FINAL REPORT

Air Weaponry Noise Source Characterization Protocol

SERDP Project SI-1397

November 2008

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14. ABSTRACT

The technical report consists of three main elements: (1) measurement of real, airborne weapon systems to characterize the noise data required for accurate modeling, including characterization of complex air-weaponry noise due to a combination of various sources and aircraft platforms; (2) modification of noise propagation algorithms and statistical representation of the distributed sources, and modifications that involve three-dimensional representations of noise sources to properly describe the air-to-ground propagation, and to account for potential shielding/interference from the aircraft itself; and (3) integration of the air-weaponry data and algorithms into a new computer model.
These combined elements enable new sets of operational scenarios to be modeled, and the capability will assist in public presentation and understanding of potential noise impacts and their mitigation.

15. SUBJECT TERMS

air weaponry; analysis; calculation; collection; data; effects; field measurements; methods; modeling; noise contour; operations; profile; range; and sources.

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Acronyms and Abbreviations

3-D – Three Dimensional

A

A-wt – A-weighted

AC – Aircraft

AFCEE – Air Force Center for Environmental Excellence

AFRL – Air Force Research Lab

AG – Air Gunnery

agm – Air Gunnery Case extension

AH – Aircraft

B

BaseOps – Base Operations

BNOISE2 – Blast Noise 2

C

C-wt – C-weighted

CERL – United States Army Construction Engineering Lab

CHPPM – Center for Health Promotion and Preventive Medicine

COTR – Contracting Officer's Technical Representative

CSEL – C-weighted Sound Exposure Level

csv – Profile subdirectory extension

D

dB – Decibel (Unit for noise intensity)

dBA – A-weighted Sound Level

dBC – C-weighted Sound Level

deg - Degree

DoD – United States Department of Defense

E

Exe – Executable file

F

FLIGHTPROF – Flight Profile Keyword

ft – Feet/Foot

G

grd – Grid

H

Hz - Hertz

I

ID – Identification

J-L

JSF – Joint Striker Force

kHz – Kilo Herz

Kilo - Kilometer

L_{dn} - Day-Night Average Sound Level (DNL)

L_{eq} – Equivalent Average Sound Pressure Level

$L_{eq}C$ – C-weighted Equivalent Sound Level

LM – Level Meter

M

Max – Maximum

Min – Minimum

MK – Mark

MR_NMAP – Military Training Route Noise Model

mrk – File Extension

N-O

NASA – National Aeronautics and Space Administration

NASATP – National Aeronautics and Space Administration Technical Papers

NAVFAC – Naval Facilities Engineering Command (U.S. Navy)

NEPA – National Environmental Policy Act

NMPlot – NoiseMap Plot

NMSim – Noise Model Simulation

P

Pa•sec – Positive Impulse per second

PI – Positive Impulse

prb – Probability

R

rms – Root Mean Square

RNM – Rotorcraft Noise Model

ROTARYWINGPROF – Rotary Wing Profile

run – Base operations profile extension

S

SARN – Small Arms Range Noise

SARNAM – Small Arms Range Noise Assessment Model

SEL – Sound Exposure Level

SERDP – Strategic Environmental Research and Development Program

SI – SERDP Project

SLM – Sound Level Meter

SON – Statement of Need

SPL – Sound Pressure Level

T

TD – Test Director

U-W

U.S. – United States

USAF – United States Air Force

WR – Wyle Report

wt – Weight

X-Z

X, Y, Z – Directions for Grid Dimensions

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2.0 Executive Summary

2.1 Background

A number of aircraft and ground-based weapon system noise models have been developed over the past 30 years to estimate noise levels from military operations. The results from these models are used to assess the potential for community and environmental impacts from existing and proposed operations. Current Department of Defense (DoD) noise models use common aircraft and weapon system source noise databases maintained by the Air Force Research Laboratory, U.S. Army Construction Engineering Research Laboratory, and Naval Facilities Engineering Command. However, these models and the source noise databases do not provide the capability to assess noise impacts due to airborne weapon operations. This project has developed a new computer model that addresses the generation and propagation of noise from air-weaponry operations. The model handles the complexity of the distributed noise events while maintaining accurate acoustical modeling that is required for environmental noise analysis.

2.2 Objective

The objectives of this project were:

- To characterize the noise generated by airborne weapon systems,
- To evaluate and refine current weapon noise propagation algorithms for airborne platforms, and
- To incorporate these refined algorithms and additional data requirements into a new noise model whose output can be integrated with the existing DoD noise models.

This integration enables completely new sets of operational scenarios to be modeled. This new capability assists in public presentation and understanding of potential noise impacts and their mitigation.

The overall project consisted of three main elements. The first element involved the measurement of real, airborne weapon systems to characterize the noise data required for accurate modeling. The characterization of air-weaponry noise is complex because of the combination of various sources and aircraft platforms. The second element focused on the modification of noise propagation algorithms and statistical representation of the distributed sources. The modifications involved three-dimensional representations of the noise sources to properly describe the air-to-ground propagation and to account for potential shielding/interference from the aircraft itself. The final element involved the integration of the air-weaponry data and algorithms into a new computer model.

The next step for this model is field validation of the model. This validation should include a mix of weapon systems and firing ranges so that the data input requirements and model output can be validated and the utility of the model demonstrated. The field measurements should include monitoring air-weaponry noise over a longer time period than was afforded in this project's third field measurement.

Once this model has been validated, it will allow the DoD to more accurately estimate the noise environment from aircraft range operations and will provide a scientific foundation for range commanders in addressing criticisms from knowledgeable citizens on the appropriateness of these estimates. These tools will assist the DoD in being responsive to the requirements of the National Environmental Policy Act (NEPA), while protecting operational readiness from unreasonable restrictions based on today's limited knowledge of air-gunnery noise effects.

The next challenge is the development of methods to combine the effects from the different noise sources that occur on an air-weaponry training range. These different sources include aircraft noise, small arms, large weapons, and explosions. Currently, these different sources are treated separately in impact analysis, and neither procedures nor methods exist to combine their cumulative effects.

2.3 Air-Weaponry Noise Characterization

Three field measurements were conducted during this project. The first two measurements collected source data on the AH-64's 30 mm gun and training rocket, F-16 20 mm gun, and the A-10 30 mm gun. The third field measurement collected air-weaponry noise data from air-weaponry training operations of the AH-64.

The results from the first two measurements provided source data for the weapon systems as well as data verification for the prediction of the air-weaponry noise. For muzzle blast, the source noise definitions for the measured weapon systems are the following:

AH-64 30mm Gun

$$PI(\theta) = 60.0dB + \begin{Bmatrix} -0.895dB + 1.51dB\cos(\theta) - \\ 0.156dB\cos(2\theta) + 0.0144dB\cos(3\theta) - 0.0427dB\cos(4\theta) \end{Bmatrix}$$

A-10 30mm Gun

$$PI(\theta) = 65.5dB - \begin{Bmatrix} -4.94dB + 5.80dB\cos(\theta) - 1.22dB\cos(2\theta) + \\ 0.566dB\cos(3\theta) - 0.348dB\cos(4\theta) \end{Bmatrix}, \text{ and}$$

F-16 20mm Gun

$$PI(\theta,\varphi) = 60.0dB + \begin{Bmatrix} -4.69dB + 6.51dB\cos\left(\theta\frac{\varphi}{|\varphi|}\right) - 1.62dB\cos\left(2\theta\frac{\varphi}{|\varphi|}\right) + 0.197dB\cos\left(3\theta\frac{\varphi}{|\varphi|}\right) - 0.337dB\cos\left(4\theta\frac{\varphi}{|\varphi|}\right) - \\ 1.61dB\sin\left(\theta\frac{\varphi}{|\varphi|}\right) + 0.291dB\sin\left(2\theta\frac{\varphi}{|\varphi|}\right) - 0.444dB\sin\left(3\theta\frac{\varphi}{|\varphi|}\right) + 0.185dB\sin\left(4\theta\frac{\varphi}{|\varphi|}\right) \end{Bmatrix}.$$

where 0° ≤ θ ≤ 180° and -90° ≤ φ ≤ 90°. In these definitions, θ is the fore/aft angle and φ is the roll angle. The primary angular dependence on the muzzle blast was θ, which is similar to ground based weapon systems. For the AH-64 and A-10 guns, no dependence was observed about the roll angle. For the F-16 gun, only a simple left/right dependence was observed.

The most complex source to model is the rocket launch and propulsion noise since these two sources are convolved in the field measurements. As a first step to characterize and model these sources, they were combined into a single sound exposure level. For the training rocket measured from the AH-64, the following source term was determined to characterize both the launch and propulsion noise:

$$CSEL(\theta) = 153dB + \begin{Bmatrix} -0.0903dB - 1.18dB\cos(\theta) - 4.40dB\cos(2\theta) \\ -0.104dB\cos(3\theta) - 1.12dB\cos(4\theta) \end{Bmatrix}$$

The final field measurements were revised and conducted at Fort Rucker Range. The goal of the final field measurements was to collect noise data from air weaponry training operations at Fort Rucker. Noise data were collected with ten Sound Level Meters (SLM) placed around the range at Fort Rucker. Firing operations on Kilo firing lane were monitored for five AH-64 training sessions, which included both gun and rocket firings. Using the basic training profiles provided by Fort Rucker personnel, the measured data were compared with the model. For the muzzle blast, the average difference between estimated and measured L_{eqC} values was less than 1 dB with a standard deviation of 7 dB. For the rocket noise, the comparison was not as good with average difference between the L_{eqC} values was -6 dB (under prediction) with a standard deviation of 9 dB. This difference was more than likely due to using the same probability distribution for both forms of firings. The rocket firing was skewed toward the start of the firing lane compared to the gun firing, so this comparison could be refined. The largest differences occur at the sites closest to the firing lane. The individual noise events measured at these sites are more sensitive to the difference between the modeled probability distribution and the actual firing points. Overall, the comparisons show general good agreement considering the limited amount of the data collected.

2.4 Propagation Algorithms

From our field measurements, we have determined that the propagation of the guns' muzzle blast and the rocket's launch and propulsion noise had minimal nonlinear propagation effects. This finding allows the use of linear propagation models for the muzzle blast and rocket noise. Thus, the propagation algorithms contained in NMSim were selected for use in the air-weaponry noise model.

For sonic boom, Carlson's simplified method provided sufficient resolution for the sonic boom from the bullets and rockets. For the model, only a few parameters are required for the accurate estimation of the sonic boom. These parameters are body length, body area, and speed profile. For rockets, a simple adjustment is required to account for the double sonic boom signature generated by the rocket body and its plume. The adjustment is simply assuming two equal booms based on the rocket body and speed profile since the measurements found that the sonic booms from the rocket body and plume were comparable.

2.5 Model Development

The main goal of this project was the development of an air-weaponry noise model that accurately calculates noise for air weaponry firings for understanding of these unique noise sources for both planners and the public. Providing an accurate noise model that can quickly create scenarios for study without sacrificing accuracy for speed is critical.

One of the complexities that exist for this type of model is that aircraft rarely fly the exact attack run profile prescribed, and in some cases, the attack run is simply a generalized fan where the pilot can approach the target from a range of headings. To solve this problem of an unknown source location, a generalized statistical firing space is used. This space is defined by the parameters of the attack run with a three dimensional Gaussian distribution of firing points. The noise footprint from this space is then calculated to represent the noise from a single bullet fired from within the space. This statistical method is not representative of a single bullet fired, but is rather the average noise expected once a statistically large number of bullets have been fired (such as after a year of simulated combat operations). The noise footprint can then be included in a larger environmental noise model that determines the noise contour from a whole range of operations.

The model consists of several different programs designed to operate together. The following is a compete list of the programs provided in the initial release:

- AG_BoomModel.exe,
- AG_DefineRun.exe,
- AG_FrontEnd.exe,
- Air_Gunnery_Model.exe,
- LayerBuilder.exe, and
- TargetBuilder.exe.

The AG_BoomModel program is designed to calculate the noise from the sonic boom from the projectiles. The noise algorithm itself is based on Carlson’s simplified sonic boom theory (1978). It uses the projectile shape factor, length, and speed profile to calculate the footprint of the sonic boom.

The AG_DefineRun program provides a graphical user interface to help the user define a statistical volume for a firing profile. This module provides the user a way to see the firing line, target, and statistical volume graphically. The program takes that information and generates a statistical volume. This volume is then separated into individual firing points within the volume. Each point is provided a statistical likelihood that a bullet was fired at that location. The total probability of the entire volume is defined as 1.00, making the likelihood that a bullet was fired somewhere within the volume 100%. The likelihood that a single bullet was fired at any one spatial location within the volume is less than 1.00, and is a function of where in the volume it is, and the definition of the distribution.

AG_FrontEnd.exe is the initial user interface for the Air Gunnery Model. It is the starting point for creating new cases or importing cases from other sources. When the program is initially launched, it shows an empty grid similar to a spreadsheet. This is the main screen for viewing operational data with the column headings providing details about each individual operation.

The Air_Gunnery_Model is the core calculation engine for determining the muzzle blast and propulsion noise. This program operates entirely from a command line. The command line argument is a control file that contains all of the information necessary to compute the noise from a single statistical volume.

The input file is fairly simple and is used for the muzzle blast calculation as well as for the sonic boom calculations. The output is an NMPlot grid file that contains all of the cases information. It lists each of the modeled firing points together with their probabilities, and it lists all of the Points of Interest.

2.6 Summary

The findings from this projects field measurements represents a significant advance in understanding the contribution of air-weaponry operations to the overall noise generated by DoD training operations. The field measurements have provided a firm technical foundation for the development of a new noise model for air weaponry noise. The new model provides a novel approach for calculating the distinct noise produced by these operations. The modeling approach utilizes a statistical volume of space for determining the distribution of firing points, which follows the same guidelines used for weapon safety footprint analysis. The noise from this statistical volume is then computed and scaled for the actual number of bullets fired. By combining the results of individual firing profiles occurring at a range, it is possible to compute the airborne weapon noise contour for an entire range.

An important step in this modeling method involves calculating and storing the individual noise footprints from each firing profile. Then allowing the user to rapidly calculate the overall noise contour based on the number of rounds fired for each profile without having to do the costly noise calculations repeatedly. The result is a noise model that retains the detail and accuracy of a simulation model without having to spend the time for each noise calculation to be completed.

The beta version of the air-weaponry noise model has been provided to the U.S. Army for their assessment and use. Along with the model, a source data collection protocol has also been provided. This protocol recommends the basic approach to collect and develop source noise data for other weapon system platforms, as well as interim methods to use until valid source data is collected.

The next step for this model is field validation of the model. This validation should include a mix of weapon systems and firing ranges, so that the data input requirements and model output can be validated, and the utility of the model demonstrated. The field measurements should include monitoring air-weaponry noise over a longer time period than was afforded in this project's third field measurement.

Once this model has been validated, it will allow the DoD to more accurately estimate the noise environment from aircraft range operations and will provide a scientific foundation for range commanders in addressing criticisms from knowledgeable citizens on the appropriateness of these estimates. These tools will assist the DoD in being responsive to the requirements of the National Environmental Policy Act (NEPA), while protecting operational readiness from unreasonable restrictions based on today's limited knowledge of air-gunnery noise effects.

The next challenge is the development of methods to combine the effects from the different noise sources that occur on an air-weaponry training range. These different sources include aircraft noise, small arms, large weapons, and explosions. Currently, these different sources are treated separately in impact analysis, and neither procedures nor methods exist to combine their cumulative effects.

3.0 Objective

The objective of this research project addresses the Statement of Need (SON) for "Prediction Model for Weapon Noise Sources from Airborne Platforms," by developing a computerized prediction model for aircraft-weapons firing noise that accurately characterizes the noise generation and propagation from these classes of noise sources.

The specific objectives of this research project can be stated as follows:

(1) To characterize the noise generated by airborne weapon systems. This includes important aspects of time-dependent waveform and spectral descriptions of the noise sources along with their dynamic directivity patterns. These data is compiled into a database that can be integrated with the noise databases used in the various DoD models. A protocol for collecting airborne weapons systems has been developed for acquiring acoustic data for future airborne weapon systems.

(2) To evaluate and refine current weapon noise propagation algorithms for application to airborne platforms. Refinements include the effects of topography and the atmosphere on the noise propagation.

(3) These refined algorithms and additional input requirements are incorporated into a new model that is integrated with other DoD aircraft noise models through the data input module BASEOPS. This integration allows a means for demonstrating the noise exposure of military aircraft operations as an aid to noise assessment and mitigation.

(4) Transition new computer model to DoD users such as CHPPM, AFCEE, and NAVFAC enabling new technology to be quickly utilized in the assessment of environmental noise impacts.

Development of this noise predictive model is required for noise management on DoD ranges. Specifically, this model helps to ensure appropriate locations for ranges prior to construction, and to enable effective, unrestricted training while minimizing noise impacts on community health and welfare. This model is structured to provide fast, accurate, and economical processing by interfacing with and leveraging emerging and existing computer noise models. In addition to the modeling capabilities, collection of source noise emission data from weapons/munitions noise to accurately model the impact of these sources must be conducted.

With the accurate characterization of the airborne weaponry noise, the output of the model is coordinated with existing noise model used for DoD noise sources. One challenge for this unique noise source is the proper metrics to describe the environmental. These metrics have not been fully determined, so the output of the model is flexible by including many acoustical metrics to describe the airborne weaponry noise. This flexible allows the model to be adapted to the desired metrics once the proper metrics are determined.

Routine testing and training range operations can generate complaints and damage claims from civilian communities around DoD installations. These claims can result in testing and training restrictions and expenditure of funds for damage. This new noise prediction model for weaponry noise from aerial platforms fills a deficiency in current noise modeling capabilities. This new capability can be used in the management of noise at DoD ranges and installations to document potential impacts that may influence testing and training. This management tool can assist the assessment of noise levels from day-to-day operations, the development of mitigation measures and in support of NEPA documentation.

4.0 Background

A number of aircraft noise models have been developed over the past 30 years to estimate noise levels from military aircraft operations near airbases, along training routes, and within special use airspaces. The predictions from these models are used to assess the potential for community and environmental impacts from current and proposed flight operations. The U.S. Army has developed noise models for blast noise and supersonic shock waves due to ground-based weapon systems. Current Department of Defense (DoD) noise models all use common aircraft and weapon system source noise databases, which are maintained by the Air Force Research Laboratory (AFRL), U.S. Army Construction Engineering Research Laboratory (CERL), and Navy Facilities Engineering Command (NAVFAC). However, none of these models and databases included the noise contribution from air-gunnery operations.

This omission of an important and significant source of noise has become more troublesome as range operations come under greater scrutiny from the public. In the Republic of Korea, strafing operations have been greatly restricted based on noise complaints from local communities. Currently, the range commanders have no tools to counter these restrictions. As part of a noise study for two Korean Ranges utilized by the U.S. military, an empirical analysis of strafing noise from A-10 and F-16 operations was conducted. Figure 4-1 compares the Sound Exposure Level of strafing noise to aircraft noise. It should be noted that noise directivity is not included in this comparison because of modeling limitations of MR_NMAP. In this figure, it can be seen that the strafing noise is approximately 30 dB greater than the aircraft noise and demonstrates that the omission of strafing noise is a major omission in the assessment of range noise.

A new model is needed that includes both the aircraft noise and the airborne weapon noise that occur in air-weaponry operations. The goal of this project was the development of an air weaponry noise model that calculates both the single event noise, as well as the cumulative noise, and provides acoustical information for both planners and the public. The basis of the model's calculations is robust measures of individual events, so that various acoustical metrics can be used to assess potential impacts. A detailed and flexible calculation tool is required because the community noise impact assessment methodology for combining impulsive noise events with longer duration aircraft noise exposure is still under development.

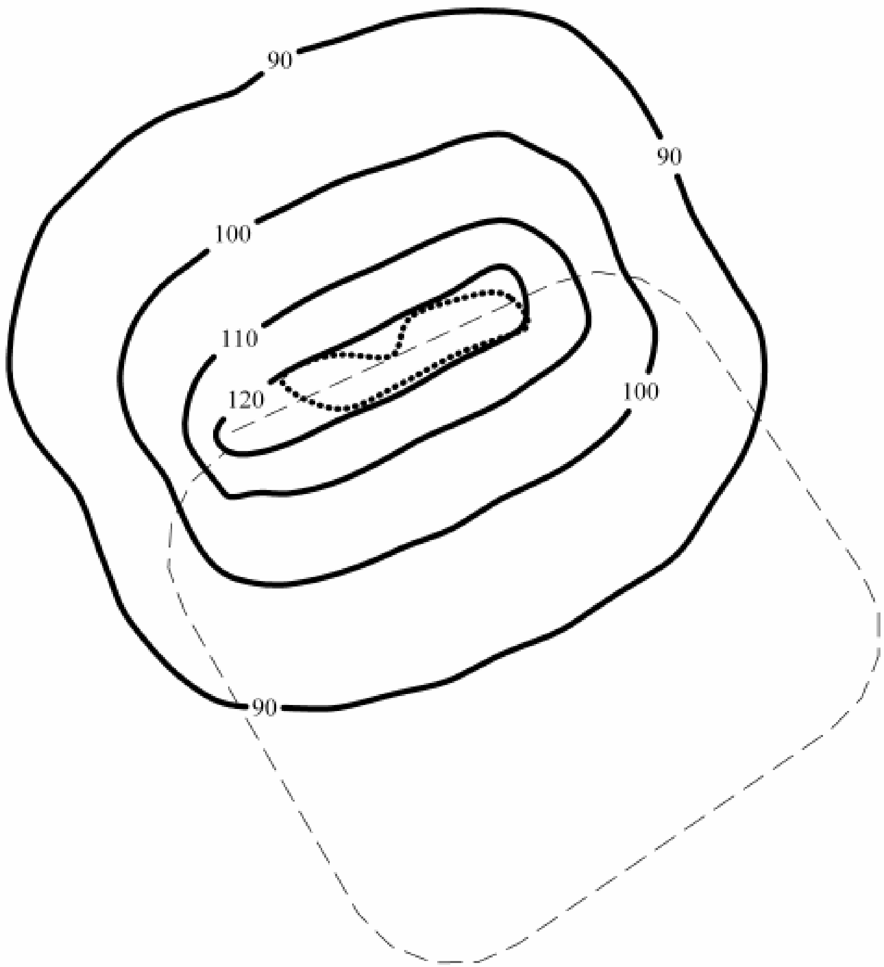

Figure 4-1. SEL Noise Footprint for A-10 Strafing Operation at Pilsung Range, Republic of Korea (Aircraft and Air Gunnery Noise Shown in Solid Black Contour Lines, Aircraft Only Noise Shown in Dotted Contour Line (90 dB SEL only), Flight Track Shown in Dashed Line)

5.0 Material and Methods

This project consists of three functional areas: Noise Source Characterization, Propagation Algorithms Modification, and Model Integration with current DoD noise models. These areas are contained within the first three technical objectives.

