Enhanced propagation of aviation noise in complex environments: A hybrid approach

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Accurate prediction of sound levels around airports and below flight paths can help faithfully represent the impact of aviation noise on communities. However, for large scale assessments, as are often performed by the U.S. Federal Aviation Administrationis environmental models, the accuracy of a model must be weighed against its efficiency. The hybrid propagation model (HPM) is capable of predicting propagation through complex environments. It is a composite of three methods—the generalized terrain parabolic equation (GTPE), fast field program (FFP), and straight ray models—each utilized in a different region of elevation angles from the source. If propagation conditions do not warrant use of the full model, one of the component models with faster runtime can be chosen as a surrogate. Analyses of cases using different source heights and including uneven terrain, refractive atmosphere, and ground type transitions, indicate when a detailed propagation model is needed, or when a simpler model is sufficient.

1. INTRODUCTION

The United States Federal Aviation Administration's (FAA) Aviation Environmental Design Tool (AEDT) and Integrated Noise Model (INM) are standard models for predicting aviation noise in the United States. To achieve fast runtimes, these tools use simplified approximations for effects of ground impedance, terrain, and meteorology in their noise propagation calculations. The Volpe National Transportation Systems Center and the FAA are currently undertaking efforts to improve the models' noise prediction capabilities.

The hybrid propagation model (HPM) is a numerical model, originally developed through a cooperative research effort with the Pennsylvania State University[1,2] to achieve more accurate predictions in complex environments. It is a combination of three composite models—the parabolic equation (PE) model, the fast field program (FFP), and a straight ray model—chosen for their complementary strengths.

While results of the HPM are more accurate, runtimes far exceed those of the INM and AEDT. Analysis of test cases covering varied propagation conditions provides a foundation upon which to develop criteria for reducing computation time. This process involves identifying conditions that do not demand the advanced capabilities of the full HPM, but rather can afford to be run by a simpler, faster method. Thus, an intelligent switching scheme can be established where the proper model is chosen based on the needs of the propagation conditions.

2. COMPONENTS OF THE HYBRID PROPAGATION MODEL

The parabolic equation method used in the HPM is a two-dimensional generalized terrain, finite difference formulation[3,4,5]. It is derived from the one-way Helmholtz equation[5] with use of an assumption that limits the validity of the model to elevation angles up to approximately $\pm 35°$ from the horizontal of the source. The PE propagates sound in the two-dimensional vertical plane by extrapolating results at one range step from results at previous range steps, and it incorporates range-dependent effects at small elevation angles from the source, such as terrain features, transitions between different types of ground, and changing meteorology. However, because it is derived from the one-way Helmholtz equation, it can only account for sound moving in the forward direction from the source to the receiver and does not include backscatter.

Because of the elevation angle limitation of the PE, the HPM utilizes the FFP in conjunction with the PE. The FFP[5,6,7] is derived from the Helmholtz equation by applying a transformation from the horizontal spatial domain into the horizontal wave number domain. It propagates sound in the two-dimensional vertical plane between stratified layers of the atmosphere. The FFP, accurate both at low frequencies and at moderate elevation angles, supplements the PE. However, it is limited to inclusion of non-range-dependent propagation effects, and errors are introduced at higher elevation angles from the effects of a window applied in the horizontal wave number domain. The valid angle range depends on the steepness of the window roll-off. The window used in this FFP formulation introduces inaccuracies at angles above 72°. However, to be conservative, a smaller angle range below 48° was used.

Finally, a straight ray model is used to fill in the regions at elevation angles greater than 48°. This model is a superposition of the direct and reflected sound at the receiver point, assuming the sound follows a straight path. While it can include the effects of a uniform, finite-impedance ground, the implementation of the straight ray model used in this research incorporates neither range-dependent effects, nor refractive atmospheres. More advanced ray models, however, are able to incorporate these propagation effects. The straight ray model was used in this research for the smallest ranges, where range-dependent effects will have a minimal effect.

The construction of the hybrid model is achieved by joining the ray, FFP, and PE components in the appropriate regions in the two-dimensional vertical plane, as shown in Figure 1. PE results are used in elevation angles of 35° and below, FFP results are used between 35° and 48°, and ray results are used above 48°. The performance of both individual PE and FFP models was verified against both analytical solutions and published results[5,8]. The ray model was verified against the PE and FFP models.

3. ANALYSIS OF TEST CASES

Seven sets of propagation conditions are considered here, summarized in Table 1. They were designed to be simple enough for pointed, systematic study, and yet representative of certain aspects of real world applications. A diagram of

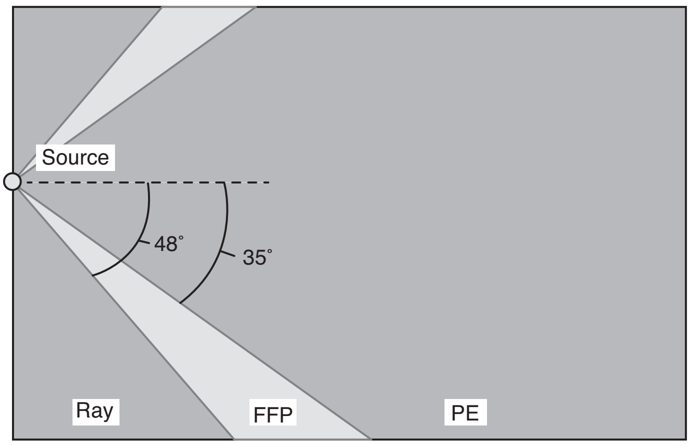

Figure 1: Combination of component models in HPM in the vertical plane.

