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Three-Dimensional Acoustic Modeling in the Atmosphere, Approaches and Issues

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Introduction

The industrial revolution led to an increasing number of airborne sound sources and sound pressure levels of man-made noise. In many cases the noise impacts are localized to those working around pieces of noisy equipment or within structures where strong noise sources are operating. A great deal of the air acoustic noise literature focuses on quieting of sources and mitigation of their impact within these localized environments. However, more and more concern has been voiced recently concerning outdoor sources of noise that impact large areas. In some cases the impacts have been so significant that they have threatened the activity causing the noise. Some examples are: construction, transportation corridors (roads and airports) and outdoor entertainment (amusement parks, rock concerts, and motor races), etc. In these cases, the impacted areas may cover hundreds of square kilometers. Also, the pattern of the noise annoyance may be very irregular, determined by complex sound speed profiles and boundary conditions which undergo significant space and time change. In the following paragraphs we will provide a few examples of noise impacts over large areas.

In November 1991 the Australian Airports Commission received approval to build a parallel runway to handle increased traffic for Kingsford Smith Airport in Sydney. Upon completion of the runway the impact of the noise from aircraft caused a public outcry. As a result, aircraft were not allowed to use the new runway until the impact could be mitigated. The government had few options: (1) shutting down the new runway and building a new airport to handle the increasing traffic load, (2) retrofitting the housing around the airport with noise insulation, and/or paying the residents a settlement for the impact, (3) establishing severe restrictions on the number and landing/takeoff patterns of the aircraft operating out of the airport. The first was not practical and thus a combination of the last two was used to mitigate the impact. The issue became so serious that it threatened the Government in power with new elections and the mitigation costs have exceeded 180 million dollars.

Another example is the automobile racing at Laguna Seca Raceway in Monterey, California. The raceway is located in a County recreational park and is under the control of the Park District. Car races and other large entertainment events take place at the facilities throughout the year. The car races have been taking place since 1969, but the housing density surrounding the Park has increased. Over the past several years, the residents have been growing more vocal about the noise impact on the surrounding area due to activities in the Park. So vocal that they want the functions stopped if the noise impact can not be mitigated. The functions at the facility represent millions of dollars in revenue to business in the county. What can be done?

These two examples represent a class of problems different from both machinery noises inside structures and short range noise impacts out of doors. To assess and mitigate the impact of noise over wide areas requires not only a good understanding of the noise mechanism and character, but also of the propagation phenomena from the source to the impacted area. One aspect of assessing the impact is to be able to model the propagation over rather large distances. Underwater acousticians have devoted a great deal of effort to modeling the propagation of sound in the ocean over large distances. The existing ocean propagation models do a remarkable job of computing the acoustic fields as a function of space and time. A very extensive literature is available for ocean acoustic modeling in comparison to the very limited literature on atmospheric acoustic propagation modeling.

This paper is an attempt to summarize some of the relevant information on available propagation models that have been applied to atmospheric propagation problems, concentrating on the three dimensional aspects of the modeling problem. We report on the issues of model input requirements, validation and computational resource requirements. The limitations of available models are discussed in relationship to some real modeling problems, such as those illustrated in the above paragraph.

We will use some measurements made at the Laguna Seca Raceway in Monterey, California as an example of the modeling challenge.