The original intent was to integrate this model directly into the new noise model being developed under SERDP project SI-1304, Advanced Acoustic Models for Military Aircraft Noise Propagation and Impact Analysis (http://www.serdp.org/Research/upload/CP-1304.pdf) (Plotkin, 2002). These models do employ similar propagation algorithms. In addition, these models will utilize the same basic user input data through BaseOps (Wasmer, 2007). However, the representation of the noise generation is different. The air weaponry noise model is based on a statistical representation of the firing operations because of the distributed nature of the operation, whereas the new advanced aircraft noise simulates the noise from a single aircraft flight operation. Moreover, the new aircraft noise model has yet to be completed.

5.1 Noise Source Characterization

The noise source characterization involved an experimental approach, by measuring real airborne weapon systems and determining the noise data required for accurate noise modeling. The characterization of air weaponry noise is complex due to the existence of multiple, sometimes simultaneous, noise sources: muzzle blast, ballistic wave, propulsion noise (missiles), explosive projectile or warhead noise, and aircraft noise.

The combination of these sources also depends on the various aircraft platforms:

- Helicopters (AH-64, AH-1, MH-53, etc.),
- Fixed-wing Attack Aircraft (A-10, F-16, F/A-18, JSF (future)), and
- Fixed-wing Gunship (AC-130).

Many of the sources are highly directive in nature and each source has distinct noise characteristics. Further, noise patterns of airborne weapons need Three-dimensional representation to properly describe the ground noise exposure and to account for potential shielding and interference from the aircraft itself. Discriminating between the multiple noise sources, and describing each one independently in a three dimensional spectral manner is the primary challenge for this project and is where the majority of the research efforts are focused.

Three series of field measurements were conducted during this project. The first series utilized an AH–64 attack helicopter and focused on small caliber gun (30 mm) and rocket firing. The second series focused on fixed wing aircraft and concentrated on the effect of airspeed on muzzle blast. This series utilized USAF A-10 and F-16 aircraft. The third series originally attempted to feature the AC-130 gunship with its multiple weapon systems. However, because of operational constraints, the third field measurements were changed to a monitoring study of air weaponry training operations at Fort Rucker Firing Range.

The primary requirement for these noise characterization measurements is to have sufficient data so that response of humans and animals can be assessed. Because an accepted noise metric and assessment procedures to determine human and animal response is currently under debate amongst the scientific community, the model is designed in a flexible manner so that it can be readily adapted as more information becomes available on the appropriate acoustic metrics for evaluating noise impacts.

Under this effort, three main products were generated:

- Comparative data for comparison with of propagation algorithms,
- Reference source noise data for measured systems, and
- Data collection protocol for other airborne weapon systems.

The database is being developed along the same lines as the database being developed under the current SERDP project SI-1304. The noise data has been formatted into reference noise for each aircraft/munition combination. A data collection protocol is established for collecting additional airborne weapon noise data for other and future systems. This protocol is provided in Appendix A.

For other current weapon systems, not measured explicitly as part of this effort, interim sources are identified. Empirical relationships have been developed so that source data may be reasonably estimated until such a time as they may be measured directly.

5.2 Propagation Algorithms Modification

The next focus area involved determining weapon noise algorithms for elevated moving sources. Existing Army noise models SARNAM (Pater and White, 2003) and BNOISE2 (Pater, White, and Miller, 2002) use well-developed algorithms to account for the propagation of muzzle blast from ground-based weapons. Originally, these models were to be modified for elevated moving sources. However, based on the results of our field measurements, the linear propagation codes utilized in NMSim (Ikelheimer and Plotkin, 2005) were used since they already included elevated sources and topography effects. For the ballistic wave, the simplified algorithms of Carlson (1978) compared well with the experimental data and were selected as the most suitable algorithm for the model. Comparison of measured data with the algorithms calculations are provided in the NOISECON 2007 paper "Airborne Weaponry Noise Measurements" (Appendix A), and the measurement protocol (Appendix B).

Prediction of propulsion noise from subsonic missiles is modeled with the NMSim algorithms. Prediction of explosive noise is currently modeled by BNOISE2. Given that these models include state of the art modeling techniques, no further development of these specific propagation algorithms (propulsion and explosive noise) were required for this project.

5.3 Model Integration

The final focus area was the integration of the propagation algorithms and databases for airborne weapons with the statistical representation of aerial firing as described in Appendix C. The integration of this model with the new advanced noise model under development through SERDP CP-1304 was completed through the data input model. The air weaponry model is structured in a modular fashion, so that the noise prediction algorithms of airborne weapon systems are isolated from the propagation algorithms for the aircraft platforms. From the user's perspective, airborne weapons operations are identified through BaseOps and further information is entered in a separate data input module for air weaponry operations. Most of the additional information is available through weapon safety footprint analysis, which defines the distribution of firing points for an individual operation. The detailed calculations of the noise have remained modular to facilitate updates and maintenance of the program.

A challenging area of the integration is the manner in which the results are presented to the user. As noted earlier, prediction methods for community and individual response have been developed, but no specific guidelines currently exist for combining impulsive noise (blast) with transient aircraft noise or continuous noise. As such, outputs of the model is highly flexible by including a multitude of output modules for both impulsive and transient noise and a module for combining the noise into a single noise descriptor. All of the output options are compatible with NMPlot for graphical representation (Wasmer, 2007).

A critical aspect of a successful noise model is ease of use and the ability to function well on most office computer platforms. This requires careful development and exhaustive testing of the Graphical User Interface through which the user defines operational information, describes the vehicles and weapon systems of interest, and controls noise assessment calculations and analyses. The emphasis on ease of use is increased with the integration of airborne weapon noise since the need to model such platforms greatly expands the potential base of clients who will use this model.

While this new modeling technology is required for modeling air weaponry operations, traditional noise dose contours in terms of cumulative L_{dn} and other metrics, such as peak noise level, will generally be required for environmental studies. SEL data from the dynamic model, written on a standard NOISEMAP grid, can be merged with NOISEMAP L_{dn} data for all other operations through use of the contouring module NMPlot. This is an established process, implicit to NOISEMAP's grid-based architecture and is within the current capabilities of NOISEMAP, SARNAM, BNOISE2, and other Federal noise impact assessment models. The new model's integrated outputs are thus be fully compatible with NOISEMAP and Army ground-based noise models, and transition to the new model will be virtually seamless as 3-D noise sources are developed for legacy aircraft.

6.0 Results and Accomplishments

The final project accomplishments are described within the three functional areas described in Section 6.

6.1 Noise Source Characterization

The final results for the source data characterization is provided in the revised invited paper provided at NoiseCon 2007, "Airborne weaponry noise measurements" (Downing et al., 2007). This revised paper is provided in Appendix A.

6.1.1 Final Field Measurements

The final field measurements were revised and conducted at Fort Rucker Range. The goal of the final field measurements was to collect training noise data for air weaponry operations at Fort Rucker. Noise data were collected with 10 Sound Level Meters (SLM) placed around the range at Fort Rucker (site LM#11 was not utilized). Figure 6-1 provides and overview of the SLM locations. Firing operations on Kilo firing lane were monitored for five AH-64 training sessions, which included both gun and rocket firings.

Figure 6-1. Air Weaponry Training Noise Data Collection SLM Sites at Fort Rucker Range

The recorded data were sorted between gun and rocket firings. No sites were located within areas where sonic booms were expected. For each observed firing, each SLM data record was examined to determine if a quantifiable event could be evaluated. This examination was required because of significant background noise that obscured many of the firing events. After this examination was completed, the measured CSEL of each event was calculated for comparison with the model output. Tables 6-1 and 6-2 provide a summary of the number of firing events identified at each SLM site for guns and rockets, respectively. Gun firings are single burst events observed to be approximately one second in duration for the training operations at Fort Rucker. Rocket firing events are the actual number of rockets fired.

Table 6-1. Observed Gun Firing Events by SLM Sites

	SLM 01	SLM 02	SLM 03	SLM 04	SLM 05	SLM 06	SLM 07	SLM 08	SLM 09	SLM 10
12-Jun	70	94	87	0	89	95	95	0	74	59
13-Jun	0	18	9	0	13	18	18	0	13	17
14-Jun	22	41	41	0	26	41	41	41	17	19
20-Jun	0	11	0	13	0	48	54	56	38	39
21-Jun	0	9	12	24	5	19	24	21	5	20

Table 6-2. Observed Rocket Firing Events by SLM Sites

	SLM 01	SLM 02	SLM 03	SLM 04	SLM 05	SLM 06	SLM 07	SLM 08	SLM 09	SLM 10
12-Jun	68	77	70	0	75	77	80	0	70	67
13-Jun	0	42	31	0	42	40	42	0	32	32
14-Jun	27	37	37	0	16	37	37	37	20	27
20-Jun	0	19	0	32	0	26	64	60	33	54
21-Jun	0	11	22	27	5	15	26	22	5	24

Using the basic profile provided by Fort Rucker personnel, the measured data were compared with the model output (which is described in Section 6.2 and Appendix C). For the muzzle blast, the measured and estimated values for the L_{eqC} are provided in Tables 6-3 and 6-4, respectively. The average difference is less than 1 dB with a standard deviation of 7 dB. For the rocket noise, the measured and estimated values for the L_{eqC} are provided in Tables 6-5 and 6-6, respectively. The comparison is not as good with an average difference of -6 dB (under prediction) and a standard deviation of 9 dB. This difference is more than likely due to using the same probability distribution for both forms of firings. The rocket firing was skewed toward the start of the firing lane compared to the gun firing, so this comparison could be refined. The largest differences occur at the sites closest to the firing lane. The individual noise events measured at these sites are more sensitive to the difference between the modeled probability distribution and the actual firing points. Overall, the comparisons show generally good agreement considering the limited amount of the data collected.

Table 6-3. Measured L_{eqC} Values for AH-64 Gun Firings on Kilo Lane at Fort Rucker Range

	SLM 01	SLM 02	SLM 03	SLM 04	SLM 05	SLM 06	SLM 07	SLM 08	SLM 09	SLM 10
12-Jun	55.3	67.3	62.0		65.6	75.5	82.5		66.2	62.4
13-Jun		53.1	42.1		41.3	67.3	80.5		48.6	57.5
14-Jun	44.3	64.1	57.5		49.4	70.1	81.2	72.2	48.7	51.9
20-Jun		45.7		54.7		64.4	84.4	69.3	58.0	60.9
21-Jun		37.0	47.1	50.6	35.2	58.7	69.8	64.7	55.0	52.6

Table 6-4. Estimated L_{eqC} Values for AH-64 Gun Firings on Kilo Lane at Fort Rucker Range

	SLM 01	SLM 02	SLM 03	SLM 04	SLM 05	SLM 06	SLM 07	SLM 08	SLM 09	SLM 10
12-Jun	59.0	62.9	59.3		63.5	69.7	74.3		62.4	55.9
13-Jun		55.7	49.5		55.2	62.5	67.1		54.9	50.5
14-Jun	54.0	59.3	56.1		58.2	66.1	70.7	68.1	56.0	51.0
20-Jun		53.5		57.2		66.7	71.9	69.4	59.5	54.1
21-Jun		52.7	50.7	59.8	51.0	62.7	68.3	65.2	50.7	51.2

Table 6-5. Measured L_{eqC} Values for AH-64 Rocket Firings on Kilo Lane at Fort Rucker Range

	SLM 01	SLM 02	SLM 03	SLM 04	SLM 05	SLM 06	SLM 07	SLM 08	SLM 09	SLM 10
12-Jun	52.5	64.9	60.5		62.7	72.9	80.5		64.7	60.5
13-Jun		50.6	42.1		37.7	66.3	79.6		46.8	54.7
14-Jun	33.6	54.2	47.7		37.0	59.7	69.5	61.2	35.0	41.4
20-Jun	25.1	51.4		60.9		61.6	85.7	69.2	56.9	60.4
21-Jun		31.7	43.4	50.2	35.1	56.2	68.2	62.9	58.0	50.8

Table 6-6. Estimated L_{eqC} Values for AH-64 Rocket Firings on Kilo Lane at Fort Rucker Range

	SLM 01	SLM 02	SLM 03	SLM 04	SLM 05	SLM 06	SLM 07	SLM 08	SLM 09	SLM 10
12-Jun	47.5	50.7	47.1		51.5	57.5	62.2		50.9	45.2
13-Jun		48.0	43.5		48.9	54.6	59.4		47.5	42.0
14-Jun	43.5	47.5	44.3		44.7	54.3	58.9	56.3	45.4	41.2
20-Jun	32.2	44.6		49.8		52.7	61.3	58.4	47.6	44.2
21-Jun		42.2	42.0	49.0	39.7	50.4	57.3	54.0	39.4	40.7

6.1.2 Source Data Collection Protocol

The recommended methods for collecting and developing source noise data for air weaponry systems are described in Appendix B.

6.2 Modifying Propagation Algorithms

The final steps of the algorithm and model development are summarized in an invited paper presented at NoiseCon 2007, "Airborne Weapons Noise Prediction Model" (Ikelheimer et al, 2007). This paper is provided in Appendix C.

6.3 Incorporation into the New Noise Model

The integration of the new model for airborne weapons into a new version of the aircraft noise model being developed under SERDP project SI-1304 will be facilitated through BASEOPS, which is the user input module for NOISEMAP, RNM, MR_NMAP, and potentially the new aircraft noise model. From the user's perspective, airborne weapons are identified for further processing for the unique parameters required by the air weaponry noise model. The detailed calculations of the noise remain modular to facilitate updates and maintenance of the program.

6.3.1 Operation of the Air Gunnery Model

The Air Gunnery model is designed to allow a user to generate the noise contours from Air Gunnery Operations. This model calculates both the effects from the muzzle blast as well as the sonic boom from the projectiles. The model operates, in general, by using a statistical representation of likely firing volumes based on existing or planned attack runs on designated targets or target areas. While this model is capable of calculating the noise from a single weapon firing, it is better suited to predicting the overall noise contour from long-term use of a gunnery range.

The model consists of several different programs designed to operate together. The following is a complete list of the programs provided in the initial release:

- AG_BoomModel.exe,
- AG_DefineRun.exe,
- AG_FrontEnd.exe,
- Air_Gunnery_Model.exe,
- LayerBuilder.exe, and
- TargetBuilder.exe.

Each of these programs will be described in the following sections.

6.3.1.1 AG_BoomModel.exe

The AG_BoomModel program is designed to calculate the noise from the sonic boom from the projectiles. The noise algorithm itself is based on Carlson's simplified sonic boom theory (1978). It uses the projectile shape factor, length, and speed profile to calculate the footprint of the sonic boom.

The model operates by calculating the isopemp of the boom footprint on the ground, then interpolates the pressure values onto a regular grid for calculation of the noise contour. The program operates from the command line using the same input file as that used by the Air_Gunnery_Model.exe and is described more fully in Section 6.3.1.6. Since it operates from the command line, it can be run separately from any other aspect of the model (provided all of the input files are present).

The output from this model is an NMPlot grid file (*.grd) with the CSEL noise footprint and a separate grid file with the maximum peak overpressure.

6.3.1.2 AG_DefineRun.exe

The AG_DefineRun program provides a graphical user interface to help the user define a statistical volume for a firing profile. This module provides the user a way to see the firing line, target, and volume graphically. The program takes that information and generates a statistical volume. This volume is then separated into individual firing points. Each point is provided a statistical likelihood that a bullet was fired at that location. The total probability of the entire volume is defined as 1.00, making the likelihood that a bullet was fired somewhere within the volume 100%. The likelihood that a single bullet was fired at any one spatial location within the volume is less than 1.00, and is a function of where in the volume it is, and the definition of the distribution.

The AG_DefineRun program operates with anywhere from zero to three command line arguments. If no command line arguments are specified, then it is up to the user to define all aspects of the new probability file. The first command line argument specifies the initial probability file that the user edits. The second command line argument is the file name of the resultant probability file after editing. The third command line argument is the BaseOps *.run file name used to define the case. The AG_DefineRun program accesses this file to find the *.ops file, then uses that file to extract the flight track used for the attack run. The program next plots that flight track on the screen.

The output from the AG_DefineRun program is a probability file (*.prb). This file defines all aspects of the statistical firing volume and is the main input for both the Air_Gunnery_Model and the AG_BoomModel programs. This file defines the aircraft/munition combination, flight profile, and target, plus the elevation file, impedance file, target file, source file, and a background layer file. It also lists the location in X, Y, and Z of every firing point, as well as its probability.

The final line of the file specifies whether or not it has been run through the noise engine. If the last line is "Complete Noise Calculation!" then the noise footprint from this volume has been calculated and does not need to be recalculated (provided the other case parameters have not changed). If the last line is "Noise not computed yet!", then this probability file has not been run through the noise engine.

Using this program is fairly simple. When a case has been loaded, the user is presented with the following screen (Figure 6-2).

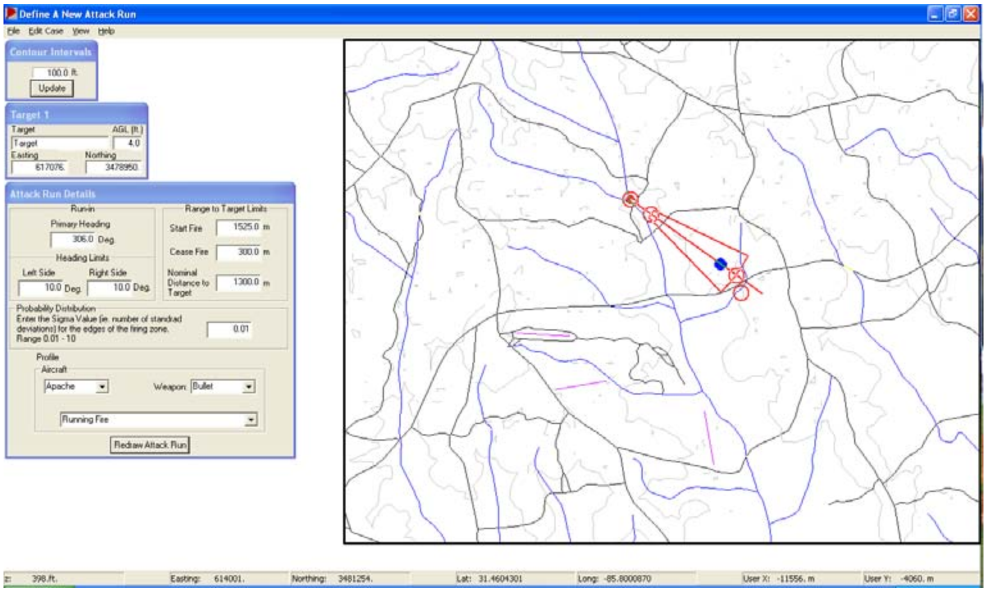

Figure 6-2. AG_DefineRun Main User Input Screen

On the right of the screen is the graphical representation of the firing profile. The red circles represent available targets, with the selected target filled with a red dot. The straight line through that circle shows the nominal flight path of the aircraft. The conical fan represents the ground footprint of the firing volume. The blue circle represents the nominal firing point. On the left are three different dialogs boxes.

The top dialog box allows the user to adjust the elevation contour intervals that are drawn on the screen. Simply change the number and click the 'Update' button to change to elevation intervals. The next dialog box shows the details of the selected target. No changes can be made to the selected target description, but selecting a different target updates this dialog box for the newly selected target. To select a different target the user should click inside the circle representing the target of choice. This automatically updates the target dialog.

The final dialog box, 'Attack Run Details,' is used to alter the parameters of statistical firing volume. The top left section is labeled 'Run-in' and is used to define the nominal direction the aircraft uses when approaching the target. The 'Heading Limits' section is used to adjust the left and right limits on the approach heading. For example, if there is a road to the left of an attack run, but open space on the right, the left angle limits may be kept close to the nominal heading while the right side limit could be further away from the nominal heading.

The 'Range to Target Limits' section is used to define the beginning and ending range for the firing area. These are the start and stop firing lines (or foul lines) for the selected target. In addition, there is a nominal range to target where the pilots are most likely to fire. This is shown on the screen with a blue filled circle. After changes have been made the user should press the 'Redraw Attack Run' button at the bottom of the dialog box to refresh the drawing of the statistical firing volume.

The 'Probability Distribution' section of this dialog box is used to define how tightly the firing is constrained within the firing volume. The distribution of the firing points within the volume is controlled by defining the standard deviation occurring at the edges of the volume. For example, if the "Sigma" value is set to 10.0, then the edges of the volume represents a level of 10 standard deviations. This would result in a majority of the firings to occur at, or close, to the nominal firing point (the filled blue circle). If, instead, this Sigma value is set to 0.01 then the firings would be uniformly distributed within the volume.

The last portion of the dialog box defines the aircraft type, firing profile, and weapon type. These are each selected from a pull-down menu. The data behind these pull-down menus is defined in a simple comma separated file within the 'Profiles' directory. More details about this file are presented in the next section.

The user can make some changes to the overall case by selecting the menu item 'Edit Case'. This brings up a dialog that allows the user to make changes to the Background Layer file (*.mrk) or the Target file. The background Layer file is the same as that used by NMSim (LayerBuilder.exe), and the program to alter the file is the same. The program to alter the Target file is TargetBuilder.exe and is described in the NMSim User Manual (Ikelheimer and Plotkin, 2005).

6.3.1.3 Profile.csv

The Profiles.csv file (located in the Profiles sub-directory) contains the details about each aircraft, the available profiles, and the available weapons and source files. The easiest way to edit this file is with a spreadsheet program. Care should be taken when altering this file as it is central to the operation of the Air Gunnery model.

Each aircraft has its own section. The section begins with a header line that is not read by the programs but aids when viewing or editing the file. The headings are 'Aircraft Name' and 'Number of Profiles'. The next line has the aircraft name, then the number of profiles to follow. The aircraft name should follow the same naming conventions used in BaseOps if a case is going to be developed from a BaseOps Case.

The next line is again a header line with the following titles: Profile Name, Min Angle, Max Angle, Min Altitude(m), Max Altitude(m). The next several lines (equal to the number of profiles defined earlier) provide details about each profile. First is a name, which provides a short description of the profile, followed by the minimum aircraft approach angle, then the maximum approach angle, the minimum altitude and the maximum altitude. If a given approach angle would put the aircraft outside of the limits defined in this sections, the program defaults to those limits.

The next line lists the number of weapons on the vehicle. This is simply an integer number, usually either 1 or 2. This is followed by the weapon definitions. The next line has either a 'Bullet' or 'Rocket' with a source file name next to it. The source file name should not have any path information as all source files should be placed in the 'Sources' sub-directory.

6.3.1.4 AG_FrontEnd.exe

AG_FrontEnd.exe is the initial user interface for the Air Gunnery Model. It is the starting point for creating new cases or importing cases from other sources. When the program is initially launched, it shows an empty grid similar to a spreadsheet as shown in Figure 6-3.

