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GUIDANCE FOR HELICOPTER COMMUNITY NOISE PREDECTION

FINAL REPORT

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EXECUTIVE SUMMARY

This document outlines recommended key community noise modeling elements required to accurately predict helicopter and tiltrotor sound which are suitable for inclusion in civilian regulatory integrated models such as the Integrated Noise Model (INM) [Boeker et al., 2008; Dinges et al., 2007] or the Aviation Environmental Design Tool (AEDT)[1] [Koopmann et al., 2015, 2012]. The National Academies of Science Airport Cooperative Research Program has established Project ACRP 02-44 in order to recognize that, in contrast to guidance related to fixed-wing aircraft, there is no peer-reviewed guidance document describing an integrated modeling technique for the prediction of helicopter noise. This project was initiated in order to document current practice, improve modeling methods, and provide guidance for improving AEDT/INM to predict helicopter and tiltrotor community sound via definition of a framework to compute aggregate annual average noise in concert with documented United States and international civilian community noise modeling needs.

This report does not attempt to identify which noise metric best predicts annoyance; it recommends a computational methodology from which suggested metrics may be accurately determined. It is our belief that incorporation of the improved modeling recommendations will also permit accurate prediction of new noise metrics in the future. This research is not intended to address military computational needs for mission survivability or probability of electronic or human aural detection.

The existing AEDT/INM framework was examined from a source – propagation – receiver perspective and recommendations are provided herein. The existing standards behind the AEDT/INM predictions [SAE, 1986; ICAO 2008; ECAC 2005] were examined, and where necessary, proposed enhancements to improve community noise modeling are provided in subsequent sections. The authors recognize that there exist higher fidelity rotorcraft noise models and current research is continually advancing the state of the art. The user input burden and access to vehicle specific data, however, must be balanced with the general requirements of community noise modeling tasks. The recommendations suggested here are in concert with today's typical community noise modeling practices, level of effort and input data constraints. Suggestions for creation of a database are described.

The framework for AEDT/INM modeling is well established for fixed wing aircraft. The historical integrated Heliport Noise Model [Fleming & Rickley, 1994] forms the basis of the AEDT/INM rotorcraft core. As with most noise models, these key elements must be included:

1. Source noise characteristics (level, directivity, spectra/metrics, conventional/tiltrotors).
2. Operational capabilities (takeoff, landing, hover in/out of ground effect, orbiting, tiltrotor-specific modes).
3. Propagation modeling (atmospheric models, natural and urban terrain, spectral domain, range).
4. Community Noise Metrics (single and multiple operation contours, standard and supplemental metrics).

This document outlines the specific recommended modeling elements and presents the rationale behind each. The modeling framework has been developed and each element was evaluated by performing trade studies assessing the impact of various modeling aspects on the noise predictions.

An outreach task was conducted in order to solicit feedback from the international rotorcraft noise modeling community on the recommended technical modeling approach details and changes for AEDT/INM. The intent was to provide an efficient mechanism for distribution of the modeling rationale and to solicit international rotorcraft noise community stakeholder feedback in response. The recommendations are intended to help guide development of a draft helicopter and tiltrotor noise standards document under the auspices of the SAE A-21 Aviation Noise and Emissions Committee. International

[1] In May 2015 AEDT 2b was released by the Federal Aviation Administration (FAA) at which time INM was "sunset" and INM support and maintenance was discontinued.

outreach consisted of an online Webinar facilitated by the National Academies of Science, presentations at technical meetings at helicopter symposia, noise and emissions and transportation related committee meetings and events and distribution of an explanatory White Paper via email.

At virtually every event the attendees supported the need for this research and these recommendations. There wasn't a single negative comment received regarding the utility and intent of this project. The necessity for a supporting database and the possible difficulty and cost for obtaining one was raised multiple times. Modelers expressed concern about the ability of a future project team to acquire such data and the manufacturers were clearly nervous about the potential cost implications if such data were required to be measured using FAR-36 procedures. Although not explicitly included in the white paper recommendations, discussions about creation of a hybrid analytical-empirical database ensued and many side-bar conversations were held by the PI with various helicopter manufacturer, academia and NASA rotorcraft noise Subject Matter Experts (SMEs) regarding possible techniques for database development including leveraging existing NASA and Army first-principles models, existing acoustic databases, available flight performance information (e.g. from helicopter flight manuals) and simplified BVI noise concepts.

The only change that was made to our recommendations in response to the international feedback was regarding tiltrotor transition noise and was addressed via the addition of a sentence to consider wing loading vs. rotor loading in the transition mode. The final seven recommendations are itemized below.

Final Recommendations

1. ***The model should be capable of computing the following metrics:*** Maximum Sound Level (L_{max}), Sound Exposure Level (SEL), Day-Night Average Sound Level (DNL or Ldn), Community Noise Equivalent Level (CNEL), Perceived Noise Level (PNL), Tone-Corrected Perceived Noise Level (PNLT), Effective Perceived Noise Level (EPNL), Weighted Equivalent Continuous Perceived Noise Level (WECPNL), Maximum C-weighted Sound Level (L_{maxC}), C-weighted Sound Exposure Level (CSEL), d-Prime Audibility (DPRIME), Number-of-events Above (NA) and Time Above a Specified Level (TAL).

2. ***It is necessary to model the lateral source characteristics*** with sufficient a) angular fidelity to capture directional Blade Vortex Interaction (BVI) noise and b) lateral extent to account for changes in vehicle roll angle. Under vehicle-specific approach flight conditions the rotor-wake interaction can cause significant increases in noise source emission over highly directive regions. Modeling of rotorcraft in regions with urban and natural terrain and inclusion of bank angle in the noise analysis can require vehicle source characteristics to be defined well outside the current 45^o extent defined in AEDT/INM.

3. ***Spectral content should include one-third octave bands down to 10 Hz.*** The low-frequency trade study demonstrated a strong sensitivity to inclusion of low-frequency effects below 50 Hz for helicopters over the range of distances (0-25,000 ft.) included in the AEDT/INM NPD database for C-weighted metrics and for the supplemental metric d-Prime. We found that variations due to incorporation of the low-frequency content exceed the established criteria for AEDT/INM spectral class selection for C-weighted metrics; therefore the rotorcraft should be modeled down to 10 Hz.

4. ***It is necessary to include the effects of approach flight path angle on source noise characteristics.*** Significant changes to the source noise emissions can occur when flight path angle (FPA) is adjusted. During BVI the blade and wake are in close proximity to one another. Changes of FPA by a few degrees can enter BVI condition and cause large changes in noise, exceeding 10 dBA and must be considered.

5. ***The changes in noise source characteristics from maneuvering flight should be included*** if: a) one needs to model or optimize low-noise rotorcraft profiles or take into account approach drag devices for BVI-avoidance, or b) Lmax and other maximum non-integrated metric values are to be predicted on a high fidelity spatial mesh in the vicinity of flight maneuvers, or c) Time above metrics are to be computed from flights whose maneuver time durations are significant. Maneuvering flight is an active area of research, and helicopter performance modeling capabilities are currently under development for AEDT and other noise models. Funded Advanced Acoustic Model (AAM) [Page, et al., 2010] maneuvering flight implementation project also suggests that simplified source equivalences based on gross kinematic parameters will be available in the near future.

6. ***It is necessary to incorporate the effect of tiltrotor transition between Airplane and Helicopter Modes in the noise model.*** Flexible profile modeling is needed to capture all possible operational procedures. Consideration should be given to the inclusion of source fidelity to capture the relative wing/rotor loading during transition mode. Changes must be made to the AEDT/INM model including the capability to handle tiltrotor movements and transition noise source emission (NPD and Spectral Class).

7. ***The method proposed by Plotkin et. al, [2013] for inclusion of higher fidelity atmospheric and terrain modeling in AEDT/INM is recommended.*** It was found that the propagation algorithms in INM and AEDT are sufficient and only specific airport considerations will necessitate the inclusion of terrain, shielding and /or variable ground impedance. Therefore no recommendation to always or never include such effects can be made, however the AEDT/INM model should be capable of higher fidelity modeling.

CHAPTER 1. Introduction

This document outlines the key modeling aspects to accurately predict helicopter and tiltrotor sound from a community noise modeling perspective.

The objective of this research is to review, evaluate, and document current helicopter noise models and identify potential improvements to AEDT/INM to better capture the unique complexity of helicopter and tiltrotor operations.

The modeling framework has been developed and each modeling element has been evaluated by performing trade studies assessing the impact of various modeling aspects (source characteristics, propagation modeling and environmental effects) on the noise predictions. A prioritized list of recommendations to be included in an improved Aviation Environmental Design Tool (AEDT) helicopter model, based on completed noise prediction sensitivity trades has been developed. These recommendations were provided to the international rotorcraft noise community stakeholders, including manufacturers, operators, academia, government agencies and relevant helicopter trade associations in the form of a white paper with supporting presentations and webinars at various technical venues. A comprehensive email list was developed in conjunction with the ACRP project panel for white paper dissemination and solicitation of feedback on the recommendations. This final report provides the key findings of the trade studies, our initial recommendations, feedback garnered through our outreach efforts, our final prioritized recommendations and recommended next steps for a database development and implementation in AEDT.

The modeling framework outlined in this report was developed to define noise modeling recommendations that can predict aggregate annual average sound levels in a variety of metrics in concert with documented United States and international civilian community noise modeling needs. Project ground rules for development of the helicopter and tiltrotor modeling procedures and framework elements include compatibility with the Integrated Noise Model (INM) [Boeker et al., 2008; Dinges et al., 2007] and Aviation Environmental Design Tool (AEDT) [Koopmann et al., 2015, 2012] software.

This research was not intended to provide recommendations as to which noise metric is best suited for assessment of community annoyance from helicopter sound predictions. The recommendations are structured to ensure sufficient source and propagation fidelity is included so that the recommended list of metrics may be computed in as accurate a manner as possible when balancing modeling fidelity and user input burden within the confines of the AEDT integrated noise model. The recommendations here are not intended to address military needs for mission survivability or prediction of sound levels for assessment of the probability of human or electronic detection.

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CHAPTER 2. Noise Prediction Metrics

All methods for predicting the noise exposure and community response to aircraft noise must take into account the magnitude, duration and frequency content of the noise from an individual event, together with the number of events on a typical day.

The first published procedure for predicting the community response to aircraft noise was developed by the United States Air Force [Pietrasanta and Stevens, 1957] in terms of the Composite Noise Rating (CNR) metric that used the Perceived Noise Level (PNL) concept for individual events. In the decade following, subjective responses to noise were taken into account with the development of the Effective Perceived Noise Level (EPNL) and Noise Exposure Forecast (NEF) metrics. Internationally, similar noise studies occurred and in 1971 the International Civil Aviation Organization (ICAO) adopted the Weighted Equivalent Continuous Perceived Noise Level (WECPNL) [ICAO, 1971, Plotkin et. al., 2011].

The most widely used metrics today for community noise in the US are the Day-Night Average Sound Level, DNL, for cumulative exposure, and Sound Exposure Level (SEL) for single events. Sound Exposure Level is an A-weighted metric, indicative of the total noise received at a given point from a single event. DNL is an A-weighted sound exposure metric for combined day/night operations with a 10 dB penalty for night-time operations and with number of events accounted for by $10\log_{10}N$. Additional procedures are often contained in the noise models for the calculation of other metrics, as itemized in Table 1 or described in the Guide to using Supplemental Metrics [Sharp et al., 2009].

In recent years there have been regions in the US with helicopter community noise problems [NRDC, 1999; HAI. v. FAA, 2013; FAA, 2013] and a recognition in the UK that research is needed for improved management of helicopter noise [DEFRA, 2008]. In the US this has prompted the FAA to recommend that "additional development of models for characterizing the human response to helicopter noise should be pursued" while noting that "the FAA will continue to rely upon the widely accepted Day-Night Sound Level (DNL) as its primary noise descriptor for airport and heliport land use planning [FAA, 2004]. This recognition has renewed research in the US to investigate the suitability of the current metrics for predicting community annoyance to rotorcraft noise and seeking alternative metrics that address characteristics such as sharpness, tonality, roughness and fluctuation strength [More, 2011] as well as non-acoustic factors of annoyance or "virtual noise" [Leverton & Pike, 2007; Leverton & Pike, 2009].

The scope of this project includes prediction of helicopter and tiltrotor noise using conventional US and International metrics, such as those defined in Table 1 grouped as Standard Community Noise Metrics and Supplemental Community Noise Metrics. The modeling technique framework to accurately capture these metrics will be the focus of the remainder of this report.

TABLE 2-1 Standard and Supplemental Community Noise Metrics and Functional Definitions

Standard Community Noise Metrics	
Metric	**Description**
Maximum Sound Level (L_{max})	The highest A-weighted sound level measured during a single event in which the sound changes with time is called the maximum A-weighted sound level or Maximum Sound Level and is abbreviated Lmax. The L_{max} is depicted for a sample event in Figure 1. L_{max} is the maximum level that occurs over a fraction of a second. For aircraft noise, the "fraction of a second" is one-eighth of a second, denoted as "fast" response on a sound level measuring meter [ANSI, 1988]. Slowly varying or steady sounds are generally measured over one second, denoted "slow" response. L_{max} is important in judging if a noise event will interfere with conversation, TV or radio listening, or other common activities. Although it provides some measure of the event, it does not fully describe the noise, because it does not account for how long the sound is heard.

Standard Community Noise Metrics	
Metric	**Description**
Maximum C-weighted Sound Level (L_{maxC})	The highest C-weighted sound level measured during a single event in which the sound changes with time is called the maximum C-weighted sound level or Maximum Sound Level and is abbreviated Cmax. While A-weighting puts emphasis on the 1,000 to 4,000 Hz range, C-weighting is nearly flat throughout the range of audible frequencies, approximating the human ear's sensitivity to higher intensity sounds.
Sound Exposure Level (SEL)	Sound Exposure Level combines both the intensity of a sound and its duration. For an aircraft flyover, SEL includes the maximum and all lower noise levels produced as part of the overflight, together with how long each part lasts. It represents the total sound energy in the event. Figure 1 indicates the SEL for an example event, representing it as if all the sound energy were contained within one second. Because aircraft noise events last more than a few seconds, the SEL value is larger than L_{max}. It does not directly represent the sound level heard at any given time, but rather the entire event. SEL provides a much better measure of aircraft flyover noise exposure than L_{max} alone.
Day-Night Average Sound Level (DNL or L_{dn})	Day-Night Average Sound Level is a cumulative metric that accounts for all noise events in a 24-hour period. However, unlike $L_{eq}(24)$, DNL contains a nighttime noise penalty. To account for our increased sensitivity to noise at night, DNL applies a 10 dB penalty to events during the nighttime period, defined as 10:00 p.m. to 7:00 a.m. The notations DNL and L_{dn} are both used for Day-Night Average Sound Level and are equivalent.
Community Noise Equivalent Level (CNEL)	CNEL [Wyle, 1970] is a variation of DNL specified by law in California [State of California 1990]. CNEL has the 10 dB nighttime penalty for events between 10:00 p.m. and 7:00 a.m. but also includes a 4.8 dB penalty for events during the evening period. The evening period is defined as 7:00 p.m. to 10:00 p.m. The evening penalty in CNEL accounts for the added intrusiveness of sounds during that period. For airports, DNL and CNEL (see below) represent the average sound level for annual average daily aircraft events. Figure 2 gives an example of DNL and CNEL using notional hourly average noise levels ($L_{eq(h)}$) for each hour of the day as an example. Note the $L_{eq(h)}$ for the hours between 10 pm and 7 am have a 10 dB penalty assigned. For CNEL the hours between 7pm and 10 pm have a 4.8 dB penalty assigned. The DNL for this example is 65 dB. The CNEL for this example is 66 dB.
Perceived Noise Level (PNL)	The Perceived Noise Level (PNL) is a rating of the "noisiness" of sound from an aircraft as opposed to the "loudness" of that sound. It is a weighted summation of the sound pressure levels in the 24 one-third octave bands centered between 50 Hz and 10 KHz. Developed by Kryter [1959] specifically for fixed wing jet aircraft flyover noise, a discussion on the PNL is found in 14 CFR Part 36, Appendix B [FAA, 1969].
Tone-Corrected Perceived Noise Level (PNLT)	The Tone-corrected Perceived Noise Level (PNLT) is the sound pressure level obtained by adding to the perceived noise level an adjustment which accounts for tonal components in the vehicle acoustic spectrum.
Effective Perceived Noise Level (EPNL)	EPNL is a metric which takes into account duration of the noise event based on a tone-corrected PNLT time history. A duration correction is based on the minimum of the event time within 10 dB of the maximum PLNT or the time when 90 dB PLNT is exceeded [FAA, 1969].
Weighted Equivalent Continuous Perceived Noise Level (WECPNL)	WECPNL characterizes flyover and run-up noise events with EPNL and PNLT, respectively. WECPNL, like CNEL, averages sound levels at a location over a complete 24-hour period, with a 5 dB adjustment added to those noise events which take place between 7:00 p.m. and 10:00 p.m. and a 10 dB adjustment added to those noise events which take place between 10:00 p.m. and 7:00 a.m. the following morning. This 5 dB and 10 dB "penalty" represents the added intrusiveness of sounds which occur during the evening and nighttime, both because of the increased sensitivity to noise during those hours and because ambient sound levels during evening and nighttime are typically about 5 dB and 10 dB, respectively, lower than during daytime hours.

Supplemental Metrics	
Metric	**Description**
D-Prime Audibility (DPRIME)	The D-prime metric describes the auditory detectability index d′ based on one-third octave band target and background spectra, taking into account the normal equal-loudness threshold of hearing [ISO, 1961; Green and Swets, 1966]. Two parameters are derived: D-prime, which is the maximum value of d′ across any of the one-third octave bands, and D-prime cumulative, which is a pressure integration across the individual bands.
Number-of-events Above (NA)	Number-of-events Above (NA) presents the number-of-events per day where the sound level in a specified metric meets or exceeds a user-specified threshold.
Time Above a Specified Level (TA_L)	The Time Above (TA) metric is a measure of the total time that the A-weighted aircraft noise level is at or above a defined sound level threshold. Combined with the selected threshold level (L), the TA metric is symbolized as TAL. TA is not a sound level, but rather a time expressed in minutes. TA values can be calculated over a full 24-hour annual average day, the 15-hour daytime and 9 hour nighttime periods, a school day, or any other time period of interest, provided there is operational data to define the time period of interest. TA has application for describing the noise environment in schools, particularly when comparing the classroom or other noise sensitive environments for different operational scenarios. TA can be portrayed by means of noise contours on a map similar to the common DNL contours. The TA metric is a useful descriptor of the noise impact of an individual event or for many events occurring over a certain time period. When computed for a full day, the TA can be compared alongside the DNL in order to determine the sound levels and total duration of events that contribute to the DNL. TA analysis is usually conducted along with NA analysis so the results show not only how many events occur above the selected threshold(s), but also the total duration of those events above those levels for the selected time period.

(Sources: Page et al., 2010b; Wyle, 2013)

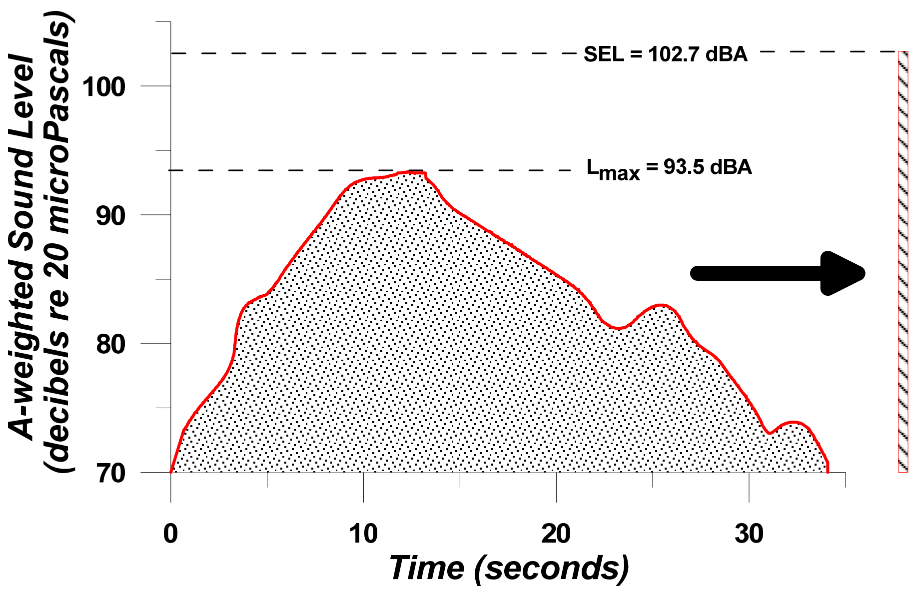

FIGURE 2-1 Example time history of aircraft flyover noise.

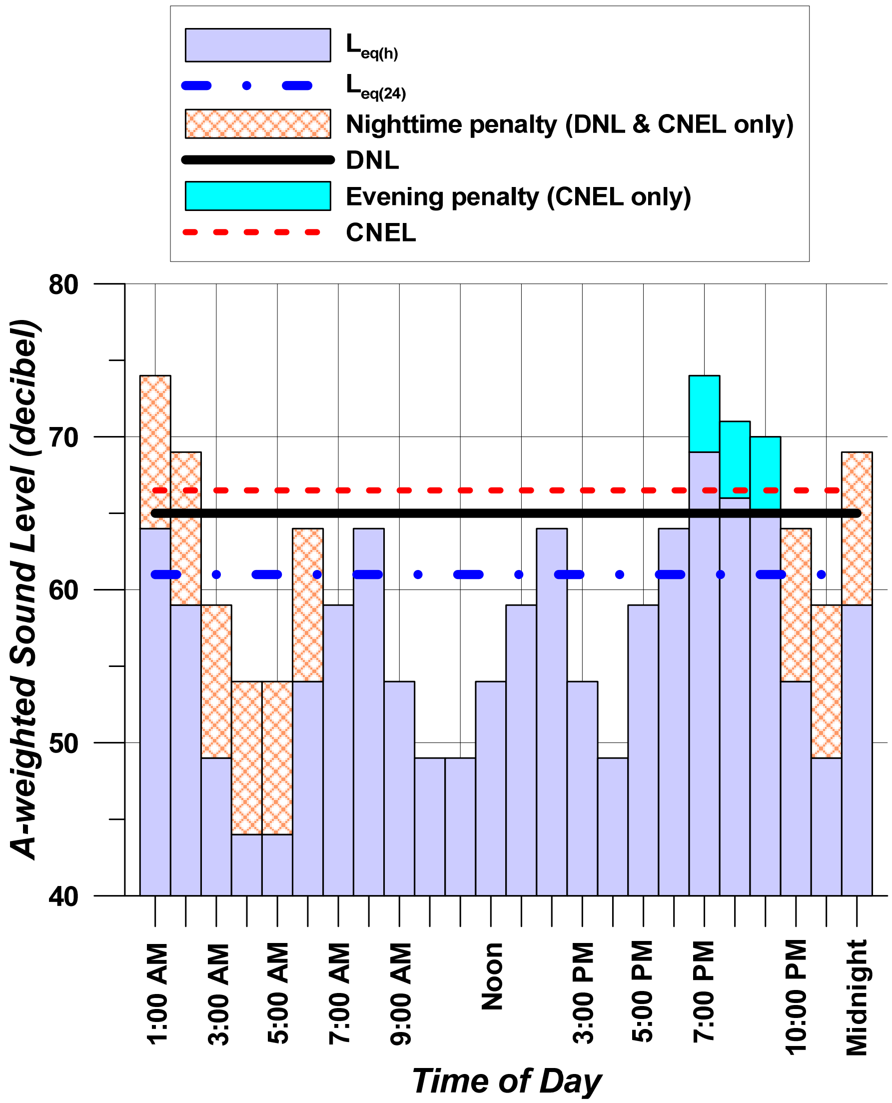

FIGURE 2-2 Example of DNL and CNEL computed from hourly equivalent sound levels.