Table 1: Terrain, ground type, and atmospheric characteristics of the seven test cases.

Terrain	Ground Type	Atmosphere
Flat	Soft	Homogeneous
Flat	Hard	Homogeneous
Hill	Soft	Homogeneous
Flat	Soft	Upward Refracting
Flat	Soft	Downward Refracting
Flat	Hard-Soft-Hard	Homogeneous
Upward Slope	Soft	Homogeneous

Table 2: Common parameters in the seven test cases.

Parameter	Value
Source heights (measured from ground surface directly below)	10, 40, 100, and 400 m
Source noise and performance data (developed from AEDT/INM source data)	747-400 overflight at 7444 lbs thrust
Receiver height (above the ground surface)	1.219 m
Effective flow resistivities (soft ground, hard ground)	150 and 20,000 cgs Rayls
Temperature	14.9°C
Noise metric	A-weighted max. sound level

the propagation conditions is included beneath the results figures: Green and brown lines represent soft and hard ground surfaces, respectively.

Each case consists of a point source at a given altitude. Results are presented as a function of horizontal range from the source for a receiver at a given height above the ground. Four source heights are considered for each case. The common parameters are presented in Table 2.

The HPM, FFP, and ray model results are plotted together for comparison, as applicable. The HPM results are composed of ray results at the smallest ranges, then FFP results for the moderately small ranges, and PE results for the remainder of the range. Arrows indicate where there are model transitions in the full HPM run. Because the model transition ranges for the lowest three sources are small compared to the overall propagation ranges, the arrows overlap to varying degrees. The FFP and ray results are calculated exclusively with the FFP and ray models, respectively.

Broadband results are presented as A-weighted maximum sound levels for the given aircraft source. These are generated by calculating the attenuations of propagation with respect to the level 1 m from the source using the HPM or component models, separately for each one-third octave band. The attenuations are applied to the source data, which also conform to the 1 m distance from the source, for each one-third octave band. Finally, all of the propagated band levels are logarithmically summed to obtain the broadband results for the aircraft source.

Because the FAA models are regularly employed for large scale calculations, runtime is an important consideration, even at a research level. The HPM has access to three different models by design: the PE is slowest, the FFP is faster, and the ray model is fastest. Accordingly, a practical question is considered: Which propagation conditions demand use of the full HPM, and for which might a faster method be substituted with minimal effect on accuracy?

In the course of analyzing the test cases, three distinct categories emerged as benefiting from use of the full model.

The first and most intuitive involves conditions where the simple geometry of direct and reflected rays is disrupted. This includes conditions where terrain features break the line of sight as well as refractive atmosphere conditions that support shadow zone formation or multiple reflections off the ground. The second category applies to changing ground surface conditions within a relevant extended region around the point of specular reflection—the Fresnel zone. The third covers terrain shapes that significantly impact the angle of reflection off a soft ground, influencing the ground effect.

Results of the two simplest cases, with flat, uniform ground and homogeneous atmosphere, serve as baselines for evaluating the added effects of more complicated mechanisms in propagation. The other five cases are presented in the context of the three identified categories. Note that for assessing aviation noise impact, focus is placed on sound levels near the ground. Different criteria may be applicable for receivers at higher altitudes.

3.1. BASE CASES: FLAT, UNIFORM GROUND, HOMOGENEOUS ATMOSPHERE

Figures 2 and 3 display results of the two simplest cases: flat terrain, homogeneous atmosphere, and a uniform soft and hard ground surface, respectively. Because they were least likely to require sophisticated modeling, these cases test the viability of the switching scheme.

For each source, levels decrease with distance, resulting from geometrical spreading and atmospheric absorption. Some fluctuations in level can be seen for all four sources, especially toward the lower ranges, as a result of the interference patterns of the discrete frequencies. The combination of twenty-four one-third octave band results, however, smoothes the severe interference pattern peaks and dips of the individual frequency bands.

In the soft ground case, Fig. 2, the results of the three models agree well, apart from FFP results at the smallest ranges, where the model's accuracy is degraded. Consequently, the HPM, FFP, and ray model lines are nearly indistinguishable. Agreement between the three models indicates that, so long as the model is considered to be accurate in the propagation region of interest, the choice of model is insignificant, making the simple ray model a good substitute for the full HPM.

A similar conclusion is reached for the hard ground conditions in Fig. 3. Here, the soft ground results are included for comparison, shown in the dotted line. The hard ground produces larger levels than the soft, as expected. Again, all three models agree within their regions of validity.

In addition to proof of concept, the results for these two cases serve to represent ray model results for the five additional test cases. The framework of this ray formulation has no established means of accepting inputs for inhomogeneous propagation conditions. Therefore, results for more complicated cases are also blind to any such effects, and are indistinguishable from results of these two cases. The extent of difference between the HPM results and the results of these base cases will indicate whether the ray model is a suitable substitute.