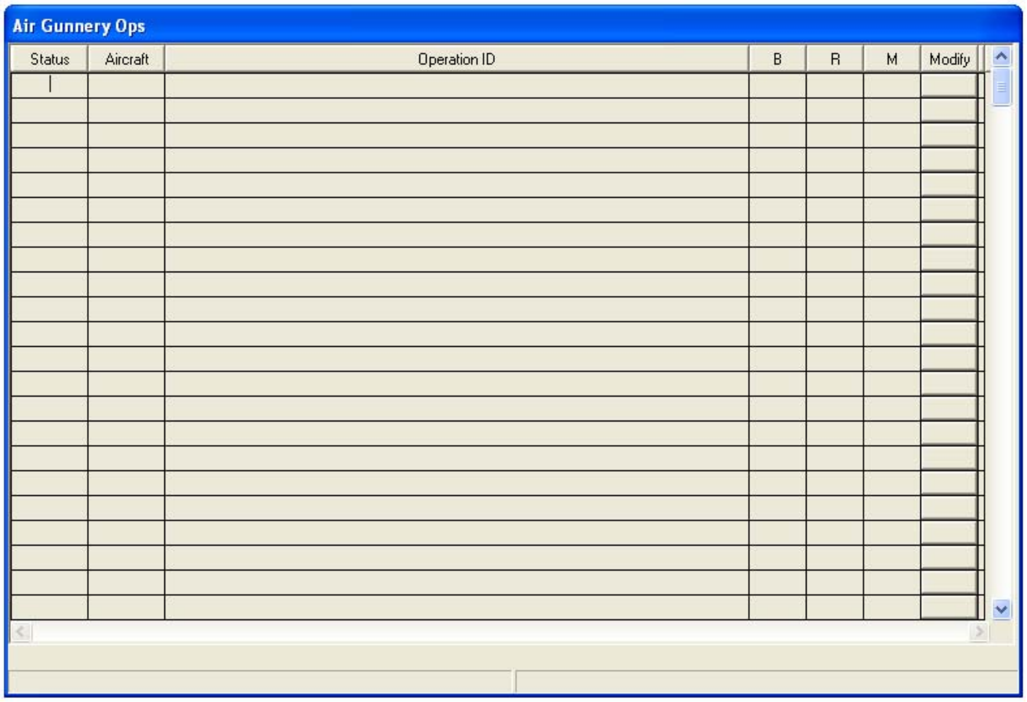

Figure 6-3. AG_FrontEnd Main Screen for User Editing of Case File

This is the main screen for viewing operational data. The headings provide details about each operation. The first heading 'Status' identifies whether this operations has had all changes completed for it and it is ready for computation. The 'Aircraft' heading shows which aircraft is associated with the operation. The 'Operation ID' provides a descriptive name for the operations. The 'B', R', and 'M' stand for Bullets, Rockets, and Missiles. These show the total annual numbers of rounds of each type fired on that operations. Finally, the 'Modify' button is used to drill down deeper at each operation and allows the user to edit some or all of the operational parameters. Clicking on any of the headings (with the exception of the 'Modify' heading) sorts all of the data contained in sheet by the elements in that column. Repeated clicking on the same heading alternates between an ascending and descending sort.

Clicking on the 'Modify' button brings up the following dialog box (Figure 6-4):

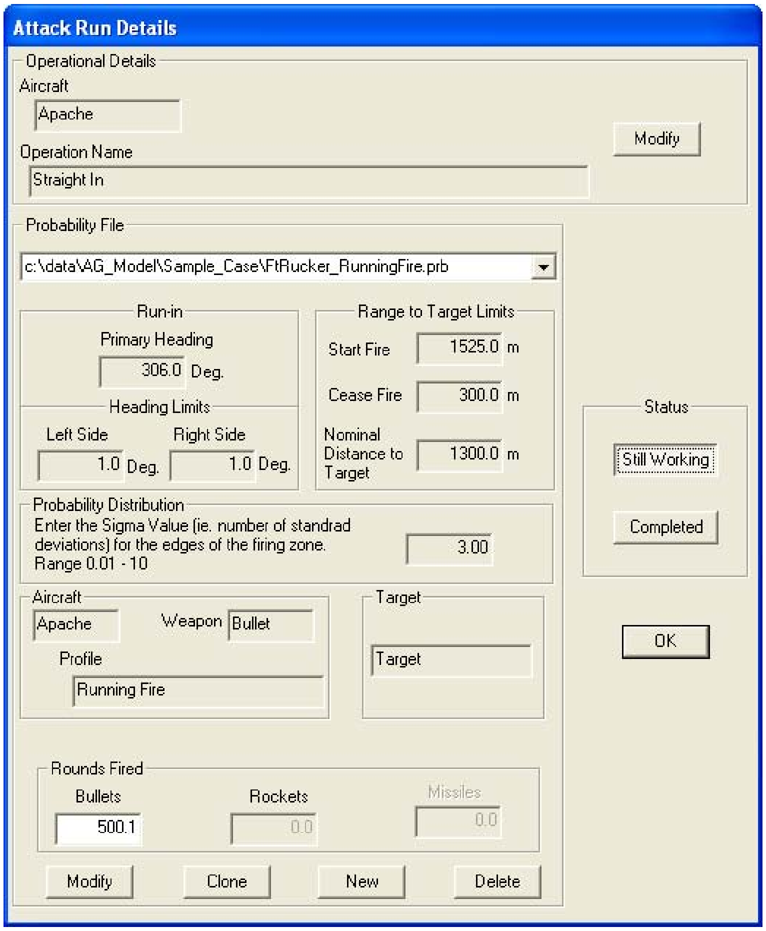

Figure 6-4. Modify Dialog Box for Defining Firing Profile

This dialog box lists the aircraft and operation name at the top. Clicking the 'Modify' button at the top allows the user to change the operation name. Below that is a pull down menu with all of the available probability files for that operation. Note that there can be several different probability files associated with any one operation. Selecting a given probability file updates the information in this dialog box and shows the parameters used to create the probability file. Below these properties are the numbers of bullets and rockets fired on this specific probability file. This can be changed by the user to reflect the actual number fired.

At the bottom of the dialog are four buttons: 'Modify', 'Clone', 'New', and 'Delete'. The 'Modify' button allows the user to make changes to the currently selected probability file. The 'Clone' button copies all of the parameters to a new, user defined file name and allows it to be edited. The 'New' button creates a new default probability file with a name defined by the user, and the 'Delete' button deletes that probability file.

To the right are the ‘Status’ section and the ‘OK’ button. Changing the status flag updates the ‘Status’ heading for this operation on the main screen, and clicking ‘OK’ returns the user to the main screen.

There are three menu options on the main screen: ‘File’, ‘Edit’, and ‘Calculate’. The ‘File’ Menu item is used to load a previously created Air Gunnery Case (*.agm), save a case, or import a case from another source.

There are two options for importing files. The first option is to import a BaseOps run file (*.run). The second option is to import a user created comma separated file (*.csv). For the *.run file, some changes must be made to the standard format to allow the Air Gunnery program to recognize specific operations as having weapons firing. These edits are defined more fully in the next section. If the user desires to import a user defined *.csv file, then the following format should be used.

The first line lists the total number of unique operations to follow. The next line defines the operation. The first item is the aircraft name, followed by a descriptive name of the operation, followed by the number of probability files associated with that operation, then the status of the operation. This final item is an integer used for identification purposes. 1 is used to define a case that has not been worked on at all, 2 is for cases that are being worked on, and 3 if for completed cases. This line defining the operation is followed by one line for each probability file associated with that operation.

Each line for a probability file first lists the complete path and name of the probability file, followed by the number of bullets, then the number of rockets associated with that file. An example file titled ‘FtRutger.csv’ is provided in the ‘Sample_Case’ sub-directory.

Under the ‘Edit’ menu item there are four additional options. These are to add an operation, delete a highlighted operation, change the cases temperature and humidity, or change the resolution of the calculation grid. Changes to temperature, humidity, or the grid density, require that the entire care be recalculated. If these elements are kept the same, and the only changes to the case are from the numbers of bullets or rockets fired, the program does not recompute the noise. Instead, it loads existing noise grids to conserve computation time.

Clicking the ‘Calculate’ button initiates the calculation routine and the user is prompted to define the output grid file name (*.grd). The program then creates the output file and run through all calculations. It also creates a log file in the same directory that shows any errors that occurred during the calculation procedure.

6.3.1.5 BaseOps RUN file (.run)*

In order to be compatible with a current military noise model, the current version of the Air Gunnery model is designed to be able to import an existing BaseOps case with a few important modifications. All changes are made to the *.ops file listed in the RUN file.

The first change is the addition of the Keyword ‘TARGET’. This keyword follows the exact same format as the ‘POINT’ Keyword, but provides the name and locations of the targets used in the gunnery operations. The next change is used to identify which operations have gunnery operations. At the end of the first line defining the operation, the name of the target for that operation is listed. The location for this depends on whether it is a fixed wing or a rotary wing operation.

For fixed wing profiles, following the FLIGHTPROF keyword, the definition line is as follows:

Column	Format	Description
1–10	A10	flight profile identification
11–20	A10	aircraft category (“BASED”, “TRANSIENT”, “CIVILIAN”, or “HELICOPTER”)
21–30	A10	flight aircraft ID
31–40	A10	pre-flight aircraft ID
41–47	Blank	
48–50	I3	pre-flight run-up duration (seconds)
51	Blank	
52–58	A7	“SECONDS”
59–60	Blank	
61–70	A10	power unit text
71-80	A10	TARGET name

For rotary wing profiles, following the ROTARYWINGPROF keyword, the definition is as follows:

Column	Format	Description
1–10	A10	flight profile identification
11–20	A10	aircraft category (“BASED”, “TRANSIENT”, “CIVILIAN”, or “HELICOPTER”)
21–30	A10	flight aircraft ID
31–40	A10	TARGET name

The program reads in these parameters and identifies which operations have gunnery operations. In addition, the program reads the temperature and humidity conditions for the case. The program then builds temporary probability files and a Target file for this case. Currently the program requires a valid Elevation and Impedance file be defined in the RUN file. When editing any of the probability files, the program will automatically import the correct flight track associated with the operation and display it on the screen.

6.3.1.6 Air_Gunnery_Model.exe

The Air_Gunnery_Model is the core calculation engine for determining the muzzle blast and propulsion noise. This program operates entirely from a command line. The command line argument is a control file that contains all of the information necessary to compute the noise from a single statistical volume.

The input file is fairly simple and is used for the muzzle blast calculation as well as for the sonic boom calculations. The first line lists the probability file of interest, with the fill path and proceeded by 18 characters (18x, a255), followed by the output file name, again with the full path and proceeded by 18 characters. Then the grid dimensions in the X and Y directions. In this case, they are integers preceded by 3 characters (3x,i4). Next is the temperature if Fahrenheit (5x, f5.1), then the relative humidity in percent (3x, f5.1), and finally the cutoff level (7x, f6.1).

This last level is used to reduce the computational load for large study areas. Any level that is estimated to be below the cutoff level is simply identified as -99.9 dB and no further computation is done.

The output is an NMPlot grid file that contains all of the information. It lists each of the firing points together with their probabilities, and it lists all of the Points of Interest.

6.3.2 Model Summary

The new model for air weaponry noise represents a novel approach for calculating the distinct noise produced by these operations. The modeling approach utilizes a statistical volume of space for determining the distribution of firing points, which follows the same guidelines used for weapon safety footprint analysis. The noise from this statistical volume is then computed and scaled for the actual number of bullets fired. By combining the results of individual firing profiles occurring at a range, it is possible to compute the airborne weapon noise contour for an entire range.

An important step in this modeling method involves calculating and storing the individual noise footprints from each firing profile. This allows the user to rapidly calculate the overall noise contour based on the number of rounds fired for each profile without having to do the costly noise calculations repeatedly. The result is a noise model that retains the detail and accuracy of a simulation model without having to spend the time for each noise calculation to be completed.

6.4 Other Activities

A final wrap up meeting for the project was conducted on 20 February 2008. The beta version of the model was delivered along with a discussion focused on the process forward to verify the model. U.S. Army Center for Health Promotion and Preventive Medicine will maintain technical oversight of the new model and explore approaches to integrate the model into its environmental noise program. The new model will also be presented to the DoD Noise Working Group to demonstrate its capabilities and the efforts required for approval of the model for general use among the services for their respective environmental noise analysis.

7.0 Conclusions

The findings from this projects field measurements represents a significant advance towards understanding the contribution of air-weaponry operations to the overall noise generated by DoD training operations. The field measurements have provided a firm technical foundation for the development of a new noise model for air weaponry noise. The new model represents a novel approach for calculating the distinct noise produced by these operations. The modeling approach utilizes a statistical volume of space for determining the distribution of firing points, which follows the same guidelines used for weapon safety footprint analysis. The noise from this statistical volume is then computed and scaled for the actual number of bullets fired. By combining the results of individual firing profiles occurring at a range, it is possible to compute the airborne weapon noise contour for an entire range.

An important step in this modeling method involves calculating and storing the individual noise footprints from each firing profile. Then allowing the user to rapidly calculate the overall noise contour based on the number of rounds fired for each profile without having to do the costly noise calculations repeatedly. The result is a noise model that retains the detail and accuracy of a simulation model without having to spend the time for each noise calculation to be completed.

The beta version of the air-weaponry noise model has been provided to the U.S. Army for their assessment and use. Along with the model, a source data collection protocol has also been provided. This protocol recommends the basic approach to collect and develop source noise data for other weapon system platforms, as well as interim methods to use until valid source data is collected.

The next step for this model is field validation of the model. This validation should include a mix of weapon systems and firing ranges so that the data input requirements and model output can be validated and the utility of the model demonstrated. The field measurements should include monitoring air-weaponry noise over a longer time period than was afforded in this project’s third field measurement.

Once this model has been validated, it will allow the DoD to more accurately estimate the noise environment from aircraft range operations and will provide a scientific foundation for range commanders in addressing criticisms from knowledgeable citizens on the appropriateness of these estimates. These tools will assist the DoD in being responsive to the requirements of the National Environmental Policy Act (NEPA), while protecting operational readiness from unreasonable restrictions based on today's limited knowledge of air-gunnery noise effects.

The next challenge is the development of methods to combine the effects from the different noise sources that occur on an air-weaponry training range. These different sources include aircraft noise, small arms, large weapons, and explosions. Currently, these different sources are treated separately in impact analysis, and neither procedures nor methods exist to combine their cumulative effects.

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APPENDIX A

Noise-Con 2007
Airborne Weaponry Noise Measurements

Reno, Nevada
NOISE-CON 2007
2007 October 22-24

Airborne Weaponry Noise Measurements [REVISED]

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ABSTRACT

Many aircraft noise models exist that estimate noise levels from military aircraft operations near airbases, along training routes, and within special use airspace, but these models do not include contributions to the noise by air gunnery and air fired missile operations. A new air-weaponry model is being developed to assess noise from these unique military operations. This paper describes the initial field measurements used to characterize air-weaponry noise sources and to evaluate propagation algorithms. Air gunnery noise data were collected from helicopter and fixed-wing aircraft operations. Missile launch noise data were collected from helicopter operations. For the air gunnery noise, important aspects of time-dependent waveforms and spectral descriptions for muzzle blasts and ballistic waves are discussed along with their directivity patterns. This analysis demonstrates that the positive impulse is the most stable metric for describing the muzzle blast. The peak is best for describing the ballistic wave; and the CSEL is best for the missile launch and thrust noise. For the propagation algorithm, the linear geometric theory of diffraction agrees well with the measured data. The development of an air weaponry model will be described in a companion paper.

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1. INTRODUCTION

A number of aircraft noise models have been developed over the past 30 years to estimate noise levels from military aircraft operations near airbases, along training routes, and within special use airspaces. Predictions from these models are used to assess the potential impact (community and environmental) of current and proposed flight operations. The U.S. Army has developed noise models for blast noise and supersonic shock waves generated by ground-based weapon systems. Current Department of Defense (DoD) noise models all use common aircraft and weapon system source noise databases, which are maintained by the Air Force Research Laboratory (AFRL), U.S. Army Construction Engineering Research Laboratory (CERL), and Navy Facilities Engineering Command (NAVFAC). However, neither the models nor the databases include the noise contribution from air-gunnery or aircraft missile firing operations.

A new model is under development to calculate the air-borne weapon noise generated by air-weaponry operations. The goal of this project is to produce an air-gunnery noise model that will calculate both the single event noise, as well as cumulative noise, and provide acoustic visualizations for both planners and the public. The basis of the model's calculations will be positive impulse, peak pressures, and spectral content, so that the various acoustical metrics can be used to assess potential impacts.

The main objectives of this tool development project include the following:

1. To characterize the noise generated by airborne weapon systems. This will include important aspects of time-dependent waveforms and spectral descriptions of the noise sources, along with their dynamic directivity patterns. The data will be compiled so that it can be integrated into the noise databases used in various DoD models. A protocol for collecting airborne weapons systems acoustics data will also be developed.
2. To evaluate and refine current weapon noise propagation algorithms for application to airborne platforms. Refinements to topography and atmospheric propagation models will be made and the model will be enhanced to include the spectral time history.
3. Incorporate refined algorithms and additional input requirements into the new advanced aircraft noise simulation model being developed under SERDP Project SI-1304.[1] This will allow a means of visualizing the noise exposure of military aircraft operations as an aid to noise assessment and mitigation.
4. Transition the new computer model to DoD users, such as AFCEE and NAVFAC, enabling new technology to be quickly utilized in the assessment of environmental noise impacts.

This paper focuses on the first objective of characterizing airborne weaponry noise.

2. MEASURED DATA

B-1 A. Measured Data

Noise source characterization will be based on actual field measurements of airborne weaponry operations. The characterization of air-gunnery noise is complex due to the existence of multiple, sometimes simultaneous, noise sources, such as muzzle, blast, ballistic wave, propulsion noise (missiles), explosive projectile or warhead noise, and aircraft noise.

The combination of these sources also depends on the aircraft platform. For this project, two field measurements were conducted. The first series of measurements involved firing of a 30 mm gun and, separately, training rockets from an AH-64 attack helicopter. Eighty-six gun firing runs and fifteen rocket firings were recorded for the AH-64 operations. The second series of measurements involved firing of the 30 mm gun from an A-10 fixed wing aircraft and a 20 mm gun from the F-16, also a fixed-wing aircraft. Twelve A-10 and fifteen F-16 strafing runs were recorded during this second series of measurements. An array of 30 microphones provided basic angular coverage of the measured air gunnery noise for the AH-64D gun firing and missiles noise. For the F-16 and A-10 measurements, an array of 22 microphones was used. Most of the microphones were ground mounted with a few mounted on poles 13 meters above the ground. To capture the high frequencies in the sonic boom and muzzle blast, acoustic data were collected using microphones with a frequency response of 5 Hz to 40k Hz and a dynamic range of 46 to164 dB. Data were recorded on a 24-bit data acquisition system at a rate of 96k samples per second.

A sample recording of an AH-64 gun firing event is shown in Figure 1. This event had the AH-64 helicopter firing its 30 mm canon in the forward firing position. For this run, 10 individual bullets were fired. In this figure, the top signal was recorded 365 meters forward of the firing point, the middle signal was recorded 90 meters forward of the firing point, and the bottom signal was recorded 60 meters behind the firing point. There is no sonic boom signature in the bottom signal, and, as expected, only the muzzle blast is seen. In the middle signal, the sonic boom and muzzle blast events overlap and have comparable peak overpressure values. At the furthest location (top), the sonic boom and initial muzzle blast are well separated, and the blast overpressures are significantly diminished.

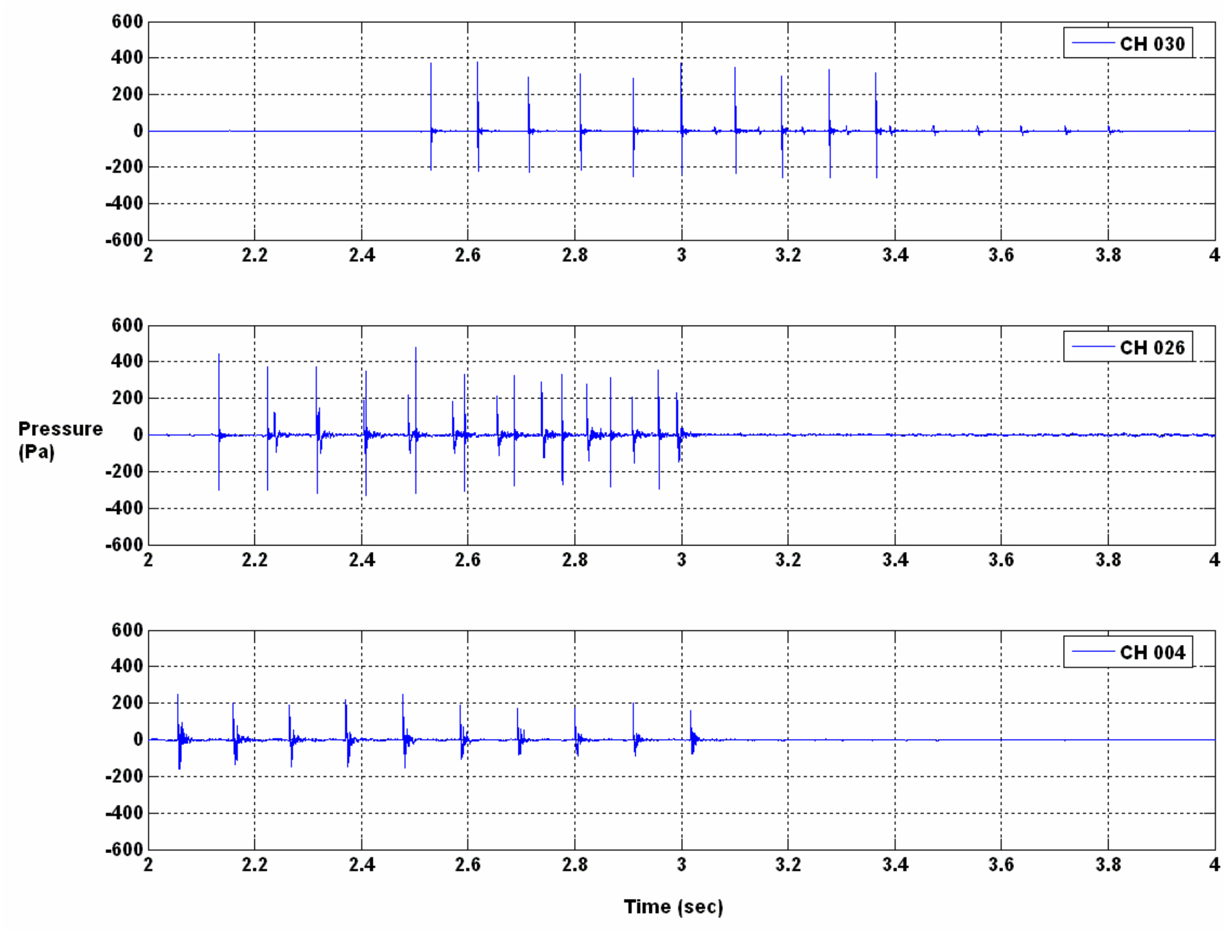

Figure 1: Sample pressure time histories for an AH-64 30 mm gun firing event.