CHAPTER 3. Modeling Techniques

There exist a wide range of rotorcraft and tiltrotor acoustic prediction tools. They include simplified table look-up methods, integrated and simulation models which rely on source noise acoustic databases, and comprehensive modeling codes which utilize first principles algorithms and model individual blade motion and trim and are coupled with far-field acoustic propagation models. A review of conventional rotorcraft and tiltrotor noise prediction models has been prepared under this ACRP project [Page et al., 2014]. The three tools which our team had access to which are used to determine sensitivity include the Integrated Noise Model (INM), [Boeker et al., 2008; Dinges et al., 2007] the Advanced Acoustic Model (AAM) [Page et al., 2010b] and HELENA [Meliveo, 2010a, 2010b & 2010c]. A comparison of predictions from INM and AAM using an omni-directional noise source is described in Appendix B.

3.1. INM

The Federal Aviation Administration's Integrated Noise Model (INM) has been the FAA's standard methodology for aircraft noise assessments in the vicinity of airports since 1978 [Boeker et al., 2008; Dinges et al., 2007]. INM is an integrated aircraft noise model with an extensive civilian aircraft source database. Integrated noise models rely on noise-power-distance (NPD) databases of normalized metrics, such as Sound Exposure Level (SEL), Effective Perceived Noise Level (EPNL), and Maximum A-weighted Sound Level (L_{Amax}) and supplemented with spectral data allowing for frequency-based noise adjustments and directivity data. These metrics are measurements intended to simulate helicopter noise certification measurements (straight-line aircraft over-flights, simulated departures and approaches), as well as noise from supplemental helicopter operations (overflights at various speeds, hover and idle events). The NPD database for rotorcraft in INM contains 3 directivity directions: 45^o right, directly undertrack and 45^o left to account for the asymmetry present in helicopter noise sources.

INM also includes the capability to model tiltrotor vehicle in both the airplane and helicopter modes, as separate user defined aircraft. Propagation from the vehicle to receivers accounts for geometric spreading, air absorption and finite ground impedance. INM can account for varying ground terrain by adjustment of the source-to-receiver slant range due to ground altitude. INM calculates the noise levels with a variety of integrated metrics at receiver positions on or above the ground at specific points of interest and over a uniform grid. The INM noise model algorithms serve as the core computational capability for AEDT.

INM and AEDT are compliant with current international aircraft modeling guidance ECAC Doc 29 [2005], ICAO Doc 9911 [2008], SAE-AIR-1845 [1986], and have been adapted for modeling helicopter noise.

3.2. AAM

The Advanced Acoustic Model (AAM) takes advantage of the significant improvements in computing capabilities and uses time simulation technology, where the noise is calculated from a series of points along the flight path, typically at one second intervals. AAM is based on three dimensional spectrally varying noise sources defined about a vehicle along a prescribed trajectory. Three dimensional source modeling includes the effect of thrust vectoring, implicit for rotorcraft and present on certain fixed-wing aircraft. It also includes the capability to model tiltrotor vehicle in both the airplane, helicopter and transition modes. Propagation from the vehicle to receivers accounts for geometric spreading, air absorption and finite ground impedance. For high thrust military aircraft, or for rotorcraft in certain flight regimes, nonlinear propagation effects associated with high noise levels are computed. AAM can optionally account for varying ground terrain or atmospheric gradient effects. AAM calculates the noise levels in the time domain and with a variety of integrated metrics at receiver positions on or above the ground at specific points of interest and over a uniform grid. Noise data for AAM is defined as 3-D noise spheres, with spectrally varying directivity as a function of vehicle operation state. Data may be obtained from flight measurements, wind tunnel measurements, via analytical modeling from first principles or via hybrid techniques employing a variety of techniques. The Acoustic Repropagation Technique (ART) software has been developed as a companion to AAM and applied to a variety of aircraft types [Page & Plotkin, 2010; Hobbs et. al., 2010].

3.3. HELENA

The accurate prediction of helicopter noise is challenging and current capabilities of community noise tools are not sufficient. This was recognized by the European helicopter community and as a response HELENA was developed [Meliveo, 2010a, 2010b & 2010c]. HELENA is a tool for HELicopter Environmental Noise Analysis of which the development started within the FRIENDCOPTER project in the Sixth Framework Programme. The aim of HELENA is to provide better means of predicting helicopter noise than is now possible with available community noise tools. HELENA is co-owned and co-developed by a consortium consisting of Agusta-Westland, Eurocopter, EADS, Turbo Meca, Anotec, DLR, CIRA and NLR. HELENA explicitly models spherical spreading, atmospheric attenuation, and source directivity. The noise source can be represented either in hemispheres or in noise carpets. The data used to create the hemispheres/noise carpets can be obtained by CFD simulation or noise measurements. It is necessary to convert the noise measurements into hemispheres. In this post-processing step, generally an averaging step is included that increases the fidelity of the source model. Propagation modeling is done explicitly and the model includes the effects of spherical spreading, atmospheric attenuation [SAE ARP 866A, Sutherland et al., 1975], ground reflection [Zaporozhets & Tokarev, 2002], and Sound refraction by the atmosphere by ray tracing [Tuinstra, 2007].

3.4. Common Source Noise Dataset Creation

In order to compare modeling results between the codes it was necessary to create a set of common input data. Table 3-1 itemizes the various noise databases associated with these three rotorcraft noise models. However not all are consistent with one another or derived from the exact same vehicle model. It was determined to utilize a consistent set of data for comparative purposes. The following five datasets, four of which were derived from full-scale flight test programs yielded empirical acoustic datasets which were available for this project:

- Helicopters:
    - MD 902 [Watts, 2007]
    - Bell 412/CH-146 [NATO 2000; Page & Plotkin, 2000]
    - Bell 430 [Watts et.al, 2012]
- Tiltrotors:
    - MV-22B [Lucas & Long, 1999]
    - LCTR2 (Analytical dataset) *LCTR2 data has been requested from NASA* [Acree, 2010]

TABLE 3-1 Acoustic Datasets for Helicopter and Tiltrotor Noise Models

	INM	AEDT	AAM	HELENA
Number of rotorcraft types in noise database	26 (civil and military)	26 (civil and military)	37 (military and civil conventional and Tiltrotor). Legacy procedures exist for converting INM and NOISEFILE data into spheres.	EC135, A109 hemispheres, EC130 Carpets
Number of helicopter substitutions	125 (Recommended substitutions for helicopters not in INM 7.0d)[1]	125 (Recommended substitutions for helicopters not in INM 7.0d)	User discretion	Single engine light and twin L/M/H Helicopters (CLEANSKY dataset)
Noise source type	NPD curve (left, center, right, static)	NPD curve (left, center, right, static)	Noise Spheres for various flight conditions	Hemispheres or carpets for various flight conditions
Directivity	For static conditions; dependent on ground type and operational mode	For static conditions; dependent on ground type and operational mode	Included in noise spheres	Included in hemispheres or carpets
Spectra type and/or Spectral classes	One-third octave-band spectral classes (7 Departure, 6 Arrival, 7 Flyover)	One-third octave-band spectral classes (7 Departure, 6 Arrival, 7 Flyover)	3-dimensional one-third octave band spectra (Narrowband and pure tone modes available)	1/3-octave band directivity matrix
Default flight profiles	Approach, departure, taxi for each helicopter type	Approach, departure, taxi for each helicopter type	None	None
Operational modes available	16 modes	16 modes	Landing, Takeoff, Level flight, Static Hover	Landing, Takeoff, Level flight, Static Hover

INM Dataset Creation from AAM

Helicopter input data for the Federal Aviation Administration's (FAA) Integrated Noise Model (INM) was created from output data generated by Department of Defense's (DOD) Advanced Acoustics Model (AAM), in order to model those helicopters in INM. A detailed comparison of AAM and INM modeling may be found in Appendix A.

Input Data

For each helicopter used in the analyses, vehicle operations were modeled in AAM to create *simulated measurement data* at specific points of interest. The events were modeled to be similar to the events specified in FAR Part 36 with simulated microphones situated accordingly. Simulation events included:

- Approach at 6 degrees and 63 kts,

[1] U.S. Federal Aviation Administration, 2013. INM Version 7.0d Software Update Release Notes, Table 6: New INM Helicopter Substitutions. *http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/inm_model/inm7_0d/media/INM70d_releasenotes.pdf.*

- Departure at 4 degrees and 60 kts,
- Level flight at 492 ft. and 129 kts,
- Level flight at 1000 ft. and 120 kts, and
- Level flight at 5000 ft. and 120 kts.

For these events, the following environmental conditions were assumed:

- Temperature of 59 degrees Fahrenheit,
- Relative humidity of 70%,
- No wind, and
- All soft ground.

Modeled acoustic time history data and helicopter position data were output from three 4 ft. receptor locations: one directly underneath the flight track, and one 500 ft. to either side of the flight track. For each helicopter, event and receptor location combination, the following acoustic and position data were created:

- Acoustic time history data:
  - Maximum A-weighted sound pressure level (L_{max})
  - Maximum tone-corrected perceived noise level ($PNLT_{max}$)
  - Un-weighted one-third octave-band sound pressure level data ranging from 10 Hz to 10 kHz
- Cumulative acoustic data:
  - Sound exposure level (SEL)
  - Equivalent perceived noise level (EPNL)
- Position data:
  - Position (x, y, z) of the helicopter in feet relative to the center receptor.

In addition, acoustic time history data was simulated at points 200 ft. from the center of helicopter every 15 degrees radially around the helicopter for static operations, when static empirical AAM data were available.

Data Development

These data were utilized to generate INM input data: (1) noise-power-distance, (2) spectral class, (3) directivity and (4) speed coefficient data. These data and the INM database submittal input form are described in detail in the INM Version 7.0 Technical Manual. A complete INM data submittal form was developed for each helicopter in this analysis.

The AAM output data was reviewed for each helicopter, event and receptor location combination at the time of L_{max} and $PNLT_{max}$ in the acoustic data. The corresponding times were then identified in the position data, identifying the helicopter position at the time of L_{max} and $PNLT_{max}$. Position data were linearly interpolated between samples, when necessary.

These data, along with key, corresponding helicopter performance data, such as helicopter speed, and meteorological data were used to develop Noise-Power-Distance (NPD) data using the LCorrect software[2]. LCorrect is an implementation of the Simplified Adjustment Procedure to compute NPD data, as described in SAE-AIR-1845 Appendix B [SAE, 1986].[3] LCorrect accounts for aircraft source noise

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[2] While the Simplified Adjustment Procedure (LCorrect code) has been used in recent years to develop NPD data for AEDT/INM, the original helicopter NPD data, developed originally for HNM was based on the methodology developed by Volpe for the FAA [Newman et.al., 1979, 1984, 1985].

[3] Appendix A contains a detailed comparison of the Duration Factor as defined in SAE AIR 1845 Appendix B with

levels, aircraft speed, atmospheric absorption, distance duration, and divergence effects to compute aircraft- and operation-specific NPD data. Since both A-weighted and perceived noise level data were provided, LCorrect was used to generate SEL, L_{max}, EPNL and $PNLT_{max}$ NPDs for each helicopter event.

In addition to NPDs, spectral assignments were made for each helicopter operational mode. Spectral classes are a set of aircraft spectra applicable to multiple vehicle types, which are grouped together based on similar spectral characteristics for similar operational modes. These data are used to compute frequency-based acoustic adjustments in INM and AEDT. The spectral class assignments were made in accordance to the procedure described in Appendix D of the INM Version 7.0 Technical Manual using the event specific spectral data at the time of $PNLT_{max}$.

$PNLT_{max}$ level flight data at a range of overflight speeds were used to compute speed coefficients for each helicopter. Speed coefficients account for changes in sound level associated with the deviation of advancing blade Mach number from that associated with the source data reference conditions, as described in Section 3.6.1 of the INM Version 7.0 Technical Manual. The coefficients are derived using a least-square, second order regression through the AAM-modeled $PNLT_{max}$ data as a function of speed. Per FAR 36 [CFR, 1969] PNLT computations are based only on one-third octave bands 17-40. Since the current version of AEDT/INM only contain data within this frequency range the use of the $PNLT_{max}$ data is appropriate. If in the future, however, if the recommendations of this study are adopted, this process should be revisited for helicopters and tiltrotors due to their low-frequency content.

For a portion of the aircraft, helicopter directivity data were also provided. For these helicopters, L_{max} and $PNLT_{max}$ data were provided at points 200 feet from the center of a modeled helicopter static operation every 15 degrees radially around the helicopter. These data are used to compute L_{max} and $PNLT_{max}$ NPDs at the 0 degree position, and a relative directivity adjustment for four different static operational modes for helicopters: flight idle, ground idle, hover in ground effect, and hover out of ground effect. These data are used to model static operations, such as hover, in INM and AEDT. When these data were not available, directivity data from similar helicopters were substituted in to the INM database submittal form.

AAM calculations for the MD 902 Helicopter.

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CHAPTER 4. AEDT/INM MODELING FRAMEWORK

The framework for AEDT/INM modeling is well established for fixed wing aircraft. The historical integrated Helicopter Noise Mode forms the basis of the AEDT/INM rotorcraft core. As with all noise models, these key elements must be included:

1. Source noise characteristics (level, directivity, spectra/metrics, conventional/tiltrotors).
2. Operational capabilities (takeoff, landing, in/out of ground effect hover, orbiting, tiltrotor specific modes).
3. Propagation modeling (atmospheric models, natural and urban terrain, spectral domain, propagation range).
4. Community Noise Metrics (single and multiple operation contours, standard and supplemental metrics).

Acoustic sensitivity studies were conducted in order to develop a physical understanding and draw conclusions about the relative importance of the various modeling elements (source, operations, environment, metrics) within the framework of INM and AEDT. The sensitivity studies were based upon decoupling the modeling of rotorcraft noise into the four areas itemized above and exercising each element independently.

The following sections in this chapter each explore a particular aspect of the key modeling elements and present the modeling recommendations for AEDT/INM followed by an explanation with examples from the specific analyses.

4.1. Source Noise Characteristics

In the realm of source noise characteristics, AEDT/INM uses integrated noise in three directions for a set of prescribed distances, with a single spectral class for absorption corrections under different atmospheric conditions. Both AAM/RNM and HELENA utilize a higher fidelity 3D spectral noise sphere to describe the acoustic character of the source. The noise sphere (Figure 4-1) contains a full spectral emission in each direction. Generally noise spheres in AAM are defined using 5-degree fore/aft and 10-degree lateral spacing. For community noise purposes noise spheres are typically defined using one-third octave band spacing.

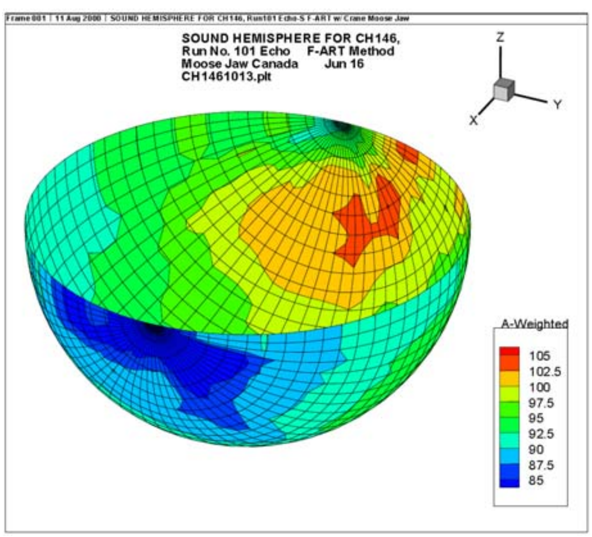

FIGURE 4-1 AAM noise sphere in 3D, Bell 412 / CH-146 data.

Vehicle nose points in –x direction, summed metric, dBA shown; Reference radius for spherical spreading is 100 Ft.

The analyses described in this section were planned so that comparisons between AEDT/INM and AAM and HELENA can help to determine modeling requirements such as:

a) How many lateral directivity NPDs are required? (Currently AEDT/INM uses three).

b) Can the current under-track spectral class be replaced with a lateral spectral class?

c) Or, are multiple spectra needed, and under which modeling situations does it matter?

4.1.1. Low-Frequency Modeling

AEDT Improvement Recommendation: It is necessary to include low-frequency noise and one-third octave bands from 10Hz in a rotorcraft community noise model.

Spectral Content Examination: Decimated Noise Data. Since helicopters have considerable low frequency content and have impulsive noise characteristics, it is important to accurately compute C-weighted noise levels for these vehicles; therefore, one must include the lower frequency noise content in the modeling. 10 Hz is a sufficient lower bound to capture the rotor noise from helicopter and tiltrotor vehicles. C-weighted metrics are currently computed by AEDT/INM, AAM and HELENA.

A series of frequency decimated Bell 412 / CH-146 noise spheres for a low speed (78 knots) and high speed (128 knots) were created with the lower one-third octave bands from 10 Hz to 40 Hz (Bands 10-16) systematically “zeroed out.” Level overflights were modeled for both speeds with the vehicle flight at 1500 Ft AGL, a uniform atmosphere (78^{o}F, 70% RH, 1013 mb) and uniform flat, soft ground. The vehicle flight is along the Y axis from the negative to positive direction. Noise levels for various metrics for points of interest located at 4 Ft AGL (Table 4-3) were obtained using AAM simulation with 0.5 sec time spacing. These POIs are situated to represent a lateral microphone array whose horizontal positions correspond to the standard distances in the INM NPDs. POIs are ordered in Table 4-3 from the right side of the vehicle to the left side of the vehicle. Note that the slant ranges from the vehicle at the point of closest approach to the POIs are larger than Y value due to the vehicle flight at 1500 Ft AGL. A representative spectrum from the analysis, extracted at the point of maximum A-weighted sound pressure level, is shown in Figure 4-2.

TABLE 4-1 Coordinates for Points of Interest (X,Y,Z)

Number	X(ft)	Y(ft)	Z(ft)
1	0.0	-25000.00	004.00
2	0.0	-16000.00	004.00
3	0.0	-10000.00	004.00
4	0.0	-6300.00	004.00
5	0.0	-4000.00	004.00
6	0.0	-2000.00	004.00
7	0.0	-1000.00	004.00
8	0.0	-630.00	004.00
9	0.0	-400.00	004.00
10	0.0	-200.00	004.00
11	0.0	0.00	004.00
12	0.0	200.00	004.00
13	0.0	400.00	004.00
14	0.0	630.00	004.00
15	0.0	1000.00	004.00
16	0.0	2000.00	004.00
17	0.0	4000.00	004.00
18	0.0	6300.00	004.00
19	0.0	10000.00	004.00
20	0.0	16000.00	004.00
21	0.0	25000.00	004.00

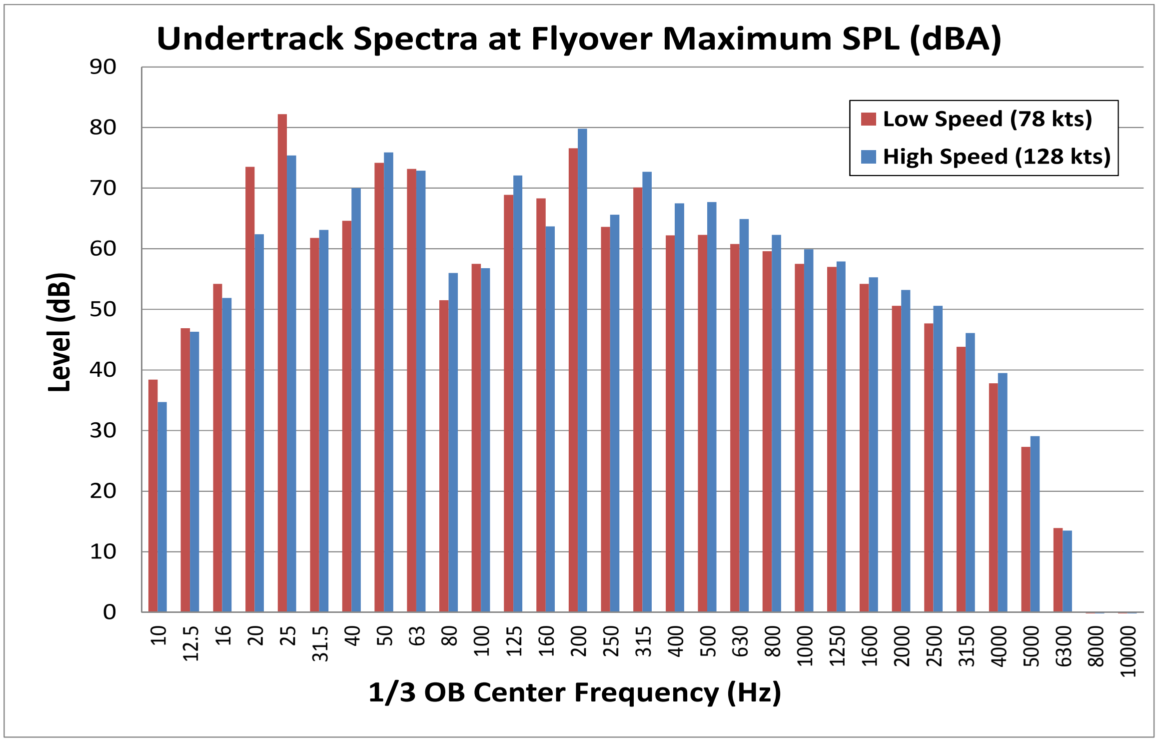

FIGURE 4-2 Undertrack spectra at point of maximum A-weighted SPL.

Bell 412 / CH-146 Low and High Speed flight (78 & 128 kts), 1500 Ft AGL level flight

A comparison of the various metrics for selected POIs is provided in Table 4-3. The vehicle source noise emission is asymmetrical resulting in different values on the right and left sides of the vehicle (Figure 4-3). The difference in the results when all one-third octave bands (10-40) are included versus including only those above 50 Hz (bands 17-40) depends on the metric:

- C-weighted and unweighted SEL values differ by 1-3 dB when low-frequency data is "zeroed-out".
- SEL, L_{max} (dBA), EPNL, PNLTmax, show no difference.

The significant differences in the C-weighted and unweighted metrics are due to the considerable energy content contained in the low-frequency bands for helicopters. Figure 4-4 illustrates the difference between A- and C-weighted curves as applied to each sound pressure level (dB) between 10 Hz and 10 kHz. As additional low-frequency bands below 50 Hz are included in the analysis, the integrated area between the A- and C-weighted curves increases dramatically. Atmospheric absorption is not as strong for low-frequency as it is for high-frequency. The combination of the significant spectral content of the helicopter source noise at low-frequencies with the absorption effects results in increasing differences between A- and C-weighted metrics at longer ranges. This trend is also applicable for D-prime audibility metric due to the stronger low-frequency noise content of helicopters.