Similarly, the FFP cannot incorporate range-dependent effects. Thus, results of these cases also reflect those of the FFP for any uneven terrain shape or ground impedance transition. The FFP can, however, incorporate effects of a refractive atmosphere, and separate FFP results are presented in the two refractive atmosphere test cases.

3.2. CATEGORY 1: SIMPLE GEOMETRY OF DIRECT AND REFLECTED RAYS IS DISRUPTED

Disruption of the simple direct and reflected ray representation

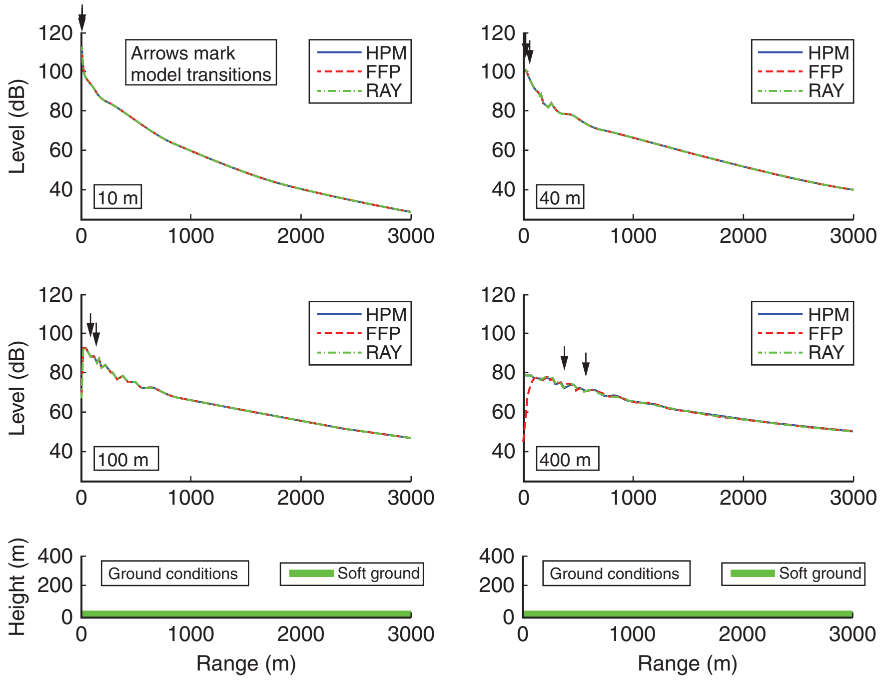

Figure 2: *Soft, flat ground and homoeneous atmosphere. HPM, FFP, and ray model results are compared for each source height: 10 m, 40 m, 100 m, and 400 m. Arrows indicate transition points between components of the HPM. A diagram of the propagation conditions is included beneath the results figures.*

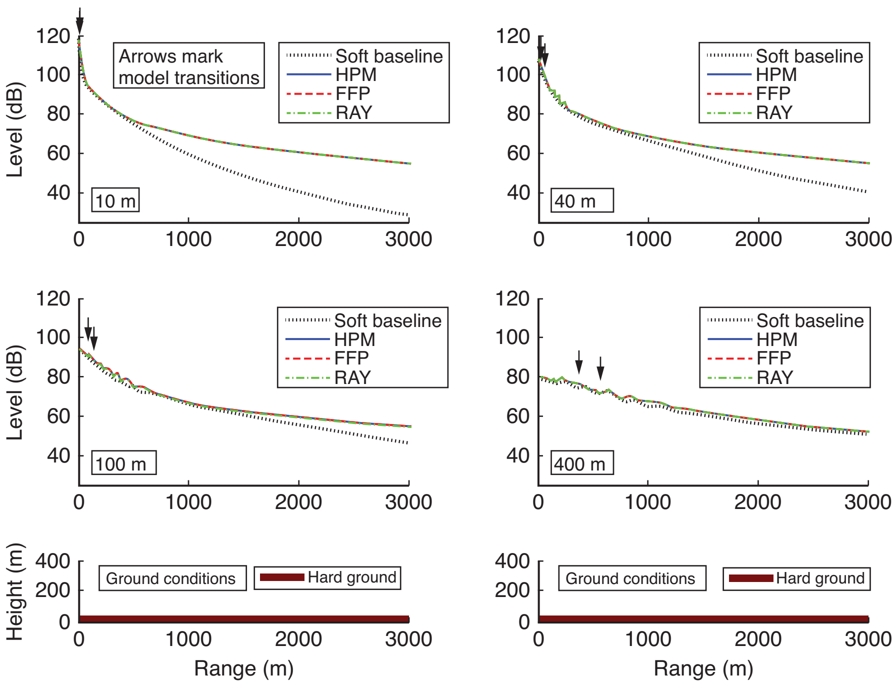

Figure 3: *Hard, flat ground, and homoeneous atmosphere. HPM, FFP, and ray model results are compared for each source height: 10 m, 40 m, 100 m, and 400 m. Arrows indicate transition points between components of the HPM. Soft, flat ground results are included for comparison. A diagram of the propagation conditions is included beneath the results figures.*

demonstrates the most striking support for use of the full HPM. Terrain obstruction and refractive atmosphere conditions fall within this category.

