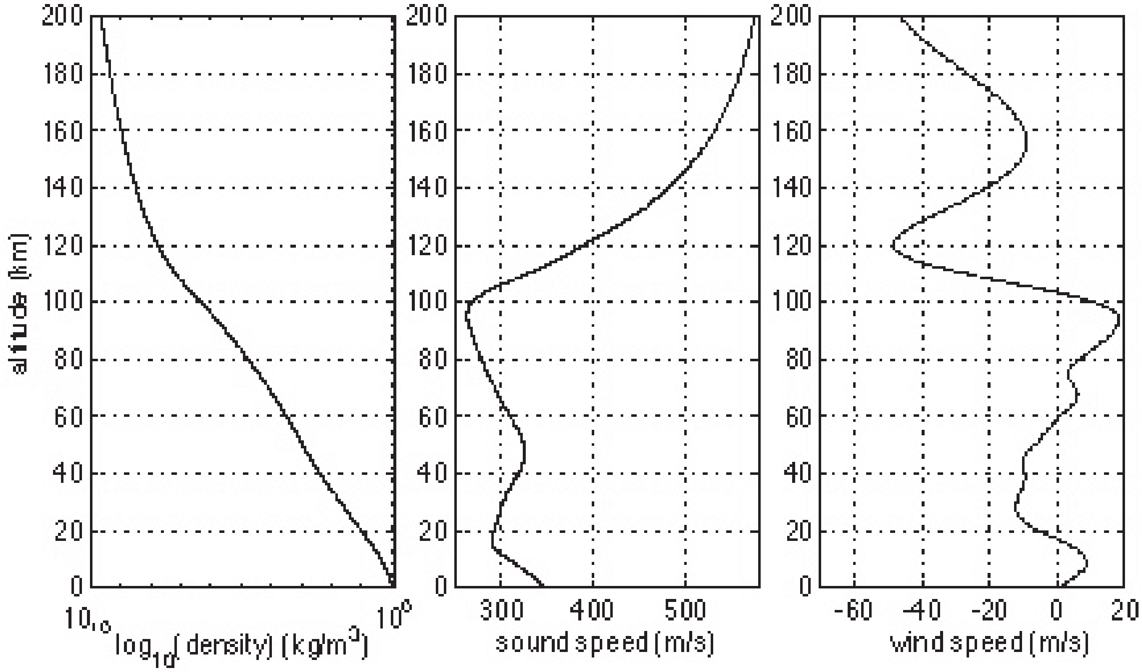

Figure 4. Profiles for atmospheric density, sound speed and wind speed.

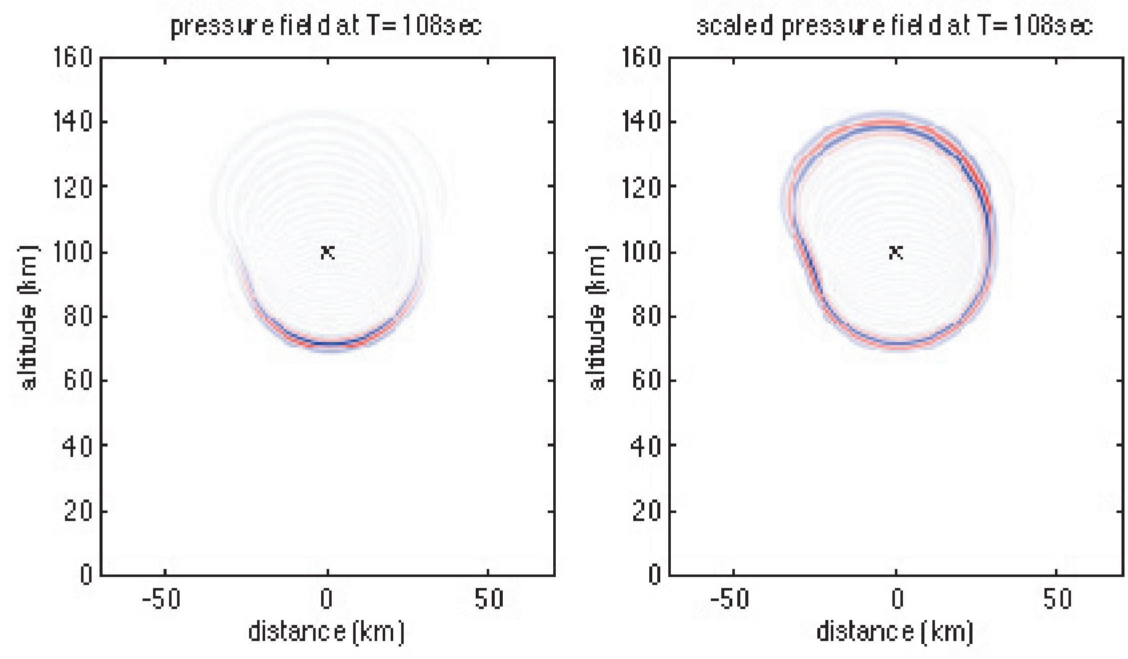

Figure 5. Pressure field (left) and the pressure field scaled by $\rho_o^{-1/2}$ (right) for a 0.1Hz source at an altitude of 100km, for medium properties as shown in Figure 4.