TABLE 4-2 Comparison of Metrics at POIs for the Bell 412/CH-146 Low-frequency Trade Study

(Starboard, negative POI values | Port, positive POI values)

POINT OF INTEREST RESULTS - High Speed, 128 kts (Sphere 112)																		
	Lmax			SEL			SEL			SEL			EPNL			PNLMAX		
POI	(dBA)			(Overall)			(dBC)			(dBA)			(dB)			(dB)		
(feet)	All Freqs	50+ Hz	Delta	All Freqs	50+ Hz	Delta	All Freqs	50+ Hz	Delta	All Freqs	50+ Hz	Delta	All Freqs	50+ Hz	Delta	All Freqs	50+ Hz	Delta
-25000	33.3	33.3	0.0	78.2	73.0	5.2	75.1	72.0	**3.1**	53.1	53.0	0.1	54.5	54.5	0.0	46.1	46.1	0.0
-2000	67.8	67.8	0.0	95.8	92.4	3.4	93.5	91.8	**1.7**	82.0	82.0	0.0	84.3	84.3	0.0	80.5	80.5	0.0
0	74.5	74.5	0.0	97.0	94.6	2.4	95.1	94.2	**0.9**	84.9	84.9	0.0	87.8	87.8	0.0	89.8	89.8	0.0
2000	64.6	64.6	0.0	92.5	90.2	2.3	90.6	89.5	**1.1**	78.7	78.7	0.0	81.0	81.0	0.0	77.6	77.6	0.0
25000	31.0	31.0	0.0	73.4	71.7	1.7	71.6	70.8	**0.8**	51.1	51.1	0.0	51.3	51.3	0.0	42.3	42.3	0.0

POINT OF INTEREST RESULTS - Low Speed, 78 kts (Sphere 120)																		
	Lmax			SEL			SEL			SEL			EPNL			PNLMAX		
POI	(dBA)			(Overall)			(dBC)			(dBA)			(dB)			(dB)		
(feet)	All Freqs	50+ Hz	Delta	All Freqs	50+ Hz	Delta	All Freqs	50+ Hz	Delta	All Freqs	50+ Hz	Delta	All Freqs	50+ Hz	Delta	All Freqs	50+ Hz	Delta
-25000	29.9	29.8	0.1	76.5	70.8	5.7	73.3	69.8	**3.5**	51.3	51.2	0.1	50.4	50.4	0.0	40.2	40.2	0.0
-2000	63.1	63.1	0.0	93.5	89.4	4.1	90.8	88.7	**2.1**	78.6	78.6	0.0	80.7	80.7	0.0	75.9	75.9	0.0
0	71.0	71.0	0.0	99.1	94.5	4.6	96.3	94.0	**2.3**	84.4	84.4	0.0	87.5	87.5	0.0	86.2	86.2	0.0
2000	60.8	60.8	0.0	92.8	90.0	2.8	90.5	89.2	**1.3**	76.8	76.8	0.0	78.9	78.9	0.0	73.4	73.4	0.0
25000	27.1	27.1	0.0	70.5	68.3	2.2	68.5	67.4	**1.1**	48.7	48.7	0.0	45.7	45.7	0.0	35.3	35.3	0.0

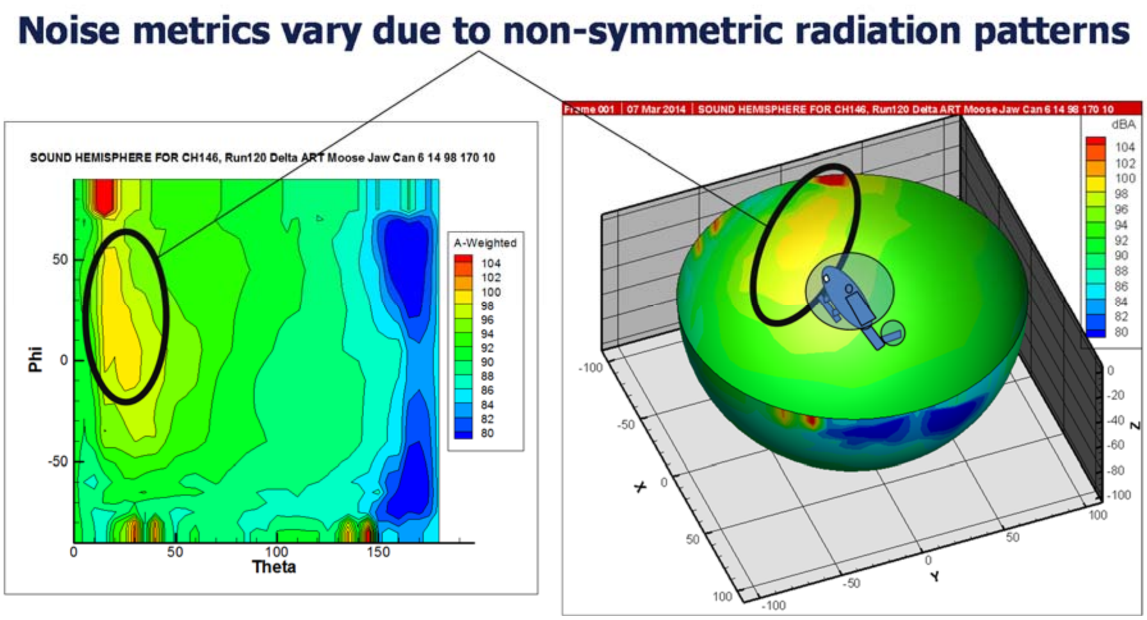

FIGURE 4-3 Bell 412 /CH-146 noise source emissivity (78 knots, dBA).

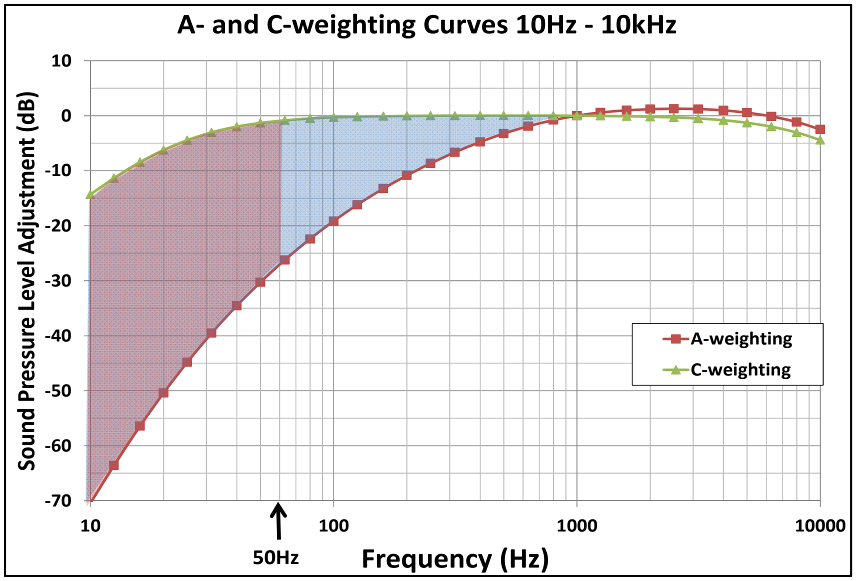

FIGURE 4-4 A- and C-weighting Curves, 10 Hz to 10 kHz.

4.1.2. Effects of Approach Angle on Source Characteristics

AEDT Improvement Recommendation: It is necessary to include the effects of approach flight path angle on source noise characteristics.

Source noise characteristics for approach modeling examination. Noise generated by helicopters is specific to the configuration and flight condition. Blade Vortex Interaction (BVI) noise is spectrally different from non-BVI landing approaches. Directivity patterns differ between BVI conditions and approach angles which do not exhibit BVI. Figure 4-5, the classic helicopter "fried egg plot" illustrates the locus of approach conditions which may result in BVI. The outer boundary defines conditions under which the main rotor impulsive noise is amplified due to the wake coming into close proximity of the blades. The maximum main rotor impulsive noise is maximum BVI when the blades interact (slide through or directly impinge upon) the wake shed from the prior blade passage. Pilots are instructed to fly neighborly and operate their vehicle in a manner that reduces noise emissions – namely to avoid BVI if possible. Community noise models are used to predict the impacts of BVI noise and are used to determine the impact from alternative low-noise profiles. Therefore the noise model must have sufficient fidelity to realize the difference between a BVI and non-BVI approach operation. To do this the source model must therefore include characteristics that vary with approach condition.

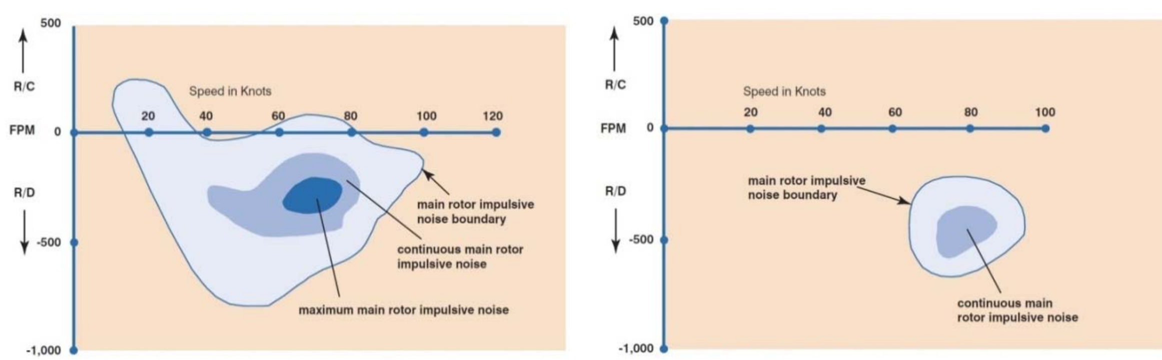

FIGURE 4-5 High-noise flight operations for medium/heavy and small/light helicopters.

Source: Fly Neighborly Guide [HAI, 2007]

The specific interaction between the rotor and the wake (the tip vortex) determines the directivity of the noise emission. Figure 4-6 illustrates two forms of BVI: Parallel and Oblique. In the parallel case the phasing between rotor blade and the wake is such that the blade hits the wake in a parallel fashion where a large angular extent of the wake is intersected by the rotor over a small rotor advance angle. This results in the green wavefront pattern and the noise propagates in the direction indicated by the arrow. For oblique BVI, the blade traces up the wake so only one part of the wake impinges on the blade at any given time. In this case the angular sweep of the blade is larger and the wave fronts (purple) are generated over a longer time (and over a larger blade angular sweep) resulting in the directivity angle shown in red.

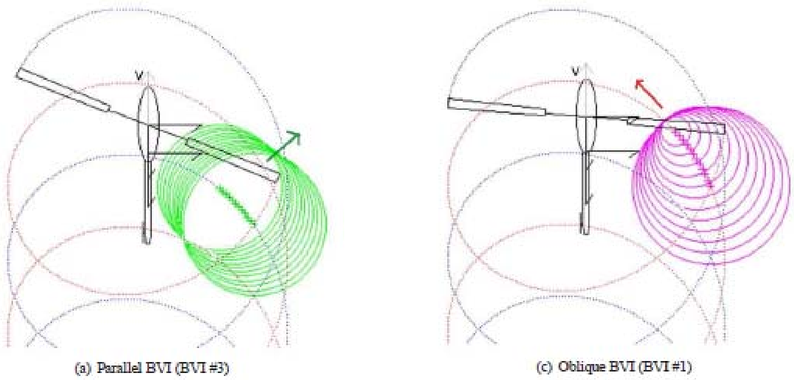

FIGURE 4-6 Parallel and oblique BVI for approach condition.

Wavefronts are indicated by green and purple circles; Arrows show the BVI propagation direction (Source: Koushik, 2007)

Given the complex nature of rotorcraft noise emission, especially under approach conditions, a trade study was conducted which utilized three different approach angle conditions for similar speeds. Three noise spheres representative of 3^o, 6^o and 9^o approach flight paths (Figure 4-7) were examined using AAM in two different ways:

- Single 6^o approach flight path with 3^o, 6^o and 9^o noise spheres used for modeling
- 3^o, 6^o and 9^o approach flight paths with appropriate 3^o, 6^o and 9^o noise spheres for modeling

The first allows us to quantify the effect of differences in the source directivity without the confounding issue of propagation differences due to different flight paths and heights above the ground. The second is a more realistic assessment. Figure 4-8 shows three Bell 412 / CH146 approach spheres (SPL, dBA).

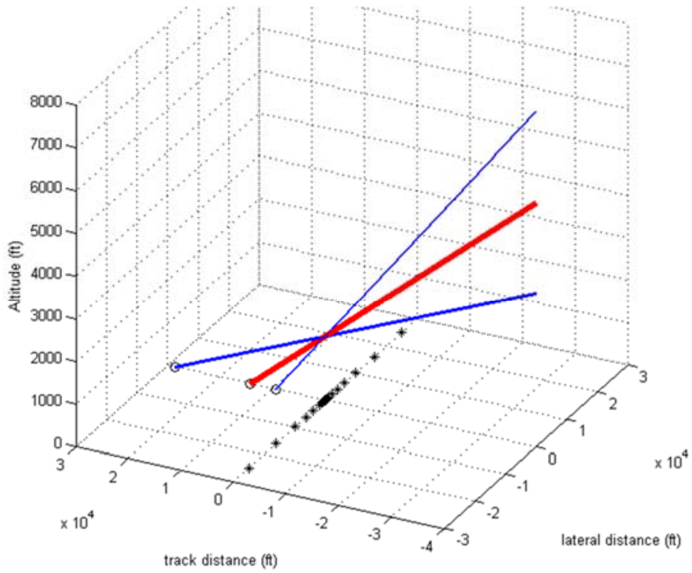

FIGURE 4-7 Three approach flight paths (3º, 6º and 9º) used in the trade study.

All tracks cross over the lateral array at 1500 ft AGL

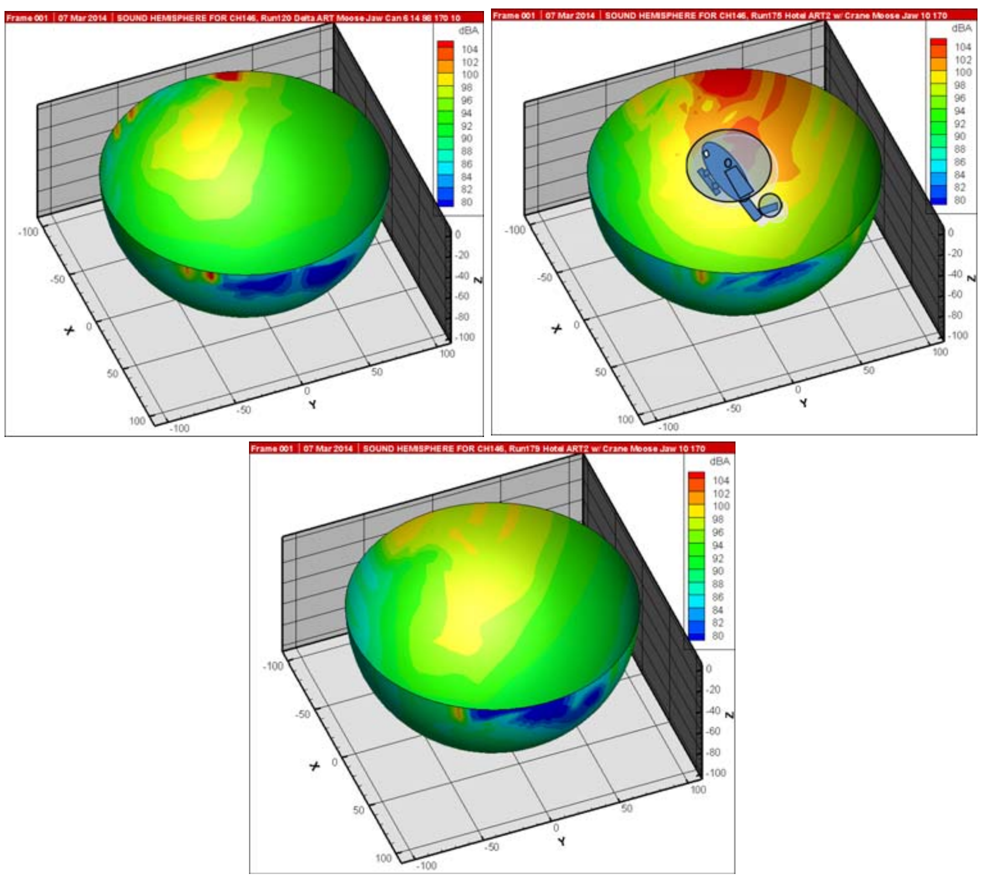

FIGURE 4-8 Bell 412 / CH-146 spheres AAM autoselected for 3º, 6º and 9º approach paths (SEL, dBA).

As was noted above, the BVI condition tends to increase noise in the higher frequencies which substantially contribute to A-weighted levels. In the rotorcraft research community, the BVISPL metric is typically used to quantify BVI impacts. BVISPL is an unweighted summation of spectral data across one-third octave bands containing frequencies from the 6th to the 40th main rotor harmonic. This is illustrated in Figure 4-9 for the Bell 412. The advantage of this metric is that it isolates and quantifies the main rotor BVI and is generally uncontaminated by loading and thickness noise and other effects which typically dominate the lower main rotor harmonics.

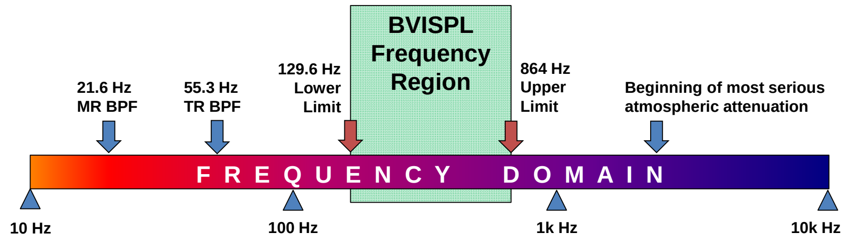

FIGURE 4-9 Bell 412 / CH-146 spectral content and BVISPL range.

Significant energy is present in the BVI bands during a 6^o approach. Figure 4-10 illustrates the ground maximum BVISPL footprint contours for a single 6^o approach flight trajectory but with "forced" 3^o, 6^o and 9^o noise spheres in the AAM modeling. Figure 4-11 presents the effects of the noise source in isolation. One can see that varying the noise sphere and using the same flight trajectory results in larger noise contours for the 6^o sphere. The corresponding Max BVISPL for the spheres on 3^o, 6^o and 9^o approach trajectories is in Figure 4-12. Here the noise source is varied along with the trajectory so the footprint differences are a combination of differing geometry and noise sources. A comparison of maximum BVISPL and SEL (dBA) levels at the POIs are portrayed in Figure 4-13. The behavior of A-weighted SEL and BVISPL is very similar: the 6^o approach results in the highest noise with asymmetric differences between the 3^o and 9^o approaches of up to 6 dB for some point of interests.

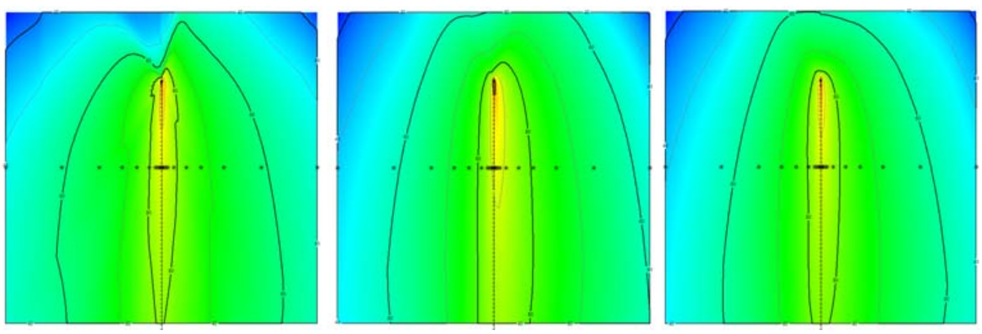

FIGURE 4-10 Max BVISPL contours using "forced" 3^o, 6^o and 9^o noise spheres on a 6^o approach trajectory.

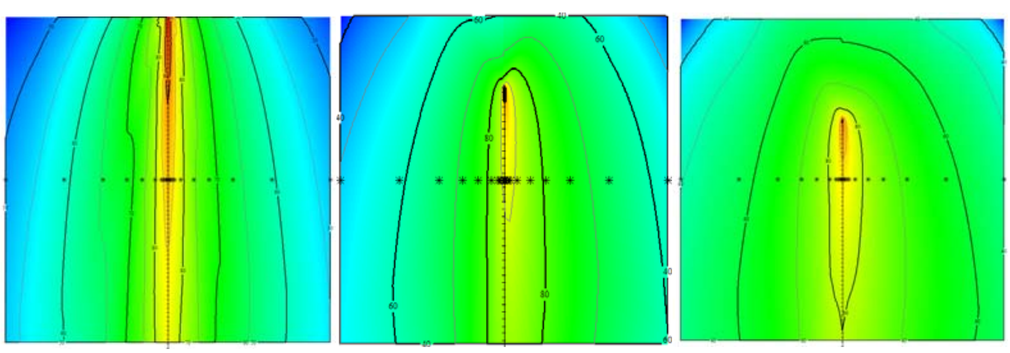

FIGURE 4-11 Max BVISPL contours using 3^o, 6^o and 9^o noise spheres on 3^o, 6^o and 9^o approach trajectories.

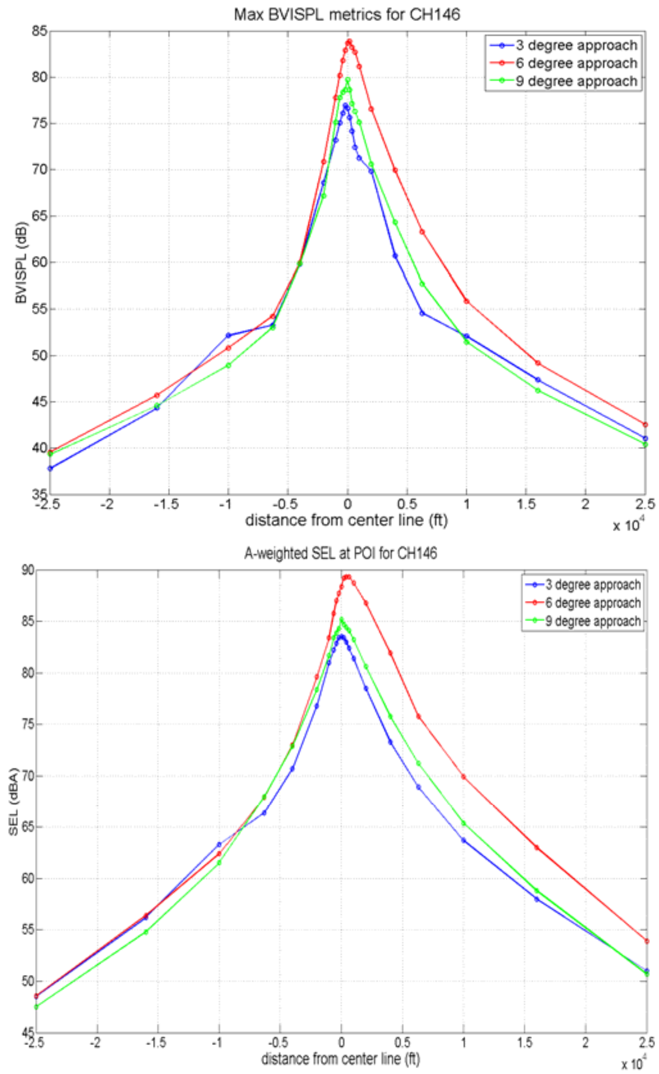

FIGURE 4-12 Max BVISPL and SEL (dBA) at lateral POIs.

Based on 3º, 6º and 9º Noise Spheres on 3º, 6º and 9º Approach Trajectories

(Starboard, negative POI values | Port, positive POI values)

4.1.3. Lateral Source Modeling Fidelity

AEDT Improvement Recommendation: It is necessary to model the lateral source characteristics with sufficient a) angular fidelity to capture directional BVI noise and b) lateral extent to account for changes in vehicle roll angle.[1]

Modeling Lateral Source Noise under varying Flight Conditions

To assess the impact of lateral source directivity modeling, the AAM noise sphere fidelity for Bell 412 / CH-146 low speed level flight (78 knots, Run 112) was reduced (decimated) and the following three conditions were considered:

[1] The present trade study will need to be expanded to include additional helicopter types and comparisons with high fidelity measurements before general recommendations for specific lateral angular spacing / number of microphones can be made.

- Original full lateral directivity (5° Lateral/Phi and 5° Fore-Aft/Theta spacing).
- 30 degree spacing.
- Right-Center-Left (45 degree spacing).

The grid topology for AAM noise spheres is shown in Figure 4-13. Figure 4-14 shows the integrated SPL (dBA) for the decimated noise spheres for the CH-146 for the cases considered in this trade study. The small dots indicate the control points on the sphere at which the source data has been defined. The fore-aft directivity is left unaltered and includes the as-measured spectral content at the 5 degree theta intervals. Within AAM the noise spheres contain levels for each one-third octave band on these control points. The AAM algorithm interpolates linearly on (phi, theta) for each one-third octave band before propagating. The AEDT/INM algorithm interpolates the NPD data linearly on phi. There is no fore-aft directivity in INM, except for static operations (hover and idle).