Modeling Acoustic Propagation in the Atmosphere

Modeling the propagation of sound through an inhomogeneous, non-stationary media with irregular boundaries is a difficult problem (Jensen, et al., 1994). Figure 1 and Table 1 are representations for comparison of the ocean and atmosphere modeling environments. This figure is a schematic showing the structure of the atmosphere if viewed right side up, and the structure of the ocean if viewed upside down. It should be noted that the ocean is largely forced through the sea surface by the atmosphere and the atmosphere is forced throughout. Within the ocean the vertical sound speed structure is strongly stratified (in most temperate oceans), and the total range of sound speed in the water column is a few tens of meters per second, or less than three percent of the mean speed (1500 m/sec). Even in parts of the ocean where the vertical gradients of temperature and salinity are small the pressure dependence of sound speed creates an upward refracting environment. Ocean currents generally play an insignificant role in determining the propagation paths; they are at most a few knots and usually much less, representing a fraction of a percent of the mean sound speed. In the air the sound speed is dependent on the temperature and humidity. The average sound speed in the atmosphere is about 350 m/s, and the range of sound speed is typically 10 percent of the mean value through the lower atmosphere with significant horizontal as well as vertical gradients. In contrast to ocean current velocities, wind velocities of several meters per second, are not uncommon and can play an important role in the refraction of the rays. It should further be noted that total kinetic energy in the ocean at mid latitude is 1/20 of that of the atmosphere (Peixoto and Oort, 1992). While sheer and turbulent intensities generally decrease with depth in the ocean, they increase vastly with height in the atmosphere. Finally, the impedance contrast at the air/sea interface is nearly constant (1.5×10^5 rayls), but the air/soil/vegetation boundary for atmospheric acoustics varies over a very wide range (10 - 30,000 rayls) depending on ground conditions and vegetation cover.

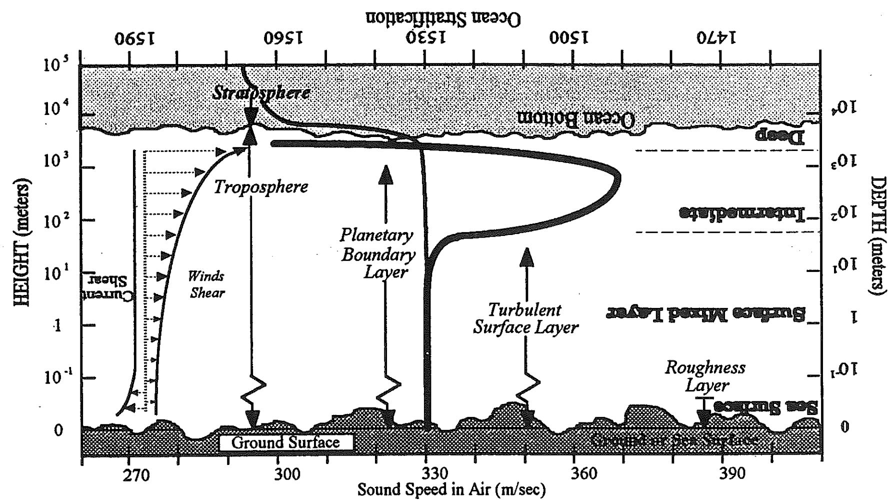

Figure 1 - Acoustical Structure in the Atmosphere and Ocean. *(Turn upside down for ocean.)*

Table 1 - Atmosphere and Ocean Parameters

Parameter	Atmosphere	Ocean
Average Vertical Sound Speed Gradient (m/sec/m (0 - 3000 m) at mid latitude location	0.002	0.023
Sound Speed Range $\frac{\Delta C}{\overline{C}}$	> 10%	< 3%
Stratification	Relatively Weak	Relatively Strong
Flow Velocity	High	Low
Shear	High	Low
Turbulent Intensity	Increase with Height	Decreases with Depth
Kinetic Energy	~ 20 × Ocean	~ 0.05 × Atmosphere
Attenuation	~ 10^2 × Ocean	~ 10^{-2} × Atmosphere
Acoustic Impedance (cgs rayls)		
Air to Surface	10 - 30,000	
Water to Air		1.5×10^5
Water to Sediment		$0.2 - 2.1 \times 10^5$

Many of the scenarios we wish to model in the ocean can be simulated with two-dimensional modeling. This is true even for very long range propagation simulations because the ocean is strongly vertically stratified. In many parts of the ocean three dimensional pictures can be accurately represented by Nx2D slices (Robinson and Lee, 1994). In the atmosphere the modeling becomes more challenging. The noise impact is generally at ground level, even though the source may be anywhere from ground level to high up in the atmosphere. It is widely recognized that the important space and time scales in the atmosphere are much shorter than the ocean.