Sample recordings of AH-64 rocket firings are shown in Figure 2, where the order of the plots is the same as in Figure 1. For the signal behind the firing point (bottom), the initial spike is the rocket ignition pulse. This is followed by the propulsion noise. In the middle plot, only the propulsion noise can be seen. In the top signal, the sonic boom is the first event occurring at 11.15s. The boom is followed by the propulsion noise and then the ignition pulse, which occurs at 11.30s. (Note that while the ignition overpressure travels at about the speed of sound, the missile and its propulsion system start out more slowly and pick up speed, reaching supersonic speed and over taking the overpressure pulse before reaching the location of microphone 30.)

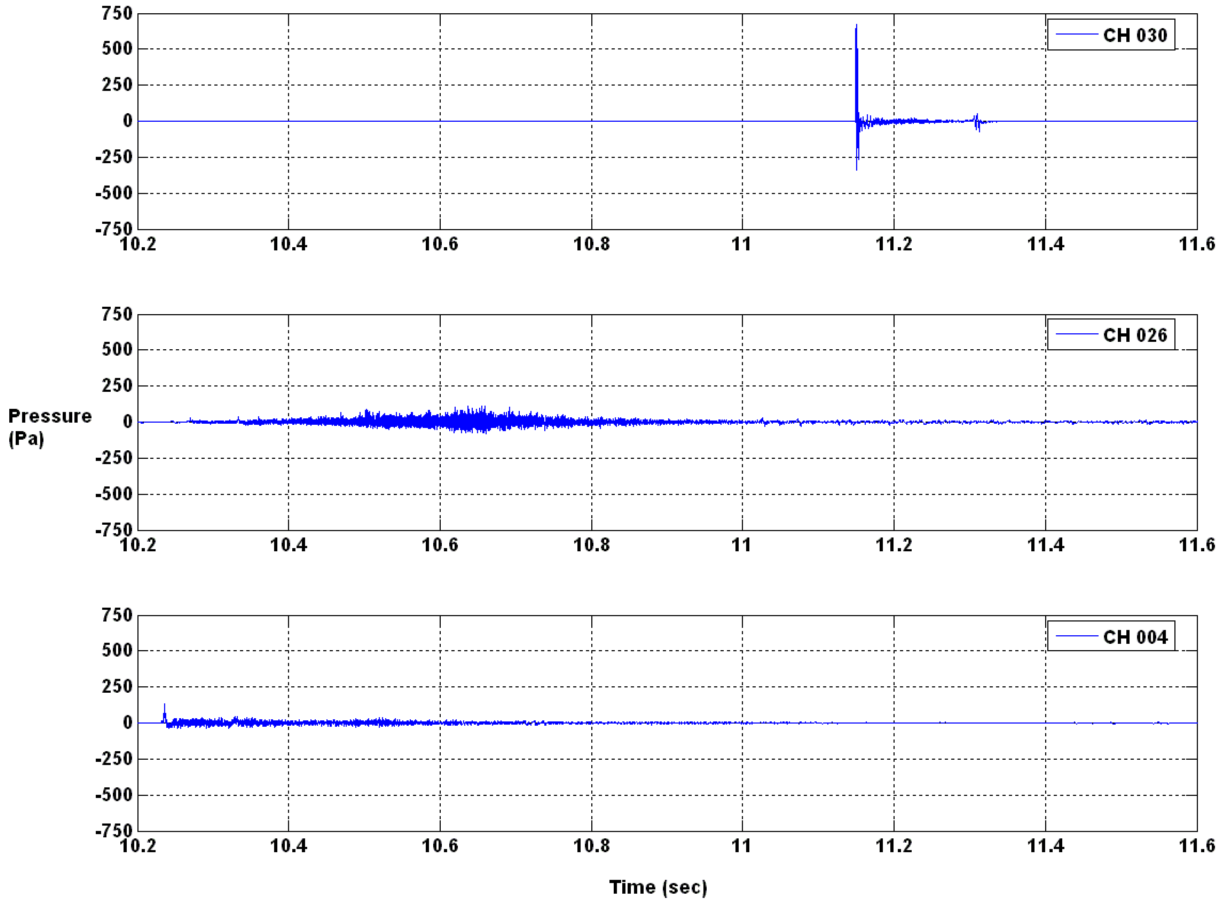

Figure 2: Sample pressure time histories for an AH-64 rocket firing event.

3. NOISE CHARACTERAZTION

B-2 A. Gunnery Muzzle Blast

For the analysis of the gun muzzle blasts, the time histories of all of the recorded data were analyzed to separate out the portions of the data where only the muzzle blast was recorded versus those where the sonic boom coincided with the muzzle blast. This separation results in the elimination of some muzzle blast data, but it is necessary because once the two signals are convolved it is impossible to evaluate them separately.

For this analysis, each muzzle blast waveform was quantified using several different metrics. The metrics included peak overpressure, sound exposure level, positive impulse, overall duration, and positive pulse duration. Historically, peak overpressure has been used to quantify the magnitude of the muzzle blast. However, using peak overpressure produced a wide scatter in the data, obscuring any possible trends. A more stable metric was determined to be the positive impulse, which involves integrating the pressure over the duration of the positive pulse. The identification of the positive impulse is shown graphically in Figure 3.

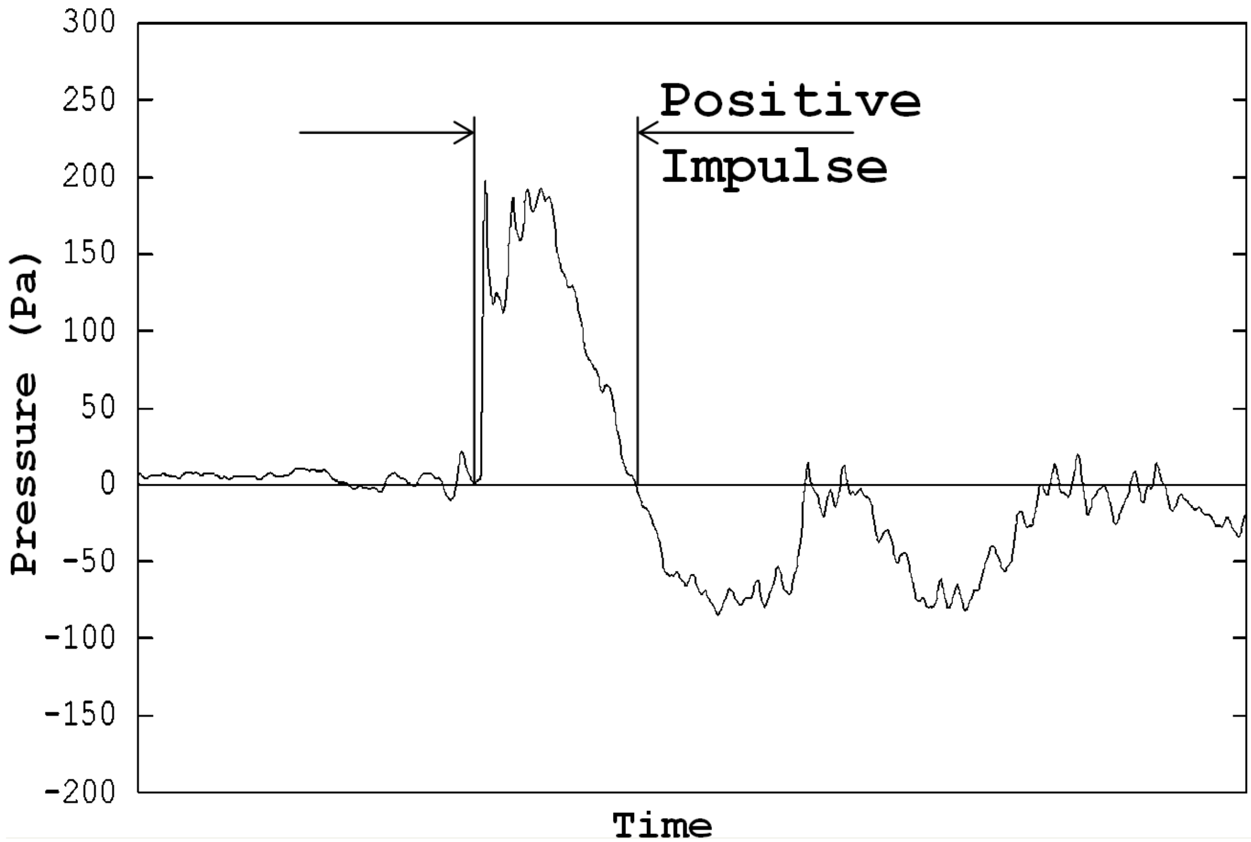

Figure 3: The identification of the positive impulse portion of a muzzle blast.

The positive impulse for each muzzle blast was calculated and used to determine the influence of directivity and aircraft operating state on muzzle blast noise levels. To isolate these trends, the acoustical data were normalized to eliminate known propagation effects. This normalization included the effects of spherical spreading, ground effects, and atmospheric attenuation. Once measurements were normalized for these propagation effects, general variations due to directivity and operating state can be evaluated. For this analysis, the coordinate system used in traditional aircraft noise models[2,3] is employed. Two angles are used to describe the directivity of the noise emissions. The angles are theta, θ, which describes the fore aft direction, and phi, φ, which describes the roll direction.

Once all of the muzzle blast data were normalized to one meter, the data were separated according to operating state (airspeed and firing altitude); but then no discernible differences could be observed between these groups. So, all of the data were analyzed together to determine one, composite directivity function. For each aircraft, the angular dependence is represented by a Fourier series approximation. For the AH-64 and A-10, the blast is symmetrical about the roll angle, φ, and is dependent on theta, θ. Thus, the Fourier series only has cosine terms. Estimates of the muzzle blast source positive impulse are obtained by combining the reference pressure with the angular dependence. The approximations of the AH-64 and A-10 muzzle blast are given in equations 1 and 2, respectively:

$$PI(\theta) = 60.0dB + \begin{Bmatrix} -0.895dB + 1.51dB\cos(\theta) - \\ 0.156dB\cos(2\theta) + 0.0144dB\cos(3\theta) - 0.0427dB\cos(4\theta) \end{Bmatrix} \quad (1)$$

$$PI(\theta) = 65.5dB - \begin{Bmatrix} -4.94dB + 5.80dB\cos(\theta) - 1.22dB\cos(2\theta) + \\ 0.566dB\cos(3\theta) - 0.348dB\cos(4\theta) \end{Bmatrix}, \quad (2)$$

where 0° < θ ≤ 180°. For the F-16, the blast is not symmetrical about the roll angle because of the placement of the gun port, which is on the left side of the fuselage underneath the cockpit. Thus, the Fourier series approximation of the F-16 includes both cosine and sine terms, as well as a dependence on roll angle, φ. The resulting approximation can be expressed

$$PI(\theta,\varphi) = 60.0dB + \begin{Bmatrix} -4.69dB + 6.51dB\cos\left(\theta\frac{\varphi}{|\varphi|}\right) - 1.62dB\cos\left(2\theta\frac{\varphi}{|\varphi|}\right) + 0.197dB\cos\left(3\theta\frac{\varphi}{|\varphi|}\right) - 0.337dB\cos\left(4\theta\frac{\varphi}{|\varphi|}\right) - \\ 1.61dB\sin\left(\theta\frac{\varphi}{|\varphi|}\right) + 0.291dB\sin\left(2\theta\frac{\varphi}{|\varphi|}\right) - 0.444dB\sin\left(3\theta\frac{\varphi}{|\varphi|}\right) + 0.185dB\sin\left(4\theta\frac{\varphi}{|\varphi|}\right) \end{Bmatrix}, \quad (3)$$

where 0° < θ ≤ 180°. These directivity models were used to predict positive impulse levels at each of the measurement locations and these predictions then plotted against the actual measurements. See Figures 4-6. It can be seen that the Fourier series model provides an excellent fit.

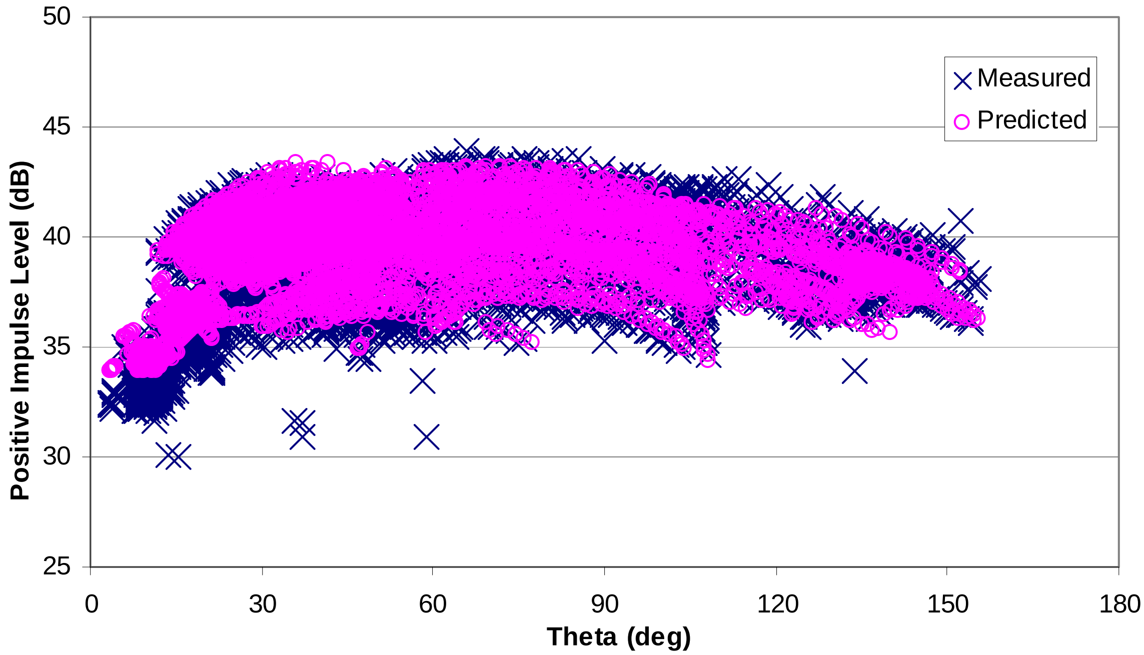

Figure 4: Predicted and measured AH-64 muzzle blast positive impulse plotted as a function of theta.

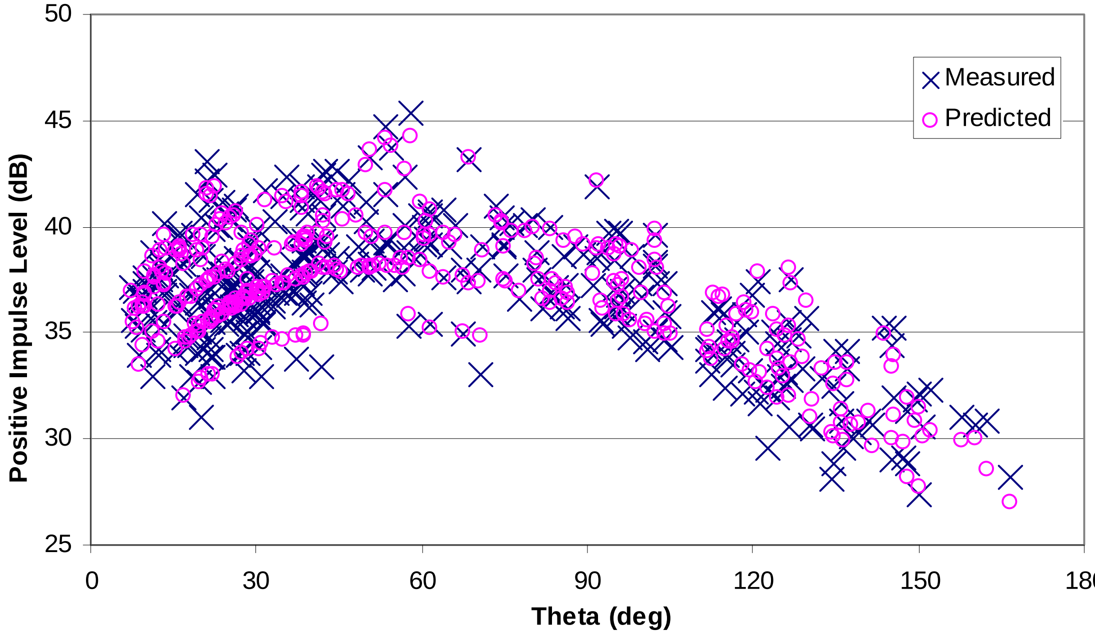

Figure 5: Predicted and measured A-10 muzzle blast positive impulse plotted as a function of theta.

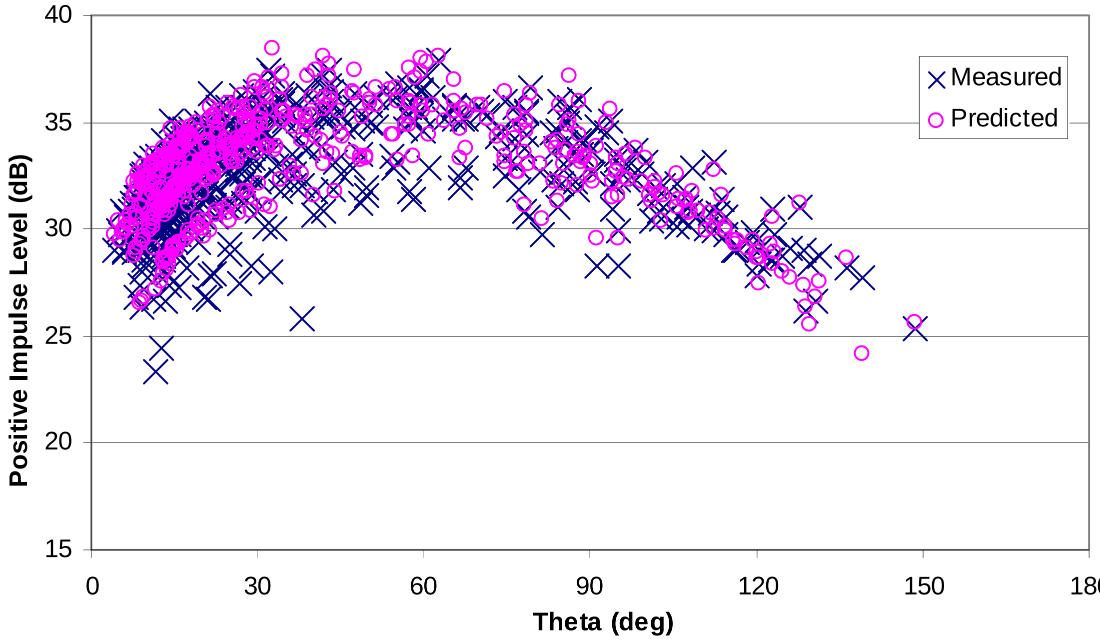

Figure 6: Predicted and measured F-16 muzzle blast positive impulse plotted as a function of theta.

Individual differences between predicted and measured impulse levels were examined in order to more precisely determine model accuracy. Five and ninety-five percentile bounds were defined, relative to the model estimate, as a function of theta for each aircraft/gun combination. These bounds denote values of positive impulse levels that equal or exceed 95% (or 5%) of the actual measured levels. See Figures 7-9. These plots show that 90% of the measured values for all of the aircraft/gun noise sources are within +/- 3 dB of the model estimates.

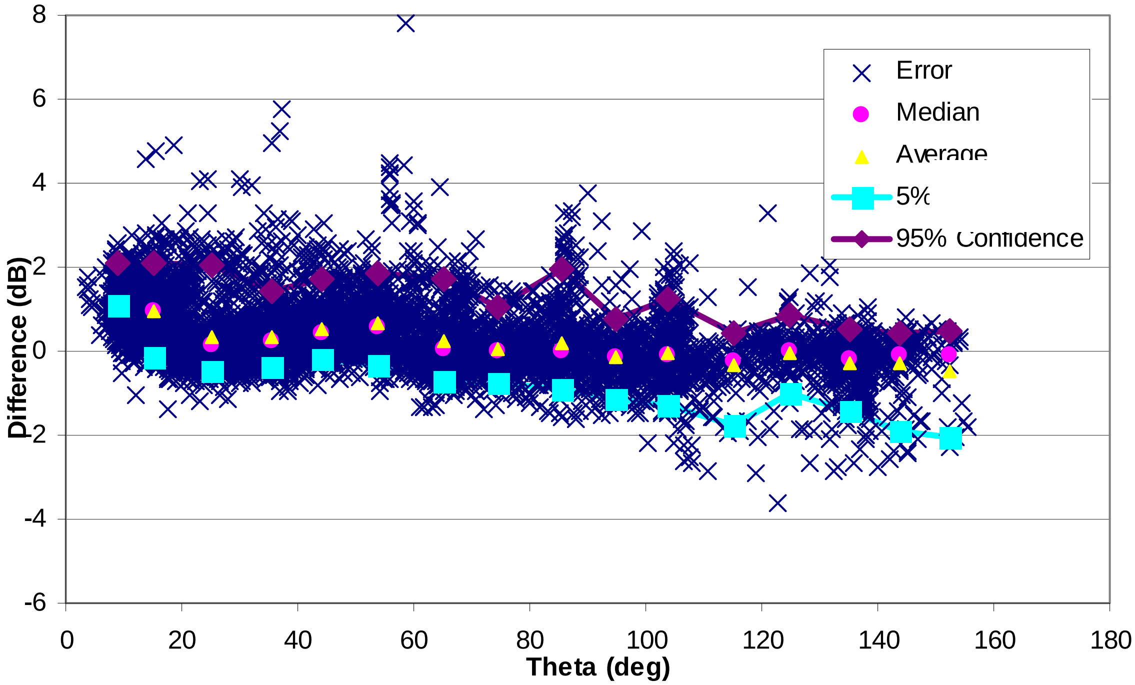

Figure 7. Differences between measured and predicted AH-64 muzzle blast impulse levels. Mean and median differences as well as 5% and 95% bounds are shown.