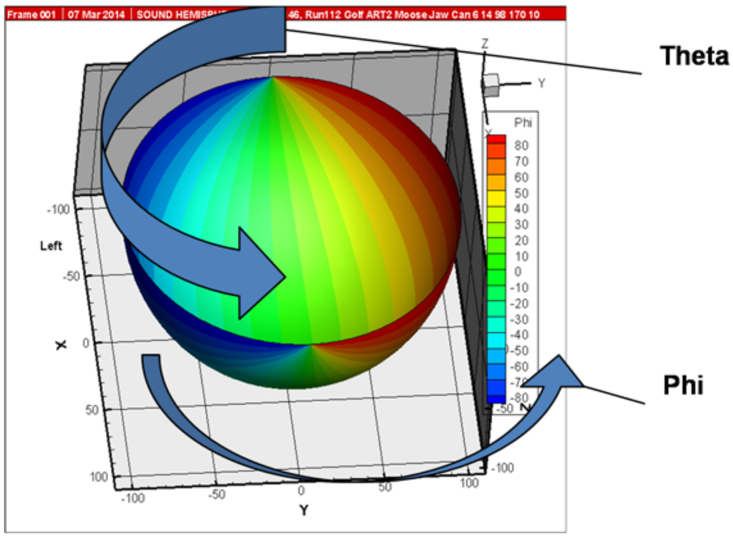

FIGURE 4-13 AAM noise sphere grid topology.

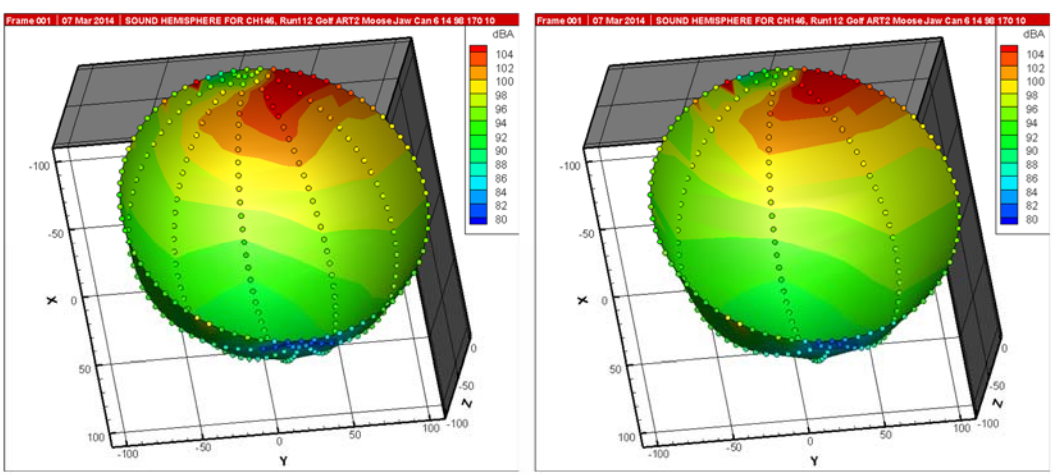

FIGURE 4-14 Decimated noise spheres, 30° and 45° spacing, SPL (dBA). [2]

Vehicle Noise at top, Control Dots indicate Data Points; High Speed, 128 kts, Run 112

[2] The contours displayed in Figure 4-16 are based on TecPlot's plotting algorithm and are not representative of the analysis or interpolation methodology used by AAM or AEDT/INM.

The results of the lateral source distribution study are provided for a variety of metrics in Table 4-3. An illustration of the metrics across all the considered lateral points of interest is provided in Figure 4-15 and 4-16. In Figure 4-17 one can see the pronounced effect of the lateral directivity on the low speed (78 knots) left (retreating blade) side of the noise sphere at lateral distances of 3000 to 7000 Ft. In this case the SEL (dBA) exhibits a larger difference than the SEL (dBC). This is due to the higher spectral content and likely due to decreased rotor-wake miss distances on the retreating side. In Figure 4-18 (high speed) the differences are in SEL (dBA) and on the advancing side of the rotor at lateral distances of 6000 to 8000 Ft. Examining the colored dots in Figure 4-16, one can see that the 30^{o} angle better captures the extent of the "hot spot" on the sphere than 45^{o}.

The lateral source directivity trade study will be continued to determine if specific lateral directivity guidance (i.e. a minimum lateral spacing and a maximum lateral extent) can be determined. This will involve examination of other high fidelity datasets, including the MD 902[3] and other commercial aircraft data held by our international team members (NLR).

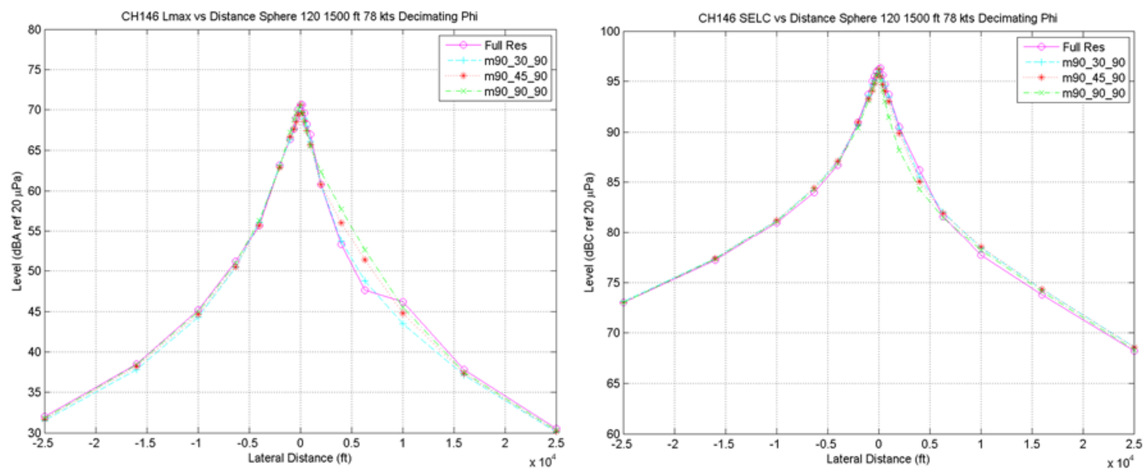

FIGURE 4-15 Metrics at lateral POIs for Phi decimated spheres, low speed.

Lmax (dBA) and SEL (dBC), 78 kts, Run 120; (Starboard, negative POI values | Port, positive POI values)

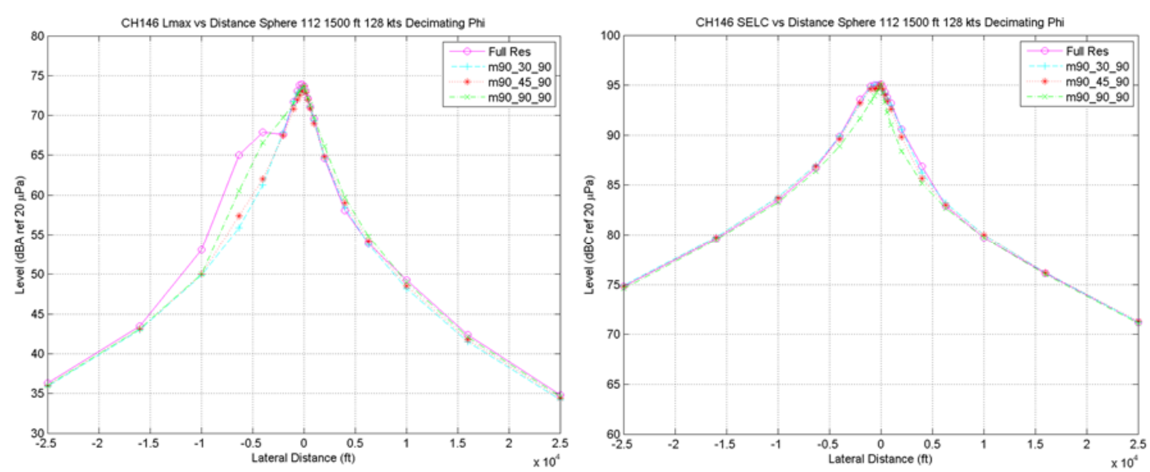

FIGURE 4-16 Metrics at lateral POIs for Phi decimated spheres, high speed.

Lmax (dBA) and SEL (dBC), Bell 412/CH-146 at 128 kts, Run 112

(Starboard, negative POI values | Port, positive POI values)

[3] NASA provided data for the MD 902 and indicated it may be shared internationally.

TABLE 4-3 Lateral Source Directivity Modeling Effect

(Starboard, negative POI values | Port, positive POI values)

POINT OF INTEREST RESULTS - High Speed, 128 kts (Sphere 112)																				
	Lmax				SEL				SEL				EPNL				PNLMAX			
POI	(dBA)				(dBC)				(dBA)				(dB)				(dB)			
(feet)	All Phi	30-Deg	45-Deg	MaxDelta	All Phi	30-Deg	45-Deg	MaxDelta	All Phi	30-Deg	45-Deg	MaxDelta	All Phi	30-Deg	45-Deg	MaxDelta	All Phi	30-Deg	45-Deg	MaxDelta
-25000	33.3	32.9	33.0	0.4	75.1	75.2	75.1	0.1	53.1	52.8	52.9	0.3	54.5	53.9	54.1	0.6	46.1	45.4	45.6	0.7
-6300	64.3	54.9	56.7	**9.4**	86.4	87.0	86.8	0.6	75.3	72.4	72.8	2.9	77.4	75.7	76.1	**1.7**	75.1	67.6	69.3	**7.5**
-2000	67.8	68.0	67.7	0.2	93.5	93.1	93.3	0.4	82.0	81.9	82.3	0.3	84.3	83.9	84.8	0.5	80.5	79.9	80.7	0.6
0	74.5	74.5	74.5	0.0	95.1	95.1	95.1	0.0	84.9	84.9	84.9	0.0	87.8	87.8	87.8	0.0	89.8	89.8	89.8	0.0
2000	64.6	64.7	64.8	0.2	90.6	90.6	89.7	0.9	78.7	78.8	78.5	0.2	81.0	81.0	80.2	0.8	77.6	77.3	77.5	0.3
6300	52.2	52.2	52.5	0.3	82.7	83.1	82.9	0.4	68.7	69.1	69.1	0.4	71.3	71.8	71.9	0.6	64.8	65.2	65.1	0.4
25000	31.0	30.8	30.9	0.2	71.6	71.7	71.7	0.1	51.1	50.9	51.0	0.2	51.3	50.8	51.0	0.5	42.3	41.5	41.8	0.8

POINT OF INTEREST RESULTS - Low Speed, 78 kts (Sphere 120)																				
	Lmax				SEL				SEL				EPNL				PNLMAX			
POI	(dBA)				(dBC)				(dBA)				(dB)				(dB)			
(feet)	All Phi	30-Deg	45-Deg	MaxDelta	All Phi	30-Deg	45-Deg	MaxDelta	All Phi	30-Deg	45-Deg	MaxDelta	All Phi	30-Deg	45-Deg	MaxDelta	All Phi	30-Deg	45-Deg	MaxDelta
-25000	29.9	29.4	29.7	0.5	73.3	73.4	73.4	0.1	51.3	50.9	51.1	0.4	50.4	49.6	50.0	0.8	40.2	39.3	39.8	0.9
-6300	49.9	49.4	49.3	0.6	83.7	84.4	84.4	0.7	68.5	68.1	68.3	0.4	70.5	70.4	70.5	0.1	61.9	62.3	62.1	0.4
-2000	63.1	63.0	63.0	0.1	90.8	90.6	91.0	0.2	78.6	78.4	78.9	0.3	80.7	80.4	81.3	0.6	75.9	75.8	76.2	0.3
0	71.0	71.0	71.0	0.0	96.3	96.3	96.3	0.0	84.4	84.4	84.4	0.0	87.5	87.5	87.5	0.0	86.2	86.2	86.2	0.0
2000	60.8	60.8	60.8	0.0	90.5	90.4	89.9	0.6	76.8	76.6	76.9	0.2	78.9	78.6	79.1	0.3	73.4	73.6	73.9	0.5
6300	45.9	47.7	51.2	**5.3**	81.6	81.9	81.8	0.3	65.2	66.5	67.9	**2.7**	67.5	69.2	70.6	3.1	59.0	60.6	64.3	**5.3**
25000	34.7	34.5	34.5	0.2	74.0	74.6	74.6	0.6	55.9	55.6	55.8	0.3	57.4	56.8	57.1	0.6	46.7	47.0	46.8	0.3

4.2. Operational Capabilities

AEDT/INM has a refined operational modeling input structure which is well suited for conventional helicopter operations: takeoff, landing, in and out of ground effect hover, and surveillance missions. At present there is no mechanism to easily model tiltrotor operations; the operations must be pieced together from a combination of fixed wing (airplane mode) and helicopter (helicopter mode) operations with separate aircraft parameters defined in INM for transition modes. The output grids may then be summed to get the cumulative noise contour. Subsequent comparisons between INM and AAM utilize this technique.

One discriminator between the models is the decoupling of the ground track (path) and the operational flight profile in AEDT/INM and the ability to also model coupled 3D trajectories in the other rotorcraft models. Considering tracks and profiles separately is standard practice when modeling airport fixed wing flight operations, but is not nearly as common in the rotorcraft industry. The profile description does however lend itself to pilot verification and checking for compliance with safe/unsafe flight profiles – aka compliance with the Manufacturer flight manual Dead Man's curve. (The Dead Man's curve describes those height-speed combinations where it is aerodynamically impossible to complete an autorotation (emergency) landing. An example is provided in Figure 4-7.)

4.2.1. Conventional Helicopter Operations

Finding: Mode based modeling as currently implemented in AEDT is sufficient.

Standard Operational Procedure Modeling / Mode Based Performance Modeling. AEDT/INM provides a set of standard operational procedures for both aircraft and helicopters. The current implementation is mode-based with limited performance and acoustic source modeling capability for changes in helicopter weight and speed. AEDT/INM modeling allows the user to define flight profiles, weights and speeds for modes of operation including Departures, Arrivals, Overflights and Hover operations including HIGE/HOGE (Table 4-4). The key limitation within AEDT/INM is database availability.

TABLE 4-4 AEDT Operational Mode Procedure Steps for Each Helicopter NPD Data Set

Operational Mode	Description	State
A	Approach at constant speed	Dynamic
D	Departure at constant speed	Dynamic
L	Level flyover at constant speed	Dynamic
G	Ground idle	Static
H	Flight idle	Static
I	Hover in ground effect	Static
J	Hover out of ground effect	Static
V	Vertical ascent in ground effect	Static
W	Vertical ascent out of ground effect	Static
Y	Vertical descent in ground effect	Static
Z	Vertical descent out of ground effect	Static
B	Approach with horizontal deceleration	Dynamic
C	Approach with descending deceleration	Dynamic
E	Depart with horizontal acceleration	Dynamic
F	Depart with climbing acceleration	Dynamic
T	Taxi at constant speed	Dynamic

4.2.2. Tiltrotor Movements including Transition between Airplane and Helicopter Modes

AEDT Improvement Recommendation: It is necessary to incorporate the effect of tiltrotor transition between Airplane and Helicopter Modes in the noise model. Spectral classes should be expanded to capture multiple modes of tilt rotor operations and lateral source characteristics should be included for each mode. Consideration should be given to incorporation into the NPD, spectral class and directivity database of the loading split between wing and rotors for transition modes.[4] Flexible profile modeling is needed to capture all possible operational procedures.[5]

Tiltrotor modeling fidelity comparison between INM and AAM. A process for modeling the MV-22 tilt-rotor aircraft with the Integrated Noise Model (INM) was examined. The MV-22 operates in three distinct configurations:

Mode 1. ‘Airplane Mode’ with the nacelle angles equal to zero (rotor shaft axis points forward) allows the MV-22 to operate similar to a fixed-wing propeller aircraft. Lift is generated from the wing profile and wing angle of attack. The rotors provide only forward thrust. In this configuration the MV-22 is capable of higher airspeeds and a larger range. Airspeed of about 120 knots is considered the lower threshold for airplane mode, below which the aircraft may generate insufficient lift for level flight.

Mode 2. ‘Helicopter Mode’ with the nacelle angles equal or close to 90 degrees (rotor shaft axis point up) allowing the MV-22 to operate similar to a helicopter. All lift is generated by the two rotors and forward thrust is due to small changes in nacelle angle in a similar manner to the collective function in a helicopter. This configuration allows the MV-22 to perform Vertical Takeoff and Landing (VTOL). The threshold for

[4] The inclusion of wing vs. rotor loading in the recommendation is based on feedback provided during the outreach phase from manufacturers Agusta-Westland, Eurocopter, Bell Helicopter plus NASA and academia.

[5] A combination of multiple user defined configurations were analyzed separately and the resultant grids summed. While this “trick” permitted modeling of a tilt-rotor operation, it was less than ideal. INM/AEDT should be adapted in the future to allow a tiltrotor with multiple modes, including helicopter, transition and airplane.

Helicopter Mode is not clearly defined but for modeling purposes it is considered to apply when the MV-22 travels slower than 60 knots and/or nacelles at an angle greater than 80 degrees.

Mode 3. 'Conversion Mode' with the nacelle angles somewhere between the two modes described above. Conversion Mode can be a brief transition from helicopter to airplane mode as the aircraft departs or can last for extended periods of time.

For the purposes of modeling the MV-22 in INM, the configuration or Mode must be determined for each portion of a flight profile. Nacelle angle is strongly, although not exclusively, dependent upon the airspeed. For this reason, airspeed is the recommended determining factor for choosing the appropriate Mode for modeling purposes. See Table 4-5 for details.

TABLE 4-5 MV-22 Configuration Mode Details

Speed (kts)	Nacelle (deg from horizontal)	Mode to Model	INM Category
120 or greater	0	Fixed Wing	Airplane
60 to 120	1 to 79	Conversion	Airplane
0 to 60	80 to 90	Helicopter	Helicopter

Noise levels. INM allows custom aircraft to be added to its noise database. The two main categories are airplanes and helicopters which each have differing capabilities and limitations. The MV-22 airplane and conversions mode will be modeled as INM airplanes while the helicopter will be modeled as an INM Helicopter.

The first step is determining the noise power distance (NPD) curves for each of the three modes in Table 4-7. The Advanced Acoustical Model (AAM) is capable of simulating MV-22 operations using actual acoustical data measured from dedicated acoustic flight tests. AAM was leveraged in this effort to generate each of the necessary metrics: A-weighted Sound Exposure Level (SEL), A-weighted Maximum Sound Level (Lmax), Effective Perceived Noise Level (EPNL), Perceived Noise Level, Tone corrected (PNLT). Level flights were simulated in AAM at the prescribed altitudes with a receiver directly below the flight path at 4 feet above the ground. The results are provided in Table 4-6 for both airplane types.

TABLE 4-6 Calculated NPD Values from AAM for MV-22 in Airplane and Conversion Modes

Mode	Metric		Distances									
	Desc	INM ID	L_200	L_400	L_630	L_1000	L_2000	L_4000	L_6300	L_10000	L_16000	L_25000
Fixed Wing (Airplane)	SEL (dBA)	S	89.0	85.5	83.0	80.2	75.7	70.5	66.4	61.8	56.4	49.4
	Lmax	M	86.1	79.7	75.5	71.0	63.8	55.9	50.1	43.8	36.8	29.9
	PNLT	P	104.5	98.0	93.5	88.6	80.7	72.1	65.9	58.5	49.3	39.2
	EPNL	E	96.6	92.9	90.2	87.2	82.1	76.3	71.6	65.7	58.2	47.8
Conversion	SEL (dBA)	S	98.9	95.6	93.3	90.6	87.0	83.4	79.9	76.7	67.4	52.8
	Lmax	M	99.1	92.7	88.6	84.3	77.8	71.0	66.1	60.6	54.2	34.0
	PNLT	P	119.1	112.7	108.4	104.0	97.0	89.8	84.5	78.5	71.3	44.9
	EPNL	E	108.2	104.9	102.6	99.7	95.8	91.7	87.9	83.8	73.3	53.4

Notes: (1) Fixed wing modeled with Nacelle of 0 degrees and airspeed at 160 kts
(2) Conversion mode modeled with Nacelle at 60 degrees and airspeed of 160 kts

The INM Helicopter type aircraft requires a similar set of values for sound levels under the aircraft as well as both left and right levels (measured 45 degrees to either side of the vehicle undertrack centerline).

The aircraft was modeled using steady level flights with two additional receivers was located 4 ft. AGL laterally offset at +/- 45 degrees. For each distance in the INM NPD table the height of the aircraft and corresponding lateral locations were adjusted to achieve the desired slant distance. The Lmax and PNLT values were extracted from the computed AAM time history file. The results are presented in Table 4-7.

TABLE 4-7 Calculated NPD Values from AAM for Helicopter Mode

SIDE TYPE	Metric		Distances									
	Desc	INM ID	L_200	L_400	L_630	L_1000	L_2000	L_4000	L_6300	L_10000	L_16000	L_25000
Center	SEL (dBA)	S	100.6	97.2	94.8	92.3	87.9	82.5	78.7	74.0	68.0	61.2
	Lmax	M	95.3	88.9	84.5	79.9	72.5	64.3	58.4	51.7	44.3	36.9
	PNLT	P	112.9	106.4	102.1	97.4	89.7	81.0	74.9	67.9	59.8	50.5
	EPNL	E	108.9	105.4	102.9	100.1	95.2	89.1	85.1	79.8	72.7	63.8
Left	SEL (dBA)	S	100.8	97.5	95.3	92.8	88.7	83.9	79.9	74.8	71.0	65.2
	Lmax	M	96.8	90.6	86.5	81.2	74.9	67.0	61.3	55.0	48.2	41.5
	PNLT	P	114.7	108.4	104.3	99.5	92.5	84.0	78.4	71.9	64.4	56.2
	EPNL	E	109.2	105.8	103.6	100.9	96.3	90.9	86.6	81.0	76.6	69.3
Right	SEL (dBA)	S	102.4	99.2	97.0	94.6	90.6	85.9	82.2	77.2	73.3	67.6
	Lmax	M	98.21	92.0	88.0	83.0	76.8	69.3	63.9	58.0	51.5	44.6
	PNLT	P	116.7	110.3	106.4	102.00	94.8	86.8	81	74.8	67.4	59.2
	EPNL	E	110.9	107.6	105.4	102.8	98.4	93.1	89	83.6	79.1	72.3

Frequency Considerations: Both INM and AAM account for frequency spectrum. To address this in INM, the frequency spectrum for SEL dBA was gathered from the 630 ft. overflight, normalized to 70 dB at 1000 Hz, and compared to existing INM frequency spectra. Figures 4-17 through 4-19 depict the MV-22 spectra along with the best fitting surrogate in the INM database for Airplane Mode, Conversion Mode and Helicopter Mode, respectively.

The Hawker Siddeley (HS748A) was selected for the MV-22 Airplane mode, the Beach Super King Air 200 (CNA441) was selected for the MV-22 conversion mode, and the Douglas DC-6 (DC6/CV340) was selected for the MV-22 helicopter mode. All surrogates are a compromise but represent the best match available.

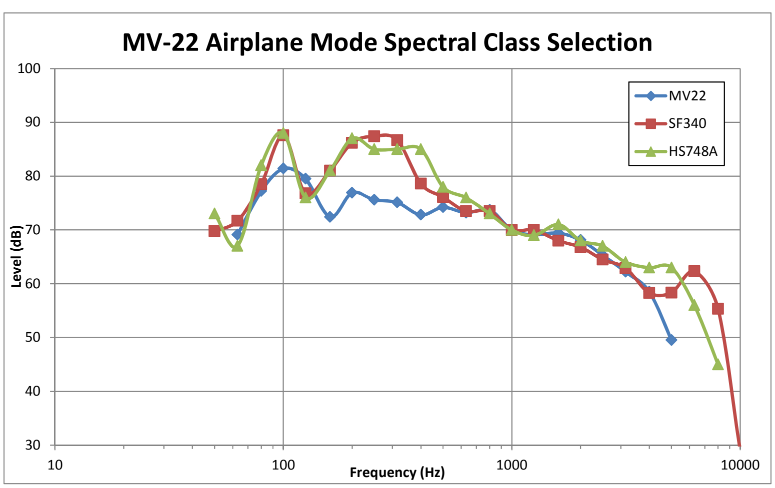

FIGURE 4-17 MV-22 airplane mode comparison of spectral class with normalized AAM data.