We need a good deal of information on the environment in order to choose the best modeling approach and to actually carry out the simulations. The issues that need to be addressed are:

— Temperature and humidity gradients in the atmosphere.
— Wind and wind shear.
— Terrain.
— The impedance contrast at the boundary.
— Treatment of the sub-surface properties.

Ocean and Atmosphere Models

The hierarchy of acoustic propagation models is shown in Figure 2 (altered from Jensen, et al., 1994). While this figure was for ocean propagation models, the models can be applied to atmospheric acoustics equally well. They all begin with the wave equation, and are based on various assumptions about the environment and frequency range of the acoustic energy. The model approaches are the Fast Field Program (FFP) or spectral model, normal mode (NM); ray, parabolic equation (PE), and direct finite-difference (FD), or finite-element (FE) solutions. Analytical models based on closed solutions to a geometric problem, and empirical models based on observational data are also used. All of these techniques have been applied extensively to model ocean acoustics, however, only the ray, analytical, and empirical techniques have found any extensive testing in the atmosphere. All of these models can cope with a vertical stratified medium, but range dependency is another issue. In a range dependent environment computational requirements increase substantially, and it raises the issue of specifying the environment over the model domain.

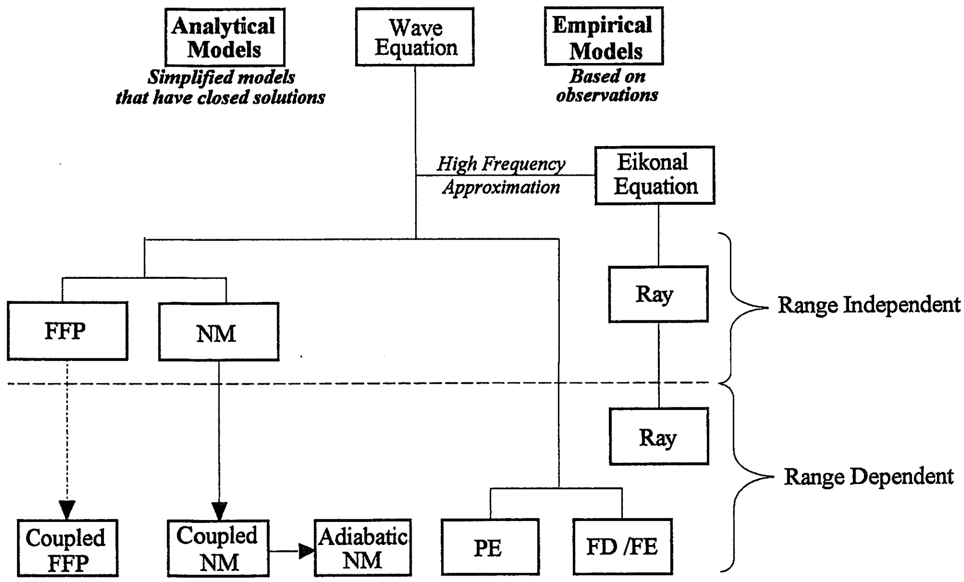

Figure 2 - Hierarchy Of Acoustic Propagation Models

Attenborough et al. (1995) recently reviewed outdoor propagation models in a paper on atmospheric benchmarks using four different sound speed profiles: Constant speed, constant positive vertical gradient (+ 0.1 sec^{-1}), constant negative gradient (- 0.1 sec^{-1}), and a bi-linear combination (+0.1 sec^{-1} to 100 m, -0.1 sec^{-1} from 100 - 300 m, and constant speed above 300 m). The ground surface was level with a complex frequency dependent impedance.