Figure 4 shows results for a hill case. For the three lower 10, 40, and 100

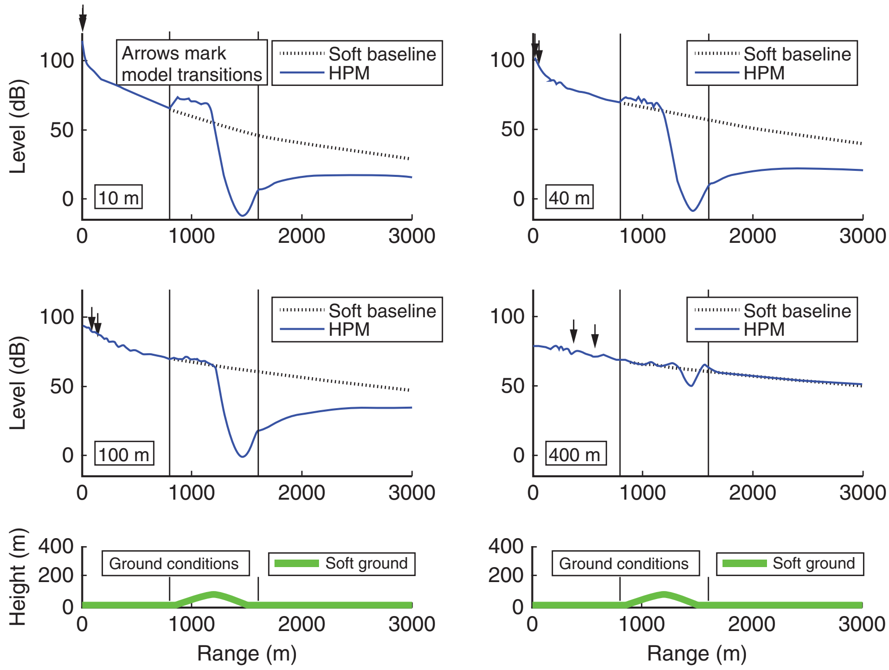

Figure 4: Soft ground with hill terrain and homoeneous atmosphere. HPM results are shown for each source height: 10 m, 40 m, 100 m, and 400 m. Arrows indicate transition points between components of the HPM. Soft, flat ground results are included for comparison. A diagram of the propagation conditions is included beneath the results figures.

m sources, the line of sight between source and receiver is blocked by the terrain. There is a significant decrease in level just beyond the peak of the hill for all three of these sources. The level begins to increase from diffraction around the hill as the terrain levels out at larger ranges. Because this case involves range-dependent effects, separate FFP and ray model results are not included. However, the significant difference between results for this case and those for the soft ground base case, included for reference, indicate that neither the FFP nor the ray model capabilities are sufficient.

Alternatively, when the source is high enough to prevent line of sight blockage, and the change in reflection angle off the hill is not significant (discussed further in Section 3.4), the results again agree closely with those of the base case and the straight ray model would be sufficient for most points in range. This is seen for the high altitude, 400 m source, where levels behind the hill agree with the soft ground base case results.

In addition to line of sight obstructions caused by terrain features, shadow zones formed in an upward refracting atmosphere, Fig. 5, also necessitate use of the full HPM. Equation (1) defines the logarithmic sound speed profile of the refracting atmosphere used in this analysis

$$c(z) = c_0 + b \ln\left(\frac{z}{z_0} + 1\right), \tag{1}$$

where $\boldsymbol{c_0}$ is the sound speed at the ground equal to 340.2 m/s, $\boldsymbol{b}$ is the logarithmic sound speed profile parameter equal to −1 m/s, $\boldsymbol{z_0}$ is the aerodynamic roughness length of the ground surface equal to 0.1 m, and z is the height above the ground.

For all four source altitudes, levels increase before the start of the shadow zone—a region into which rays cannot reach—and then fall steeply in the shadow zone. The FFP results, nearly