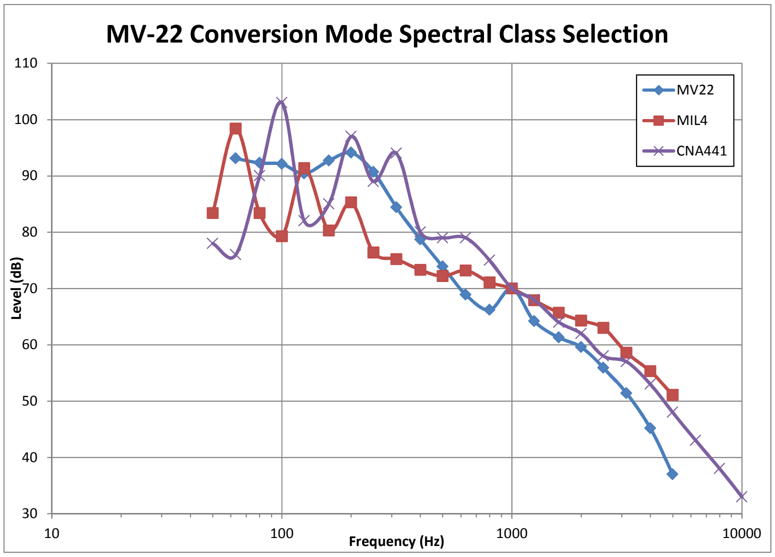

FIGURE 4-18 MV-22 conversion mode comparison of spectral class with normalized AAM data.

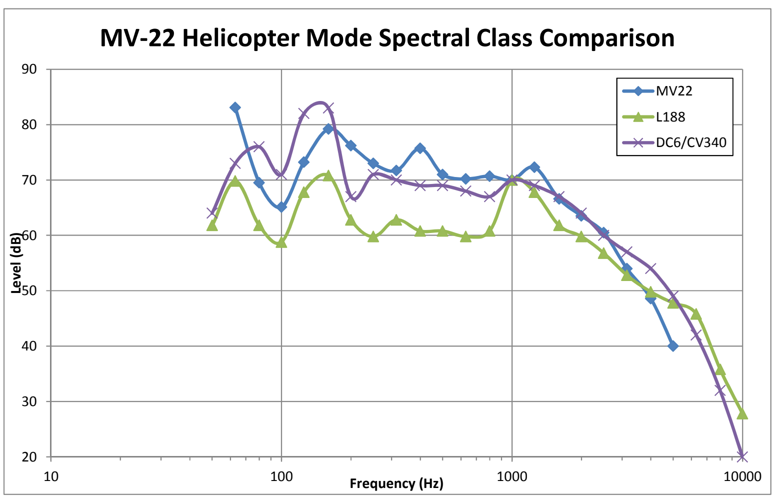

FIGURE 4-19 MV-22 helicopter mode comparison of spectral class with Normalized AAM Data.

Directivity: INM includes a directivity adjustment at each 15 degrees increment that is applied during helicopter ground run-up, hover, and while the aircraft is departing from the ground. The MV-22 was simulated in a hover at 4 ft. AGL with an array of receivers along a 200 ft. radius centered at the aircraft spaced every 15 degrees. There are currently no hovering spheres available in the AAM database so the slowest sphere with the nacelle at 85 degrees was used. The average of all 24 SEL dBA values was determined and the difference measured computed. Table 4-8 presents the resulting SEL adjustments imported into INM for the custom MV-22 helicopter aircraft.

TABLE 4-8 MV-22 Helicopter Mode Directivity Adjustments

C000	L015	L030	L045	L060	L075	L090	L105	L120	L135	L150	L165	L180
-1.7	-2.9	-3.0	-2.8	-3.2	-3.1	-2.7	-1.7	-1.7	-0.4	-2.0	-1.8	-0.1
C000	R015	R030	R045	R060	R075	R090	R105	R120	R135	R150	R165	R180
-1.7	-0.2	3.1	3.6	3.3	4.7	4.0	2.7	1.8	1.6	2.4	0.5	-0.1

INM Profile Modeling: Three typical MV-22 flight profiles were selected from a recent MV-22 military operations noise study [Czech & Kester, 2012] which include a departure, straight-in or non-break arrival, and a Touch and Go pattern. To approximate the AAM flight profiles in INM, each portion of the profile is broken down into its appropriate configuration mode. Using Table 4-6 as a guide, the profiles were separated at each location where the MV-22 airspeed changed through 60 or 120 knots (threshold for Modes). In some cases a profile point was not available so the values were linearly interpolated. In order to model segments of profiles in INM, each segment was entered as a separate profile. The Conversion and Fixed Wing portions were modeled as overflights beginning or ending in the air at the location where they transition to a different mode. For the helicopter mode profiles, the profiles were required to adhere to INM requirements for helicopter profiles. Specifically, the arrival profiles must start at a specific altitude and then do a level segment, and they must come to zero speed at a specific altitude before doing a required vertical descent to the ground. The departure profiles must start at flight idle and zero speed and altitude, and must end on a level flight segment. The detailed INM profiles are included in Tables 4-9 through 4-11. Additionally, the MV-22 was simulated in both AAM and INM for three level flyover conditions as listed in Table 4-12.

TABLE 4-9 MV-22 INM Arrival Profile Modeling

Modeling Mode	Step Number	Mode Distance (ft)	Total Distance (ft)	Altitude (ft)	Speed (kts)	Duration (s)	Helo Step Type
Fixed Wing	1	0.0	60000.0	2000.0	220.0	N/A	N/A
Fixed Wing	2	28000.0	32000.0	2000.0	220.0	N/A	N/A
Fixed Wing	3	44000.0	16000.0	1200.0	170.0	N/A	N/A
Fixed Wing	4	48000.0	12000.0	1000.0	150.0	N/A	N/A
Fixed Wing	5	49286.0	10714.0	786.0	120.0	N/A	N/A
Conversion	1	0.0	10714.0	786.0	120.0	N/A	N/A
Conversion	2	1714.0	9000.0	500.0	80.0	N/A	N/A
Conversion	3	5914.0	4800.0	300.0	80.0	N/A	N/A
Conversion	4	7714.0	3000.0	200.0	60.0	N/A	N/A
Helo	1	0.0	3000.0	200.0	60.0	N/A	Start Altitude
Helo	2	5.0	2995.0	200.0	60.0	N/A	Level Fly
Helo	3	1800.0	1200.0	150.0	50.0	N/A	Approach Descent Deceleration
Helo	4	3000.0	0.0	20.0	0.0	N/A	Approach Descent Deceleration
Helo	5	3000.0	0.0	0.0	0.0	5.0	Approach Vertical

TABLE 4-10 MV-22 INM Departure Profile Modeling

Modeling Mode	Step Number	Mode Distance (ft)	Total Distance (ft)	Altitude (ft)	Speed (kts)	Duration (s)	Helo Step Type
Helo	1	0.0	0.0	0.0	0.0	1.0	Flight Idle
Helo	2	2499.0	2499.0	160.0	60.0	N/A	Departure Climb Acceleration
Helo	3	2500.0	2500.0	160.0	60.0	N/A	Level Fly
Conversion	1	0.0	2500.0	160.0	60.0	N/A	N/A
Conversion	2	500.0	3000.0	188.0	71.0	N/A	N/A
Conversion	3	2500.0	5000.0	300.0	115.0	N/A	N/A
Conversion	4	3318.0	5818.0	364.0	120.0	N/A	N/A
Fixed Wing	1	0.0	5818.0	364.0	120.0	N/A	N/A
Fixed Wing	2	8182.0	14000.0	1000.0	170.0	N/A	N/A
Fixed Wing	3	19182.0	25000.0	2000.0	170.0	N/A	N/A
Fixed Wing	4	24182.0	30000.0	2000.0	220.0	N/A	N/A
Fixed Wing	5	54182.0	60000.0	2000.0	220.0	N/A	N/A

TABLE 4-11 MV-22 INM Closed Pattern Profile Modeling

Modeling Mode	Step Number	Mode Distance (ft)	Total Distance (ft)	Altitude (ft)	Speed (kts)	Duration (s)	Helo Step Type
Helo	1	0.0	0.0	0.0	0.0	1.0	Flight Idle
Helo	2	0.0	0.0	20.0	0.0	5.0	Depart Vertical
Helo	3	250.0	250.0	30.0	45.0	N/A	Departure Climb Acceleration
Helo	4	749.0	749.0	150.0	65.0	N/A	Departure Climb Acceleration
Helo	5	750.0	750.0	150.0	60.0	N/A	Level Fly
Conversion	1	0.0	750.0	150.0	65.0	N/A	N/A
Conversion	2	1250.0	2000.0	300.0	115.0	N/A	N/A
Conversion	3	3050.0	3800.0	520.0	115.0	N/A	N/A
Conversion	4	6506.0	7256.0	1000.0	115.0	N/A	N/A
Conversion	5	10306.0	11056.0	1000.0	115.0	N/A	N/A
Conversion	6	12034.0	12784.0	300.0	80.0	N/A	N/A
Conversion	7	12445.0	13195.0	233.0	60.0	N/A	N/A
Helo	1	0.0	13195.0	233.0	60.0	N/A	Start Altitude
Helo	2	5.0	13200.0	233.0	60.0	N/A	Level Fly
Helo	3	200.0	13400.0	200.0	50.0	N/A	Approach Descent Deceleration
Helo	4	1312.0	14512.0	20.0	0.0	N/A	Approach Descent Deceleration
Helo	5	1317.0	14512.0	0.0	0.0	5.0	Approach Vertical

TABLE 4-12 Modeled MV-22 Overflight Conditions

Helicopter	height	airspeed	Nacelle
	1000	50	75
Conversion	height	airspeed	Nacelle
	1000	100	60
FixedWing	height	airspeed	Nacelle
	1000	170	0

Comparison and Interpretation of Tiltrotor Modeling Techniques: Using the NPD values, frequency spectrum surrogate, and the directivity adjustments computed from AAM, INM was used to compute SEL at discrete Points of Interest (POI) as well as generate a grid of SEL dBA values for three common MV-22 operations (departure, arrival, and Touch and Go closed pattern) and the overflight conditions.

SEL contours comparing INM and AAM are provided in Figures 4-21, 4-22 and 4-23 for an arrival, departure and closed pattern, while comparisons at POIs are provided in Table 4-13 for these same three operations. Table 4-14 presents the SEL comparison results between AAM and INM for the three level operations.

For the Level Fixed Wing Mode, INM and AAM result in SELs less than 1.5 dB difference at all points. For Level Helicopter and Conversion modes at the centerline of (X=0), INM and AAM have the closest match and vary 2 dB or less. However, for the lateral points of interest, there is more than 5 dBA difference between the Helicopter mode modeling and 4 dBA difference in modeling for the Conversion mode. One of the reasons why the helicopter mode has some of the largest difference between the two models closer into the runway is due to physical modeling differences in the aircraft motions. INM requires helicopter arrival profiles to end with zero velocity at zero altitude and departures to start at idle on the ground. This is not how the MV-22 AAM operation is typically flown or was modeled in AAM (Table 4-15). Another reason for the variance is due to having to choose a surrogate spectral class, none of which are very close to the spectral class of the MV-22. The third contributor to the differences between AAM and INM modeling is due to the increased fidelity of the AAM source noise parameters. Within INM only three noise spheres may be used to develop the NPD data. A representative case was chosen for each, however within AAM a total of 49 noise spheres (Table 4-16) are available for MV-22 noise modeling.

Figure 4-20 shows the differences in Arrival SEL contours between the AAM (colored) and INM (dashed) modeling. The INM contours are approximately 5-10 dB larger than the AAM contours, but match up better during the fixed wing mode further down the arrival track. One of the major reasons for the differences between the contours is due to the required helicopter modeling technique in INM. INM requires arrival helicopter profiles to end at zero speed at a certain altitude, and the last step then must be a vertical descent to the ground. In AAM, however, the MV-22 aircraft can end the profile at any altitude and speed. Another reason is the difference in spectra for the two different modeling techniques. AAM can use the calculated MV-22 spectra, but the INM modeling must use the closest existing spectra. INM only has access to three of the MV-22 modes or "spheres" which are the three modes used: helicopter, conversion, and fixed-wing. However, AAM can use the full set of 49 spheres. The AAM noise spheres also contain full spectral directivity whereas INM NPD only has right-center-left directivity in helicopter mode and no directivity for airplane mode.[6] This results in smoother looking contours in INM when compared with AAM contours.

Figure 4-21 presents the INM and AAM SEL contours for the departure operation. As with the arrival

[6] Lateral directivity for fixed wing jet aircraft in INM is handled separately from the NPD data and depends on whether the engines are wing or tail mounted.

profile, the departure INM contours are 5-10 dB larger than the AAM departure contours closest to the start of the departure, but compare favorably further down the track. As before the helicopter mode profile had to be modeled differently than the AAM profile due to helicopter procedural constraints in INM. The departure profile for helicopter mode must start at idle on the ground and at zero speed. This is different than the AAM modeling where the MV-22 started at 20 ft. altitude and at 5 knots.

Figure 4-22 shows the AAM and INM SEL contours for a closed pattern operation. The INM contours are mostly wider in the X direction. The helicopter mode was used as both an arrival and a departure for this closed pattern profile, so the modeling constraints of INM doubly affected the contour comparison for this profile.

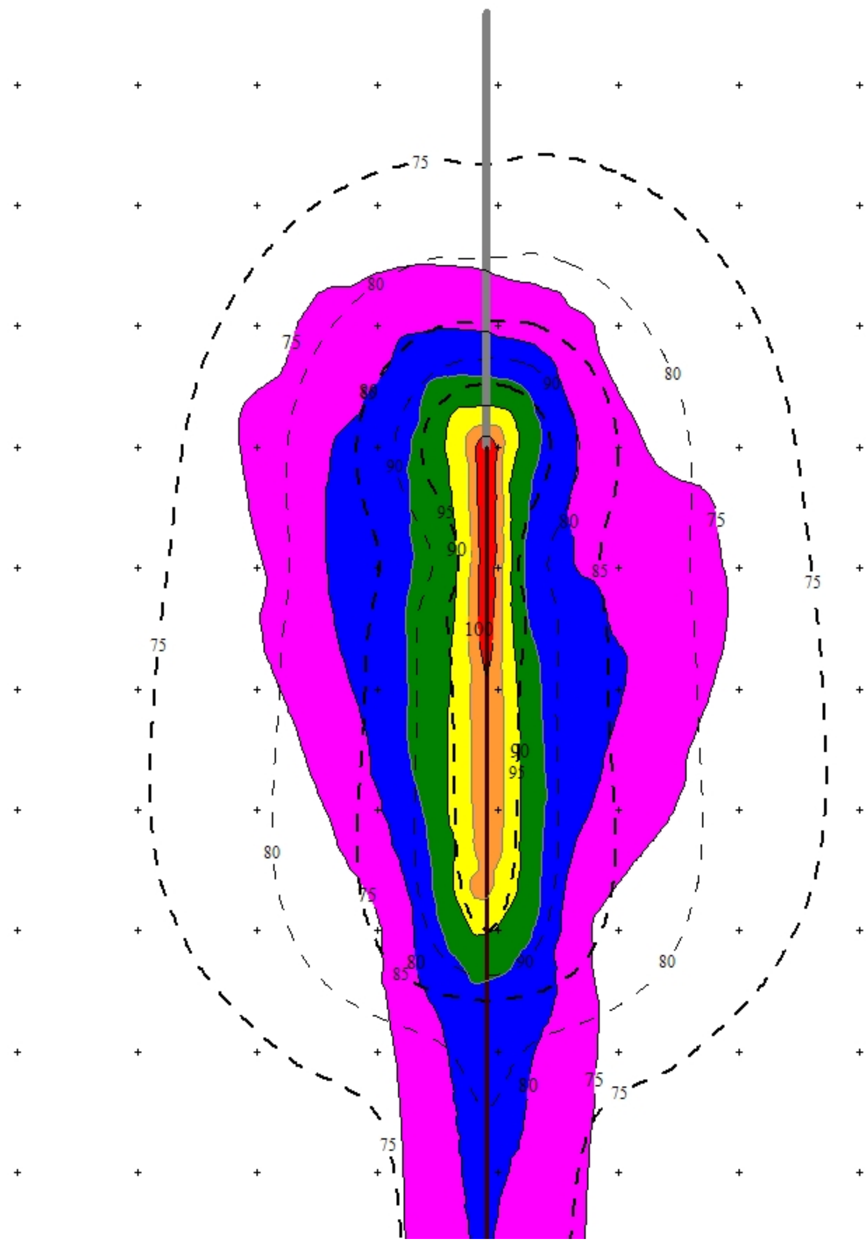

FIGURE 4-20 MV-22 SEL (dBA) for an arrival operation.

AAM: Colored Contours, INM: Dashed Lines; Flight Track: Brown. Tick mark spacing = 2500 Ft.

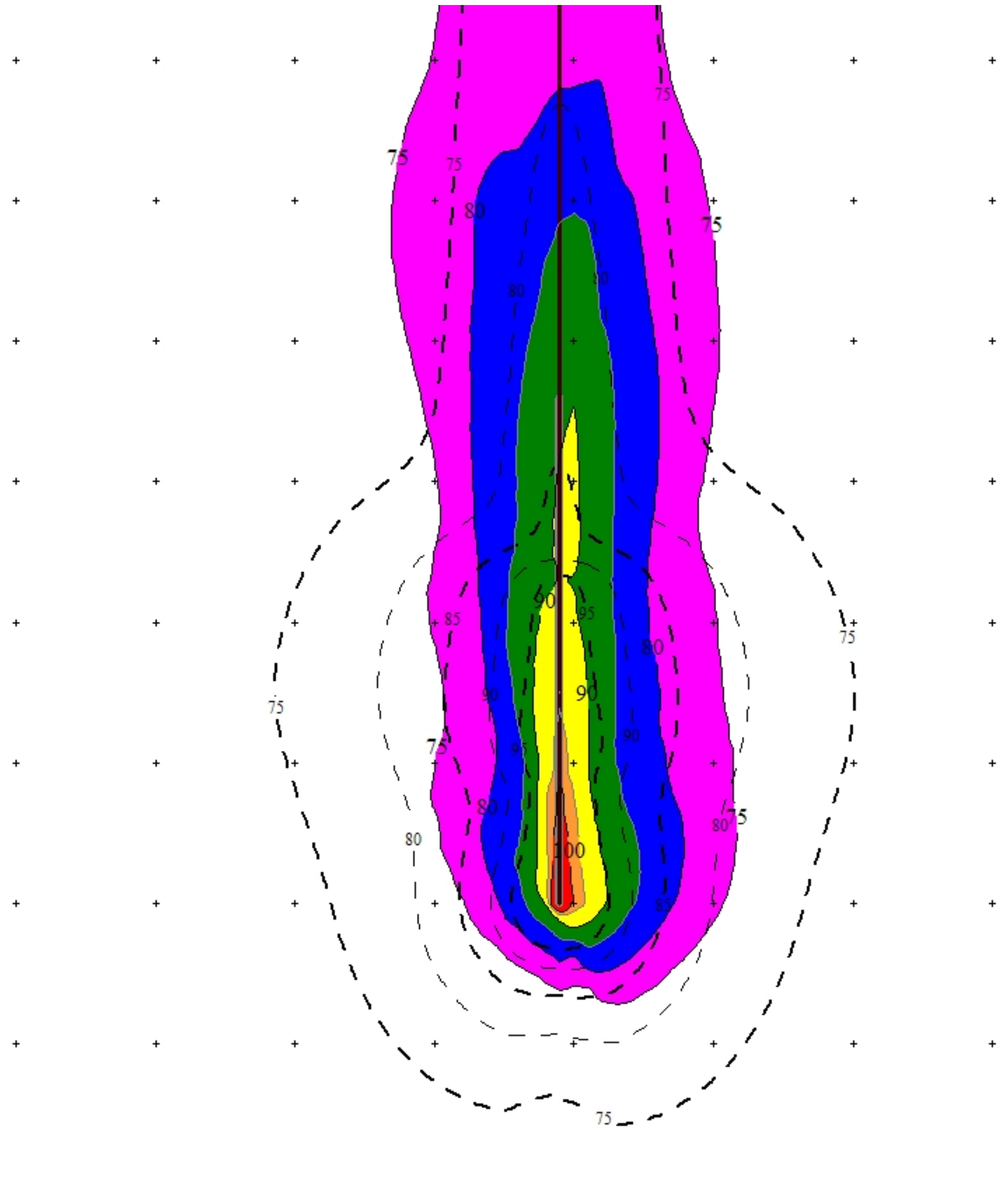

FIGURE 4-21 MV-22 SEL (dBA) for a departure operation.
AAM: Colored Contours, INM: Dashed Lines; Flight Track: Brown. Tick mark spacing = 2500 Ft.

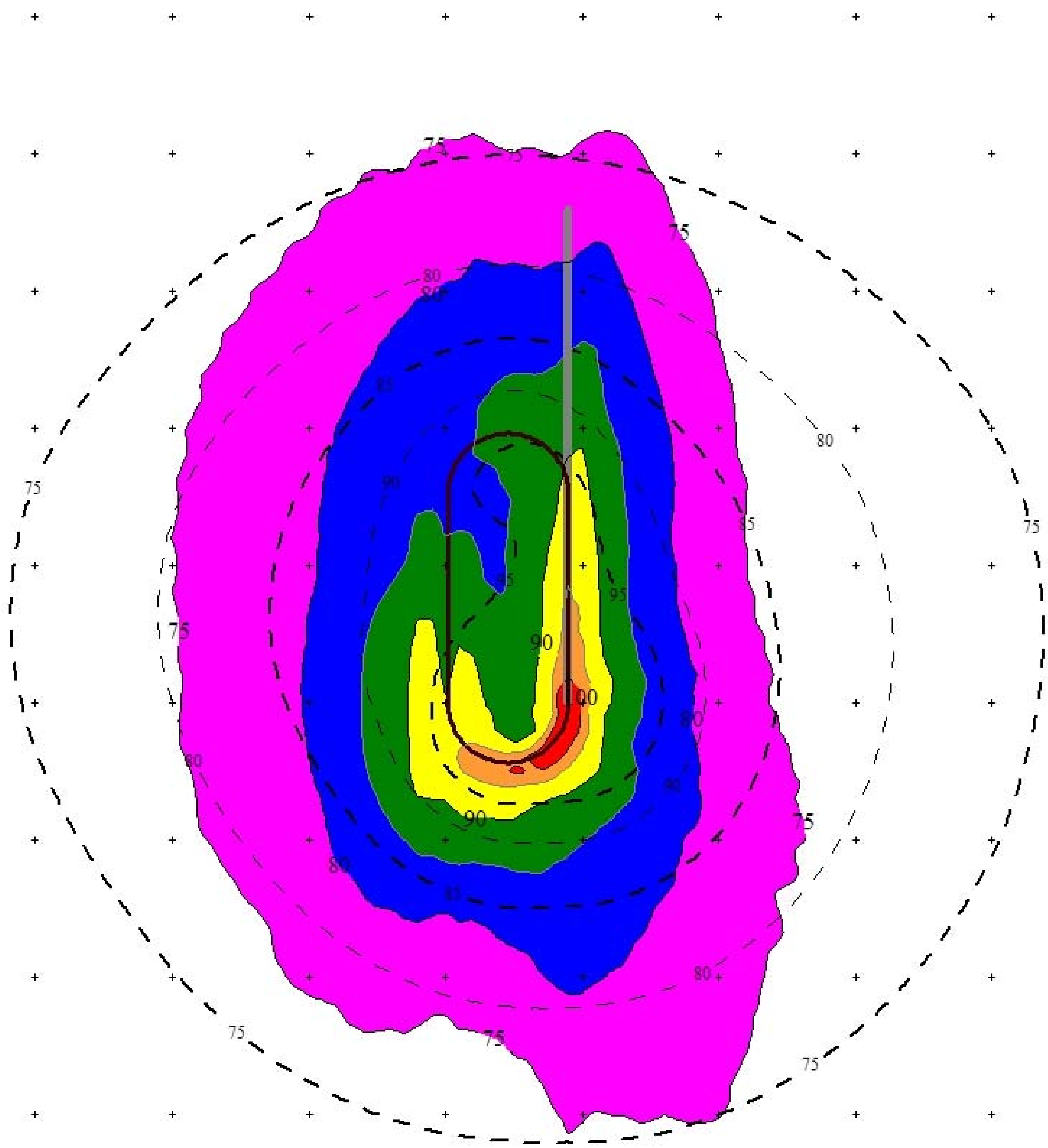

FIGURE 4-22 MV-22 SEL (dBA) for a closed pattern.