These are obviously idealized environments that represent relatively simple modeling problems. The first three of these profiles are especially useful in benchmarking since these profiles all have analytic solutions. For all the cases studied, it was found that the Fast Field Program FFP and PE algorithms agree to within the numerical accuracy (0.5 dB) over the full range of frequencies. The results of these benchmark simulations are encouraging in that the different models agree with each other in these idealized environments over the ranges and frequencies of the benchmarks. Figure 3 is a summary of the applications and limitations of various propagation codes used by Attenborough et al., (1995) to atmospheric noise problems.

It should be noted that three dimensional effects were not considered in any of the benchmark evaluations.

Whereas in the ocean fully three dimensional models are now "state of the art" (Robinson and Lee, 1994), we have found very limited literature on the three-dimensional computation of atmospheric acoustic propagation. The Hamiltonian Ray Trace Program (HARPO) can be used to compute propagation in three dimensions if the sound velocity information is provided and the high frequency approximation is appropriate. There are several reasons for this fact. First the issues in atmospheric acoustics have mainly been short range propagation between a source and receiver at known locations, where 3D effects have not been important. Secondly, the application of 3D techniques in the ocean is a relatively recent development that has not been picked up by the atmospheric modeling community (Lee and Schultz, 1995). Thirdly, the range dependence found in the atmosphere make this a very difficult application.

Models	Type	Applications		Present Limitations	Computationally Proportional to:
		Near Range (<200m)	*Far Range (>200m)*		
Fast Field (FFP)	Full Wave Equation Approximation	Applicable & Practical	Applicable & Practical	Range Independent	# Integration Points # Frequencies
Normal Mode	Analytic Wave Solution	Far Field	Applicable & Practical	Approximated sound speed profiles to allow for airy solutions	# Modes # Frequencies
Parabolic Equation (PE)	Full Wave Equation Approximation	Applicable & Practical	Applicable & Practical	For long range & high frequency, computationally demanding	# Frequencies Range Wavelength
Ray	Ray Approximation	Applicable & Practical	Applicable & Practical	High Frequency Approximation	# Rays Range

Figure 3 - Acoustic Propagation Models For Modeling Atmospheric Noise
From Attenborough, et al., 1995

In our review of atmospheric acoustic modeling problems, we categorize four classes. These are:

- Indoor - structurally constrained,
- Outdoor - short range O(10 m),
- Outdoor - medium range O(100 m), and
- Outdoor - long range O(1 km).

The factors that resulted in these categories are shown in Table 2.

Table 2- Classes of Atmospheric Noise Problems and Their Descriptions

Class of Problems	Description
Indoor	Short paths O(m); simple or complex structures with well-defined boundaries; structural coupling, narrow or broadband sources, generally in a controlled environment, fidelity may be an important issue; refraction unimportant; reflection and near field effects very important.
Outdoor - Short Range	Paths O(10 m); source and receiver geometry usually fixed and known; the noise is airborne, but boundaries and structures may have a significant impact; sound speed gradients generally not important; empirical, analytical, and ray representations have been used.
Outdoor - Medium Range	Paths O(100 m); geometry important, source often moving; source may be narrow or broadband, the sound is airborne but probably interacts with the terrain, vegetation, and soil; variability important; temperature, humidity, wind, and turbulence may be important; ray, PE, and FFP approaches have been used.
Outdoor - Long Range	Paths O(1 km); geometry important, often three-dimensional; source usually moving, may be aircraft; usually broadband and lower frequency; terrain, vegetation, and soil characteristics important; sound speed profile and variability important; temperature, humidity, wind velocity and turbulence important; PE, FFP in mode solutions.

The Laguna Seca Races — Noise Impact

The Laguna Seca Racetrack is approximately 1 mile from Highway 68. The layout and orientation of the race track and park can be seen in Figure 4.

