inter.noise 2000
The 29th International Congress and Exhibition on Noise Control Engineering
27-30 August 2000, Nice, FRANCE

I-INCE Classification: 2.4

PREDICTION OF SOUND FIELDS IN THE PRESENCE OF TERRAIN FEATURES WHICH PRODUCE A RANGE DEPENDENT METEOROLOGY USING THE GENERALISED TERRAIN PARABOLIC EQUATION (GT-PE) MODEL

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Keywords:
METEOROLOGY, BLAST, MODEL, PROPAGATION

ABSTRACT

Undulating terrain produces a range dependence mainly in the vertical wind speed profiles. Provided the airflow remains approximately laminar it is possible to calculate the terrain modified wind speed profiles from their flat ground counterparts. A pilot study has been carried out to investigate the effect of range dependence for two simple terrain cases. Field predictions are obtained using the Generalised Terrain Parabolic Equation (GT-PE) numerical model, which allows predictions for any smooth terrain profile with any meteorology. The study has been designed to identify the effects of the range dependent meteorology on the near ground sound field.

1 - INTRODUCTION

The Generalised Terrain Parabolic Equation model was first developed in 1994[1,2,3] and has been extensively used for predictions over smooth terrain in the presence of real meteorology both at Salford and by many other research groups. The GT-PE uses a terrain following transformation (sigma transformation) which avoids many of the pitfalls inherent in methods based on fitting circular sections to the terrain profile. The GT-PE is more accurate and can run at faster speeds than any of these methods.

The original model was substantially improved by use of a cubic spline algorithm to not only smooth out terrain slope discontinuities but to also provide the derivatives needed in the algorithm with much greater accuracy than those previously obtained with approximate finite methods.[4,5]. The cubic spline modified GT-PE is described in section 2 below. At this stage our first FORTRAN implementation of the model, capable of running on a PC, was produced, which was the forerunner of the latest GT-PE software application package[6].

From the time the GT-PE was first used for realistic terrain and meteorology it was clear that, though the PE calculation itself was both accurate and efficient, the predictions contained systematic errors. These resulted from the use of a range independent meteorology based on the zero−plane (flat ground) profiles. The GT-PE can of course use a range dependent meteorology but this was not available at that time. The extent of these errors became apparent in a pilot study conducted for a bell shaped ridge with range dependent profiles provided by the Meteorological Office at Bracknell. A specially adapted version of the GT-PE, which could accept this met data, was used in this study [7]. The results of this project are summarised in section 3.

New work on terrain meteorology at Salford will, in the near future, produce met models capable of generating suitable range dependent met. In the meantime in order to make our software applications viable an approximate algorithm has been developed [8], which generates range dependency in the met allowing for the effect of the terrain. The GT-PE algorithm has been modified to accommodate this new met front end and the latest version of our GT-PE software[6] incorporates this new algorithm. The new approximate met algorithm is described in section 4 below.

2 - THE CUBIC SPLINE GT-PE

The GT-PE uses a sigma transformation from the x, z domain to a new transformed domain ξ, η where $\xi = x$ and $\eta = z - H(x)$ where $H(x)$ is the terrain profile height as a function of range x. This transform is applied to the 2D Helmholtz equation for the velocity potential $\psi(x, z)$ to give the corresponding equation in terms of the transformed velocity potential $\psi(\xi, \eta)$. This potential is then separated into an exponential carrier multiplied by a modulator term φ (see references 1 and 2), $\psi(\xi, \eta) = \varphi(\xi, \eta) \exp(ik_0 x)$ where k_0 is the wavenumber at a reference height. Substitution of this split potential allows a new modulator wave equation for φ to be obtained

$$\frac{\partial^2 \varphi}{\partial \xi^2} + 2ik_0 \frac{\partial \varphi}{\partial \xi} - 2H' \frac{\partial^2 \varphi}{\partial \xi \partial \eta} + L_1(\eta)\varphi = 0 \tag{1}$$

where H' is the first derivative of H with respect to ξ and L_1 is the η dependent operator

$$L_1 = \alpha(\xi) \frac{\partial^2}{\partial \eta^2} - \beta(\xi) \frac{\partial}{\partial \eta} + \gamma \tag{2}$$

The coefficients α, β are functions of $H'(\xi)$ and $H''(\xi)$ and γ depends only η.

$$\alpha = 1 + (H')^2, \ \beta = 2ik_0 H' + H^{'}, \ \gamma = k(\eta)^2 - k_0 \tag{3}$$

The procedure described in reference 9 was used to derive a second-order accurate wide angle PE by integrating (1) over a range step from $\xi = a$ to $\xi + \Delta\xi = b$. These integrals are of the form

$$I_n = \int_a^b R(\xi)\, \varphi^{(n)} d\xi$$

where $R(\xi)$ is either α or χ, and

$$\varphi^{(n)} = \frac{\partial^n \varphi}{\partial \eta^n}\ ,\ \chi(\xi) = H'' - 2ik_0 H'$$

From this integrated equation we can obtain the finite difference core PE given in reference 2 which contains these same integrals which have to be evaluated numerically. The derivatives H' and H'' are obtained very accurately at each range step using the cubic splines fitted to the function $H(\xi)$. The procedure for obtaining these derivatives is given in reference 4.