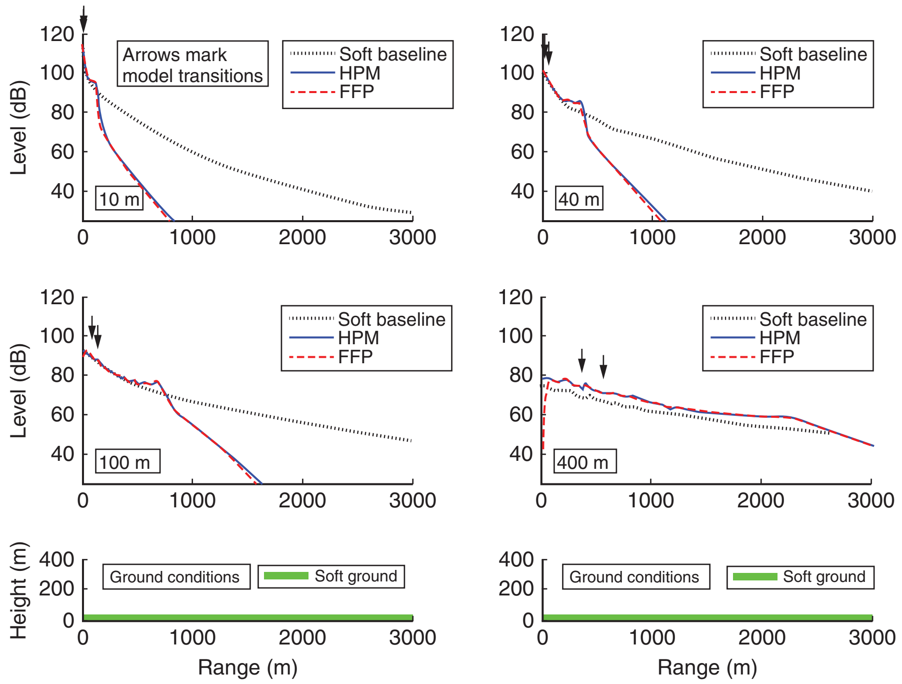

Figure 5: Soft, flat ground and an upward refracting atmosphere. HPM and FFP results are compared for each source height: 10 m, 40 m, 100 m, and 400 m. Arrows indicate transition points between components of the HPM. Soft, flat ground and homogeneous atmosphere results are included for comparison. A diagram of the propagation conditions is included beneath the results figures.

indistinguishable from those of the HPM, are accurate under these conditions and can be used in place of the full HPM. The ray model, however, is not able to capture the effects of the refractive atmosphere and would significantly over-predict levels inside the shadow zone.

The opposite effect is felt for a downward refracting atmosphere, shown in Fig. 6. The logarithmic sound speed profile of Eq. (1) is also used in this test case, with parameter b equal to 1 m/s. Levels decrease towards the beginning of the range, before multiple reflections cause an increase in level. Again, the FFP accurately predicts this behavior and can be used as a substitute for the full HPM. The ray model over-predicts noise levels at shorter ranges and under-predicts at longer ranges where there are multiple reflections.

The effects of the downward refracting atmosphere are not as extreme as the upward refracting atmosphere. For the highest altitude source, the results of the HPM and FFP match well with the soft base case results over the majority of the range, though they do eventually dip below. Without further investigation into criteria for where transition to a simpler model is acceptable under refractive conditions, it is inadvisable to use a propagation method that cannot include these effects.

3.3. CATEGORY 2: GROUND IMPEDANCE TRANSITIONS FALL WITHIN THE FRESNEL ZONE

Properties of the ground surface within a Fresnel zone, an extended region around the point of specular reflection, affect absorption and phase of sound reflected off the ground. All ground types within this region must be accounted for, while those outside can be neglected. If the source and receiver are both low, the Fresnel zone extends over a longer stretch of ground and will span multiple ground types if transitions occur near the receiver. Under such conditions, the range-dependent effect of ground type

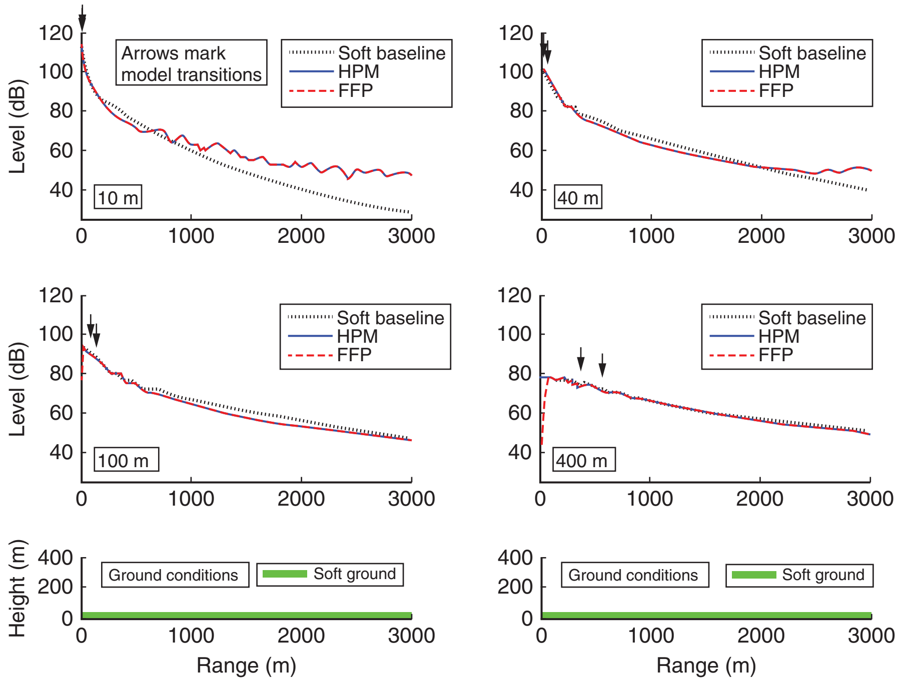

Figure 6: *Soft, flat ground and a downward refracting atmosphere. HPM and FFP results are compared for each source height: 10 m, 40 m, 100 m, and 400 m. Arrows indicate transition points between components of the HPM. Soft, flat ground and homogeneous atmosphere results are included for comparison. A diagram of the propagation conditions is included beneath the results figures.*

transitions requires the full HPM. A simpler model can be applied when the source is high and the receiver is far from a transition.

