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Performance Assessment of Communication Enhancement Devices: TEA HI Threat Headset

Hilary L. Gallagher
Richard L. McKinley
Warfighter Interface Division
Battlespace Acoustics Branch
Wright-Patterson AFB, OH

Melissa A. Theis
Oak Ridge Institute for Science and Education
Oak Ridge, TN

Billy J. Swayne
Ball Aerospace Technologies
Dayton, OH

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711 HUMAN PERFORMANCE WING,
HUMAN EFFECTIVENESS DIRECTORATE,
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433
AIR FORCE MATERIEL COMMAND
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//signed//
Hilary Gallagher
Work Unit Manager
Battlespace Acoustics Branch

//signed//
Robert C. McKinley
Chief, Battlespace Acoustics Branch
Warfighter Interface Division

//signed//
William E. Russell, Chief
Warfighter Interface Division
Human Effectiveness Directorate
711 Human Performance Wing

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Hilary L. Gallagher
Richard L. McKinley
Melissa A. Theis *
Billy J. Swayne**

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Battlespace Acoustics Branch
Wright-Patterson AFB OH 45433

*Oak Ridge Institute for Science and Education
Oak Ridge, TN 37831
**Ball Aerospace Technologies
Dayton, OH

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14. ABSTRACT
Hearing protection and communication enhancement devices were designed for military personnel who need to maintain natural hearing while protecting their ears from impulsive and continuous noises like gunfire, explosions, vehicles, and machinery. There were potential advantages for this technology in military applications. Objective performance data provided an assessment of the performance of these devices. The TEA HI Threat headset performance was assessed for the following parameters: continuous noise attenuation; impulsive peak insertion loss; sound localization; and speech intelligibility. The TEA HI Threat headsets reduced the noise level in the ear when the user was exposed to continuous and/or impulsive noise. The devices also reduced spatial aural cues required to accurately localize sounds essential to maintaining situational awareness. The localization performance was degraded in comparison to the open ear performance. The results from the speech intelligibility measurements for the TEA HI Threat headsets were acceptable (i.e. ≥80% correct) in low to moderate noise environments, however at 105 dB, the average scores did not meet the acceptable performance criterion.

15. SUBJECT TERMS Active hearing protection, electronic hearing protection, noise attenuation, localization, blast, impulse, speech intelligibility

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EXECUTIVE SUMMARY

Understanding the noise attenuation performance of a hearing protection and communication device has been important in order to protect the user from excessive noise exposure. Active electronic hearing protection devices have been designed to allow for enhanced communication and situational awareness, while at the same time protecting the auditory system from both impulsive and continuous noise. The objective of this study was to assess the TEA HI Threat Communication headset for: continuous noise attenuation, impulsive peak insertion loss, auditory localization, and speech intelligibility. The TEA HI Threat headsets reduced the noise level in the ear when the user was exposed to continuous and/or impulsive noise. The devices also reduced critical aural cues required to localize sounds essential to maintaining situational awareness. The active headsets may amplify low level sounds, but the localization performance was degraded in comparison to the open ear performance. The results from the speech intelligibility measurements for the TEA HI Threat headsets were acceptable in low to moderate noise environments, however at 105 dB, the average scores did not meet current military standards. The data collected in this assessment should be used to determine how and when such devices could be integrated successfully into a mission.

1.0 INTRODUCTION

Military personnel have been working in unpredictable noise environments, which require a more flexible type of hearing protection in order to complete a normal duty day without the risk of permanent hearing loss. It was necessary to obtain accurate and complete measures of the total performance capabilities of hearing protection and communication devices and their effect on the user to ensure that military personnel could maintain mission effectiveness while preventing noise induced hearing loss. A multifactorial assessment approach was used to adequately determine if currently available tactical hearing protectors meet the needs of these personnel, including the following measurements: continuous noise attenuation, impulsive peak insertion loss, auditory localization, and speech intelligibility.

Continuous noise attenuation measurements characterized how much protection a hearing protection device (HPD) provided in an environment where the ambient noise levels were fairly stable (for example, riding in a HMMWV or a helicopter, or working in a machine shop). These measurements were conducted in accordance with American National Standards Institute (ANSI) standard S12.6-2008[1] Method A.

Impulsive peak insertion loss measurements demonstrated how much a hearing protection device provided against impulsive noises (for example, gun shots or explosions), and were measured in accordance with ANSI S12.42-2010.[2] Understanding the noise attenuation of a hearing protector (both continuous and impulsive) was important in order to estimate the user's noise dose. Noise dose was calculated using the estimated level of noise under the hearing protector (using methods described in ANSI S12.68[3]) and the duration of time spent in that noise environment. Speech intelligibility measurements were conducted in accordance with ANSI S3.2-2009[4] and aided in the understanding of the communication performance for users wearing a hearing protection and communication device in multiple noise environments.

Wearing hearing protection and communication devices could degrade the user's ability to localize and detect ambient sounds important for situation awareness. Understanding these potential degradations would promote a more informed selection hearing protection for the warfighter. The competing requirements between providing adequate hearing protection for the expected noise environment and maintaining a level of situation awareness appropriate for the mission needed to be considered relative to the mission requirements. Measurements were made to quantify the effects of hearing protection devices on auditory localization and on the amount of time required to locate a visual target with a collocated sound.