A 3rd order accurate Euler-McLaurin evaluation of the above integrals was used at the limits a, b for a range interval. Reference 5 gives a derivation of the integral coefficients in terms of the new derivatives of H, evaluated at a, b. Comparison of GT-PE predictions using the numerical integration used in reference 2 with those using the new integrals for a simple bell shaped ridge show that the original method gives increased error as the terrain steepens. These errors are most noticeable close to the hill.

3 - PILOT STUDY FOR A BELL SHAPED RIDGE WITH RANGE DEPENDENT MET

A pilot study to investigate the effects of met range dependence for a bell shaped ridge is described in reference 8. A smooth terrain profile similar to that used in reference 2 was used.

The terrain profile was given by

$$z(x) = H\cos^2\left[\frac{\pi(x - x_{top})}{2W}\right] \tag{4}$$

for locations lying within the width of the hill, W, and at other locations $z(x)=0$. H is the maximum hill height occurring at a location x_{top}. For this study x_{top}=4 or 7.5 km, H=300 m and W=3 km. The Met Office at Bracknell produced range dependent met profiles at 300 m intervals using their FLOWSTAR model. The starting zero-plane met was based on neutral conditions with an adiabatic lapse rate of -0.0098 degrees C/m and a ground surface wind speed of 10 m/s taken at 10 m above ground giving an approximate logarithmic wind speed profile near the ground. The range dependent profile data was picked up by the modified GT-PE program, which used interpolations to obtain the met profiles and hence the sound speed profile at each range step.

GT-PE predictions were obtained at 50 and 200 Hz for the two terrain cases corresponding to the two x_{top} values and these were compared with the corresponding predictions with no range dependence. In Figures 1 and 2, predicted attenuations are shown for the case $\mathrm{x_{top}}$=4 km at 50 Hz. Figure 1 is for no range dependence and Figure 2 is for the range dependent case. The smooth curve is the free field loss.

In front of the hill there is little difference between the curves however immediately behind the hill the shadow loss in the range dependent case is, unexpectedly, about 10 dB more than for the non range dependent case. Further away from the hill the two curves have roughly the same average values but the range dependent curve is smoother, the interference effects evident in the non range dependent case having been disrupted by the introduction of the range dependence-this would be expected. In Figures 3 and 4 the corresponding 200 Hz attenuation curves are shown. We can draw almost exactly the same conclusions as in the 50 Hz case.

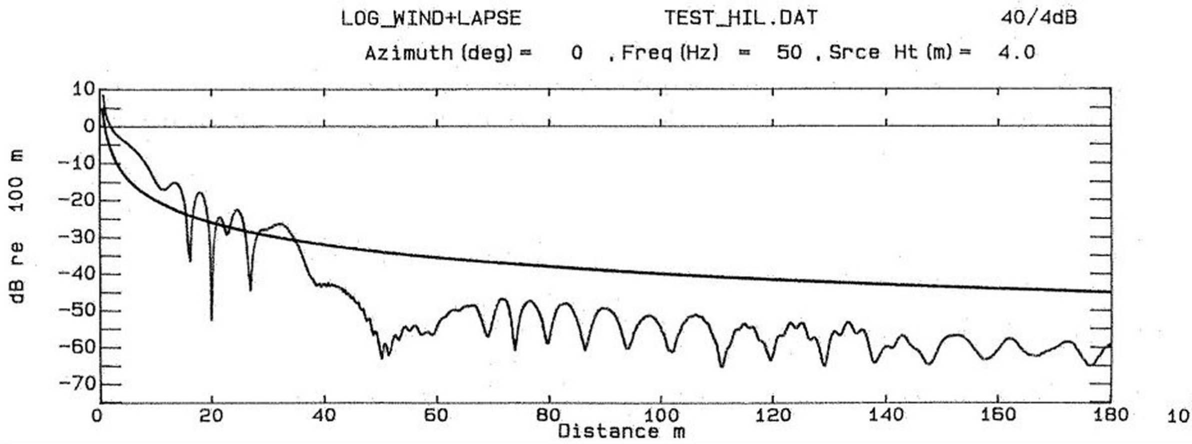

Figure 1: Non range dependent met prediction at 50 Hz for the test hill; prediction is given at height of 2 m above ground surface.