Figure 7 shows results for the case with two ground type transitions: hard to soft ground at 600 m, and back to hard ground at 1800 m. The dotted black line and the red dashed line show results for the soft and hard base cases, respectively. In the plots of the lower 10 and 40 m sources, the extended effect of a ground transition can be seen most clearly at the second transition, where the angle of reflection is shallower and the difference in predicted level for soft versus hard ground is larger. Here, the effect of the previous ground type is felt long after the transition occurs. A simple model using either soft or hard ground would not fully capture this effect.

Alternatively, the full HPM is not required for the highest 100 and 400 m sources. For these sources, the effect of the previous ground type is felt for a very short range. The ray model can be substituted for the full HPM at most points in range, using the ground impedance below the receiver.

3.4. CATEGORY 3: TERRAIN SIGNIFICANTLY AFFECTS THE ANGLE OF REFLECTION OFF A SOFT GROUND

Line of sight obstruction is not the only notable terrain effect. Absorption from a soft ground is a function of the angle of reflection off the ground, increasing with shallower angles. Therefore, if the shape of a terrain feature significantly alters the angle of reflection, the corresponding effect on absorption must be incorporated. The angle of reflection off hard ground has a smaller effect. Figure 8 shows a terrain case where the ground is flat at smaller ranges, then slopes upward, and levels out again at larger ranges. The terrain feature breaks the line of sight for the lower two 10 and 40 m sources, and the level decreases over the second flat

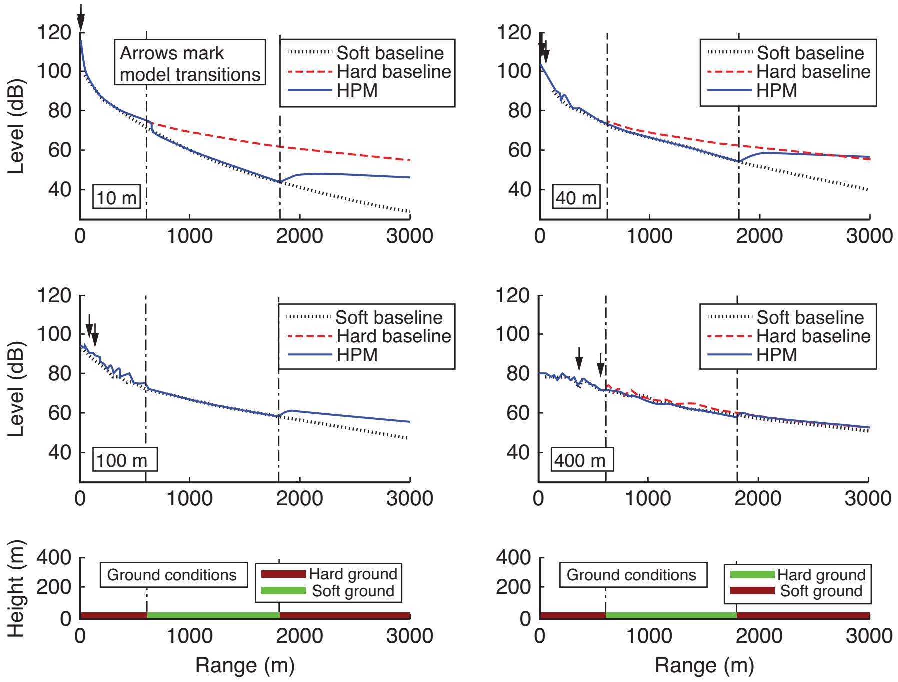

Figure 7: *Hard to soft to hard ground transitions with flat terrain and homoeneous atmosphere. HPM results are shown for each source height: 10 m, 40 m, 100 m, and 400 m. Arrows indicate transition points between components of the HPM. Soft, flat ground and hard, flat ground results are included for comparison. A diagram of the propagation conditions is included beneath the results figures.*