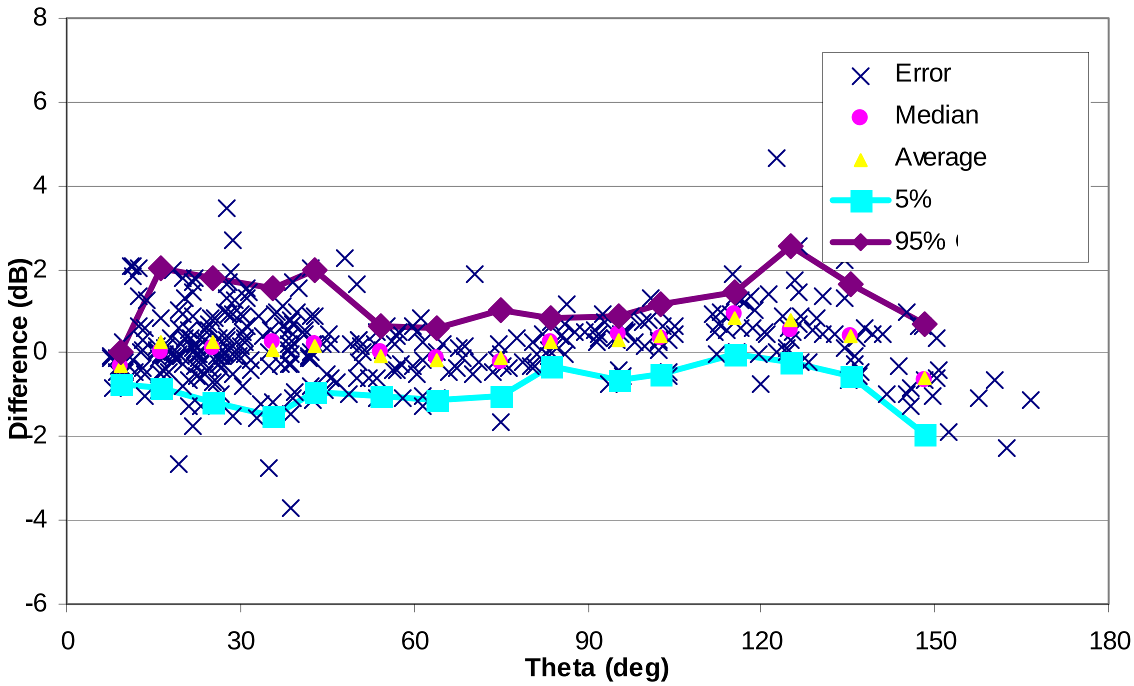

Figure 8. Differences between measured and predicted A-10 muzzle blast impulse levels. Mean and median differences as well as 5% and 95% bounds are shown.

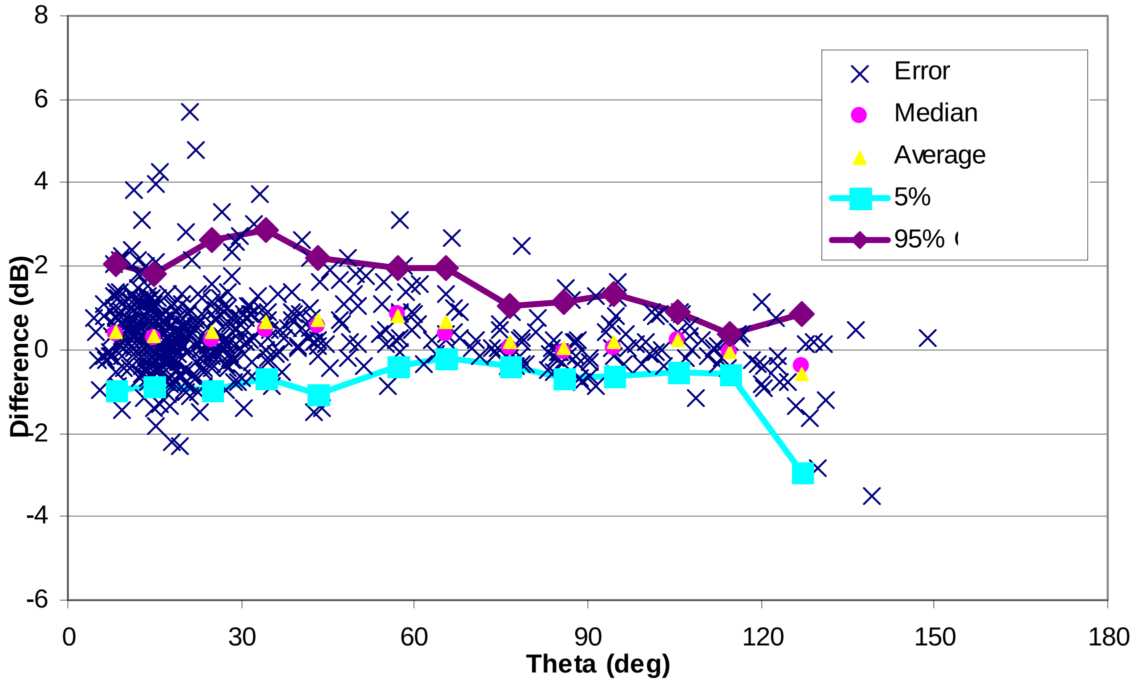

Figure 9. Differences between measured and predicted F-16 muzzle blast impulse levels. Mean and median differences as well as 5% and 95% bounds are shown.

B-3 B. Gunnery Sonic Boom

The bullets for all three aircraft/gunnery combinations travel at supersonic speeds, so that a sonic boom propagates to the ground forward of the firing point. The sonic boom from the projectile is referred to as the ballistic wave. For the AH-64, the ballistic wave of each of the bullets in a firing was identified. However, the rapid firing rate of the F-16 and A-10 guns resulted in greater overlapping of the individual muzzle blast waveforms, so the boom metrics were only calculated for the first and last ballistic waves in a firing. The metrics include peak overpressure, sound exposure level, positive impulse, and positive pulse duration. The measured data were compared to basic sonic boom theory[4.] The comparisons demonstrate good agreement with simple theory. Figures 10 and 11 show the comparison between measured and theory of peak overpressure and duration, respectively for AH-64 gun firings. These comparisons demonstrate that simple sonic boom theory will work for air gunnery operations.

B-4 C. Missile Noise

Analysis and characterization of the various components of the helicopter launched missile noise (ignition overpressure, propulsion, sonic boom) is difficult, because: for locations relatively close to the launch, the ignition over-pressure pulse and the subsequent propulsion noise overlap, while for the measurement locations farther away and in the firing direction, the signal is dominated by the sonic boom. Only initial results are available for the helicopter launched missile noise. Measurements were made for static firings (helicopter in hover) and for firings in forward flight; but only static firing measurements and analysis, results are presented here.

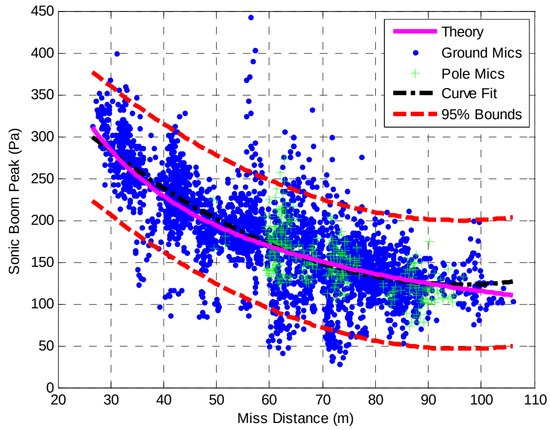

Figure 10. Forward fire, ballistic wave peak overpressure of AH-64.

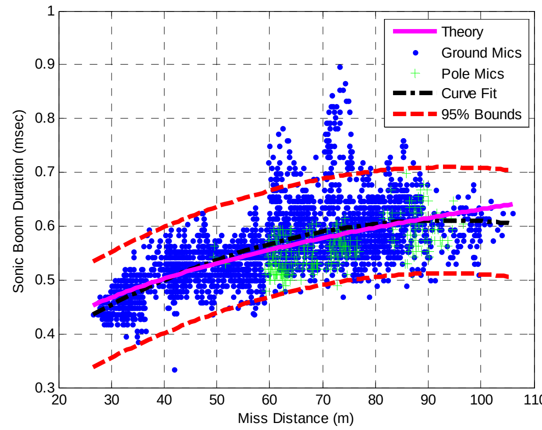

Figure 11. Forward fire, ballistic wave positive pulse duration of AH-64.

Figure 12 shows one of the boom signature recorded at the most distant measurement location. The first positive impulse is the boom from the leading edge of the missile. The rear missile shock (starting just after 11.151 s in the plot) is nearly lost in the positive impulse generated by the expanded plume. The rocket exhaust pressure is much greater than atmospheric, so that the plume expands rapidly downstream of the nozzle exit plane.

As a first cut at characterizing the noise at locations close to the firing location (i.e., those without sonic booms), un-weighted, C-weighted, and A-weighted "event" SELs were calculated. For the SEL calculations, the 10 dB down time period was determined from running rms levels (0.1 sec linear average, 90% overlap) for each recording. Figure 13 shows an example of rms levels and the 10 dB down time period. Once the SELs were calculated, they were normalized to 1 meter and examined for directivity effects. Figure 14 shows the theta dependence of the SELs, which reflect both ignition and propulsion noise. The source noise defined by CSEL is defined by the following equation:

$$CSEL(\theta) = 153dB + \{-0.0903dB - 1.18dB\cos(\theta) - 4.40dB\cos(2\theta) - 0.104dB\cos(3\theta) - 1.12dB\cos(4\theta)\}$$

for $0° \leq \theta \leq 180°$.

4. SUMMARY

An extensive database of air-weaponry noise data has been collected with the goal of creating a new environmental noise model. Four weapon systems were measured: the 30mm gun and Hydra 70 rocket on the AH-64 helicopter, the 30 mm gun on the A-10 and the 20 mm gun on F-16. A wide range of metrics were examined to determine which would be best suited for modeling. For gun fire, the positive impulse was selected as the most stable metric and useful for modeling. For each of aircraft gun combinations, a Fourier curve fit for directivity was created that accurately recreated the measured muzzle blast noise. The sonic boom from the gun fire was also examined. A simplified sonic boom model developed by Carlson was provided a good fit to the measured peak overpressures, as expected. Finally, the noise from rocket fire was examined in an initial step, and it was observed to have some complex features such as the ignition noise and sonic boom. In the initial analysis, ignition and propulsion noise were combined in an event SEL and a directivity pattern was developed. The sonic boom is composed of two basic N-waves and will required modifications to Carlson's model for proper characterization of a rocket's sonic boom signatures.

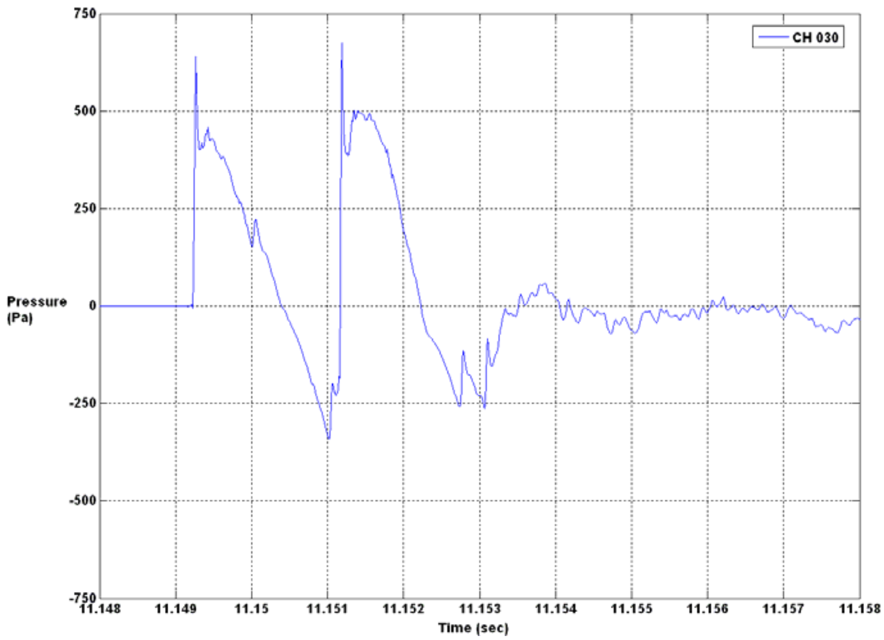

Figure 12. Sonic boom waveform for AH-64 training missile.

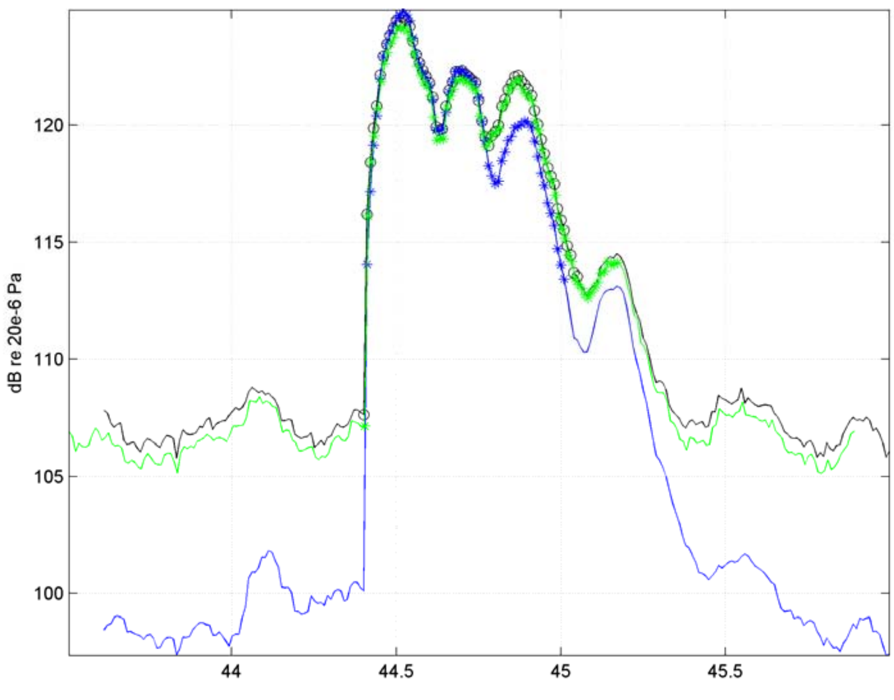

Figure 13. Rms (0.1s with 90% overlap) SPL for ignition and propulsion noise for an AH-64 missile firing. The black line is the un-weighted SPL, green is the C-weighted, blue is A-weighted. Symbols are used to show the 10 dB down time periods.

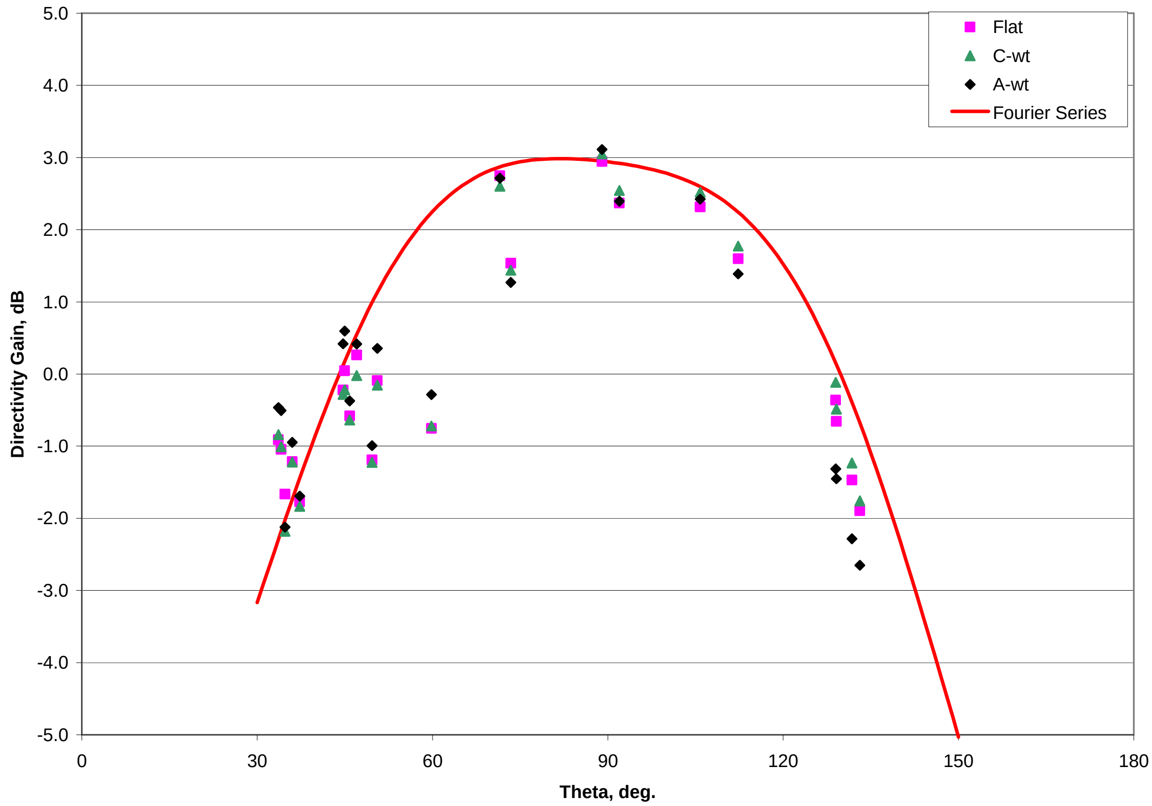

Figure 14. AH-64 missile ignition and propulsion noise directivity gain factor.

ACKNOWLEDGEMENTS

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APPENDIX B

Airborne Weaponry Source Noise Data Collection Protocol

Airborne Weaponry Source Noise Data Collection Protocol

1.0 Introduction

A major issue of concern to the Department of Defense (DoD) is the impact of noise from military operations on local communities and the environment. Consequently, the DoD supports the continuing development of the science of noise impact analysis and the application and implementation of scientific principles in environmental impact analysis. These development efforts have resulted in the DoD being in the forefront of the scientific community, as well as the general public, in increasing the understanding of noise and its impacts. Part of this ongoing support lead to a coordinated DoD noise program that is described in DoD Instruction #4715.13 (DoD, 2005).

A number of aircraft and ground-based weapon system noise models have been developed over the past 30 years to estimate noise levels from military operations. The results of these models are used to assess the potential for community and environmental impacts from current and proposed operations. Current DoD noise models all use common aircraft and weapon system source noise databases maintained by the Air Force Research Laboratory (AFRL), U.S. Army CERL, and Navy Facilities Engineering Command. These models and the source noise database do not provide the capability to assess noise impacts due to air-borne weapon operations. A new computer model has been developed to model air weaponry noise. One of the key components for the new model is accurate characterization of the noise source. During the development of the model, four noise sources were measured and characterized. The following noise sources were characterized:

AH-64: 30 mm gun,

AH-64: training rocket,

A-10: 30 mm gun, and

F-16: 20 mm gun.

Lessons learned from these measurements have been used to develop a recommended approach for collecting additional source data from other air weaponry. This technical report focuses on the data collection procedures required to characterize noise generated by air weaponry training operations and the use of interim source data.

2.0 Procedures Used in Model Development

2.1 AH-64 Measurements

The field measurements with an AH-64D were conducted in cooperation with U.S. Army Garrison Fort Rucker on 7 and 8 February 2005. These measurements included gun and rocket firing over a 3D measurement array of 30 microphones. For this series of measurements, the focus was on muzzle blast, projectile sonic boom, and rocket noise. The test included 86 gun firing runs and 15 rocket firings. The array was designed to capture the angle variation of the muzzle blast for proper source characterization as well propulsion noise from the rocket. The array was composed on 30 microphones as shown in Figure 2-1.

Twenty-six microphones were mounted on the ground and four microphones were mounted 39 ft. above the ground. Figure 2-2 shows a ground and pole mounted microphones used for both the helicopter and attack aircraft tests. Figure 2-3 shows the field layout for the hover, diving and running fire test runs, and Figure 2-4 shows the field layout for the side fire test runs.

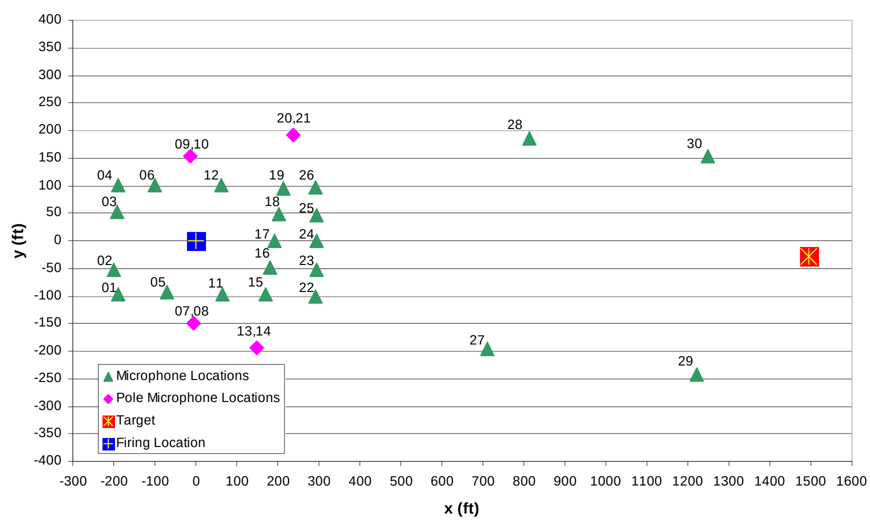

Figure 2-1. Schematic of Helicopter Gunship Measurement Array Layout with Firing and Target Points

Figure 2-2. Photographs of Microphone Placement in the Field: Ground-based (left) and Pole-Mounted (right)