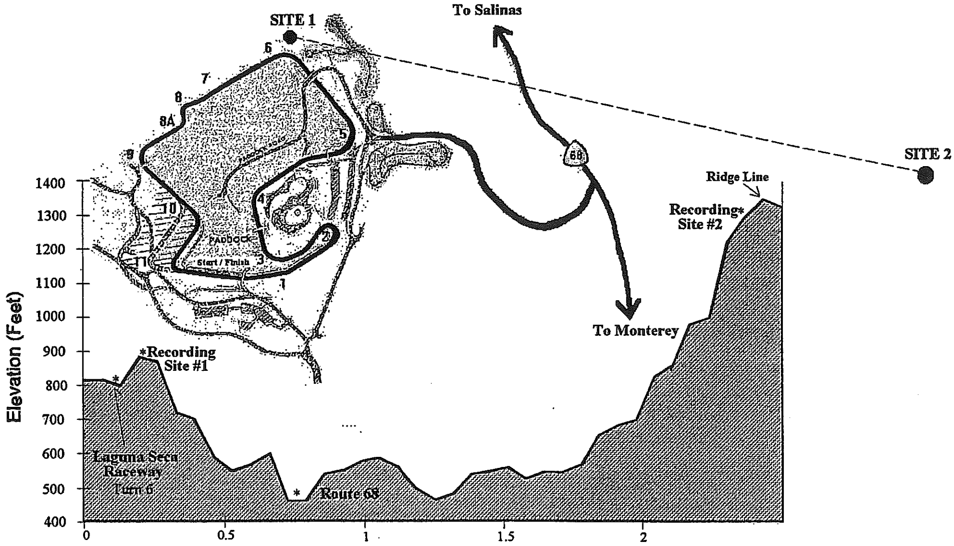

Figure 4 - Laguna Seca Racetrack (upper) and Terrain Between Measured Sites (lower)

In addition to auto racing, the park offers camping facilities, an amphitheater for musical events, a firing range, and an off-highway vehicle area. Among these, of most concern to the surrounding communities are the car races and the summer outdoor concerts. Complaints about excessive noise have come mainly from residents living to the east-southeast of the track along Highway 68. Housing in this rural area is low density with one or more acre per home. A ravine lies between the racetrack and the houses of note. We will use the Indy Car races at Laguna Seca Raceway to illustrate this complexity of the atmospheric noise problem.

Laguna Seca Recreation Area is a 542 acre facility on lands that were once part of Fort Ord. Under the operation of the Monterey County Parks Department since 1973, it is located to the North of State Highway 68 and six miles east of Monterey. Within twenty miles of Monterey Bay, the topography is characteristic of coastal valleys consisting of rolling hills with shrubs [Manzanita, Coyote Bush], low-lying oak groves [Coast Live Oak, Scrub Oak], and pastures of wild grasses and flowers. The climate is maritime. Approximately 4 km to the South of the raceway lies a ridge rising to more than 400 meters.

In an effort to better understand the propagation issues and local impacts, we took some measurements during the races of October 6-9, 1994. One of the monitoring sites was located near turn six (a site identified as one of the nosiest on the track) and another site was approximately 2 kilometers to the southwest. Figure 4 shows the terrain profile from the turn six site to the distant site. This shows a relief of approximately 350 meters. Wind and temperature measurements (five minute averages) were collected at each of our monitoring sites every thirty minutes during the races. Weather observations were also collected at Fritzsche Airfield, on Fort Ord, just 11 kilometers Northwest of the track. This station collects continuous temperature, humidity and wind profiles using "state of the art sensors". This data showed a great deal of variability throughout the race.

High speed race cars are unusual sound sources. The noise emitted by a race car has a very broad spectrum with some very strong line features that are caused by a number of sources. The noise emissions are related to a number of different components on the cars and processes. Noise emissions in passenger cars at low speed are predominantly the engine exhaust, cooling fan and engine radiation, while at high speed tires, aerodynamic noise, and engine noise are often dominant (Lyon, 1973 and Wilson, 1989). For race cars turbo chargers, drive train, turbulence, roll vortices, and other factors become important.