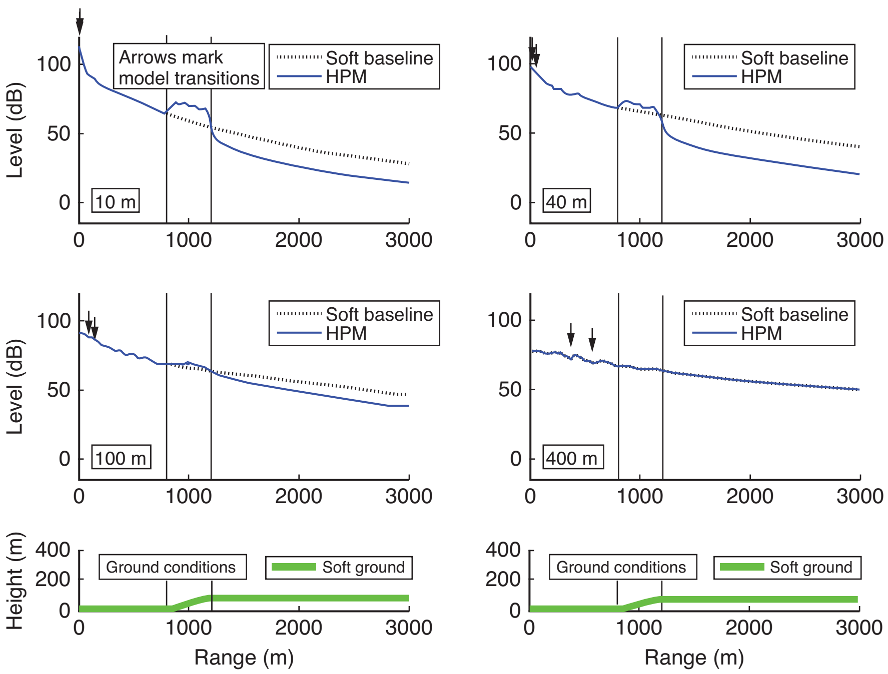

Figure 8: *Soft ground with upward-sloping terrain and homoeneous atmosphere. HPM results are shown for each source height: 10 m, 40 m, 100 m, and 400 m. Arrows indicate transition points between components of the HPM. Soft, flat ground results are included for comparison. A diagram of the propagation conditions is included beneath the results figures.*

region of ground. The level increases, however, over the region of upward sloping ground, where the angles of reflection are steeper.

The impact of terrain shape on ground absorption is seen most clearly for the 100 m source, where the line of sight is never broken. Because the source is only 30 m above the 70 m high elevated ground—significantly less than 100 m above the flat ground—the angle of reflection is shallower, causing increased ground absorption and lower levels. Neither the ray model nor the FFP capture this effect. The effect fades for the highest altitude, 400 m source because the source is still high above the elevated ground, and the angle of reflection remains steep. Here, the ray model can be used in place of the full model, despite the presence of the terrain feature.

The effect of reflection angle is also present in the hill case. In Fig. 4, the steeper angle of reflection off the front of the hill has a level-increasing effect for the lower 10, 40, and 100 m source heights, just as for the upward sloping ground case. For the highest 400 m source there is a downward blip in level over the back of the hill where the line of sight is barely broken and the angle of reflection off the terrain is significantly shallower, causing increased ground absorption.

3.5. SPECIAL INSTANCE: HIGH ALTITUDE SOURCES

Figure 9 shows the results of all seven cases for the highest altitude, 400 m source. Here results across varied propagation conditions show similarities, lending further support for the intelligent switching scheme. There are some departures from the group—the refractive atmosphere cases have lower levels at the longer ranges and the downward blip appears beyond the peak in the hill case. However, excluding these expected deviations, the results have a group span in level of only about 3 dB over the full range of propagation. Furthermore, the grouping of results tightens toward the longer ranges.

Figure 10 shows a zoomed in view of the last 100 m in range, from 2900 to 3000 m. Two distinct groupings emerge. The first, at the levels between approximately 50 and 51 dB, comprises the three homogeneous atmosphere cases with propagation over soft ground. Despite different terrain shapes, these results agree well at the largest ranges. The second group, at the higher levels between 52 and 53 dB, comprises the two homogeneous atmosphere cases where the receiver is over hard ground.

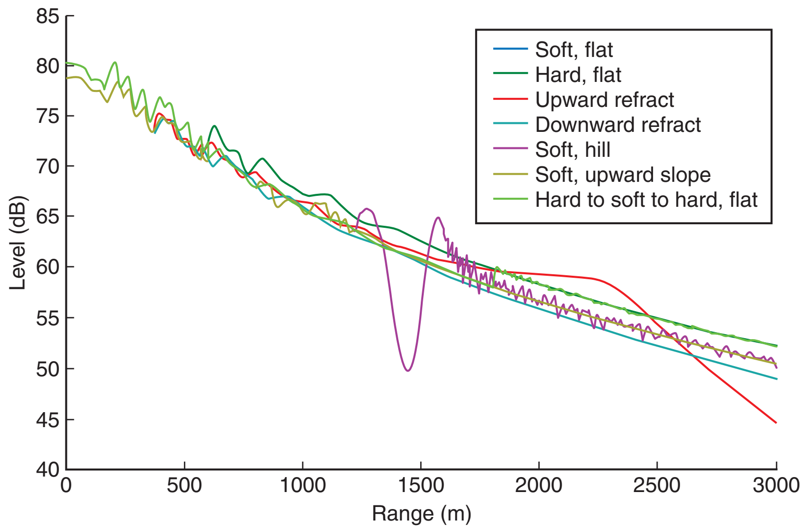

Figure 9: Results for the highest altitude, 400 m height source. All seven cases plotted together.

