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UNDERSTANDING THE FAST FIELD PROGRAM

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The fast field program (FFP) for atmospheric acoustics was developed to predict the combined effects of refraction and reflection from the ground. Three unexplained observations quickly arose. Predictions in the shadow zone were inconsistent and difficult to perform. Comparison of the results of an eighteen–month study at Bondville field station to predictions showed that measured levels for high frequencies in upward refracting conditions were much higher than predicted. Analysis of blast noise data taken at Ft. Bliss, Texas over land and Aberdeen Proving Ground, Maryland over water showed that both predictions and measurements displayed less enhancement for downward refracting conditions than would be expected from ray tracing arguments. Analytic approximations for upward and downward refracting atmospheres were developed to test the FFP and to investigate these phenomena. The analytic calculations have clarified the mechanisms affecting sound propagation in upward and downward refracting atmospheres. In addition, the study of these solutions lead to the direct interpretation of the wave number spectrum which in turn has lead to a method of including turbulence in fast field programs.

1. INTRODUCTION

It may seem presumptuous of me to present a paper entitled "Understanding the fast field program" since the principles of the fast field program (FFP) for underwater acoustics were published in 1980 [1] and the adaptation of these principles for atmospheric use was published in 1985 [2] and 1986. [3] Two excellent tutorials have been published by scientists from the University of Illinois [4] and the University of Salford [5] and I refer you to these for a detailed description of the inner workings of FFP.

My goal in this talk is to briefly describe some of my research involving the FFP over the last decade, and to share how each topic contributed to the development of the calculation average turbulence effects in a refracting atmosphere. [6]

2. DESCRIPTION OF THE FAST FIELD PROGRAM

The fast field program assumes a horizontally homogenous layered atmosphere with varying sound speed. The cylindrically symmetric wave equation is Hankel transformed into the transform pair:

$$\hat{p}(K, z) = \int_0^\infty p(r, z) J_o(Kr)\, r\, dr$$

$$p(r, z) = \int_0^\infty \hat{p}(K, z) J_o(Kr)\, K\, dK .$$

$\hat{p}(K, z)$ obeys the one dimensional differential equation:

$$\frac{d^2 \hat{p}(K, z)}{d z^2} + \left(k^2(z) - K^2\right) \hat{p}(K, z) = -2\,\delta(z - z_s),$$

with the complex impedance boundary condition at the ground and a radiation boundary condition at the top layer. K is a horizontal wavenumber which corresponds to real propagation angles for $K < k_{max} = \omega/c_{min}$. The solution for $\hat{p}(K, z)$ in a layered atmosphere is the principal topic of Refs. 1–5. Fig. 1 displays the magnitude of $\hat{p}(K, z)$ for a downward refracting atmosphere. In the fast field program, the integral is performed using a fast fourier transform.

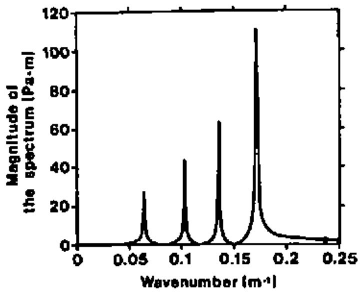

Fig. 1 Wavenumber spectrum of the fast field program.

3. PROBLEMS

The predictions of the fast field program were compared to measurements under upward and downward refracting conditions at Bondville. See Fig. 2. The predictions agreed well at low frequencies and for all downward refracting conditions. At intermediate to high frequencies, the FFP underpredicted the sound levels. Also, the FFP predictions had "wiggles" at low levels deep in the shadow zone.

It was clear that turbulence contributed to the increased levels; however it was not clear if the predictions were correct for no turbulence. Since the FFP is range independent, it appeared that it could not be used to predict turbulence effects since turbulence removes the range independence.

Blast noise propagation data taken over land at Ft. Bliss, TX and over water at Aberdeen Proving Ground, MD was compared to the prediction of a pulse fast field program. [7] The prediction and measurements only displayed slight enhancements for low level inversion conditions (inversion height < 40m). Ray tracing analysis would lead one to expect large enhancements for all inversions.

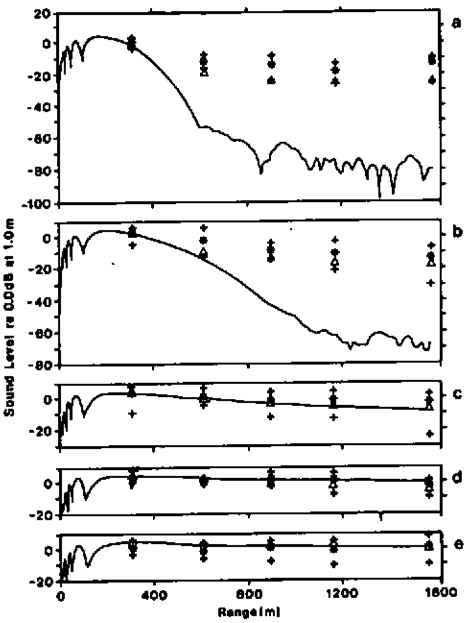

Fig. 2 Comparison of the data for Bondville, IL with coherent parabolic equation predictions and with the turbulent FFP calculation. f = 630 Hz. (a) a = −0.8 m/s, (b) a = −0.4 m/s, (c) a = 0 m/s, (d) a = 0.4 m/s, and (e) a = 0.8 m/s.