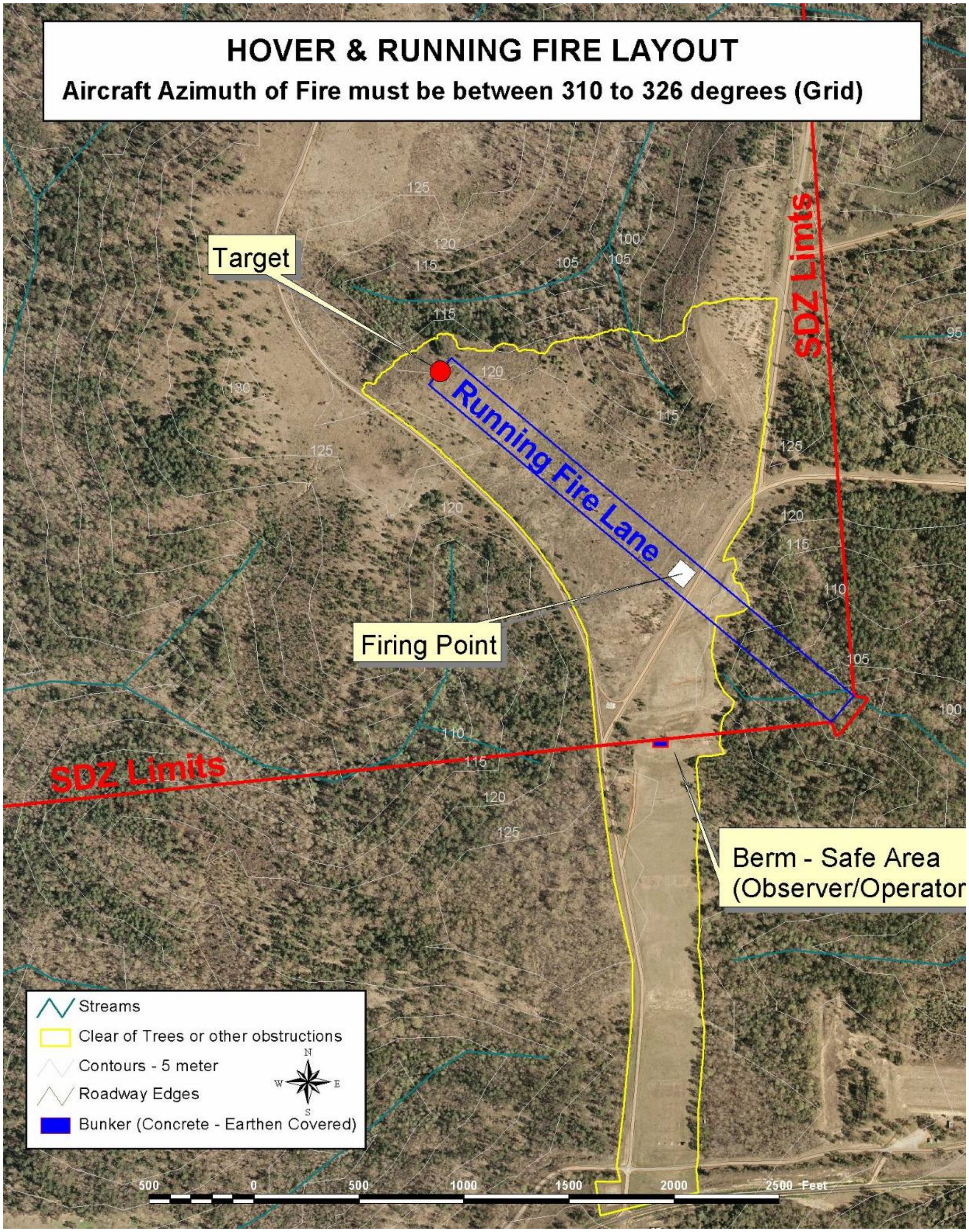

Figure 2-3. Field Layout for Hover, Diving, and Running Fire Test Events

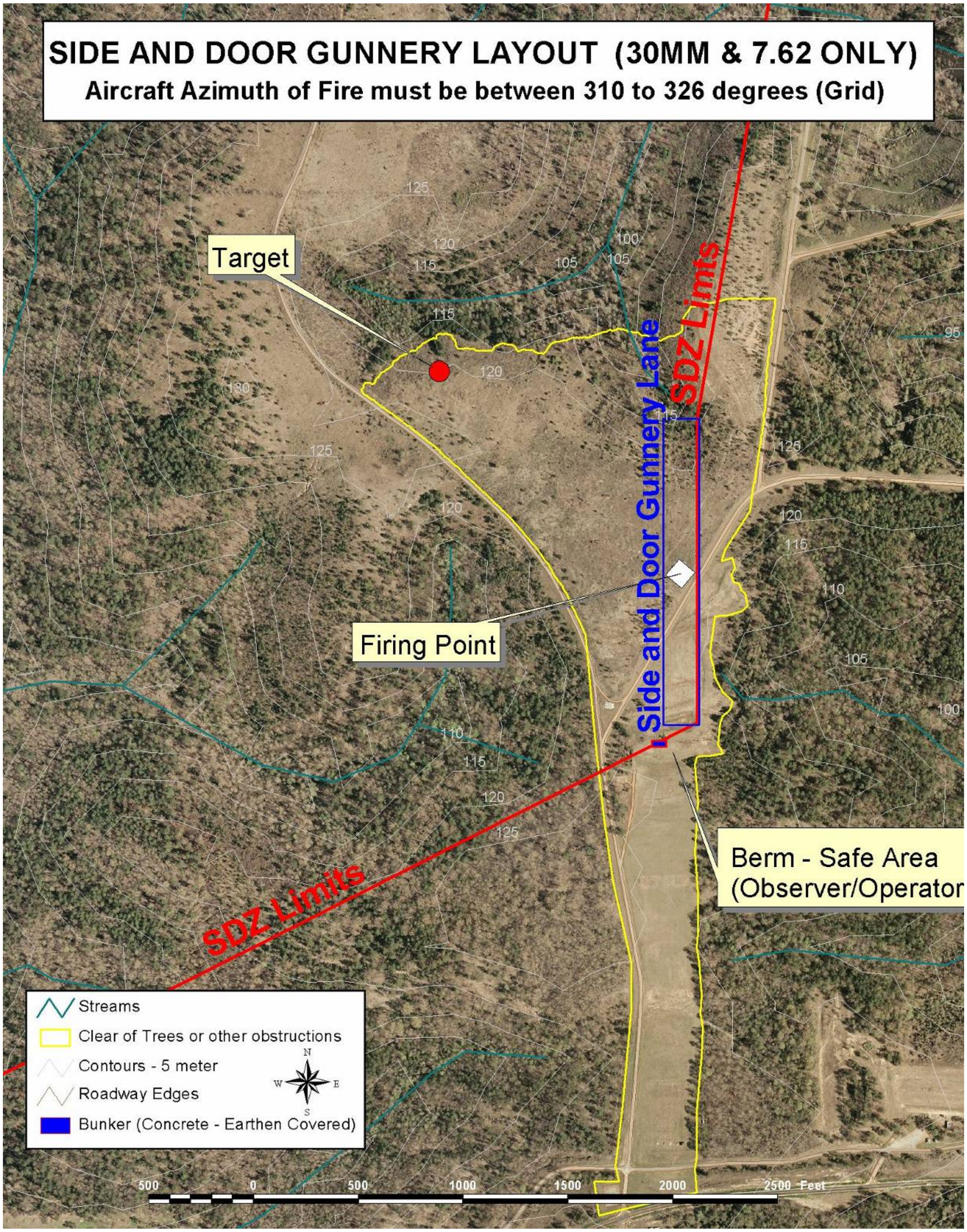

Figure 2-4. Field Layout for Side Firing Test Events

The measurement array, with microphones behind, beside, and in front of the firing, provides good coverage of the directivity pattern of the muzzle blast. This coverage is demonstrated in Figure 2-5, which shows the angular resolution of the array based on the designed firing point.

The measurement points downrange of the firing point capture the sonic boom footprint and rocket propulsion noise.

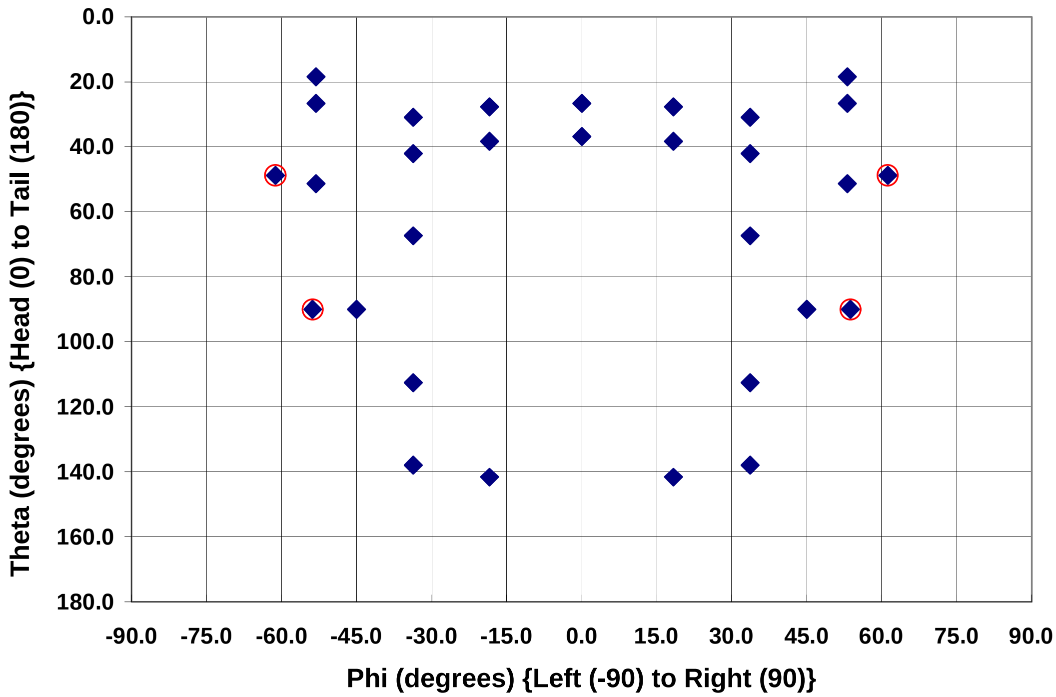

Figure 2-5. Angular Coverage of Muzzle Blast from Microphone Array

During the test, we were able to measure the firing of MK66 training rockets and 30mm M788 target practice rounds. From this test, the most stable physical measure of the blast signature was the Positive Impulse (PI) as shown in Figure 2-6. The PI data exhibited less scatter than the peak pressure and integrated Sound Exposure Levels (SEL) data. Thus, the analysis used the PI level to characterize the directivity pattern of the muzzle blast. For the 30 mm, M788 target round the following directivity pattern was determined for the reference PI at 1m:

$$PI(\theta) = 60dB + \begin{Bmatrix} -0.895dB + 1.51dB\cos(\theta) - \\ 0.156dB\cos(2\theta) + 0.0144dB\cos(3\theta) - 0.0427dB\cos(4\theta) \end{Bmatrix} \quad for\ 0° \le \theta \le 180°,$$

where θ is the fro to aft angle and the reference PI is 60 dB re 20µPa•s.

This pattern only has fro to aft angular dependence with no rotation dependence. For other metrics, simple correlations were used to relate their values to PI. For example, the C-weighted SEL (CSEL) was determined by correlating the measured CSEL values with their corresponding PI values as shown in Figure 2-7 which provided the following correlation function with PI level:

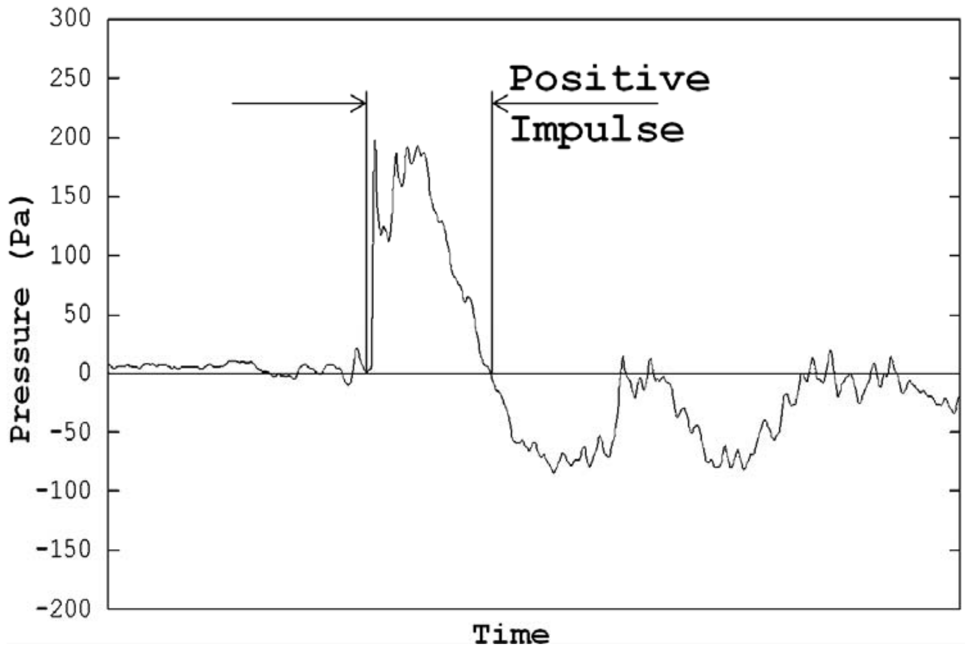

Figure 2-6. The Identification of the Positive Impulse Portion of a Muzzle Blast

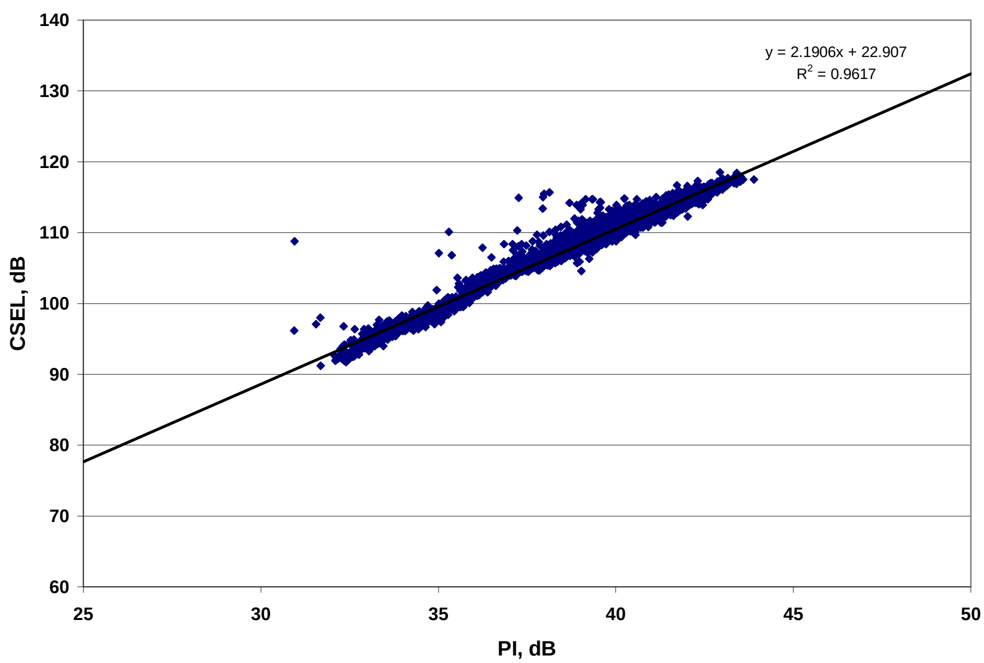

Figure 2-7 CSEL Correlation with PI for AH-64 Muzzle Blast

The training rocket firing noise was found to be most appropriately characterized by CSEL due to a complication resulting from a convolution of the ignition noise with the propulsion noise. At most, of the measurement points the ignition noise was obscured by the propulsion noise because of the fast acceleration of the rocket. Thus, for the rocket noise characterization, both the ignition and propulsion noise are included in the CSEL. If this convolution leads to inaccurate *results, further work will be required to separate these two unique noise sources. Using this approach, the following directivity pattern was found for the rocket firing noise:*

$$CSEL_{rocket}(\theta) = 134\ dB + \begin{Bmatrix} -0.0903\ dB - 1.18\ dB\cos(\theta) - 4.40\ dB\cos(2\theta) - \\ 0.104\ dB\cos(3\theta) - 1.12\ dB\cos(4\theta) \end{Bmatrix} \quad for\ 0° \le \theta \le 180°.$$

For sonic boom, the measurements agree with simple theory as expected. For the model, Carlson's Simplified Sonic-Boom Prediction algorithms were applied (Carlson, 1978). Figure-2-8 shows the comparison of the bullet sonic boom peak overpressure for predicted and measured values. Figure 2-9 shows the same comparison for the boom durations. Both of these figures demonstrate that Carlson's algorithms will work for this model.

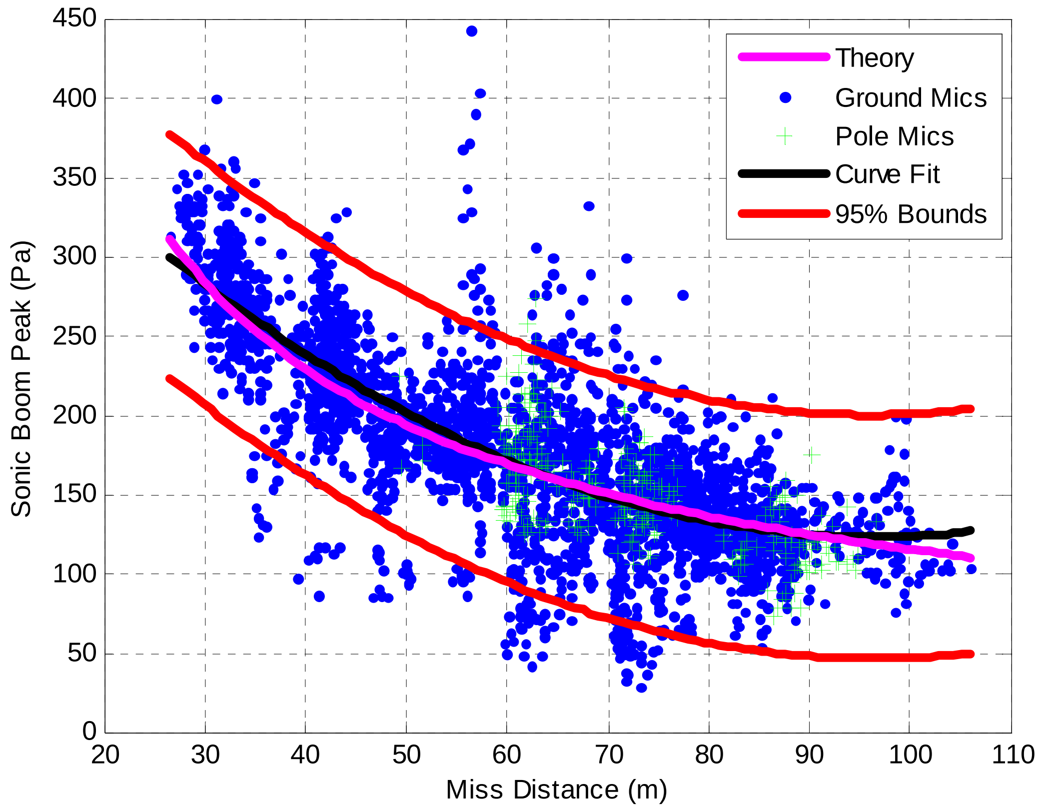

Figure 2-8. Comparison of Sonic Boom Peak Overpressure Between Predicted and Measured Values for 30mm Bullet from AH-64

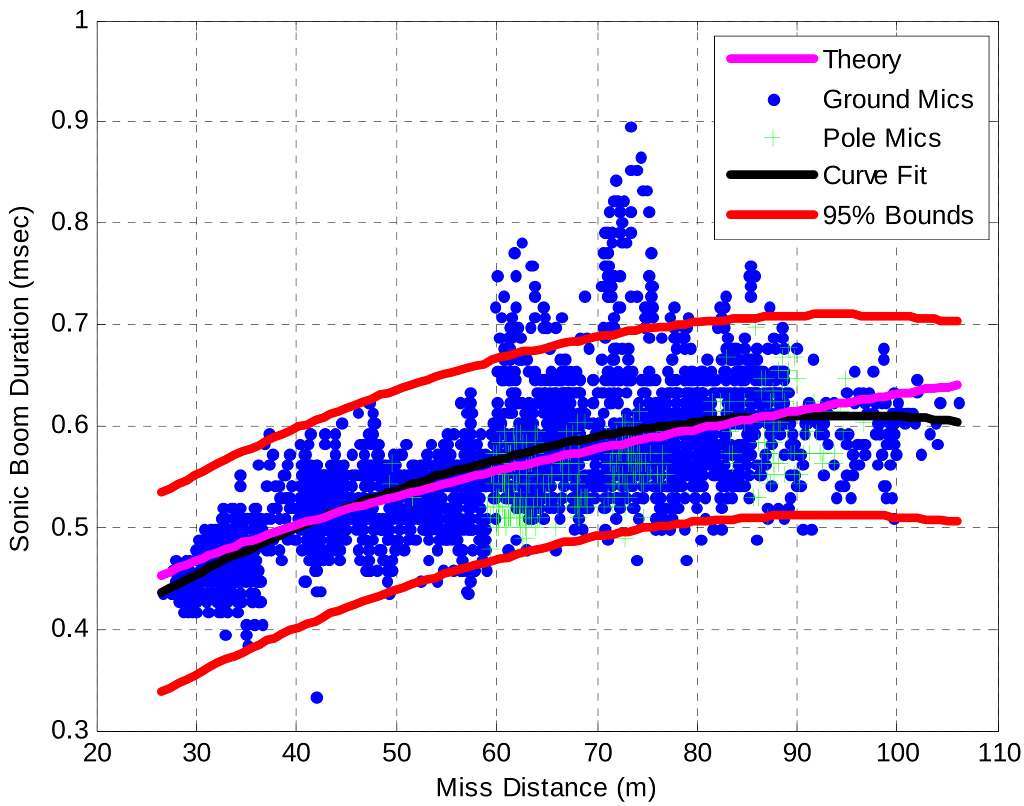

Figure 2-9. Comparison of Sonic Boom Durations Between Predicted and Measured Values for 30mm Bullet from AH-64

2.2 Fixed-Wing Aircraft

The field measurements of strafing runs by F-16 and A-10 aircraft were conducted in cooperation with National Guard Grayling Range on 28 and 29 June 2005. For this series of measurements, the focus was on strafing noise. The test included 15 strafing runs from an F-16 and 12 runs from an A-10. For this measurement, the array had a larger area to account for the variations in firing location because of the higher speed of the fixed-wing aircraft. The array was composed of 22 microphones as shown in Figure 2-10. Eighteen microphones were mounted on the ground and four microphones were mounted on 39 ft. poles.

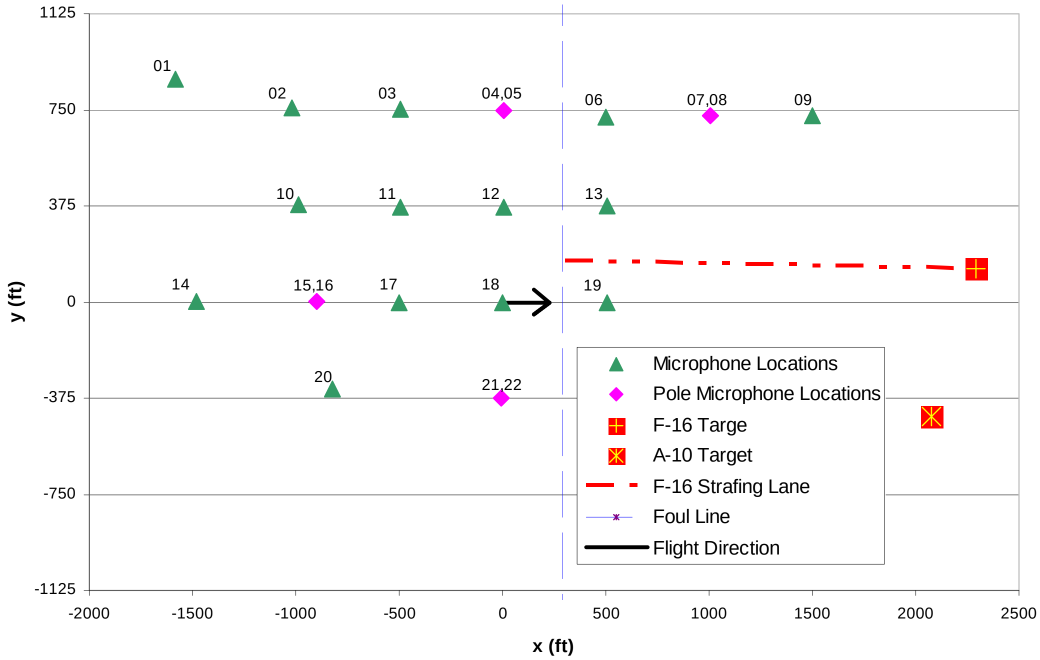

Figure 2-10. Measurement Array for Attack Aircraft Gun Noise

For this series of measurements, the focus is on muzzle blast and the effects of higher airspeeds. The test operations were low angle strafing with variations in pilot technique providing variation in altitude. For the A-10 muzzle blast, the directivity pattern for PI at 1m is the following:

$$PI(\theta) = 65.5dB - \begin{Bmatrix} -4.94dB + 5.80dB\cos(\theta) - 1.22dB\cos(2\theta) + \\ 0.566dB\cos(3\theta) - 0.348dB\cos(4\theta) \end{Bmatrix} \quad for\ 0° \le \theta \le 180°.$$

This pattern is also symmetric about the roll axis (left to right). For the F-16, the directivity is complicated by the placement of the muzzle relative to the aircraft. The muzzle is on the left side of the fuselage below the cockpit. This placement results in some differences in the roll axis. However, based on the measurement this dependence is fairly simple and is provided by the following equation:

$$PI(\theta,\varphi) = 60.0dB + \begin{Bmatrix} -4.69dB + 6.51dB\cos\left(\theta\frac{\varphi}{|\varphi|}\right) - 1.62dB\cos\left(2\theta\frac{\varphi}{|\varphi|}\right) + 0.197dB\cos\left(3\theta\frac{\varphi}{|\varphi|}\right) - 0.337dB\cos\left(4\theta\frac{\varphi}{|\varphi|}\right) - \\ 1.61dB\sin\left(\theta\frac{\varphi}{|\varphi|}\right) + 0.291dB\sin\left(2\theta\frac{\varphi}{|\varphi|}\right) - 0.444dB\sin\left(3\theta\frac{\varphi}{|\varphi|}\right) + 0.185dB\sin\left(4\theta\frac{\varphi}{|\varphi|}\right) \end{Bmatrix} \quad for\ 0° \le \theta \le 180°,$$

where φ is the roll angle with negative φ to the left and positive φ to the right. This pattern is compared with the normalized measured values in Figure 2-11.