Densities and temperature profile data for a location near the Piñ on Flat IMS infrasound station (I57US) were derived from the MSIS-90 atmospheric model, which were made available through http://nssdc.gsfc.nasa.gov/space/ model/models/msis.html. Wind data were derived from the Horizontal Wind Model (HWM) 1993 program (Hedin *et.al.*, 1996). The results shown in Figure 5 are for the pressure field at 108 sec after the "explosion". As indicated, the pressure field is asymmetric due to the effects of wind, although the Mach number is for this example are less than M=0.15 at all altitudes. The pressure field is shown in the panel at left, the pressure field normalized by $\rho_o^{-1/2}$ is shown in the panel at right. As indicated the scaled pressure field is a much more uniform quantity and the code is thus somewhat more stable with this scaling**.**

Concluding Remarks

There is an increased need for precise synthesis of the infrasound wavefield as an essential tool for thorough investigations of signals from particularly important events, especially signals recorded within several hundred kilometers of the source. Further development of the FDTD method offers several clear advantages. FDTD methods can naturally accommodate non-linear effects known to be important above the stratosphere, as well as back scattering and effects due to topography. Besides being useful as a stand-alone technique for simulating infrasound propagation, the precise solutions the FDTD method provides can be used to benchmark other approaches, which rely on approximations to the equations governing propagation in exchange for greater computational speed.

The FDTD code will be further developed to allow for variable ground topography, which will enable us to compute the deflection or scatter of the sound speed from a topographic boundary. (So far the code only allows for the ground to be represented as a flat, rigid boundary.) Furthermore, sound attenuation will be incorporated into the code, as well as the effects of gravity and viscosity, as necessary to model observed effects. Finally, the code will be extended to three dimensions, at least initially for smaller scale problems.

Given the computational demands of this method, it will be used initially to focus on propagation to just beyond the first stratospheric bounce, or up to approximately 300 km. The focus will be on computational accuracy, but with the goal of producing an algorithm that can be executed on commonly available desktop computers. It is important not to shy away from algorithms that are computationally demanding, if they can deliver a higher quality product, as computational power will only increase with time.

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Contact the author:

Catherine de Groot-Hedlin, Ph.D.
Laboratory for Atmospheric Acoustics
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, CA 92093-0225, USA

Email: cadegroothedlin@ucsd.edu
Office: 858-534-2313

2005 Infrasound Technology Workshop in Tahiti

Michael A. H. Hedlin

(Adapted from the first emailed announcement by Jacques Bouchez, Director of DASE.)

Dear Colleagues, The 2005 Infrasound Technology Workshop, hosted by CEA/DIF/DASE, will be held in Papeete, Tahiti, French Polynesia, France from Monday November 28 to Friday December 2, 2005. The venue of the workshop will be the Hotel Sofitel Maeva Beach. For more information about the workshop please visit the website:
http://www-dase.cea.fr/infrason/index.html

For further information, please feel free to contact the Workshop Coordinator:
E.mail : tahiti-infrasound.workshop@cea.fr

We hope you can attend this promising Workshop and I look forward to seeing you in November. Adapted from the first emailed announcement by Jacques BOUCHEZ, Director of DASE.

Contact the author:

Michael A.H. Hedlin, Ph.D.
Laboratory for Atmospheric Acoustics, Chair
Institute of Geophysics and Planetary Physics
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive
La Jolla, CA 92093-0225, USA

Email: hedlin@ucsd.edu
Office: 858-534-8773
Cell: 858-204-5375
Fax: 858-534-6354

Latest Addition to NCPA Infrasound Team

Hank Bass

Thomas M. McGee received a B.Sc. in Geophysical Engineering, (St. Louis U., 1961), worked on seismic oilexploration crews in the Rocky Mountains and on the Gulf Coast, became a party chief for Geophysical Service Incorporated and served on the first digital marine seismic crew in the Gulf of Mexico. He returned to St. Louis U. in 1966, completed doctoral exams in 1968 and was appointed NATO visiting lecturer at the Univ. of Utrecht, The Nertherlands, in 1969. In the 1970s and 1980s he was marine geophysicist to the Geology Dept. at the Univ. of British Columbia, founded Thalassic Data Limited (Vancouver, B.C.) and consulted in the planning and execution of engineering surveys at sea. In 1987 he returned to Utrecht as head of marine geophysics and received a Ph.D. degree in 1991. He continued teaching and consulting in Europe until accepting a research position in 1997 at the Center for Marine Resources and Environmental Technology of the Univ. of Mississippi and, in December, 2004, was appointed senior scientist at the National Center for Physical Acoustics.
http://www.olemiss.edu/depts/ncpa/

Contact the author:

Prof. Henry Bass, Ph.D.
National Center for Physical Acoustics, Director
University of Mississippi
Coliseum Drive
University MS 38677

Email: hbass@olemiss.edu
662-915-5840 (voice)
662-915-7494 (fax)

Contact T. McGee:

Thomas M. McGee, Ph.D.
Senior Scientist
National Center for Physical Acoustics
University of Mississippi
Coliseum Drive
University MS 38677

Email: tmcgee@olemiss.edu
662-915-1697