Figure 5 shows the sonogram of the signal (essentially the intensity of the sound at a given frequency). The source is broadband with strong components at approximately 350 Hz, 700 Hz, and 1,000 Hz. These frequencies are most likely a combination of the cars acoustic power profile, drag profile, and tire vibrations. The background noise is apparent up to about 4 seconds when the car passes around turn 6 and shifts into higher gear as it accelerates up the hill. The race car actually is no longer in sight when the sounds arrive at the distant site.

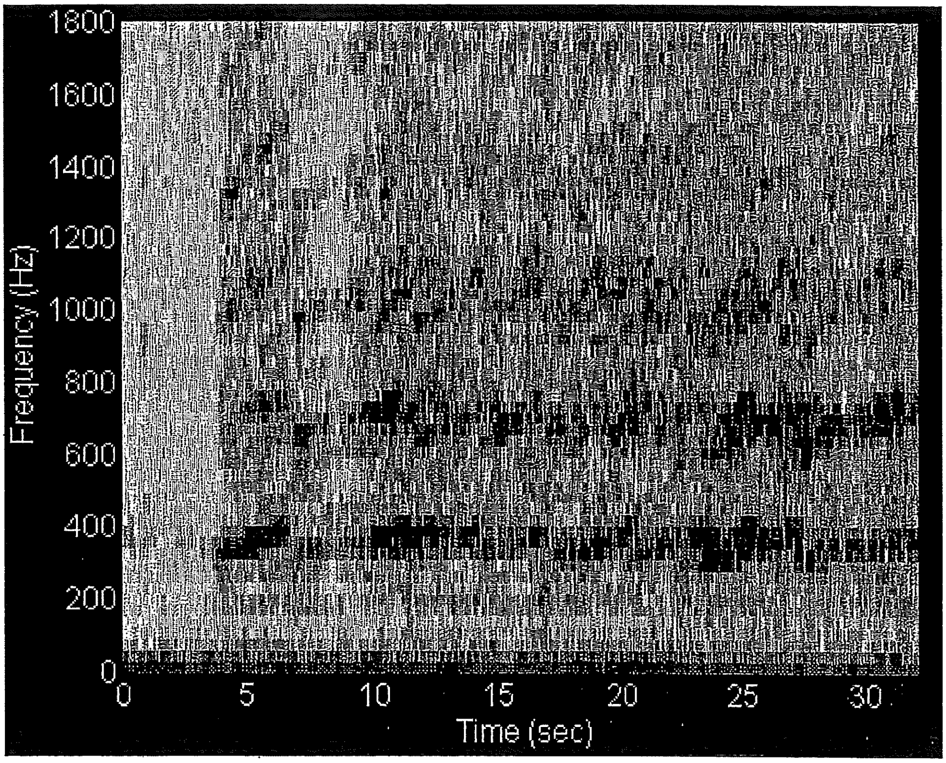

Figure 5 - Laguna Seca Indy Car Sonogram Measured at Turn 6
(Dark areas represent high intensity levels and white represents low intensity levels.)

Discussion of Modeling

Modeling the impact of aircraft landing at a major airport or car races on the surrounding populated areas is a difficult problem. These and other wide area impact noise problems are certainly three dimensional. We need not only the temperature and humidity distribution to calculate the sound speed distribution and absorption, but we must know the wind and turbulence levels because they can play a major role. For the Laguna Seca experiment we had this information from a well-maintained calibrated meteorological site.

Using this data we were able to compute the sound speed profile (including the wind contribution) over the course of the experiment. However, the profile of observations was still only available from the one site (a few other surface meteorological stations are available) and extrapolation would be necessary to model the 3-D impact.

The terrain undoubtedly played an important role in the propagation and we were able to derive the terrain from available section maps of the area. One of the most difficult issues is to incorporate the ground surface characteristics (vegetation, soil type, and moisture). Approximations can be developed for the soil and vegetation of the Chaparral environment surrounding the park. Perched on a marine sedimentary table, the track is predominantly cut out of limestone. The landscape is covered in manzanita, coyote bush, coast live oak, scrub oak, and toyon trees, with wild grasses covering the ground.