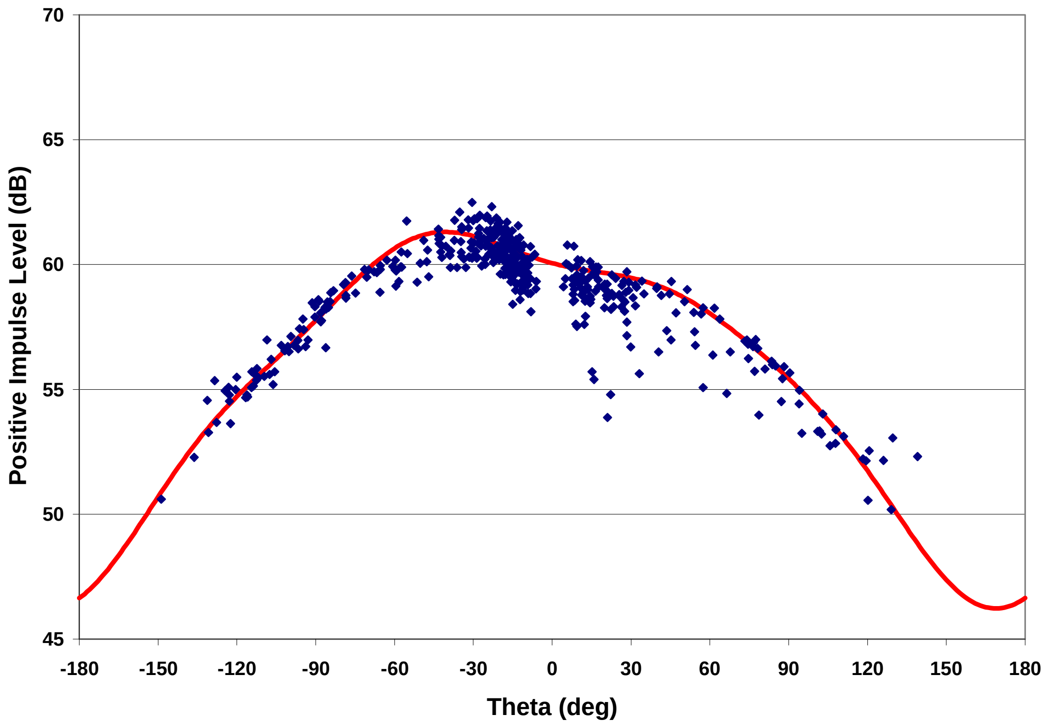

Figure 2-11. Positive Impulse Directivity Pattern for the F-16 20 mm Gun, Where the Dots Represent Normalized Measured Values and the Line is the Fourier Series Curve Fit

2.3 Lessons Learned from Field Measurements

Overall, the field measurements provided sufficient data to describe the muzzle blast and sonic booms for gun firing and provided data to determine the proper propagation algorithms to be incorporated into the air weaponry noise model. For the rocket noise data, two of the sources (ignition and propulsion) are convolved but separating them may not be required for environmental noise analysis. Three major lessons were learned from the measurements. The first one is more measurements need to be collected behind the firing points since this direction is the primary concern for U.S. ranges. The second lesson is the mounting of the microphone up high to avoid ground effects for the measurements and record free-field signals. The third lesson is the requirement for detailed tracking data to significantly reduce data processing time and uncertainty.

2.3.1 Rear and Lateral Measurement Points

For the first lesson, Figures 2-1 and 2-10 show that most of the measurement points were forward of the firing point. These points were selected primarily to collect data for evaluating propagation algorithms. For source noise, data the measurements need to concentrate on the rear and lateral portions of the noise source.

2.3.2 Elevated Microphones

For the second lesson, Table 2-1 provides a comparison between the measured values of the collocated microphones (one on the ground and the other elevated 39 ft. off the ground). The elevated microphone recorded a free field signature with no ground effects, whereas the ground signature is expected to have pressure doubling. For PI is pressure doubling is expected to be 3 dB. However, as noted in Table 2-1, the average differences are 2.8 to 2.7 dB with large standard deviations ranging from 0.6 to 1.5 dB. To avoid the complication of ground effects on the recorded signatures, it is recommended that the microphones are elevated above the ground in order to record free-field waveforms.

Table 2-1 Comparison of Free-field versus Ground Values for Muzzle Blast Measurements

Aircraft	Average Differences (dB) [Ground - Free-field]	Standard Deviation of Differences (dB)	Number of Comparison Points
AH-64	2.8	0.6	626
A-10	2.8	1.5	37
F-16	2.7	0.9	64

2.3.3 Determination of Firing Point Location

The third lesson involves the processing required when detailed tracking and firing data is not available. In our field measurements the limited tracking and timing data collected by the aircrews was insufficient to resolve the firing accurately. Two approaches were tried to resolve the firing points: video and acoustical triangulation. The video method is not useable because of the wide field of value required. The acoustical triangulation method provided an accurate answer, but it required significant processing time.

The measured acoustical data were used to determine the firing locations for each pass because of the lack of detailed tracking data from the test aircraft. Acoustical triangulation was used to identify the actual firing location of the gun muzzle. Two types of signals were recorded by the microphone array: a ballistic wave and a muzzle blast. The ballistic wave is due to the sonic boom from the bullet, and the muzzle blast is the acoustic wave produced by release of the gasses propelling the bullet from the chamber. For microphones behind and beside the firing point, only the muzzle blasts are recorded. For microphones in front of the firing point, the ballistic wave and muzzle blast waveforms were recorded. For these points, the ballistics wave will occur first and the muzzle blast second. The time separation in the two waveforms depends on both forward and lateral distance from the firing point. Examples of the recorded waveforms from a gun firing are shown in Figure 2-12. The top recorded signature is a muzzle blast that was recorded by a microphone located behind the firing point. The bottom signature includes both a ballistic wave and a muzzle blast that was recorded in front of the firing point. In this signature, the N-wave shape is the bullet's sonic boom generated by its supersonic velocity. The duration of the ballistic wave is approximately 1 ms. The muzzle blast signature, which arrives later than the ballistic wave, has the initial shock front with a more rounded shape and longer duration of approximately 3 ms. For microphones close to the firing point, the ballistic and muzzle blast waveforms overlap.

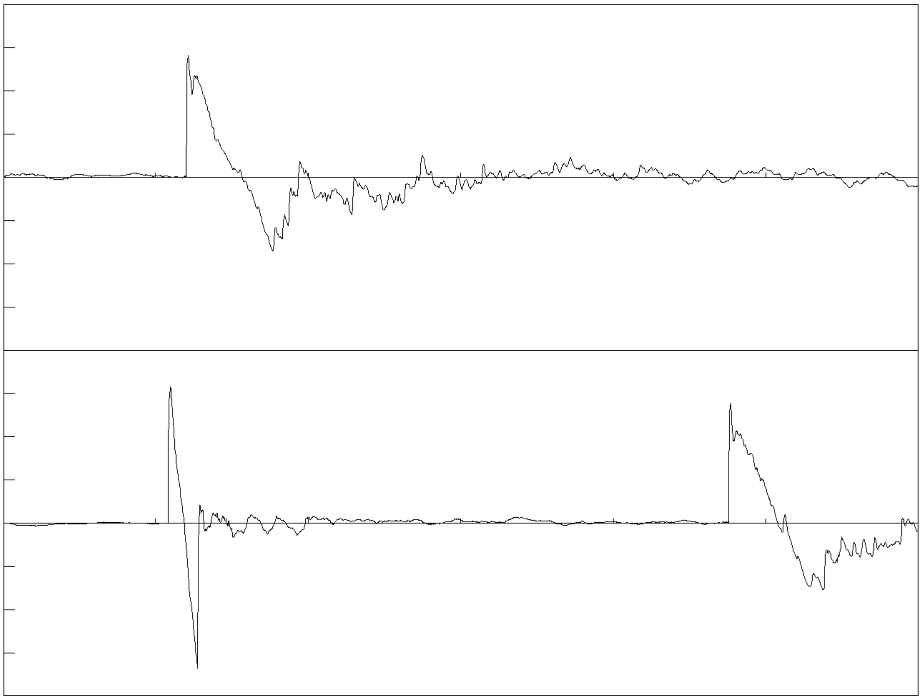

Figure 2-12. Examples of Recorded Signatures From AH-64D Gun Firing

For the acoustical triangulation calculation, the front shock of the recorded muzzle blast was used as the timing event since the muzzle blast propagates at the speed of sound from the firing point. In the calculation, a box of grid points is centered on the suspected firing point with one-meter spacing along each of the box's axes. For each grid point, the theoretical difference in arrival times for all pairs of microphones was compared with the measured differences in arrival times at these same microphones. Figure 2-13 shows a schematic of this geometry. The mean and standard deviation of the absolute comparisons were calculated for all. The grid point with the lowest standard deviation was deemed the best estimate for the actual location of the muzzle when the weapon was fired.

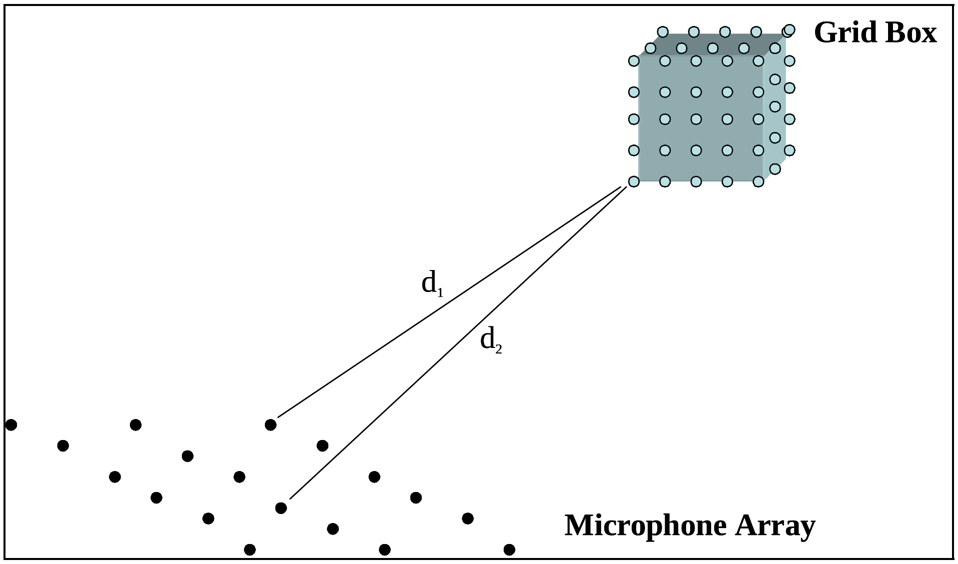

Figure 2-13. Geometry of Acoustical Triangulation Calculation

For this process, each individual front shock of a muzzle blast had to be identified for each recorded signature. For one firing event, consisting of ten shots, this process required the inspection and identification of up to 1200 waveforms. Clearly, this was a time consuming process. Moreover, from the preliminary assessment of the triangulation approach, it was found that the acoustical triangulation calculation was sensitive to small variations in the time identification of the front shock of the muzzle blast. These time variations may have resulted from distorted signatures, atmospheric turbulence and/or marking errors. As a check on this variation, if any calculate versus measured arrival time difference was greater than 0.01 seconds, then that difference pair was flagged for further inspection. This inspection would determine whether one or both of the arrival times noted for the microphones were too distorted and were in error. If any adjustment was made to either arrival time identification, then the triangulation was recalculated for that firing point.

To determine whether this method of picking the minimum standard deviation was finding either global or local minima, the standard deviations for the entire box of grid points were plotted and contoured for visual inspection. Figure 2-14 shows the surface contours for the calculated standard deviation. As one can see, the contour values decrease as their enclosing surfaces approach the smallest standard deviations. This indicates that the procedure was localizing on a global minimum for the firing point solution.

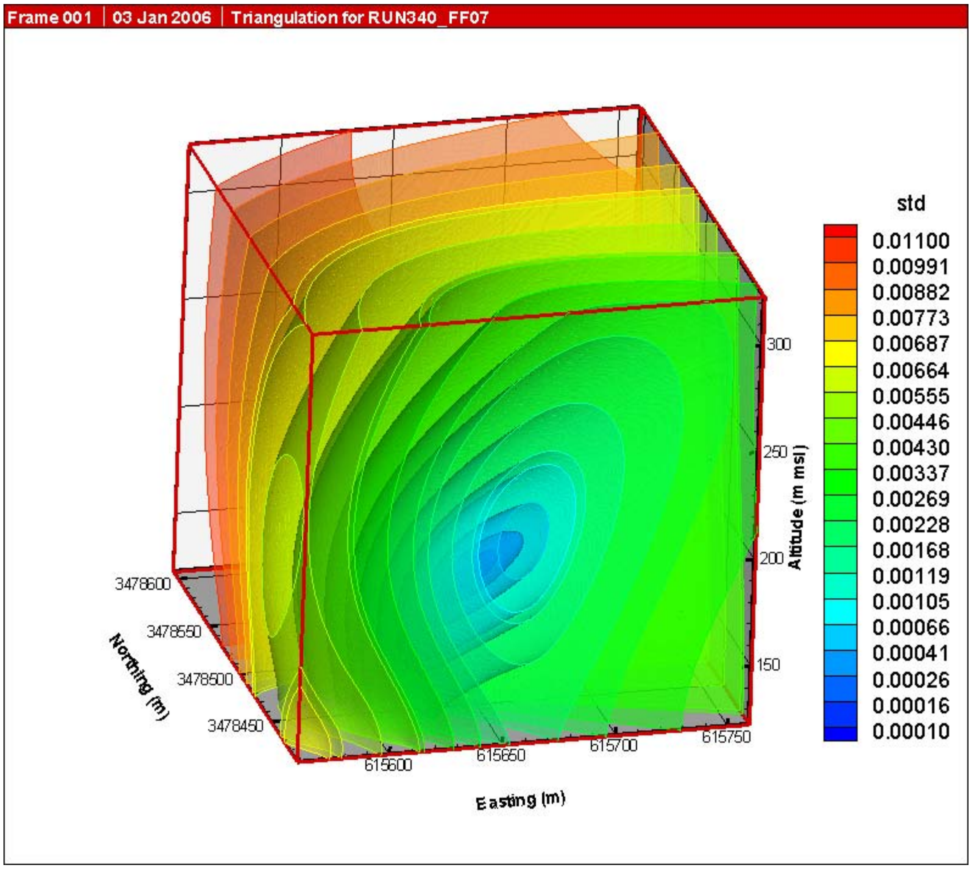

Figure 2-14. Three-dimensional Surface Contours on the Standard Deviation of the Arrival Time Comparisons.

Using this process, the best-fit firing points were determined for at least two test runs for each test condition. With the firing point identified within a reasonable fidelity, the recorded waveforms can be analyzed to determine directivity effects from airborne weapons systems.

Thus, if no detailed tracking and timing data are available for future source data collection, then the above processing method can be used.

3.0 Recommend Approach

From the findings of our initial research, collecting air weaponry source noise is straight-forward. A simple test matrix is required for the data collection and the data analysis is basic. The first requirement for the data collection is an open flat area for the measurement array. The second requirement is obtaining repeated firings of the air weapon of concern (here the understanding of the air weapon includes the airframe and munition combination). The third requirement involves the data acquisition system used to measure the acoustical data.

3.1 Measurement Array

The measurement array needs to concentrate on the rear portions of the firing noise since this is the primary concern of range noise impacts. The array also needs to be symmetric about the firing line to verify left/right symmetry in the emitted noise. The primary focus is the muzzle blast for gun fire and propulsion noise for rockets/missiles. Thus, a recommended array is shown in Figure 3.1. This array is composed of 31 microphones with 22 at or behind the planned firing point. For the microphone mounting, it is recommended that the microphones be elevated at least 30 ft. so that free field waveforms can be obtained and ground effects can be avoided in the data analysis.

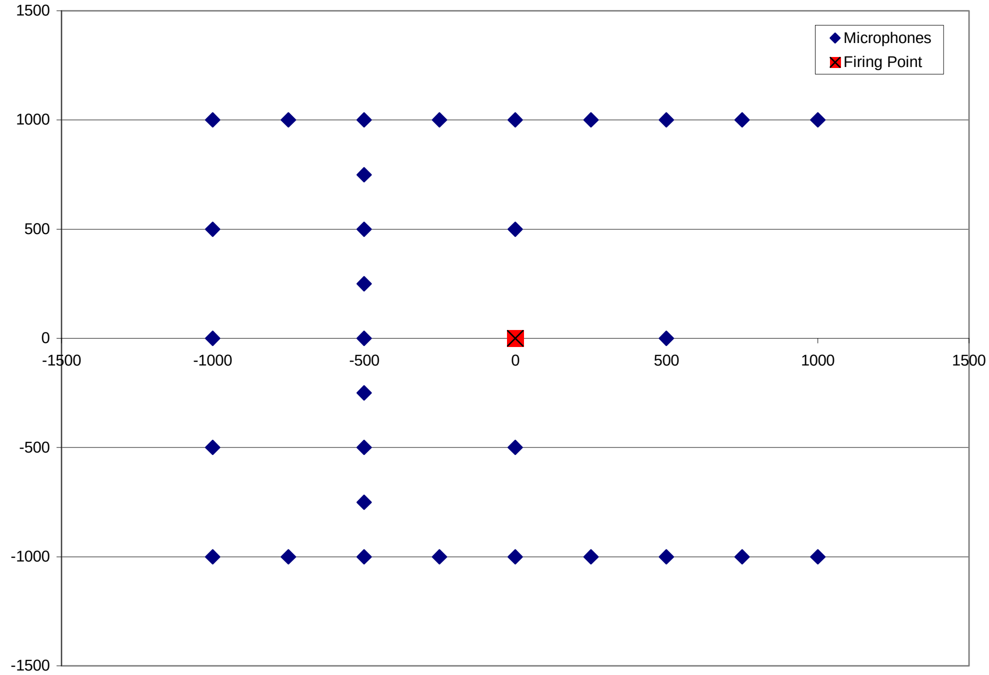

Figure 3.1 Recommended Measurement Array for Air Weaponry Source Noise Data Collection

The actual distances need to be scaled with the planned firing altitude to maximize the angular coverage for the array. For the array shown in Figure 3.1, the firing height is at 500 ft. above the ground, which provides a fore and angular coverage from 44° to 155°. To expand the coverage either the altitude has to be decreased or the distances expanded. The expansion of the array will be limited by cable length.

3.2 Test Matrix

From the field measurements, little effect was observed based on the firing profile, so a single profile can be used for the data collection. For gun firings, 30 repeated runs should be sufficient to develop the angular dependence. For rocket/missile firings, 10 firings should be sufficient. Our experience in the difficulty of obtaining rocket/missile firings suggests that in practice fewer firings may available. For a reduced number of firings, the array could be modified to place more microphones on one side to take advantage of the expected symmetric noise emission.

3.3 Data Acquisition

3.3.1 Acoustical Data

The recommended acoustical instrumentation specifications are provided to ensure the proper fidelity of acoustical data is obtained. The frequency range of the acoustical data should cover 10 Hz to 40 kHz. The upper limit is required to accurately measure the shock structure of the muzzle blast and propulsion noise. The dynamic range of the data acquisition system should be 120 dB, which should cover from 45 dB to 165 dB.

If protection grids and/or windscreens are used on the microphones, then their effect on the directivity pattern and frequency response should be documented for the data analysis. It is expected that the inclusion of windscreens will reduce the higher frequency response range while providing better measurement of the lower frequencies.

The type and length of signal cables from the microphone power supplies to the data recorder can influence the frequency response of the recorded signal. Thus, this effect must be documented to ensure the desired signal frequency response is not diminished.

3.3.2 Supporting data

Measurement of aircraft and firing position is preferred to accelerate the data analysis as discussed in section 2.3.3. The tracking data must have an accuracy of ±3 m for the firing point. In addition to the firing point data, firing rate and duration should be collected. If this data is not feasible for the test, then the acoustical triangulation method discussed in section 2.3.3 can be used.

During all flyovers, pilots should note their airspeed and firing altitude for feedback to the test director.

Weather and atmospheric data are crucial to the accurate analysis of the acoustical data since the atmosphere greatly influences the recorded sound levels. As long as the firing altitudes are fairly low, surface data and aircraft observations should be sufficient for the data analysis. The surface data should include temperature, wind speed and direction, relative humidity, and turbulence indices. The observed aircraft data should include temperature and wind speed and direction.

Ambient background noise data needs to be collected throughout the test. These measurements need to document the steady background sounds occurring at the test site so that their influence on the recorded sound levels can be accounted for in the data analysis. These recordings need to avoid any transient noises occurring at the test site.

4.0 Measurement Procedures

The measurement procedures for the data collection are simple and straight-forward. Once the array is ready for data collection, the testing can commence with simple procedures. These procedures should be discussed with the aircrews before the tests to ensure equal understanding of the goals of the data collection and the operational constraints of the training operation. The procedures should include at a minimum the following points.