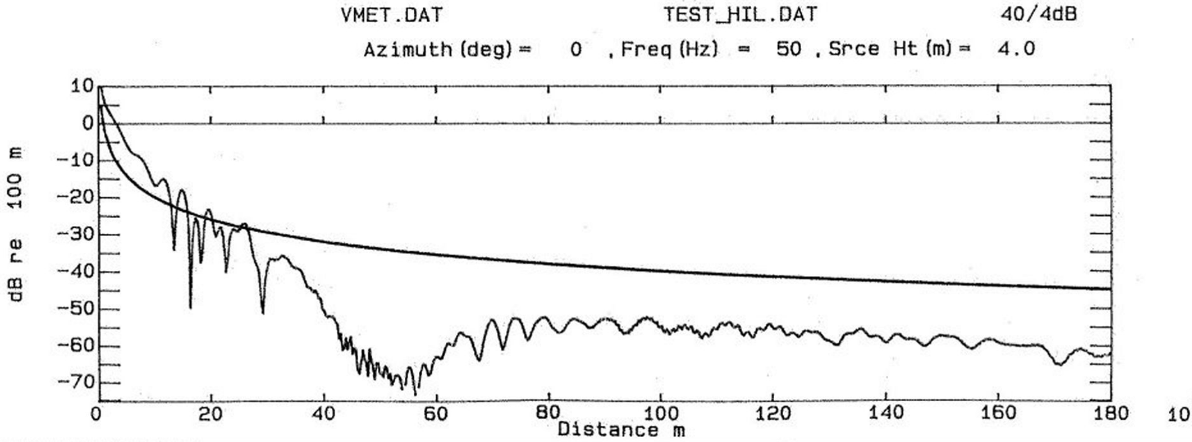

Figure 2: Range dependent met prediction at 50 Hz for the test hill.

4 - AN APPROXIMATE ALGORITHM FOR CONFIGURING AUTOMATIC RANGE DEPENDENT MET

Examination of the wind speed profiles produced by FLOWSTAR in the above case[8] shows that

1. the bottom part of the zero-plane profile of depth $H(x)+z_C$ is compressed into the bottom part of the profile at range x of depth z_C, (approximately 100 m) starting from the terrain height $H(x)$,
2. the wind speed at all heights z above $H(x)+z_C$ for flat ground, become the wind speeds at heights z above the zero plane.

The above leads to a very simple compression algorithm which requires the height z above the zero plane to be transformed to a new height z_{new} above the terrain at location x:

$$z_{new} = \nu z \ , \ \nu = \frac{z_C}{H\left(x\right) + z_C} \tag{5}$$

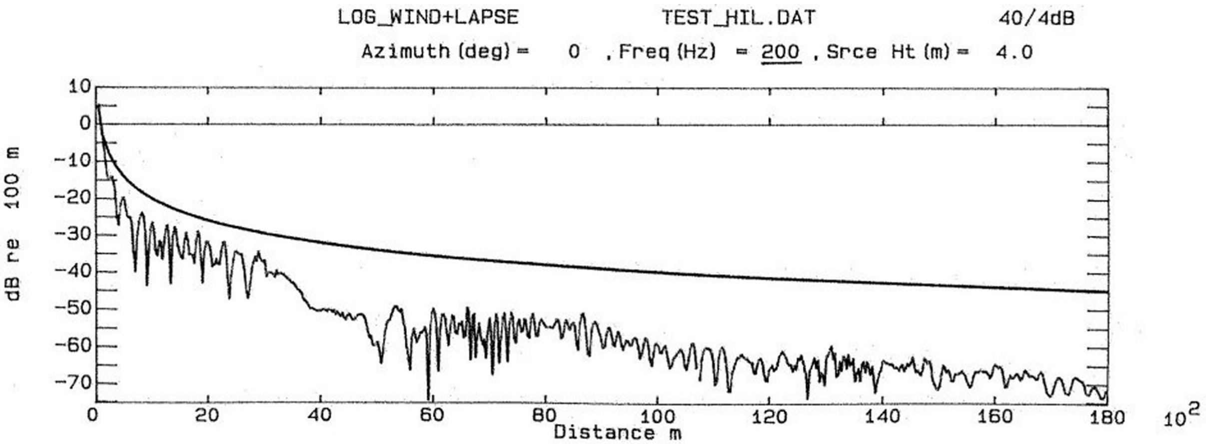

Figure 3: Non range dependent met prediction at 200 Hz for test hill.