We used the derived ray speed profile (sound speed plus wind component) in the Hamiltonian Ray Tracing Program (Jones, et al. 1986). The ray paths show that if the sound is going to reach the homes most impacted, it is probably by refracted arrivals or sound from the track channeled down the canyon to impact the homes (See Figure 6). This coupled with the terrain would explain why some homes were more impacted than others located even closer to the track. This result is of practical value since the officials at Laguna Seca were considering the possibility of a barrier to mitigate the impact of the races. These results suggest that a barrier at turn 6 would be of little value.

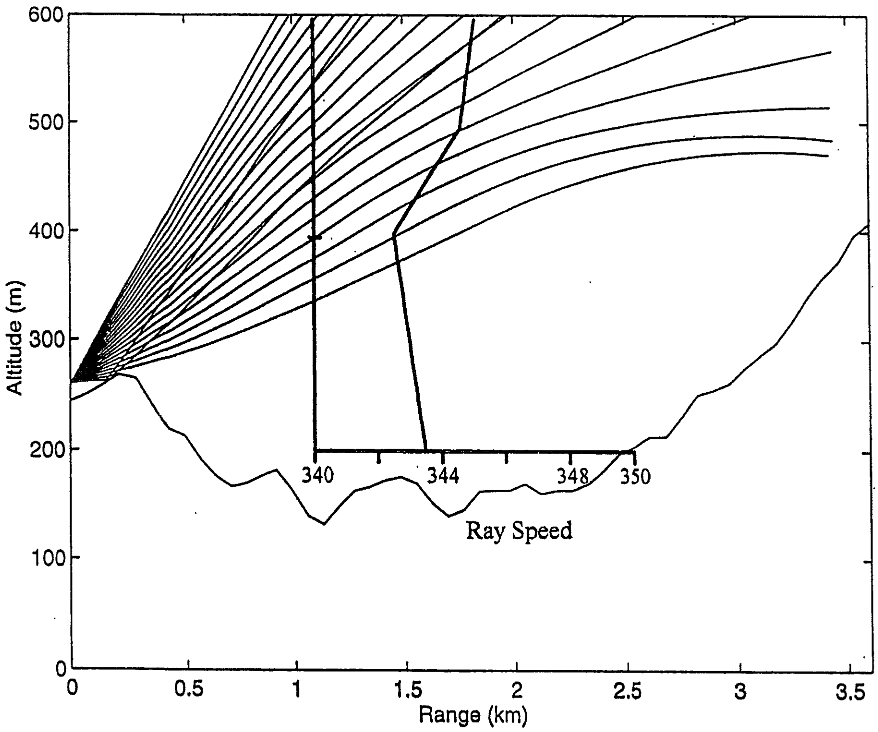

Figure 6 - Ray Speed and HARPO Ray Paths for Time of Race

Conclusions and Recommendations

Atmospheric modeling of airborne noise for medium and long range problems presents a difficult task to acoustic modelers. Perhaps no more difficult than has been found by ocean acoustic modelers, but the range of parameters and variability make it more challenging. We can only anticipate that noise will become an ever growing problem as population grows and urbanization continues. It will be highly cost effective for developers and governments to be able to model a wide variety of noise problems. As with the ocean acousticians, one of the most difficult issues is the characterization of the environment. Modern meteorological observational systems seem capable of providing the regional data inputs. Although atmospheric acousticians have benchmarked some of the more recent acoustic models, the choice of the right model in the "real world" will depend on the nature of the problem and available data. We will learn much from experience in applying various models to "real world" problems. However, many observational and modeling issues remain. If we are going to adequately deal with large area impacts the atmospheric noise impact models must develop the three dimensional modeling techniques that have been evolving in the ocean acoustics community (Robinson and Lee, 1994; Lee and Schultz, 1995).

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