AAM: Colored Contours, INM: Dashed Lines; Flight Track: Brown. Tick mark spacing = 2500 Ft.

TABLE 4-13 MV-22 AAM and INM SEL (dBA) predictions – modeled flight operations.

POI Name	POI Location		Arrival			Departure			Closed Pattern		
	X (ft)	Y (ft)	AAM	INM	Diff	AAM	INM	Diff	AAM	INM	Diff
C-1000	0	1,000	88.7	98.8	10.1	105.3	108.2	2.9	97.3	105.3	8.0
C-5000	0	5,000	71.0	77.0	6.0	91.5	98.6	7.1	89.1	92.2	3.1
C-10000	0	10,000	61.8	67.8	6.0	88.4	83.0	-5.4	75.0	74.8	-0.2
C-20000	0	20,000	52.3	57.1	4.8	76.5	77.2	0.7	60.3	61.4	1.1
C-30000	0	30,000	46.1	50.9	4.8	80.8	74.6	-6.2	51.8	54.2	2.4
L-30d	-577	30,000	48.7	51.0	2.3	80.2	74.3	-5.9	52.0	54.2	2.2
L-45d	-1,000	30,000	48.7	51.0	2.3	79.9	73.8	-6.1	52.0	54.2	2.2
L-60d	-1,732	30,000	48.8	51.1	2.3	78.7	72.5	-6.2	51.7	54.2	2.5
R-30d	577	30,000	46.0	51.2	5.2	80.5	74.3	-6.2	51.8	54.3	2.5
R-45d	1,000	30,000	46.0	51.3	5.3	80.6	73.8	-6.8	51.9	54.3	2.4
R-60d	1,732	30,000	45.9	51.5	5.6	79.3	72.5	-6.8	51.9	54.3	2.4

TABLE 14 MV-22 AAM and INM SEL (dBA) point of interest predictions – level overflight operations.

POI Name	POI Location		Level Helocopter Mode			Level Conversion Mode			Level Fixed Wing Mode		
	X (ft)	Y (ft)	AAM	INM	Diff	AAM	INM	Diff	AAM	INM	Diff
C-1000	0	1,000	92.2	101.5	9.3	88.5	96.9	8.4	85.6	83.3	-2.3
C-5000	0	5,000	91.5	93.2	1.7	90.4	92.8	2.4	81.4	80.0	-1.4
C-10000	0	10,000	91.6	93.2	1.6	90.6	92.7	2.1	81.4	80.0	-1.4
C-20000	0	20,000	91.6	93.3	1.7	90.7	92.7	2.0	81.4	80.0	-1.4
C-30000	0	30,000	91.6	93.3	1.7	90.7	92.7	2.0	81.4	80.0	-1.4
L-30d	-577	30,000	89.1	92.6	3.5	90.8	92.0	1.2	80.1	79.1	-1.0
L-45d	-1,000	30,000	87.2	91.6	4.4	88.6	90.9	2.3	78.5	77.8	-0.7
L-60d	-1,732	30,000	84.0	89.1	5.1	85.6	88.9	3.3	74.7	75.3	0.6
R-30d	577	30,000	90.7	93.8	3.1	92.5	92.0	-0.5	80.5	79.1	-1.4
R-45d	1,000	30,000	89.2	93.4	4.2	88.9	90.9	2.0	79.2	77.8	-1.4
R-60d	1,732	30,000	86.4	91.0	4.6	85.0	88.9	3.9	75.9	75.3	-0.6

TABLE 4-15 MV-22 AAM Arrival and Departure Profiles

Departure Profile				
dist	height	airspeed	Roll	Nacelle
0	20	5	0	87
3000	188	71	0	77
5000	300	115	0	70
14000	1000	170	0	0
25000	2000	170	0	0
30000	2000	220	0	0
60000	2000	220	0	0
Arrival Profile				
dist	height	airspeed	Roll	Nacelle
60000	2000	220	0	0
32000	2000	220	0	0
16000	1200	170	0	10
12000	1000	150	0	20
9000	500	80	0	79
4800	300	80	0	80
3000	200	60	0	87
1200	150	50	0	90
0	20	5	0	90

TABLE 4-16 Inventory of MV-22 AAM Noise Spheres

Run Number	Flight Path Angle Deg.	Nacl Tilt Angle Deg.	Speed Knots	Climb Rate ft/min
120	-1	0	174	-307.1
212	0	0	149	0
211	0	0	172	0
122	0	0	185	0
123	0	0	208	0
124	0	0	226	0
210	0	0	270	0
121	1	0	147	260
209	1	0	234	414.4

Run Number	Flight Path Angle Deg.	Nacl Tilt Angle Deg.	Speed Knots	Climb Rate ft/min
119	1	0	270	478
328	-4	60	108	-760.5
133	-3	60	119	-628.4
131	-3	60	121	-641.1
326	-2	60	108	-380.4
324	-2	60	109	-383.6
320	-1	60	107	-190
129	-1	60	119	-210.9
125	0	60	132	0
319	0	60	134	0
130	2	60	112	396.7
325	2	60	120	425.7
323	2	60	124	436.8
132	3	60	111	587.8
327	4	60	122	859
332	-4	75	85	-599.4
334	-4	75	87	-614.2
137	-3	75	101	-533.7
330	-2	75	88	-311.8
135	-2	75	101	-356.1
322	0	75	76	0
128	0	75	83	0

Run Number	**Flight** Path Angle Deg.	**Nacl** Tilt Angle Deg.	**Speed** Knots	**Climb** Rate ft/min
127	0	75	101	0
321	0	75	102	0
136	2	75	92	326.7
329	2	75	103	362.7
138	3	75	95	502.6
331	3	75	99	523.7
140	4	75	96	678.8
333	4	75	101	713.4
403	-7	85	55	-673.8
203	-6	85	63	-661.8
201	-5	85	64	-565.4
336	-4	85	52	-366.2
404	-4	85	69	-488.3
141	-2	85	64	-226.5
335	2	85	67	237.3
142	3	85	60	315.5
402	3	85	71	377.3
202	4	85	58	412.8

4.2.3. Maneuvering Flight

Recommendation: The changes in noise source characteristics from maneuvering flight should be included if: a) one needs to model optimized low-noise rotorcraft profiles which take into account approach drag devices for BVI-avoidance b) Lmax and other maximum non-integrated metric values are to be predicted on a high fidelity spatial mesh in the vicinity of flight maneuvers and c) Time above metrics are to be computed from flights whose maneuver time durations are significant.

Examination of source noise characteristics under maneuvering flight conditions. Researchers in the US [Watts et al., 2012; Sickenberger, 2013; Greenwood, 2011] are investigating maneuvering flight – both steady and unsteady maneuvers – and developing analytical modeling techniques and gathering experimental databases for development of maneuvering flight capabilities for advanced rotorcraft simulation noise models. High fidelity acoustic measurements of helicopter flight tests have been conducted by NASA and other government agencies for the purposes of advanced noise modeling. These activities include gathering source characteristics and investigation of the acoustic impact from rotary wing flight operations, including recent advances modeling helicopter maneuvering flight noise [Watts, 2012]. Maneuvering flight noise modeling capability within AAM is under current development by Wyle under Army/NASA funding and is anticipated to be included in AAM Version 2 in the future. While the current version of AAM (1.4.18) does orient the source noise sphere according to the kinematics of the maneuvering flight operation, it does not change the fundamental noise source emission for such conditions, and so cannot illuminate this issue. Considerations of maneuvering effects are therefore limited to examination of current state of the art predictions and empirical measurements, rather than modeling in a community noise model. In the next few years this capability will be available and this topic can be revisited.

In the absence of a validated maneuvering community flight noise model, one can examine the noise source characteristics both from measurement and from first principles modeling in conjunction. The frequency of occurrence and duration of maneuvering flight encountered during typical community noise applications, affect the modeling requirements.

Data from recent flight tests such as the NASA Bell 430 Eglin test [Watts, 2012] may be used to quantify potential noise impacts of including such maneuvering flight effects in the modeling. Research indicates that maneuvering flight changes the rotorcraft blade and vortex state, which can cause dramatic changes in the noise level and directivity at the source (Figure 4-23) and changes of up to 5 dB (OASPL) to the ground noise time history (Figure 4-24) when compared with not including the maneuvering noise source changes.

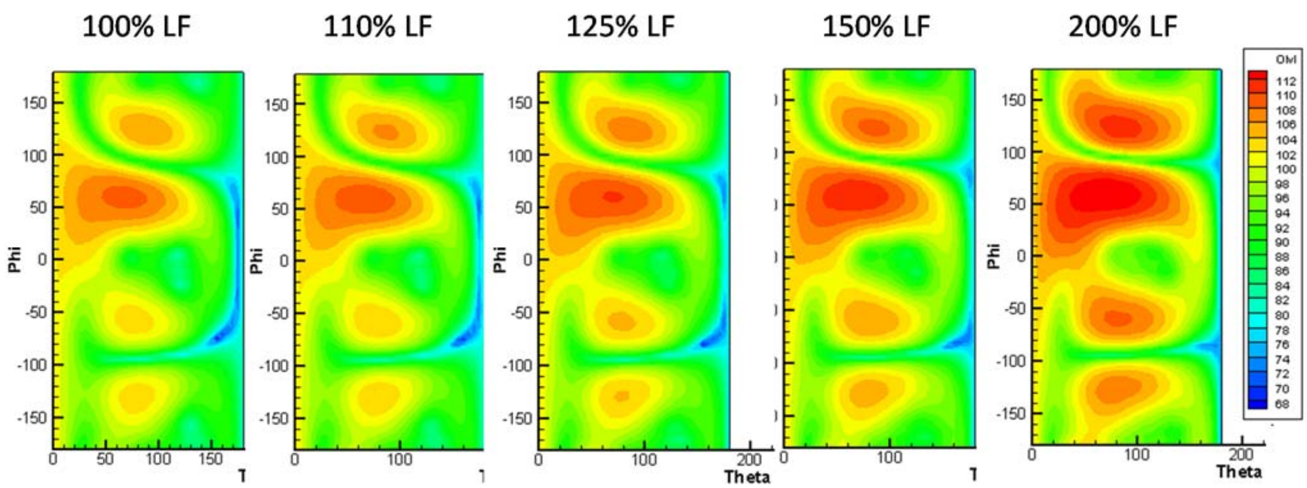

FIGURE 4-23. Variation in noise source charateristics (OASPL) with changing Load Factor (LF).
Analytical Modeling using FRAME, Main Rotor Noise Source Only, Bell 430;
Phi:Starboard-Port, Theta: Fore-Aft.; 100% Load Factor is level flight, Positive Load Factors are Pull-Up Operations. Source: NASA

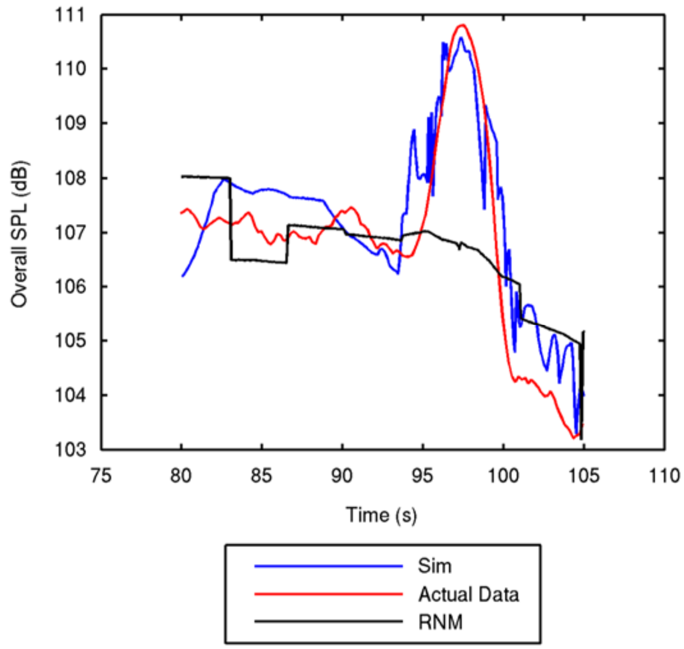

FIGURE 4-24 Maneuvering Flight Time History Comparison: Legacy RNM/AAM, FRAME and Measurement
Bell 430 Pitch-Up during NASA 2011 flight test [Watts, 2012]. Source: NASA.

The equivalency between flight path angle and deceleration has been identified and such quasi-static acoustic mapping (QSAM) capability has already been incorporated in AAM/RNM [Gopalan, 2004] for advanced noise sphere datasets containing additional helicopter performance parameters. A performance modeling capability within HELENA also has capability to compute the noise impacts from such operational considerations.

4.3. Propagation Modeling

The components to be considered in rotorcraft propagation models include the following elements:

- Terrain, including to a limited degree, acoustic shielding in urban situations;
- Ground surface (hard to soft);
- Air absorption (as a function of temperature and relative humidity);
- Wind; and
- Temperature gradients.

4.3.1. Higher Fidelity Atmospheric and Terrain Modeling

AEDT Improvement Recommendation: The method proposed by Plotkin et al., [2013] for inclusion of higher fidelity atmospheric and terrain modeling in AEDT/INM is recommended.

A recent study [Plotkin et al., 2013] examined detailed weather and terrain analysis for aircraft noise modeling. Although that study examined commercial fixed wing operations the conclusions also apply to rotorcraft and tiltrotor community noise modeling within AEDT/INM. The feasibility of incorporating detailed weather propagation modeling (which are inherently point-to-point), within FAA's integrated noise modeling tools, (which compute noise from entire flight segments), was examined and recommendations were developed for inclusion of detailed weather effects in AEDT/INM.

The report noted that while short segment modeling is always feasible, it can result in computational times as long as (sometimes longer than) a full simulation model. The study recommendation is to apply a small number of propagation points within segments of practical length, using a dB weighted average method, using three points (CPA and segment ends) for segments up to 2000 feet, representing an order of magnitude reduction in computational effort compared with the simulation model. The feasibility of this simplification relies on a laterally homogeneous atmosphere, i.e., horizontally stratified over a flat ground surface. This horizontal homogeneity permits a one-time pre-computation of propagation as a function of source elevation and the distance and bearing to the receiver. Propagation through a 3-D atmosphere would not allow this simplification, and also raises the issue that propagation to different points is not smoothly varying functions of bearing. Similarly, this kind of simplification is not generally amenable to propagation over irregular terrain. Segmentation for propagation over terrain must be on a scale comparable to (or finer than) the lateral scale of the terrain.

4.3.2. Urban Terrain Modeling

<u>AEDT Improvement Recommendation</u>: Inclusion of shielding effects due to Buildings and Urban Terrain Features are recommended for inclusion in rotorcraft community noise models.

Under ACRP 02-11 [Page et al., 2009] impacts of a range of scenarios were determined in order to gauge the importance of such a modeling capability from the community noise perspective. Several of those studies are applicable to helicopter and tiltrotor operations, even though they considered fixed-wing noise sources. The effects of echoes, reflections and reverberation were not examined due to the lack of a current noise model. Findings from Page, et al. [2009] are summarized below.

Airports and the surrounding communities are often urban in nature and frequently contain high-rise buildings in addition to terminals, hangers and other forms of acoustic shielding on or adjacent to airport property. Such scenarios include heliports in urban environments and operations where helicopters fly along the coastline bluffs at low altitudes and residential homes are exposed to noise from the rotor plane. The geometric proximity of these features, specifically if they block the line of sight between a flight vehicle and a receptor, can have a significant impact on the noise contours. Due to the wide variety of site specific conditions it is not be possible to draw a firm conclusion to always or never include building shielding or ground cover in community noise analysis.

An acoustic simulation study was performed for a series of annual commercial flight operations at an international airport while taking into account the effect of building shielding on sound propagation. While this study modeled only commercial fixed wing flight operations, they did include the on-runway portion of the operations. The geometric arrangement of the airport is such that the predominant impact to the contours on either side of the runways is from aircraft directly on the runway or at an altitude below the height of the nearby buildings. The noise modeling shown here utilizes a simple Maekawa shielding (line of sight blockage) model and with buildings modeled as a series of thin screens, as is supported by this theory. Figures 4-25 and 4-26 contrast the CNEL noise contours from only the top 10 contributors for analyses with and without building effects included. A time sequence of still images from a single arriving flight is shown in Figure 4-27. Even though this analysis was conducted for jet aircraft, the propagation and shielding effects are directly applicable to rotorcraft and tiltrotor operations in the proximity of urban terrain with high rises commonly found near heliports.

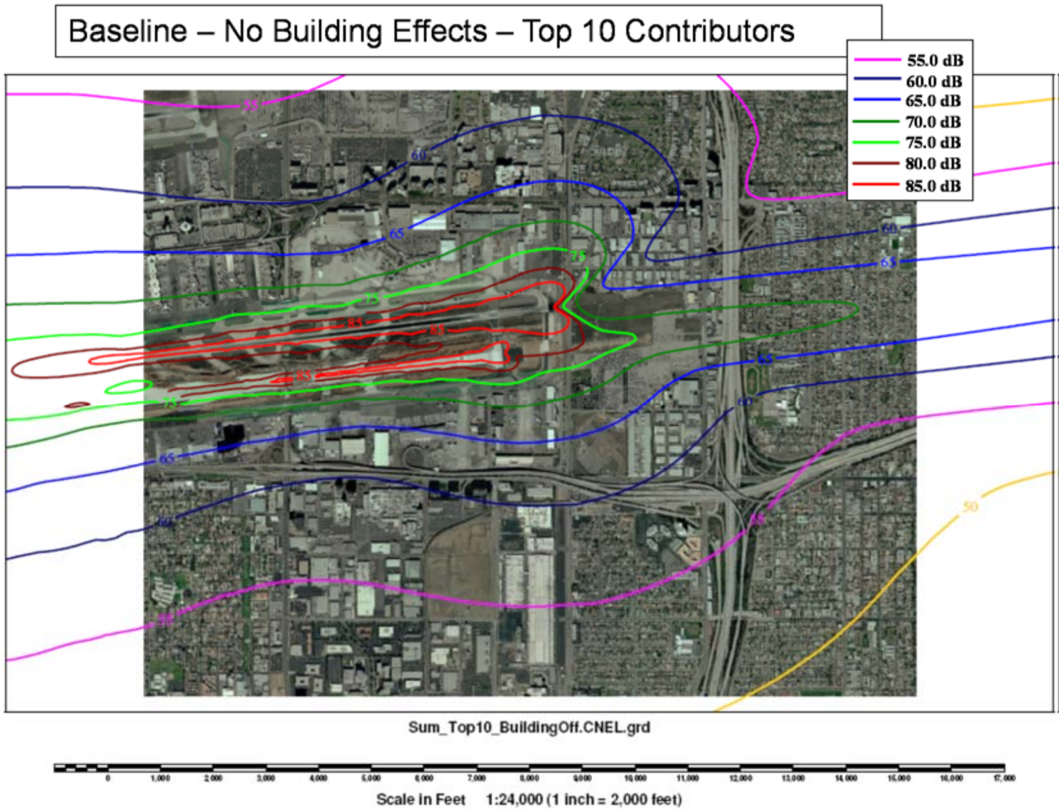

FIGURE 4-25 Flight operations with no building shielding; top 10 contributors.

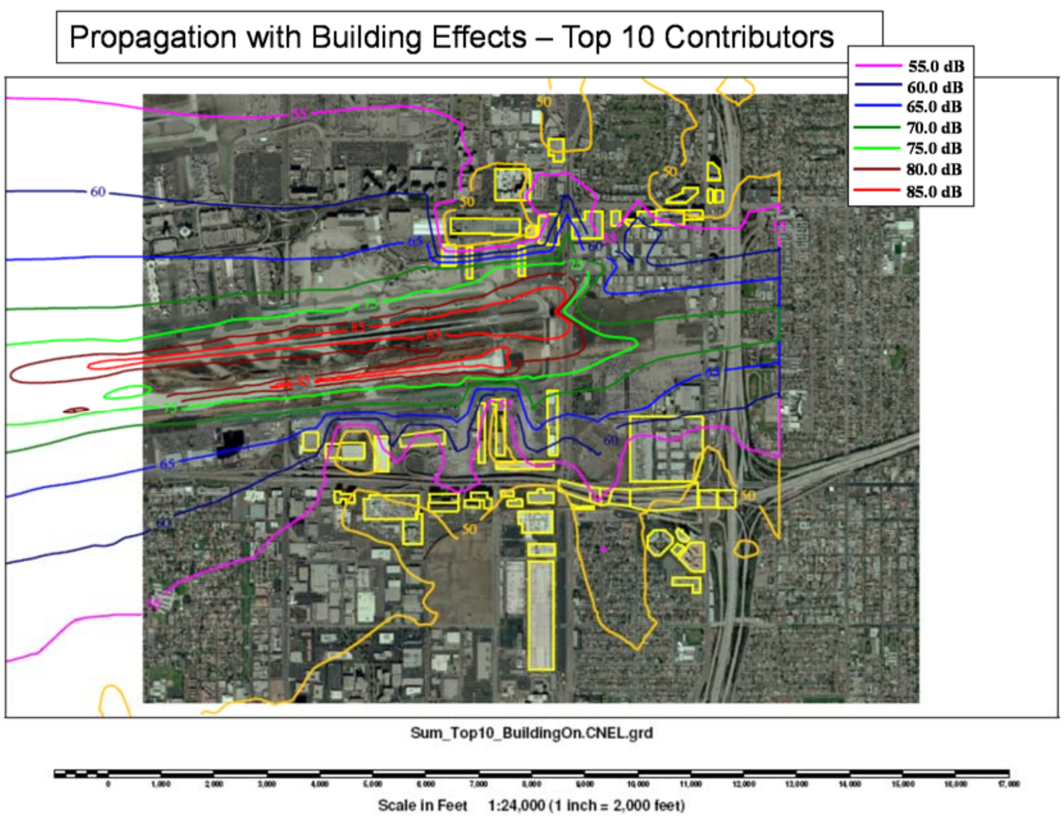

FIGURE 4-26 Flight operations, with building shielding; top 10 contributors.