4. RESEARCH

Residue Series Comparison

Steve Franke developed a residue series solution for upward refraction [8] and compared this to the FFP predictions. See Figs. 3 and 4. This comparison showed three important things

1. The FFP has a noise floor (−130 dB in SPL),
2. Layer thickness must be smaller than a wavelength,
3. Gradients thinner than a wave layer thickness have little effect on sound propagation.

The wave layer thickness is:

$$\ell = \left(2\, k_o^{\,2}\, |a|\right)^{-1/3}$$

where k_o is the wavenumber at the ground and $|a|$ the absolute value of the sound speed gradient at the ground.

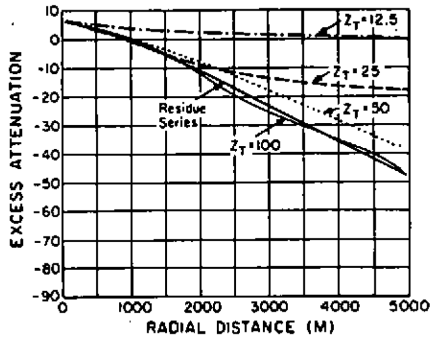

Fig. 3 Excess sound attenuation versus range at 40 Hz. The residue series result for indefinitely decreasing sound speed is shown along with the FFP results for layer thicknesses of 12.5, 25, 50 and 100 m.

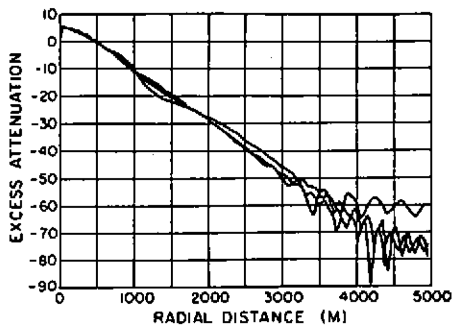

Fig. 4 Excess sound attenuation versus range at 40 Hz for the linearly decreasing profile and for two homogeneous layer approximations using 12 and 22 layers.

Normal Mode Comparison

The success of the residue series research suggested that the downward refracting gradient solution be compared to the FFP. [9] Fig. 1 is the $\hat{p}(K, z)$ for a linear downward refracting gradient. It was observed that the peaks in the wavenumber spectrum correspond to normal modes which are vertical resonances of the atmosphere. The fact that the half width corresponds to the absorption or linear loss easily follows from this identification.

Since each mode corresponds to energy launched at a particular angle, the horizontal wavenumber can be used to calculate an angle of propagation at the source: $\cos(\theta) = K/k$, where $k = \omega/c$. c is the speed of sound at the source height.

Another important result of this research was that the lowest normal mode is strongly coupled to the ground and undergoes large losses. For downward refraction to lead to high levels, the sound speed inversion must be higher than the mode height of the second mode. Again the wave layer thickness is a measure of the height of the first mode.

Turbulence

Recently, we have applied what we have learned to the problem of turbulence. [6] Comparison of the FFP to the residue theory and to the normal mode theory led to a concrete interpretation of the spectra $\hat{p}(K, z)$. Each point on the spectrum corresponds to a wave contribution launched at a real angle (as long as $K < k_{max}$).

Each contribution can be treated as a ray in the scattering theory developed by Daigle [10] and extended by Clifford and Lataitis [11] for rays in a non–refracting atmosphere. [9]

$$\left\langle \overline{p^2(r,t)} \right\rangle = \frac{1}{2}\,\mathrm{Real}\left(\frac{1}{\pi r} \int_0^\infty \int_0^\infty \hat{p}(K)\, \hat{p}^*(K') \;\; x \;\; e^{-i(K-K')r}\; T(K,K') \sqrt{K}\sqrt{K'}\, dK\, dK' \right)$$

$T = \exp\left[-\sigma^2(1-\rho)\right]$, $\sigma^2 = \left(\sqrt{\pi/2}\right)\left\langle \mu^2 \right\rangle L L_o$, $\left\langle \mu^2 \right\rangle$ the variance of the index of refraction, K the wavenumber, L the path length and L_o the Gaussian turbulence scale.

The phase coherence between paths is

$\rho = \sqrt{\pi}\,\frac{L_o}{2h}\,\mathrm{erf}(h / L_o)$ where h is the average path separation.

h is estimated by finding the path separation oF two circular rays leaving the source at the launch angle and intersecting the receiver. See Fig. 5. The results seem to be insensitive to this choice.

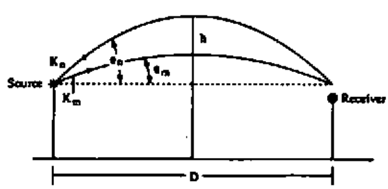

Fig. 5 Construction used to calculate the maximum spatial separation *h* for two different wavenumbers.

Attempts to get this calculation to agree with data lead us to a final piece in interpreting the wavenumber spectrum. Recall that portions of the spectrum beyond K_{max} are necessary to achieve good convergence of the integral, but do not correspond to waves propagating at real angles. We could only achieve good agreement with data by omitting off diagonal elements involving scattering of the large horizontal wavenumber components. The agreement is illustrated in Fig. 1, with which I began the talk.

5. CONCLUSIONS

Comparison of the fast field program with analytic results for upward and downward refraction helped to develop an understanding of the physical interpretation of the wavenumber spectrum. This physical interpretation made it possible to develop a calculation to predict sound propagation in a turbulent refracting atmosphere.

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