For the inflight firing test points, the aircraft will begin from a holding fix (to be determined). At the start of a pass, the pilot will approach the array once the test director confirms the data collection is ready. The aircrew will adjust the aircraft operational state to obtain the desired firing profile. At the firing point, the pilot will initiate firing (duration to be 0.5 to 1 second). After firing, the pilot is to maintain steady flight conditions for approximately 10 seconds to ensure aircraft transient noise does not interfere with firing noise recordings. At the firing point, aircrews must record the following cockpit data (if available): Outside Air Temperature, Indicated Airspeed, True Airspeed, Ground Speed, Altitude, and Configuration. It is important that these parameters be recorded, or relayed by radio to the ground crew. A datasheet for this information will be provided before the test and is to be completed during the test.

The communication procedures to be followed for an individual test points are the following:

(1) Before the aircraft starts its run, the aircrew notifies the ground crew that it is at "the holding fix",

(2) Test Director (TD) will announce “ready” when measurement team is ready for the pass,

(3) Once the pass is commenced, the aircrew will announce “in bound.” The measurement team is to maintain silence during the flyover and monitor the recording using headphones,

(4) Near the firing point, the aircrew will announce “hot” directly before firing,

(5) The pilot will call “break” 10 seconds after firing. The TD will inquire from measurement team about data quality for pass. Any observations should be noted and adjustments to equipment made. The pilot will be contacted should there be any necessary changes to the flight profiles,

(6) TD will announce next run to aircrews. Aircrew will confirm condition and commence next test point, and

(7) The holding area and the firing point latitude and longitude coordinates will be provided before the scheduled test date.

5.0 Data Analysis

From the field data, it was demonstrated that the effects of atmospheric absorption and nonlinear propagation were small for the propagation distance utilized in the data collection. Moreover, by collecting data with elevated microphones, the data can be normalized using simple geometric spreading assumptions. This simplifies the data analysis considerably.

5.1 Muzzle Blast

The data analysis is straight-forward and basic for muzzle blast. Once the firing point is determined, the individual muzzle blasts can be evaluated to determine the following values:

- Positive Impulse (Pa•sec),
- Sound Exposure Level (dB, dBC, dBA),
- Peak overpressure, Pa, and
- Impulse Duration (msec).

From the field measurement observations, the positive impulse (PI) was the most stable metric, and it should be used to determine the directivity pattern of the noise emission. Once PI is normalized for distance, the angular dependence can be determined for both the fore and off and left/right angular directions. Once the directivity is determined, the source values for the other metrics can be determined through simple correlations with PI. Since the data acquisition includes full waveforms, additional metrics can be determined if different metrics are found that better estimate human reactions to air weaponry noise.

5.2 Rocket/Missile Noise

Noise from rocket/missile firing is more complicated because of the convolution of the launch and propulsion noise. The launch noise is emitted from a point in space whereas the propulsion noise is emitted along the flight trajectory of the rocket. Preliminary application of the rocket/missile noise models it as emitted from the launch point. This first estimation provides a conservative estimate of the noise behind the firing point, but it underestimates the noise toward the target. For community noise this estimation seems reasonable. Rocket/missile noise is characterized using SEL (flat, C-wt, and A-wt). As additional data are collected, procedures may be developed to deconvolve the launch and propulsion noise.

5.3 Sonic Boom

Detailed sonic boom waveforms form the projectiles are not required for proper modeling. The field measurements have demonstrated that sonic boom theory is sufficiently covers these projectiles, so the only parameters required are the projectiles dimensions.

6.0 Interim Source Data

For the current use of the model before further source data can be collected, several sources are available to generate interim source data. For muzzle blast, it is recommended to use source muzzle blast data included in BNoise2 and SARN computer models. For the interim data use a weapon system of similar caliber and propellant strength. For rocket/missile noise, the development of estimated noise levels and spectra should use the estimating procedures outlined by McInerny, Lu and Olcmen (2004).

References

Carlson, H.W., "Simplified Sonic-Boom Prediction," NASA TP 1122, NASA Langley Research Center, Hampton, VA, 1978.

Department of Defense, DoD Noise Program, DoD Instruction Number 4715.13, November 15, 2005.

McInerny, S.A., Lu, G., Olcmen, S., "Rocket and Jet Mixing Noise, Background and Prediction Procedures," Final Report for Contract UM 03-08-013, Dept. of Aerospace Engineering and Mechanics, The University of Alabama, 30 August 2004.

APPENDIX *C*

▪ Noise-Con 2007
Airborne Weapons Noise Prediction Model

Reno, Nevada
NOISE-CON 2007
2007 October 22-24

Airborne Weapons Noise Prediction Model

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ABSTRACT

The development of an air-gunnery noise model that calculates both single event noise as well as cumulative noise is described. The basis of the model's calculations will be the positive impulse and spectral time histories. Based on field measurements, correlations between the positive impulse and other acoustical metrics are developed so that various acoustical metrics may be used to assess potential impacts. The model is composed of a two step modeling processes. The initial step calculates a noise footprint for a unique operation at a given range (e.g. A-10 low angle strafe on lane 3 at Poinsette Range). This calculation includes the effects of linear propagation, topography, and spatial distribution of the firing points in the calculation of the noise footprint. The next step sums all of the operations scaled by their number of occurrences. Using this two step process, a detailed noise calculation is performed only once, but a user can easily and quickly recalculate the noise contour for different operational scenarios while maintaining highly accurate results without the need for a complete reanalysis.

1. INTRODUCTION

A number of aircraft noise models have been developed over the past 30 years to estimate noise levels from military aircraft operations near airbases, along training routes, and within special use airspaces. The predictions from these models are used to assess the potential for community and environmental impacts from current and proposed flight operations. The U.S. Army has developed noise models for blast noise and supersonic shock waves due to ground-based weapon systems. Current Department of Defense (DoD) noise models all use common aircraft and weapon system source noise databases, which are maintained by the Air Force Research

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Laboratory (AFRL), U.S. Army Construction Engineering Research Laboratory (CERL), and Navy Facilities Engineering Command (NAVFAC). However, these models and databases do not include the noise contribution from air-gunnery operations.

This omission of an important and significant source of noise has and will become more troublesome as range operations come under greater scrutiny from the public. In the Republic of Korea strafing operations have been greatly restricted based on noise complaints from local communities. Currently, the range commanders have no tools to counter these restrictions.
A new model is needed that can calculate the air-borne weapon noise that occurs in air-weaponry operations. The goal of this project is the development of an air-gunnery noise model that will calculate both single event and cumulative noise in addition to providing acoustic visualizations for both planners and the public. Providing an accurate noise model that can quickly create scenarios for study without sacrificing accuracy for speed is critical.

One of the complexities involved is aircraft rarely fly the exact attack run profile prescribed, and in some cases the attack run is simply a generalized fan where the pilot can approach the target from a range of headings. To solve this problem of an unknown source location, a generalized statistical firing space is used. This space is defined by the parameters of the attack run with a three dimensional Gaussian distribution of firing points. The noise footprint from this space is then calculated to represent the noise from a single bullet fired from within the space. This statistical method is not representative of a single bullet fired, but is rather the average noise expected once a statistically large number of bullets have been fired (such as after a year of simulated combat operations). The noise footprint can then be included in a larger environmental noise model that determines the noise contour from a whole range of operations.

2. NOISE MODEL FORMULATION

B-5 A. Statistical Volume

The first step in calculating the noise from a full air-gunnery range is to calculate the three-dimensional statistical volume for each unique firing profile. A graphical user interface has been created to design these attack runs. Figure 1 shows part of a screen capture of this interface.

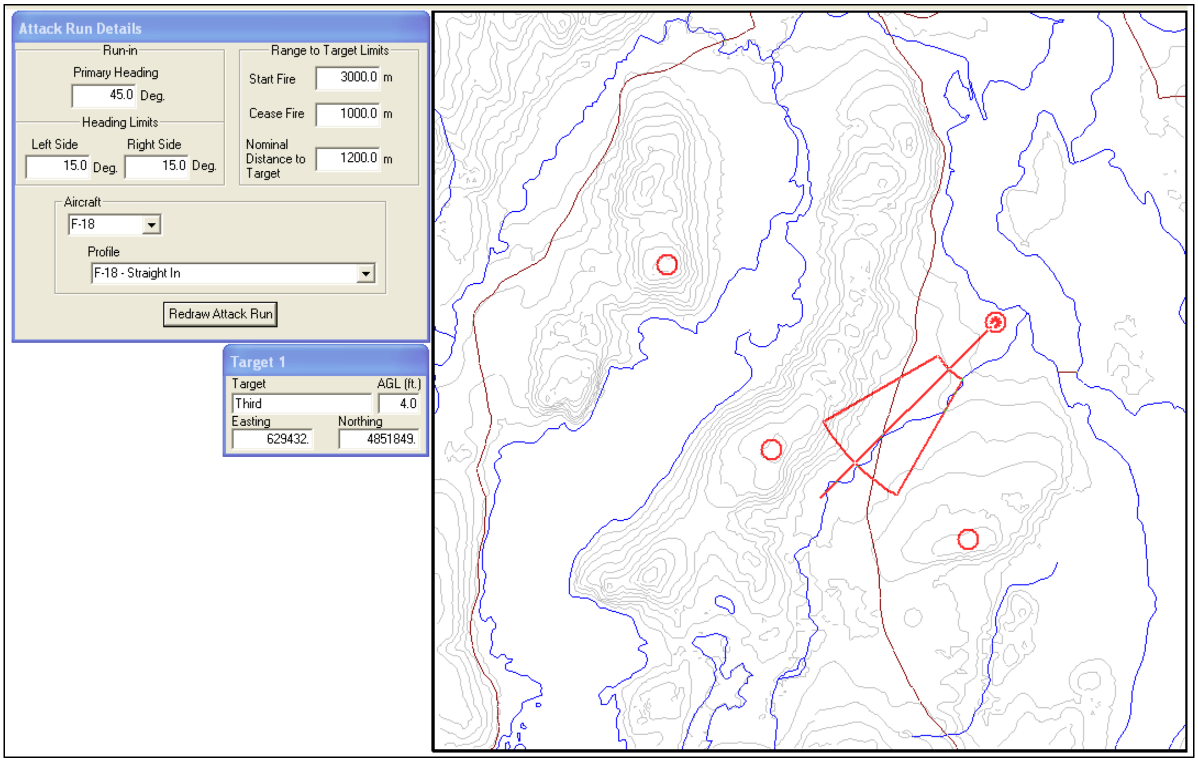

Figure 1: Screen capture of the attack-run design window for the new Air-Gunnery Noise Model.

Through this interface, the user first selects the aircraft type, then the attack profile for that aircraft type. For example, a straight in approach or high angle strafing run could be selected. The attack profile is used to determine the flight angle that the aircraft will take as it approaches the target and is specific to each aircraft and attack run type (e.g. low-angle strafe). There are also upper and lower flight angle limitations to this, helping to complete the three-dimensional volume defined by this attack run.

The approach vector of the attack is then selected, along with start-fire and cease-fire lines, as well a range of heading angles available for approaching the target. Finally, there is a nominal firing distance to target, which is the optimal distance to fire from and is used in the statistical calculations.

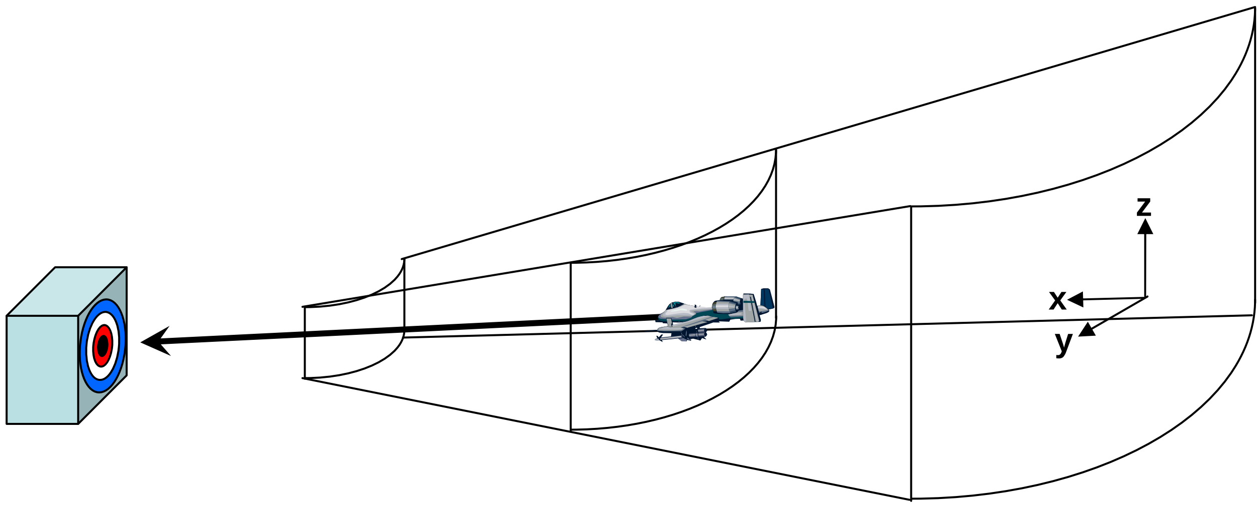

Figure 2: Representative statistical volume for an A-10 strafing run.

This volume represents the most likely location that the aircraft will be when it fires its gun. It is defined as a fan with circular arcs. Once this volume is defined, it is then sliced into 'rectangular' slices in the Y-Z plane. These slices are actually curved segments, centered on the target being fired at. However, these slices can be unfolded into true rectangles. Each of these slices has a probability that a bullet was fired within it based on how far it is from the nominal firing distance. For example, moving the nominal firing distance to the front of the firing volume will skew the statistics so that positions in the front have a higher probability than positions towards the rear of the volume.

Each rectangular slice also has its own two dimensional probability distribution. Figure 3 shows a representation of the firing point distribution in both the flight path direction (x) and the planar directions (y and z). With the selection of the approach heading and the range of left-right vectors it is possible to skew these probabilities as well. The probability that a bullet is fired on any give position of this rectangle is then related to how close to the nominal approach vector it is. For simplicity the graphic in Figure 3 simply shows a symmetric distribution in both the X direction and in the Y- Z plane.

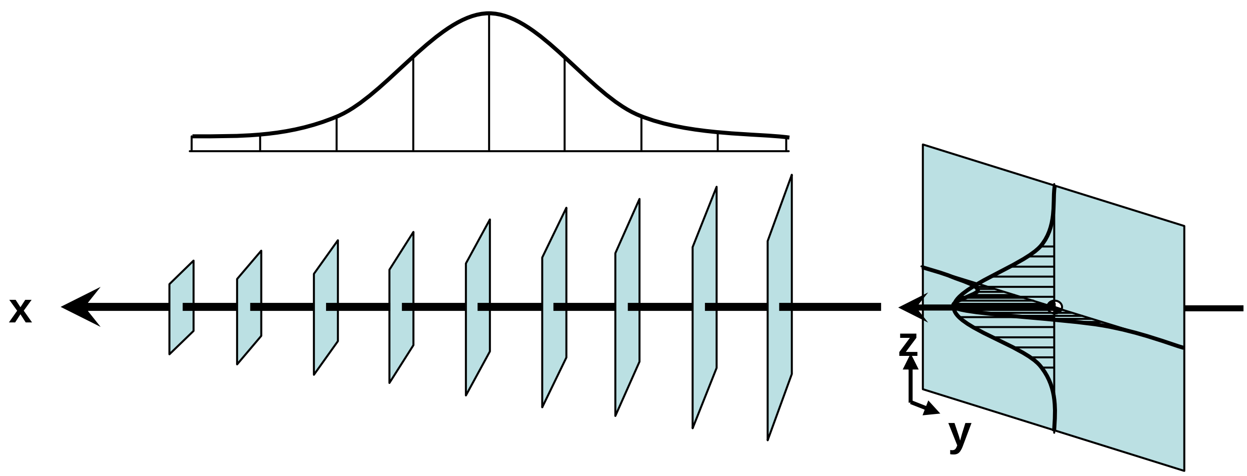

Figure 3: Probability distributions for the axial (x) and planar positions (y and z) of the aircraft firing points.

The rectangles are subdivided into individual grid points where the probability is specifically defined based on the probability distributions. The probability that a bullet is fired at any arbitrary grid point within the statistical volume is then the multiplication of the probability of the slice where the bullet is fired times the probability of the grid point where the bullet is fired.

The end result is a three dimensional set of grid points, each with its own probability. The probability of all of the grid points in this volume are then normalized such that they all sum to one. The result is therefore a three dimensional probability distribution for where a single bullet was fired.

B-6 B. Noise Calculation

Once the probability distribution is completed, the model is ready to compute the noise footprint. First, the noise from each grid point in the probability distribution is propagated to a grid on the ground. The propagation algorithms used here are the same used in NMSim[1] and take into account atmospheric absorption, terrain effects, and the effects of differing ground impedance. After the noise grid for each firing point in the statistical volume is calculated, the entire grid noise level is multiplied by the probability fraction for that firing point. Then the noise grids from all of the firing points in the statistical volume are summed up. The result is a statistical representation of the noise on the ground from the firing of a single bullet. This is NOT representative of a single bullet, and can not be used for a single event. This result is only valid for a statistically large number of bullets fired from a large number of different attack runs on the same pattern.

The computational time required for this analysis can be long – on the order of hours per attack run depending on the level of detail needed for the noise contours. Doing an entire range could be prohibitively costly in terms of time when there are several different attack run possibilities. However, once one of these single-bullet footprints has been computed for a given attack run, the results can be stored in a grid and do not need to be recomputed. The results are stored in a noise library that contains all of the footprints from all of the possible attack runs at a given range.

To compute the overall noise contour for a range, the model multiplies the results for each attack run by the total number of rounds used on that run, then sums the result with the similar results from all of the other attack runs. The computational burden is limited to the time when the range data is initially entered, and the time required to create a new noise contour is minimal since it only requires some computationally quick multiplications and additions. The final results are then stored in a standard NMPlot[2] grid format. The results form the air-weaponry calculations can be easily combined with results from other noise models, such as one that computes the noise from the aircraft itself.

B-7 C. Sample Results

For a test case, a target was set up for strafing runs from an Apache helicopter. Three distinct attack runs were set up. One attack run has a nominal heading of 135 degrees (magnetic), and another from 45 degrees (magnetic). Each of these was designed to allow a +/- 10 degree variation in the approach angle. The third run was designed with a nominal approach heading of 315 degrees (magnetic), but with only a +/- 2 degree variation allowed in the approach vector. It was assumed that an equal number of rounds were fired from each of these attack runs. The results for this one target are shown in Figure 4.

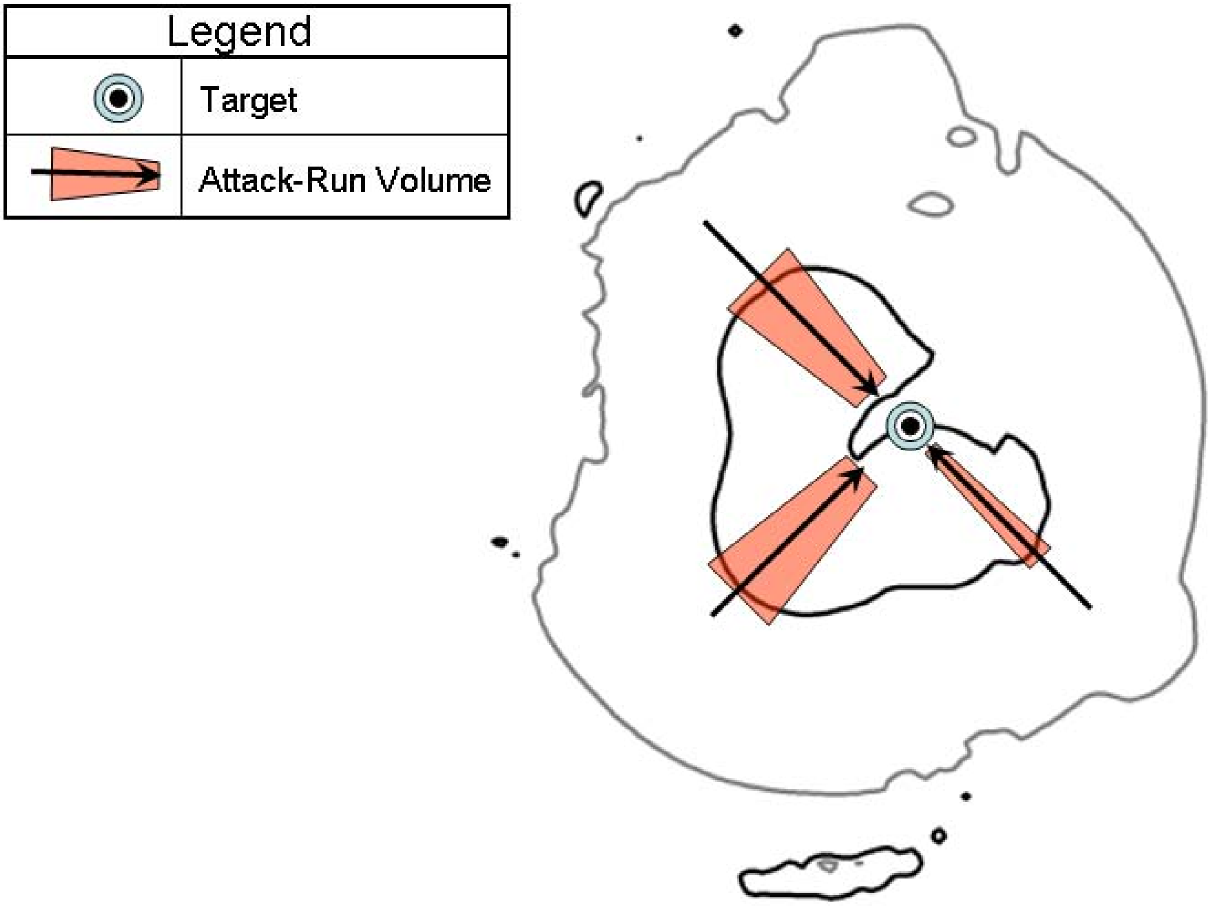

Figure 4: Sample noise contours for a single target with three different attack runs.

The results from each of the three attack runs are visible in this plot as distinct lobes in the noise contour. There are added complexities to the contour due to the effects of terrain and over-water propagation. While this is representative of only a single target in an air-weaponry range, combining multiple targets will produce the expected noise footprint for the entire range.

CONCLUSION

A novel approach has been presented for calculating the noise footprint from air-weaponry operations. The approach utilizes a statistical volume of space for determining the distribution of firing points. The noise from this statistical volume is then computed and scaled for the actual number of bullets fires. By combining the results of several of these statistical volumes it is possible to compute the noise contour for an entire range.

An approach of storing the individual noise footprints from each statistical volume allows the program to rapidly calculate the overall noise contour without having to do the costly noise calculations repeatedly. The result is a noise model that retains the detail and accuracy of a simulation model without having to spend the time for each noise calculation to be completed.

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