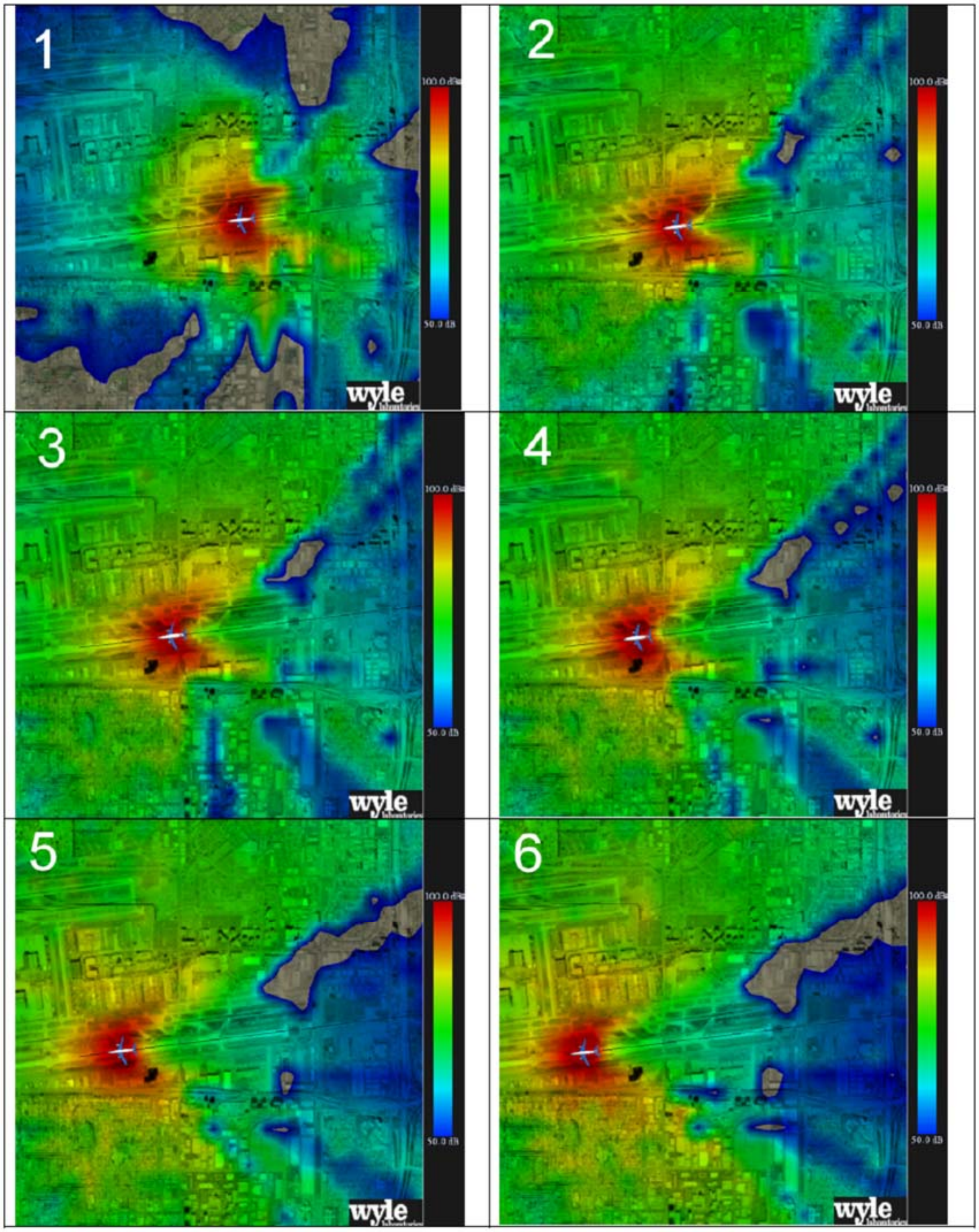

FIGURE 4-27 Series of acoustic simulation SEL (dBA) contours with building shielding.
(Single approach operation at different times)

4.3.3. Propagation Over Varying Ground Surface Types

AEDT Improvement Recommendation: The ability to compute the effects of propagation over varying ground surface types including water is recommended.

Ground cover also impacts sound propagation. Water is considered an acoustically hard surface and sound traveling over bodies of water does not attenuate as rapidly as sound traveling over grassy or forested terrain. A concurrent study ACRP 02-52 "Improving AEDT Noise Modeling of Hard, Soft, and Mixed Ground Surfaces" is currently underway at Wyle. This study is taking an in-depth look at surface characteristics impacts on modeling within integrated models. However there is some modeling information readily available for over water propagation.

Under a prior study, ACRP 02-11 [Page et al., 2009], propagation over water was examined. Salient conclusions are repeated here. A measurement project was conducted in 2004 for the US Navy [Downing et al., 2004] in order to assess the effects of aircraft sound propagation over water. Measurements of 349 commercial aircraft departure operations at Ronald Reagan Washington National Airport & Bolling Air Force Base were obtained for elevation angles from 4^{o} – 6^{o}. Here the lateral source characteristics for aircraft with wing and tail mounted engines were adjusted from the original study based on the INM lateral directivity difference. Figure 4-28 shows the geometric layout of the runway, flight track, Potomac River and microphone positions. The primary objective of the study was to experimentally determine suitable ground impedance parameters for representing the surface of the water as an acoustically hard surface using the DoD Integrated model; NOISEMAP 7.

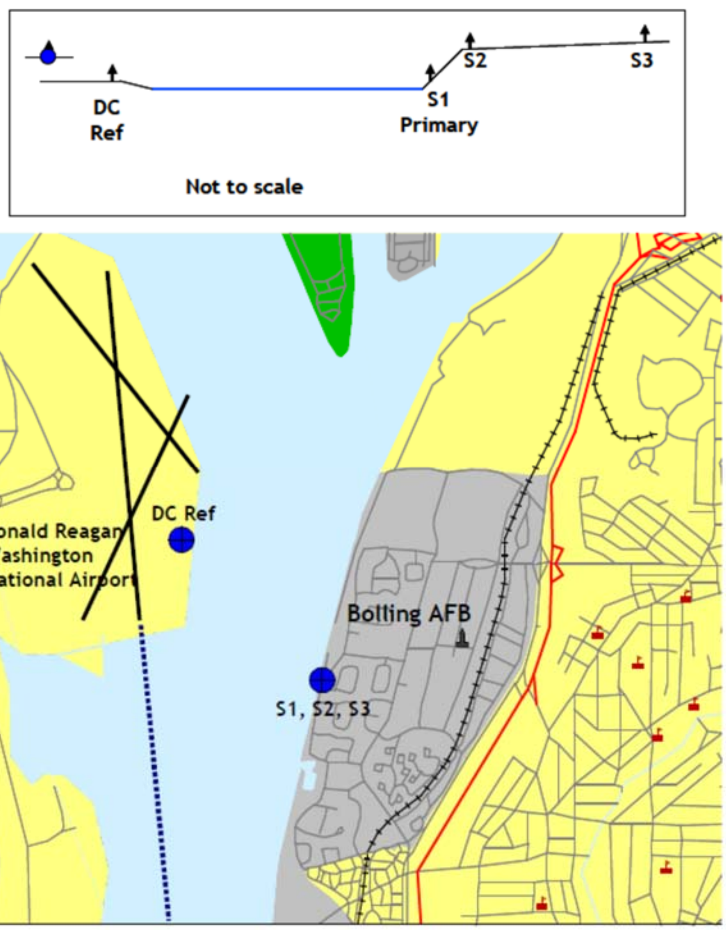

FIGURE 4-28 Overwater propagation measurement configuration.

It is the predicted changes between propagation over ground and water which illustrate a nominal 2 dB effect of ground impedance on sound propagation for sources at low elevation angles (Table 4-19). Aircraft with fuselage mounted engines are 1.5 dB quieter in the plane of the wing than aircraft with wing mounted engines. One can see in Table 4-17 that the over water propagation accounts for approximately a 2 dB increase in SEL compared with propagation over acoustically soft ground for the geometric arrangement at DCA and for this particular group of operations.

TABLE 4-17 Predicted differences in SEL over Ground and Water for All Flight Operations

Predictions modified based on INM source lateral directivity for Wing/Fuselage Engines

Measured SEL – Calculated Over Water SEL ***(Predictions exactly match Reference SEL)***			**Over Water Pred. SEL – Over Ground Pred.** **SEL (dB)** **(Consistent Set of Operations with different ground characteristics)**		
Site S1	**Site S2**	**Site S3**	**Site S1**	**Site S2**	**Site S3**
-0.8 ± 0.3 dB	-1.2 ± 0.3 dB	-2.15 ± 0.3 dB	-2.2 ± 0.3 dB	-2.0 ± 0.3 dB	-1.5 ± 0.3 dB

4.4. Community Noise Metrics

Acoustic metrics were described in Section 2. A combination of both standard community noise and supplemental metrics recommended for inclusion are itemized in Table 4-18. With the exception of Number of Events Above a Specified Level (NA)[7], these are already included in the INM/AEDT modeling framework. In Section 4.1 the spectral source noise modeling frequency range was discussed as it relates to these noise metrics.

TABLE 4-18 Community Noise Metrics and Functional Definitions

Baseline Metric	**Supplemental Metric**
Maximum Sound Level (L_{max})	D-Prime Audibility (DPRIME)
Sound Exposure Level (SEL)	Number-of-events Above (NA)
Day-Night Average Sound Level (DNL or L_{dn})	Time Above a Specified Level (TA_L)
Community Noise Equivalent Level (CNEL)	
Perceived Noise Level (PNL)	
Tone-Corrected Perceived Noise Level (PNLT)	
Effective Perceived Noise Level (EPNL)	
Weighted Equivalent Continuous Perceived Noise Level (WECPNL)	
Maximum C-weighted Sound Level (L_{maxC})	
C-weighted Sound Exposure Level (CSEL)	

[7] NA may be computed externally from AEDT/INM.

CHAPTER 5. Outreach and Feedback

An outreach task was conducted in order to solicit feedback from the international rotorcraft noise modeling community on the recommended technical modeling approach details and changes for AEDT/INM outlined in this document. Outreach consisted of an online Webinar facilitated by the National Academies of Science, presentations at several technical meetings at helicopter symposia and noise and emissions and transportation related committee meetings and events (Table 5-1) and via an international email distribution.

Emails from the Principal Investigator were sent to more than 150 individuals in the United States, Europe, Japan and Korea at rotorcraft and tiltrotor manufacturers, to researchers involved in helicopter noise modeling, to airport and heliport operators in the US, to academic helicopter noise researchers, to the US Department of Defense representatives including the Army, Navy and Air Force, to the UK Ministry of Defense and to various agencies involved with helicopter operations, research, regulation and oversight including the Federal Aviation Administration, the Department of Transportation, US National Park Service and NASA. All were provided an electronic copy of the white paper and a request to provide feedback to the ACRP project team by 28 May 2015.

Additionally, the white paper was distributed to members and affiliates of the following helicopter, aviation noise and environmental committees via various channels of communication with a request to provide written feedback to the ACRP project team by 28 May 2015:

- American Helicopter Society Acoustics Technical Committee.
- Helicopter Association International, Fly Neighborly Committee.
- International Civil Aviation Organization (ICAO) and the European Civil Aviation Conference (ECAC) AIRMOD Group.
- National Academies of Science (NAS) Transportation Research Board (TRB) Standing Committee on Environmental Impacts of Aviation (AV030).
- NAS TRB Standing Committee on Transportation-Related Noise and Vibration (ADC40).
- Society of Automotive Engineering A-21 Measurement and Aircraft Noise/Aviation Emission Modeling Committee.

TABLE 5-1 ACRP 02-44 Helicopter Noise Modeling Outreach Events

Event	Date(s)
30th Annual University of California (UC) Symposium on Aviation Noise and Air Quality, California	1-4 March 2015
Outreach Briefing at DOT, Volpe Center, Massachusetts	19 March 2015
Email Outreach	21-23 April 2015
Online Webinar	28 April 2015
American Helicopter Society Annual Forum, Special Session: Rotorcraft Community Noise, Virginia	4 May 2015
SAE A-21 Aircraft Noise Measurement and Aircraft Noise/Aviation Emission Modeling Committee Meeting, Cologne Germany	4 May 2015
TRB ADC040 Committee Meeting, Washington D.C.	4 May 2015
American Helicopter Society Annual Forum, AHS Acoustics Technical Committee Meeting, Virginia	6 May 2015

5.1. Feedback Summary

The specific events where briefings and outreach activities were conducted are itemized in Table 5-1. After review of the recommendations, key questions posed during the outreach events were: “Do you agree with our recommendations?” and “Did we miss anything that should be included?” and “Do you have any other concerns?" Historically there have been concerns raised over lack of fidelity in AEDT/INM and we wanted to make sure our recommendations have addressed those items since the next step after this ACRP funded project concludes is entry of a supplemental modeling document into the International Standards Review process.

During multiple outreach events we were clearly reminded that the specific recommendations have "reach back" implications in terms of data input requirements to the FAA in terms of manufacturer measurement and/or modeling costs. Additionally, it was clarified in response to questions that these recommendations were for modeling purposes only and were not intended to and do not include any recommendations for changes to the existing helicopter FAR-36 Noise Certification process.

Table 5-2 contains a summary of the feedback received at each of the outreach events. The recurring themes include the following:

- At virtually every event the attendees supported the need for this research and these recommendations. There wasn't a single negative comment received regarding the utility and intent of this project, however attendees expressed skepticism over the likelihood of future funding to develop the required database and AEDT software modifications to implement these recommendations.
- The necessity for a supporting database and the possible difficulty and cost for obtaining one was raised multiple times. Modelers expressed concern about the ability of a future project team to acquire such data and the manufacturers were clearly nervous about the potential cost implications if such data were required to be measured using FAR-36 procedures. Although not explicitly included in the white paper recommendations, discussions about creation of a hybrid analytical-empirical database ensued and many side-bar conversations were held by the PI with various helicopter manufacturer, academia and NASA rotorcraft noise SMEs regarding possible techniques for database development including leveraging existing NASA and Army first-principals models, existing acoustic databases, available flight performance information (e.g. from helicopter flight manuals) and simplified BVI noise concepts (i.e. utilizing BVI fried-egg plots).[1]
- No additional metrics were suggested for inclusion in AEDT at this time.
- The inclusion of low-frequency noise down to 10Hz was deemed important however a question was raised whether this could be accomplished for the Military helicopters in the database given possible DoD data classification/security guidelines. The project team agrees that this concern will need to be addressed during future database development.
- Feedback supported the need for improved lateral directivity in the model. There was discussion regarding the anticipated specific wording of future noise modeling standard and associated AEDT database input forms regarding lateral directivity. The ACRP Project team recommendation is that the specific determination of number and location of lateral positions (as a function of flight condition) be left to the vehicle manufacturer with language defining minimum lateral noise sensitivity (in much the same way as FAR-36 lateral fixed wing measurements are defined). This yielded comments that the specific language included in a future noise standard regarding the database lineage and acceptable development process will be met with heightened scrutiny to ensure a) that onerous burden for obtaining such data isn't placed on the manufacturer and b) there are sufficient requirements to ensure lateral directivity is indeed captured in the model database (and the system can't be "gamed").
- The flight path angle modeling sensitivity was met with overwhelming support. Feedback recognized the lack of ability in AEDT to capture low-noise approach profiles – a critical mode from the community noise modeling perspective. This topic again led to discussion about the associated database for AEDT.

[1] The Fried Egg plot describes the conditions (rate of climb and forward flight speed) for which BVI noise/strength occurs (Figure 7).

- In the context of tiltrotor noise modeling, the subject of relative loading balance between the rotors and the wing lift was first raised during the webinar by NASA Ames /Academia. During the AHS Forum events this point was reiterated by SMEs at NASA Langley, Agusta-Westland and Boeing Vertol (Mesa). Research dating back to the XV-15 development has shown that the noise source emission in transition mode is strongly affected by how much lift the rotors are carrying versus the wing [Edwards et al., 2001; Gervais & Schmitz, 2002; Gervais 2004].

TABLE 5-2 ACRP 02-44 Helicopter Noise Modeling Outreach Event Feedback

Event	Notes
30th Annual University of California (UC) Symposium on Aviation Noise and Air Quality California	Poster Session; Handout White Papers / Briefing Materials. Stakeholders: Airport noise managers, Airport noise roundtable/community group representatives, noise consultants, FAA/DOT, Transport Canada. Feedback: General agreement in the need for improvement and interest in the recommendations. No specific actions suggested.
Outreach Briefing at DOT, Volpe Center Massachusetts	Two hour briefing; white paper distribution. Stakeholders: Volpe Measurement and Modeling Division staff and AEDT developers. Feedback: Potential AEDT changes were discussed at length and no programmatic show-stoppers were identified. Discussion covered future rotorcraft and tiltrotor database needs, specific modeling parameters, future development process and structure compatible with recommendations. Suggestion to leverage AEDT Helicopter Performance Modeling improvements for Emissions (in process) for maneuvering flight (FAA/AEE funds, PI: D.Senzig).
Online Webinar	One hour Online Webinar; email white paper distribution. 45 mins briefing; 15 mins Q&A Stakeholders: 70 webinar connections, many with multiple people together (estimated 80 or 90 attendees) including Industry, Academia, Government Agencies. Feedback both during the webinar and via email follow-up was positive with many saying this project & recommendations to AEDT/INM helicopter modeling is long overdue. Several attendees expressed concerns regarding the necessary database to realize the improved modeling recommendations and the associated manufacturer burden for providing data. Agreement that both BVI and airspeed effects including maneuvering flight modeling (accel/decel) is needed. Tiltrotor transition noise is a strong function of rotor vs. wing loading and should be modeled. Strong concurrence that data measured outside FAR-36 environmental specifications should be accepted as manufacturer input data for AEDT.
American Helicopter Society Annual Forum Special Session: “Rotorcraft Community Noise” Virginia	Briefing ~15 minutes, white paper distributed upon request. Stakeholders: 25 attendees industry, academia & government Feedback: General agreement that the model must include flight path angle noise sensitivity. Support for inclusion of acceleration/deceleration effects in noise model. Need tiltrotor wing/rotor loading balance in transition modeling.
SAE A-21 Aircraft Noise Measurement and Aircraft Noise/Aviation Emission	Briefing ~30 minutes, White paper distributed via email Stakeholders: A-21 members, primarily fixed wing aircraft, no helicopter manufacturers in attendance

Event	Notes
Modeling Committee Meeting Cologne Germany	EASA just launched a contract to develop a European Helicopter Noise model over the next 2 years. Hope that the ACRP supplemental guidance document could inform international guidance documents, as well as AEDT development. Attendees to bring feedback request home to their organizations.
TRB ADC040 Committee Meeting Washington D.C.	Briefing ~ 15 minutes, white paper distribution. Attendees: non-noise NEPA assessments, air quality and water quality aviation matters. Attendees to bring feedback request home to their orgs.
American Helicopter Society Annual Forum AHS Acoustics Technical Committee Meeting Virginia	Briefing ~30 minutes, white paper distributed via email. Stakeholders: Leading Subject Matter Experts in Rotorcraft Aeroacoustics. Glad to see ACRP addressing AEDT helicopter limitations, engaging manufacturers and helicopter SMEs on noise. Strong agreement that approach noise is a critical condition to capture/model properly. Using the "Fried egg plot" +/- n dB is likely a reasonable way to capture BVI / non-BVI noise (method to include both FPA and V in AEDT database). Note from manufacturers: plots haven't been mapped for all aircraft. Recurring question: how will one develop the noise database for AEDT? Recommendation for hybrid analytical-empirical database development received "General agreement in principle" from Boeing, UMD, NASA, Sikorsky & Airbus.

5.2. Changes in Recommendations due to Feedback

The only change from the recommendations outlined in the White Paper is in the tiltrotor recommendation, via the addition of a sentence to consider tiltrotor wing loading vs. rotor loading in the transition mode. This change is based on specific feedback from rotorcraft noise experts in academia, two NASA centers and two rotorcraft manufacturers (one written, one verbal) and is being made despite a conflicting recommendation from the FAA.

The revised recommendation is worded in such a way as to permit a simpler model if during the database development phase that proves reasonable because not all combinations of wing/rotor loading are used in commercial operations and because the transition noise region is small enough or close enough to a vertiport facility or the operational mode truly creates minimal community noise.

The SME experts' opinions coupled with Agusta-Westland's (Manufacturer of the AW 609 civil tiltrotor) indicated willingness to work with AEDT developers necessitated inclusion of what we hope is a pragmatic revision. The new recommendation is as follows:

It is necessary to incorporate the effect of tiltrotor transition between Airplane and Helicopter Modes in the noise model. Flexible profile modeling is needed to capture all possible operational procedures. Consideration should be given to the inclusion of source fidelity to capture the relative wing/rotor loading during transition mode. Changes must be made to the AEDT/INM model including the capability to handle tiltrotor movements and transition noise source emission (NPD and Spectral Class).

CHAPTER 6. Recommendations and Next Steps

This research has revealed that the primary weakness within current AEDT/INM capabilities for rotorcraft and tiltrotor noise modeling is related to source noise modeling: spectral content, lateral directivity and operational sensitivity. The following seven recommendations, listed from highest to lowest priority have been compiled and adapted based on feedback garnered from the international rotorcraft noise modeling community as a result of an outreach task described earlier in this report.

1. The model should be capable of computing the following metrics: Maximum Sound Level (L_{max}), Sound Exposure Level (SEL), Day-Night Average Sound Level (DNL or Ldn), Community Noise Equivalent Level (CNEL), Perceived Noise Level (PNL), Tone-Corrected Perceived Noise Level (PNLT), Effective Perceived Noise Level (EPNL), Weighted Equivalent Continuous Perceived Noise Level (WECPNL), Maximum C-weighted Sound Level (L_{maxC}), C-weighted Sound Exposure Level (CSEL), d-Prime Audibility (DPRIME), Number-of-events Above (NA) and Time Above a Specified Level (TAL).

2. It is necessary to model the lateral source characteristics with sufficient a) angular fidelity to capture directional Blade Vortex Interaction (BVI) noise and b) lateral extent to account for changes in vehicle roll angle. Under vehicle-specific approach flight conditions the rotor-wake interaction can cause significant increases in noise source emission over highly directive regions. Modeling of rotorcraft in regions with urban and natural terrain and inclusion of bank angle in the noise analysis can require vehicle source characteristics to be defined well outside the current 45^o extent defined in AEDT/INM.

3. Spectral content should include one-third octave bands down to 10 Hz. The low-frequency trade study demonstrated a strong sensitivity to inclusion of low-frequency effects below 50 Hz for helicopters over the range of distances (0-25,000 ft.) included in the AEDT/INM NPD database for C-weighted metrics and for the supplemental metric d-Prime. We found that variations due to incorporation of the low-frequency content exceed the established criteria for AEDT/INM spectral class selection for C-weighted metrics; therefore the rotorcraft should be modeled down to 10 Hz.

4. It is necessary to include the effects of approach flight path angle on source noise characteristics. Significant changes to the source noise emissions can occur when flight path angle (FPA) is adjusted. During BVI the blade and wake are in close proximity to one another. Changes of FPA by a few degrees can enter BVI condition and cause large changes in noise, exceeding 10 dBA and must be considered.

5. The changes in noise source characteristics from maneuvering flight should be included if: a) one needs to model or optimize low-noise rotorcraft profiles or take into account approach drag devices for BVI-avoidance, or b) Lmax and other maximum non-integrated metric values are to be predicted on a high fidelity spatial mesh in the vicinity of flight maneuvers, or c) Time above metrics are to be computed from flights whose maneuver time durations are significant. Maneuvering flight is an active area of research, and helicopter performance modeling capabilities are currently under development for AEDT and other noise models. Funded Advanced Acoustic Model (AAM) [Page, et al., 2010] maneuvering flight implementation project also suggests that simplified source equivalences based on gross kinematic parameters will be available in the near future.

6. It is necessary to incorporate the effect of tiltrotor transition between Airplane and Helicopter Modes in the noise model. Flexible profile modeling is needed to capture all possible operational procedures. Consideration should be given to the inclusion of source fidelity to capture the relative wing/rotor loading during transition mode. Changes must be made to the AEDT/INM model including the capability to handle tiltrotor movements and transition noise source emission (NPD and Spectral Class).

7. The method proposed by Plotkin et al., [2013] for inclusion of higher fidelity atmospheric and terrain modeling in INM/AEDT is recommended. It was found that the propagation algorithms in INM and AEDT are sufficient and only specific airport considerations will necessitate the inclusion of terrain, shielding and /or variable ground impedance. Therefore no recommendation to always or never include such effects can be made, however the AEDT/INM model should be capable of higher fidelity modeling.

This ACRP Project team suggests that these recommendations be implemented in the near term in order to address the growing need for accurate rotorcraft community noise modeling. We have identified the following steps towards achieving an improved helicopter and tiltrotor modeling capability in AEDT:

1. Develop a methodology for development of a comprehensive AEDT helicopter and tiltrotor database. Examine existing rotorcraft noise databases and research and develop specific processes for creation of an AEDT noise database which includes the expanded data itemized in the project recommendations (spectra, NPD mode data and directivity information) for existing and retired vehicles. The methodology should be flexible and applicable to a variety of cases for which limited and extensive acoustic empirical data are available. The process should be tested using select rotorcraft and validated with measurement data. Develop specific AEDT input data requirements (empirical and analytical). The process should be peer reviewed and reflect stakeholder input.
2. Exercise the process for an expanded AEDT helicopter and tiltrotor fleet. Document and provide tools that can be used in the future to create additional database parameters for new and derivative rotorcraft.
3. Perform the necessary AEDT software modeling updates which implement the modeling recommendations and take advantage of the expanded database. AEDT code updates should be conducted after development of the methodology but in concert with creation of the full helicopter and tiltrotor noise database.