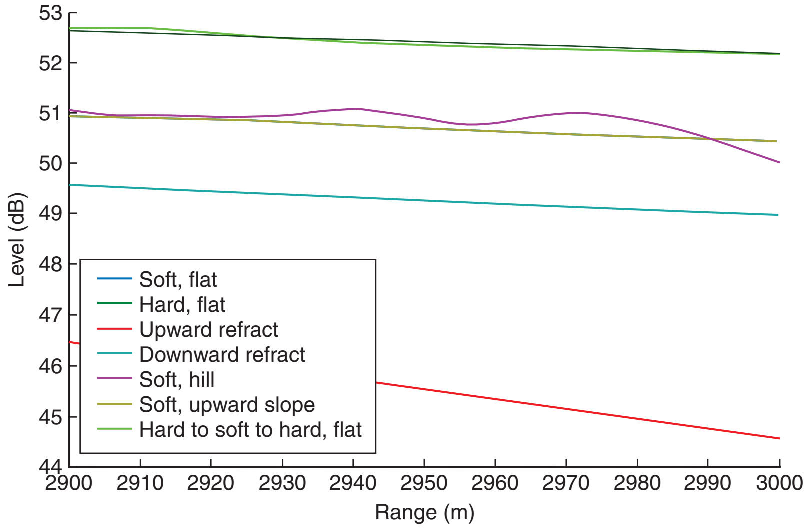

Figure 10: Results for the highest altitude, 400 m height source ñ zoomed-in view at ranges 2900 to 3000 m. All seven cases plotted together.

These cases show agreement despite having different ground type properties over a large stretch of range. Within both groups, results deviate by less than 1 dB. The two outliers consist of the refractive atmosphere cases, where the downward and upward refracting atmosphere cases show less than a 1.5 and 6 dB differences with the soft base case, respectively.

4. CONCLUSION

The results of the HPM and its component models were analyzed for seven test cases, four source heights, and a single aircraft spectrum of the 747–400, with the goal of identifying conditions for which a simpler model could be used in place of the full HPM with little effect on results. This investigation was another step in the continued effort to increase the accuracy of the standard noise propagation module in the FAA's environmental models, while maintaining manageable runtimes.

Three categories were proposed for which the full model was required: 1) conditions where the simple geometry of direct and reflected rays is disrupted, including line of sight blockage by terrain features and refractive atmosphere conditions; 2) conditions where a low source height causes multiple ground types to fall within the Fresnel zone; and 3) conditions where terrain shapes significantly impact the angle of reflection off a soft ground.

The HPM and its composite models were the focus in this paper. However, the objectives of this work are familiar to any model development where tradeoffs between accuracy and runtime are of primary concern. The organization of results to highlight model-switching opportunities and points of caution provides a starting point for development of switching schemes between other propagation methods to help manage the sometimes diminishing returns of advanced models.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] Rosenbaum, J. E., A. A. Atchley, and V. W. Sparrow, "Enhanced sound propagation modeling of aviation noise using a hybrid

Parabolic Equation-Fast Field Program method,' Inter-Noise conference proceedings, Ottawa, ON (2009).

[2] Rosenbaum, J. E., "Enhanced propagation modeling of directional aviation noise: A hybrid parabolic equation-fast field program method,' Ph.D. dissertation, The Pennsylvania State University (2011).

[3] West, M., K. Gilbert, and R. A. Sack, "A tutorial on the parabolic equation (PE) model used for long range sound propagation in the atmosphere," Applied Acoustics, 37(1), 31–49 (1992).

[4] Sack, R. A., and M. West, "A parabolic equation for sound propagation in two dimensions over any smooth terrain profile: the generalized terrain parabolic equation (GT-PE)," Applied Acoustics, 45(2), 113–129 (1995).

[5] Salomons, E. M., Computational Atmospheric Acoustics, Kluwer Academic Publishers (2001).

[6] Franke, S. J. and G. W. Swenson, Jr., "Brief tutorial on the Fast Field Program (FFP) as applied to sound propagation in the air," Applied Acoustics, 27(3), 203–215 (1989).

[7] West, M., R. A. Sack, and F. Walkden, "The Fast Field Program (FFP). A second tutorial: Application to long range sound propagation in the atmosphere," Applied Acoustics, 33(3), 199–228 (1991).

[8] Attenborough, K., S. Taherzadeh, H. E. Bass, X. Di, R. Raspet, G. R. Becker, A. Güdesen, A. Chrestman, G. A. Daigle, A. L'Esperance, et al., "Benchmark cases for outdoor sound propagation models," J. Acoust. Soc. Am., 97(1), 173–191 (1995).

NHBC RESEARCH REPORTS A REDUCTION IN HOMEOWNER NOISE COMPLAINTS

The UK's NHBC Foundation has reported a drop in noise complaints by owners of new attached homes following the introduction of new industry standards in 2003. During the latter part of the 20th century, noise transmitted between attached homes was a growing concern and the subject of many complaints to local government environmental health officers. In extreme cases, there were health implications for occupants subjected to noise nuisance. In response, the Government introduced higher standards for sound insulation. The NHBC Foundation report Sound Progress looks at feedback to NHBC from owners of new homes built since the introduction of these standards to see whether these changes have led to a reduction in concerns. The main finding from this study is a significant reduction in noise-related concerns from owners of new attached homes since 2004: For attached homes first occupied in 2004, about 7 households per 1000 contacted NHBC about noise problems. For homes first occupied in 2010, this was down to 4 per 1000. Since 2004, there were progressively fewer concerns related to sound transmitted through the structure from adjoining homes. The research also looked at noise contacts from owners of new detached homes. These owners were more likely to contact NHBC in relation to noise issues than those living in attached homes, and creaking floors were the most common problem highlighted. Of the noise concerns raised by owners of both attached and detached homes (including a variety of noises from the fabric and services) most could be avoided by taking additional care during construction and following accepted good practice.