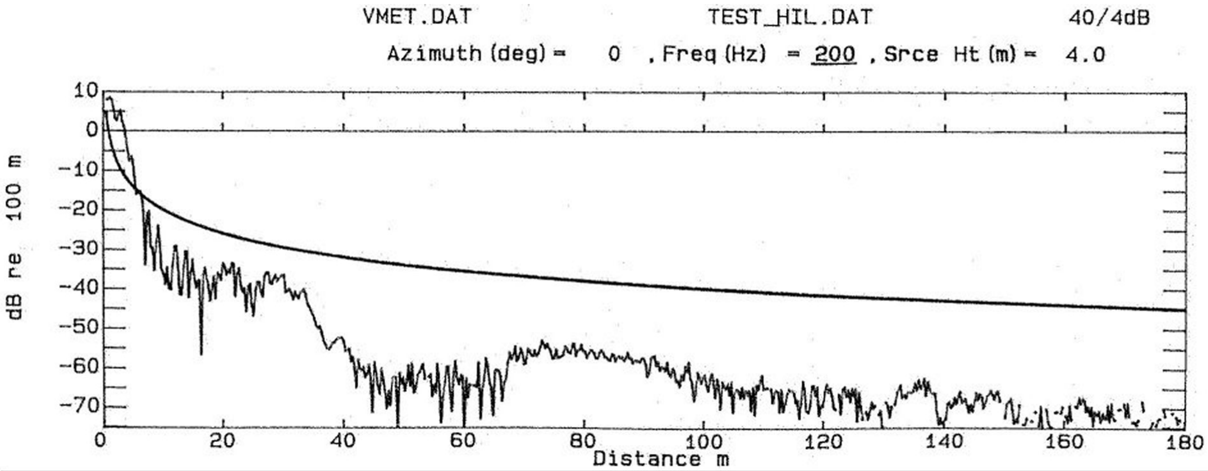

Figure 4: Non range dependent Met prediction at 200 Hz for the test hill.

This compression can be explained by considering the steady flow of air in thin layers. As the flow strikes the hill these layers become compressed, the compression increasing with height, $H(x)$. Higher up in the atmosphere, where the terrain gradient can no longer exert a compression effect on the layers, the wind speed remains unchanged.

The above compression does not make proper allowance for the enforced near logarithmic behaviour of the wind speed close to the ground surface which dominates at all $H(x)$ values, just as it does over flat ground. The above compression therefore produces an anomalous bulge in the bottom $1/3^{\text{rd}}$ of the compression depth, z_C, when $H(x)$ is less than half the maximum hill height. This bulge must be removed since it can lead to a spurious turning point in the sound speed profile. An ingenious adaptive algorithm has been devised to restore the correct near ground wind speed behaviour at the same time retaining the above compression effects-it is described in reference 8. For the test hill in the pilot study the agreement between the FLOWSTAR range dependent met and that from the adaptive compression algorithm was almost perfect. The only disagreement was at large $H(x)$ values close to x_{top} where FLOWSTAR gave an increase in wind speed at z_C of approximately 10% over the corresponding zero plane value. This increase continued for all values of z greater than z_C and would therefore appear to be a systematic error.

Strictly a separate compression process should be applied to the temperature profiles before calculation of the sound speed. A temperature compression algorithm is being developed at Salford and will be added at a later stage. For the moment the above wind speed algorithm is applied to the zero plane sound speed instead of the wind speed. This assumes that the near surface wind speed profile has the greatest slope changes and that the temperature slope change is relatively small. In the neutral met case in the pilot study this will be so but in general it will not.

The above comparison was confined to the downwind case-there is no problem however in calculating the sound speed for any azimuth resolving the wind vector into the propagation plane in the usual way. The GT-PE with the new compression algorithm was rerun for the above test cases and the predictions were identical to those using the FLOWSTAR data.

5 - CONCLUSION

The approximate algorithm for producing range dependent met has been shown to work well and produces met profiles very close to those generated by FLOWSTAR. In addition the modified GT-PE model using the range dependent met profile generator has been shown to produce the correct attenuation predictions which were indistinguishable from those produced in our pilot study with the FLOWSTAR met. The validity of the range dependent met must however be subject to the following limitations implicit in the derivation of the algorithm.

1. It is based on neutral or slightly stable zero plane met and has been constructed assuming the near surface wind speed profile has a dominant effect on the sound speed profile.
2. It uses a sound speed compression to provide the temperature gradient profile compression whereas separate wind speed and temperature profile compression algorithms should be used.
3. It assumes that a single isolated ridge is the only terrain feature present.

The first two limitations are being addressed and new more accurate algorithms are being developed at Salford. CG Collier[10] has shown that the algorithm described here is consistent with other rough surface met models and that the above limitations may well not turn out to be a severe problem in terms of the magnitude of the GT-PE prediction errors. CG Collier has also shown that the above algorithms could be modified using Grimond and Orke's [11] nomograms to make allowance for the effects of adjacent hills.

ACKNOWLEDGEMENTS

The authors wish to thank the Ministry of Defence, Department of Defence Health and Safety for their financial support for the pilot study. The authors would also like to thank Professor C. G. Collier, University of Salford (previously at The Meteorological Office, Bracknell) for his help in the construction of the new range dependent profile algorithm and for his suppport of this work.

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