The ideal project team should be comprised of acoustic noise measurement and modeling experts, researchers with tool and data access and ability to conduct higher fidelity first principles noise modeling, rotorcraft and tiltrotor manufacturers and members of the AEDT development team.

CHAPTER 7. Acronyms and Abbreviations

AAM	Advanced Acoustic Model
AEDT	Aviation Environmental Design Tool
BVI	Blade Vortex Interaction (BVI)
BVISPL	Blade Vortex Interaction Sound Pressure Level
CAEP	Committee on Aviation Environmental Protection
CFD	Computational Fluid Dynamics
CNEL	Community Noise Equivalent Level
CSEL	C-weighted Sound Exposure Level
DNL	Day-Night Average Sound Level
DOD	U.S. Department of Defense
DPRIME	d-Prime Audibility
EPNL	Effective Perceived Noise Level
FPA	Flight Path Angle
FRAME	Fundamental Rotorcraft Acoustic Modeling from Experiments
HELENA	HELicopter Environmental Noise Analysis
HIGE	Hover In Ground Effect
HOGE	Hover Out of Ground Effect
INM	Integrated Noise Model
ICAO	International Civil Aviation Organization
Lmax	Maximum Sound Level
LmaxC	Maximum C-weighted Sound Level
Ldn	Day-Night Average Sound Level
NA	Number-of-events Above
NEPA	National Environmental Policy Act
NPD	Noise-Power-Distance database
OASPL	Overall Sound Pressure Level
PNL	Perceived Noise Level
PNLT	Tone-Corrected Perceived Noise Level
POI	Point of Interest
SAE A-21	Aircraft Noise Measure Noise Aviation Emission Modeling
SEL	Sound Exposure Level
SME	Subject Matter Expert
TAL	Time Above a Specified Level
WECPNL	Weighted Equivalent Continuous Perceived Noise Level

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CHAPTER 9. Appendices

APPENDIX A: Propagation and Distance Duration Factor

APPENDIX B: Baseline AAM-INM Propagation Comparison

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APPENDIX A: Propagation and Distance Duration Factor

In order to create an aircraft for use with the INM program, noise power distance (NPD) curves must be tabulated for each condition of the aircraft to be modeled. The Simplified Adjustment Procedure (LCorrect) method is described in Appendix B of SAE 1845 [SAE, 1986]. Using a spectral time history representing the noise emissions from an aircraft operating at a steady state condition at a reference distance from the vehicle, the noise metrics at other distances can be found. The noise exposure metric at the reference distance is adjusted to other distances by accounting for atmospheric absorption and spherical spreading and duration.

The duration adjustment is defined by equation B7 of SAE 1845 and is repeated here:

$$L_{AEr} = L_{AET} + (L_{Amx}r - L_{AmxT}) + 7.5 \log10(d_{rm}/d_{Tm}) \qquad \text{(Equation A1)}$$

where

L_{AEr} is the exposure metric (A-weighted SEL in this case) at the desired distance.

L_{LAET} is the exposure metric corrected for speed at the reference distance.

L_{Amxr} and L_{AmxT} are the maximum (A-weighted) levels at the desired and reference distances, respectively.

d_{rm} and d_{Tm} are the desired and reference distances, respectively.

The 7.5 factor in the distance adjustment is based on empirical data[1].

In order to demonstrate that the propagation algorithms in AAM are consistent with the Simplified Adjustment Procedure – necessary for confident creation of INM NPD data using AAM - a set of level flights were modeled using the MD-902. Level flights were simulated in AAM using reference speed and meteorological conditions for vehicle altitudes corresponding to the standard NPD distances above a centerline receiver located 4 ft. AGL. The AAM L_{max} predictions from the 500 ft. AGL simulation were then converted to SEL values at the other distances using Equation A1. The methods agree within 0.1 dBA for propagation distances up to 10,000 ft. and within 1.2 dBA for propagation distances up to 25,000 ft (Table A1). It is likely that differences at the longer propagation distances could be due to errors in the 7.5 duration factor in Equation A1.

TABLE A1 Metric Comparison of AAM Simulation with Analytical Distance Duration Factor
MD 902 level overflight, undertrack receiver at 4 ft. AGL

AAM Simulated Values			**Distance Duration Calculated from 500'**
Altitude (ft agl)	Lmax (dBA)	SEL (dBA)	SEL (dBA)
200	82.3	86.4	86.6
400	76.1	82.6	82.7
500	73.9	81.2	n/a
630	71.7	79.7	79.8
1000	67.2	76.7	76.8
2000	59.9	71.7	71.7
4000	51.7	65.7	65.8
6300	45.7	61.2	61.3
10000	39.0	56.2	56.1
16000	31.4	50.5	50.0
25000	23.6	44.8	43.6

[1] The factor depends on spectrum and absorption. NMAP utilizes an empirical factor of 6 [Czech and Plotkin, 1998].

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APPENDIX B: Baseline AAM-INM Propagation Comparison

Throughout this report comparisons are made between INM, AAM and HELENA outputs. Because these are fundamentally different models (INM - integrated, AAM and HELENA - simulation) and because the core propagation algorithms and source modeling fidelity varies, a comparison using an omni-directional source was made. An omni-directional noise sphere containing only the spectrum from INM Spectral Class 302 (the level flight spectral class used to model the MD-902 in INM) was created and formatted accordingly for use by AAM and HELENA. Spectral time histories were generated in AAM for use in creating a source in the INM database as described in Section 3.4. Level trajectories were modeled in both programs using a 120 knot speed at 492 ft., 1000 ft., and 5000 ft. altitudes above soft, flat terrain. In order to better identify the differences in the propagation models as a function of lateral distances up to 40,000 ft. at a set of points of interests (POIs) were used to generate SEL values for level flight trajectories this trajectory (Figure B1). The differences seen in the SEL versus lateral distance in Figure B1 are due solely to propagation modeling differences between INM, AAM and HELENA and do not include the effects of source characteristics (level, spectra or directivity).

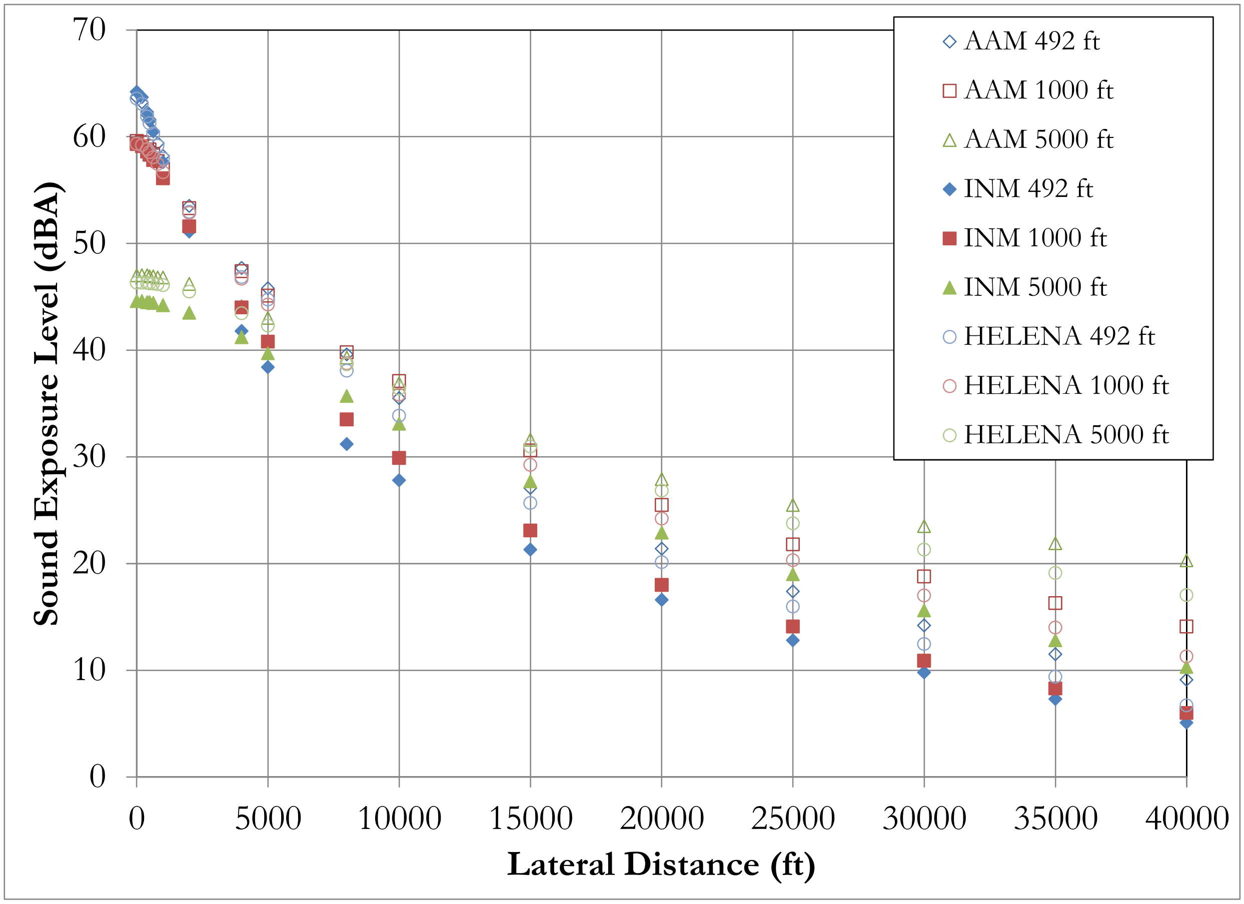

FIGURE B1 INM, AAM and HELENA SEL versus lateral distance.
Level Flights at 492 ft., 1000 ft. and 5000 ft. AGL
Omni-directional source with a spectrum equal to INM's #302 spectral class

To better isolate the effects of lateral attenuation, the data in Figure B1 was normalized to the level at the POI with the 45 degree elevation angle (e.g., the POI at 492 ft. lateral distance for the trajectory modeled as 492 ft. above ground level). A graph using logarithmic values of the lateral distance with these normalized levels is shown in Figure B2. Note that the 492 ft. altitude curves (blue) are coincident at the 492 ft. lateral distance; the 1000 ft. curves (red) are coincident at the 1000 ft. lateral distance and the 5000 ft. altitude curves (green) are coincident at 5000 ft. lateral distance. The SEL (dBA) comparisons between AAM and HELENA agree fairly well except for slight differences at high frequencies, due to numerical differences in handling of the computational 0 dB noise floor. The SEL (dBA) difference level between AAM/HELENA and INM propagation for the lower altitude flight (492 ft. AGL) do not agree well with increasing lateral distance; whereas, the difference between the INM and AAM/HELENA curves decreases as the modeled altitude increases. These differences between the propagation predictions between INM and AAM/HELENA may be attributed to ground effect modeling.

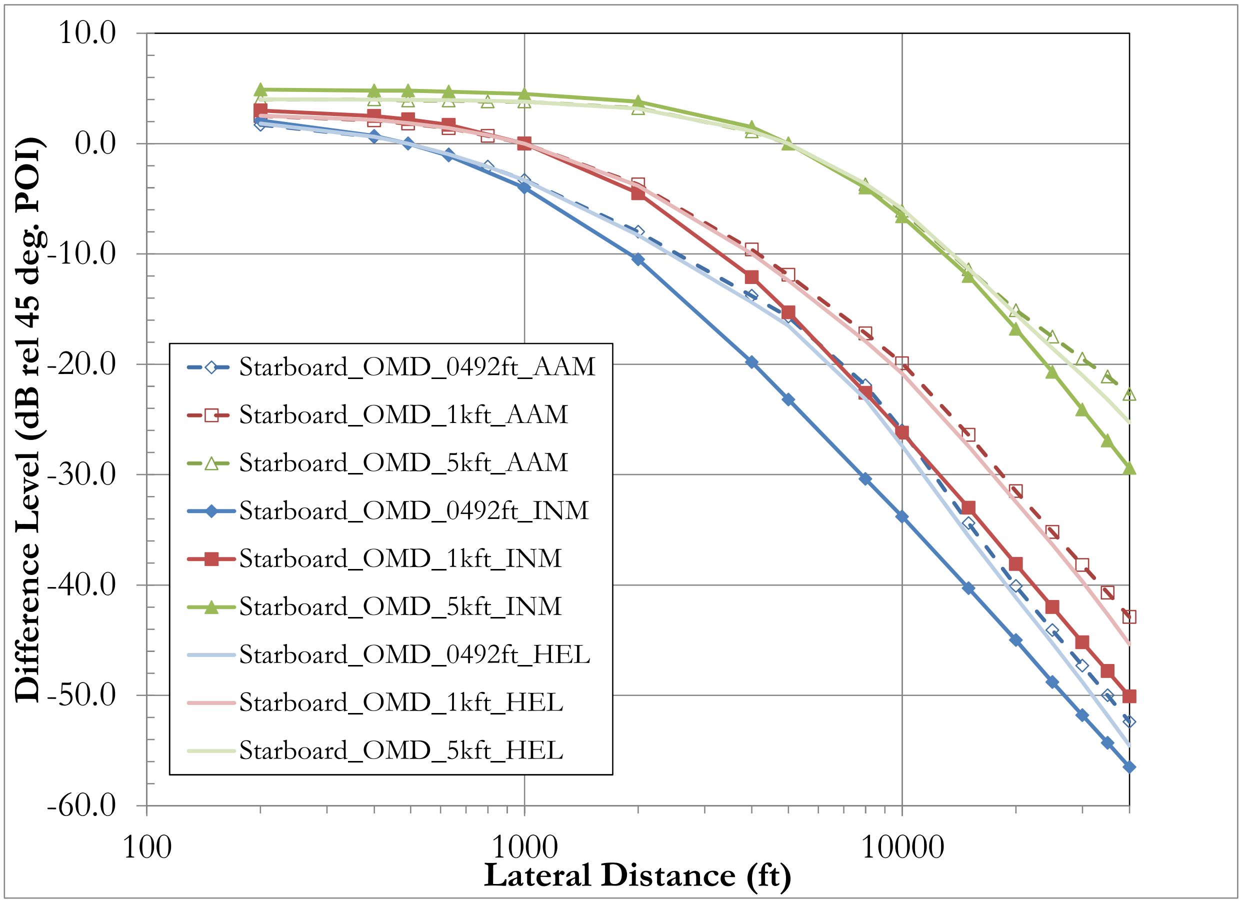

FIGURE B2 INM, AAM and HELENA difference level SEL (dBA) from 45° POI versus lateral distance.
Level flights at 492 ft., 1000 ft. and 5000 ft. AGL. Omni-directional source using INM's #302 spectral class

The curves shown in Figure B3 are the results of modeling the MD-902 using the empirical noise spheres with the same trajectories used to generate the results shown in Figure B2. The MD-902 sphere used contains the noise characterization of the helicopter during 120 knot level flight. This sphere was used in AAM to generate a helicopter for INM's database using the procedure outlined in Section 3.4 for use in INM. The differences between Figures B3 and B2 are a result of the modeled directivity of the helicopter. In the case of INM, source directivity is defined via the NPD curves for 45° Right – Center – 45° Left. The directivity in the AAM and HELENA MD-902 contains 5-degree spacing in both directions on the noise spheres. The POIs modeled in Figure B3 are to the starboard side of the helicopter. For comparison, the same lateral distances to the port side of the helicopter were modeled with the same trajectories. The results for the port side POIs are shown in Figure B4. Since the INM right and left correspond to the 45° angle, the lateral distance matching the flight altitude show no difference in source directivity between AAM/HELENA and INM, as expected. For angles below the aircraft, inboard of the 45° angle source directivity does not amount to a considerable difference in prediction levels between INM and AAM/HELENA for lower flight altitudes. However, as the flight altitude increases, and the propagation distance to the 45° POI increases, the difference between INM and AAM/HELENA attributable to source directivity can be on the order of +/- 1 dBA SEL. For distances outside of the 45° slant angle (up closer to the rotor plane) the differences can be significant, for the MD-902 on the order of 3-5 dBA SEL. These differences will be exacerbated if the source emission angle from the helicopter to the receiver moves up the side of the vehicle, towards the rotor plane, such as when the vehicle is flying at a bank angle or in a canyon. The magnitude of these differences and the specific angular behavior is flight condition and vehicle specific.

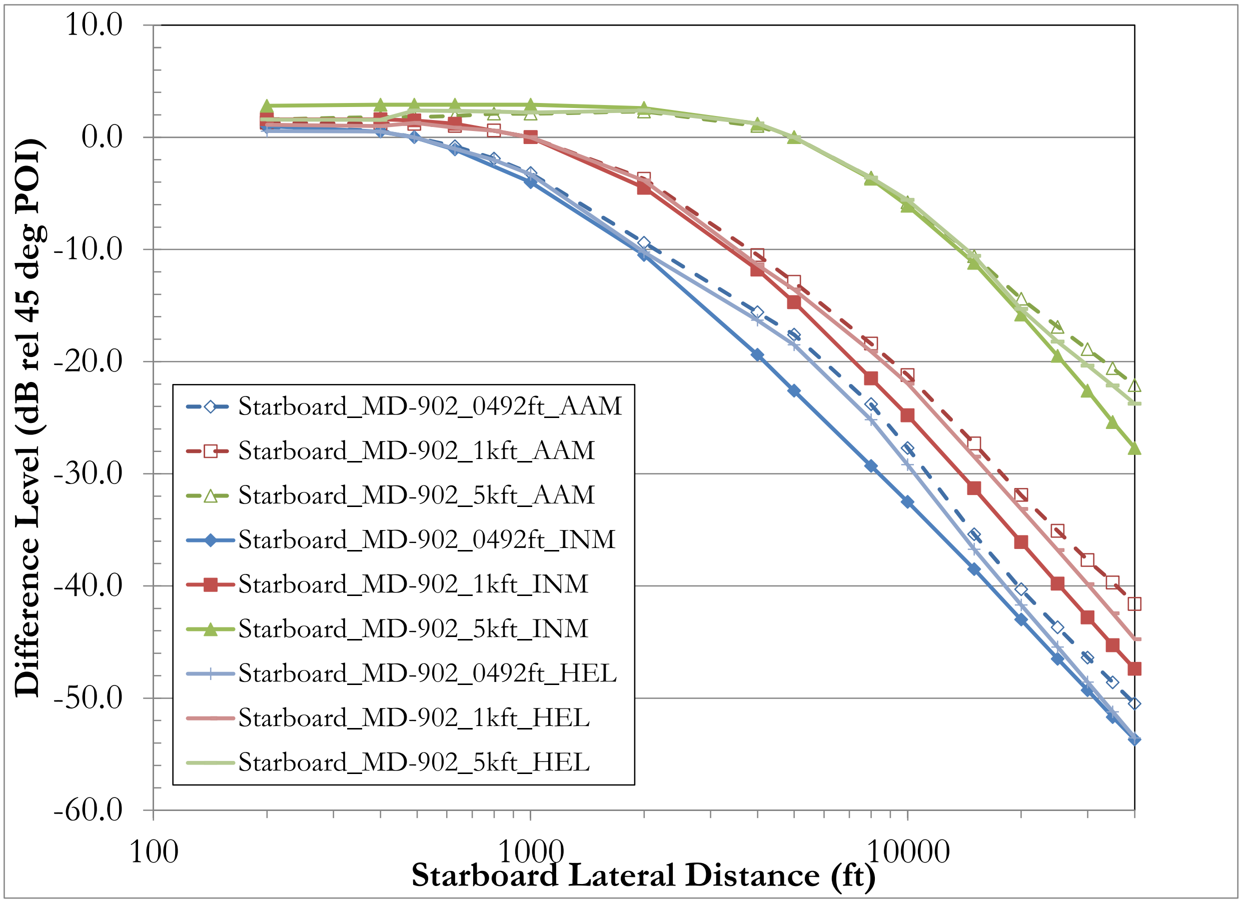

FIGURE B3 INM, AAM and HELENA SEL versus lateral distance to the starboard side of the helicopter.
Level flights at 492 ft., 1000 ft., and 5000 ft. AGL; MD-902 source sphere for 120 knot level modeled

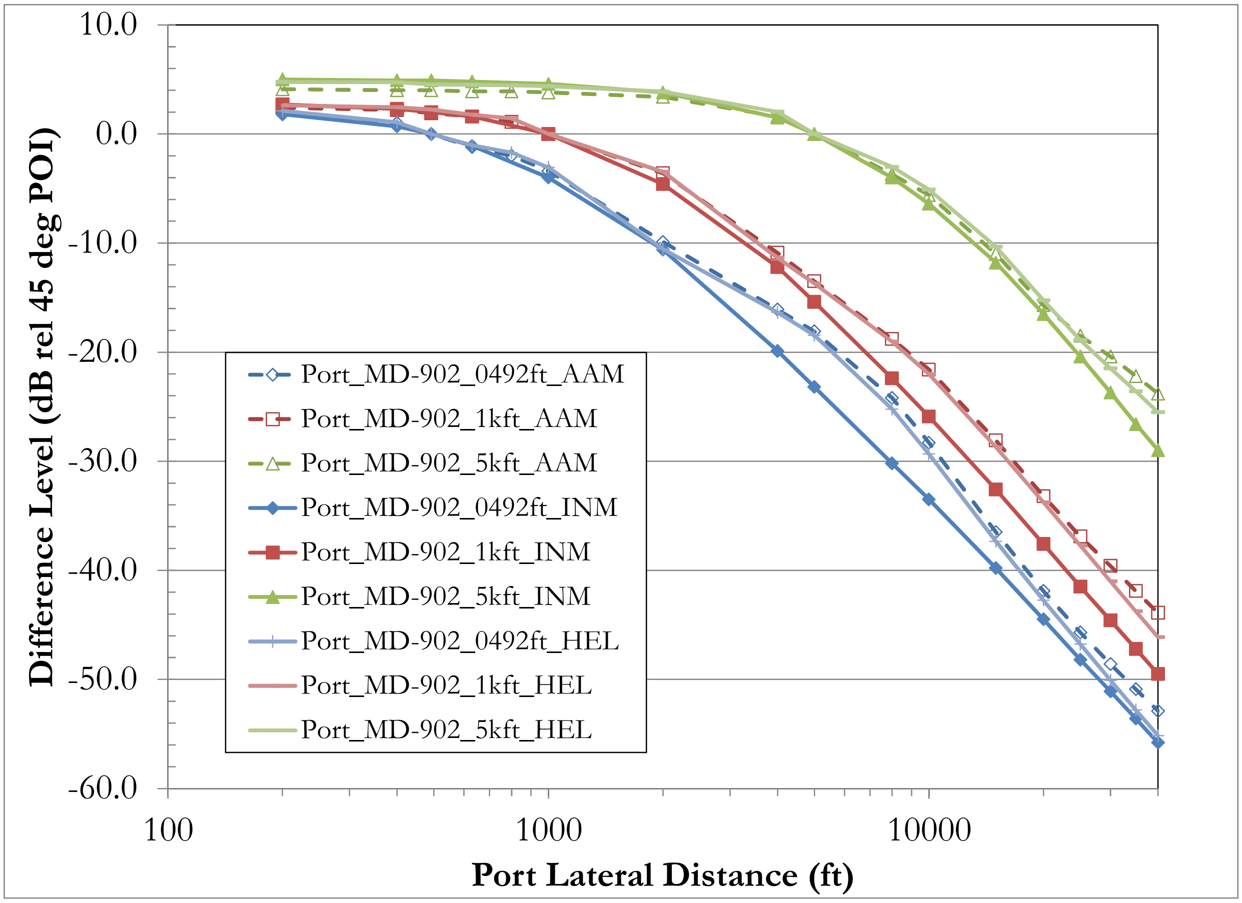

FIGURE B4 INM, AAM and HELENA SEL versus lateral distance to the port side of the helicopter.
Level flights at 492 ft., 1000 ft., and 5000 ft. AGL; MD-902 source sphere for 120 knot level flight modeled