2.0 BACKGROUND

Military ground operations have frequently occurred in complex environments where the balance between operational effectiveness and personnel safety was not clear. The goal of effectively protecting the hearing of personnel has been complicated by the need for warfighters to maintain situation awareness aided by auditory localization acoustic cues in the ambient environment (Figure 1). Firing a small number of rounds from a weapon has been shown to cause temporary hearing loss. This temporary change in hearing threshold could have impaired the ability to acoustically monitor the environment. Repeated unprotected exposures to small arms fire could have eventually resulted in permanent hearing loss. Noise exposures from larger weapons and blasts could have instantly caused permanent hearing loss if no protection was worn.

Figure 1. Special Operations Forces using Communication Devices in an Operational Environment

The objective of this study was to assess the TEA HI Threat headsets for the following parameters: continuous noise attenuation; impulsive peak insertion loss; sound localization; and speech intelligibility. These devices were developed to improve situation awareness by providing a hear-thru, or active listening capability while mitigating hearing loss and tinnitus caused by exposure to loud, steady-state and impulsive noise. Active devices should theoretically have provided improved performance in the areas of communications and auditory localization versus passive hearing protection devices and should have provided adequate attenuation for continuous and impulsive noise.

The requirements associated with the military's use of tactical hearing protection and communication devices fueled the development of new performance metrics and measurement methods in order to best determine the impact of these devices on the mission[5]. These systems have been actively providing some level of ambient listening capability in an attempt to restore the ability of an operator to localize sounds[6,7]. Several metrics and measurement methods were employed to quantify the effects of these devices on operator performance. The first was a measure of localization error. This metric quantified the amount of errors >45 degrees between the target location and the listener's response. A second metric was the number of front-back reversals of the target location that an individual demonstrated during the task. The third metric was a measure of reaction time, time to find a visual target, when sound was collocated with the visual target. The listener had to use the auditory localization information to locate the target and subsequently identify the target in this task. The reaction time was a salient measure of the quality of the localization cue[8-12].

AFRL conducted a series of measures to describe the performance of hearing protection and communication devices. The measures included passive continuous noise attenuation, impulsive peak insertion loss, input/output gain function, localization error with short duration (250 ms) and long duration (>1 sec) stimuli, reaction time from an aurally guided visual search task with distracters, and speech intelligibility.

3.0 METHODS AND RESULTS

The TEA HI Threat headset was developed to improve situation awareness by providing a hear-thru, or active capability while mitigating hearing loss and tinnitus caused by exposure to loud, steady-state and impulsive noise. The general approach for this assessment was to use ANSI standard measurement procedures for continuous noise attenuation, impulsive peak insertion loss, and speech intelligibility performance and to use AFRL defined procedures for localization. Performance results of these devices should be used to determine which protectors would be made available to the warfighters and the results may also lead to improved design criteria for the next generation of hearing protection and communication devices.

The overall methods and results are described in the following sections. The first section describes the hearing protectors that were used in the study. The second section describes how the device settings were configured for the evaluation. The subsequent sections describe each measurement method including a description of the subjects, the facilities, and the details of the specific measurement methods and results.

3.1 Communication Device

The TEA HI Threat was a closed circumaural headset with gel ear cushions. The headband of each device was adjustable to accommodate a range of head sizes and could be worn behind the head as well as over the head. The headsets were equipped with an ambidextrous noise-canceling boom microphone and had the capability to send and receive external communications via a connecting wire and a plug that enabled the user to connect to a compatible portable radio or intercom system. The headset also featured a level-dependent stereo, ambient "hear thru" setting that functioned independently of the radio.

The headsets were designed to be worn alone or in combination with an Advanced Combat Helmet (ACH), Figure 2. The Ops-Core Fast ACH was selected for the measurements. The TEA HI Threat headset could be worn with the headband under the ACH or mounted directly to the helmet's Accessory Rail Connector (ARC) system. This ARC configuration was designed to address the challenges in donning and doffing the helmet in addition to reducing "hot spots" created by the head band rubbing under the helmet.

Figure 2. TEA HI Threat headset with and without Ops-Core ACH and the ARC HTH System

3.2 Device Gain Setting

The TEA HI Threat headsets were equipped with a hear-thru setting designed to amplify soft sounds and conversational speech while allowing loud sounds to pass through without amplification. To normalize the hear-thru setting, a unity gain measurement was collected in the Audio Localization Facility (ALF) at Wright Patterson Air Force Base (WPAFB). The unity gain of the device referred to the volume setting at which the input/output gain curve of the device best matched the input/output gain curve of the Knowles Electronic Manikin for Acoustic Research (KEMAR). Matching the gain structure created a baseline volume setting and provided the most accurate comparison of how devices performed in relation to other devices.

KEMAR was equipped with two G.R.A.S Type 26-AC preamps and 40AO prepolarized pressure microphones positioned inside the head with the microphone diaphragms aligned to each ear canal. KEMAR's gain structure was obtained by measuring specific locations of sounds in ALF with the manikin's ears unoccluded. The unity gain for the TEA HI Threat headset was determined by activating the hear-thru setting, equipping KEMAR with the device, and collecting the same series of sounds. Starting from either the maximum or minimum volume, the level of the device was adjusted until the gain structure of the device matched that of KEMAR, Figure 3. The data below demonstrated that the maximum minus 2 setting (line with squares) most closely approximated the open ear response (dashed line). The TEA HI Threat headset was set at maximum minus 2 for the auditory localization measurements.

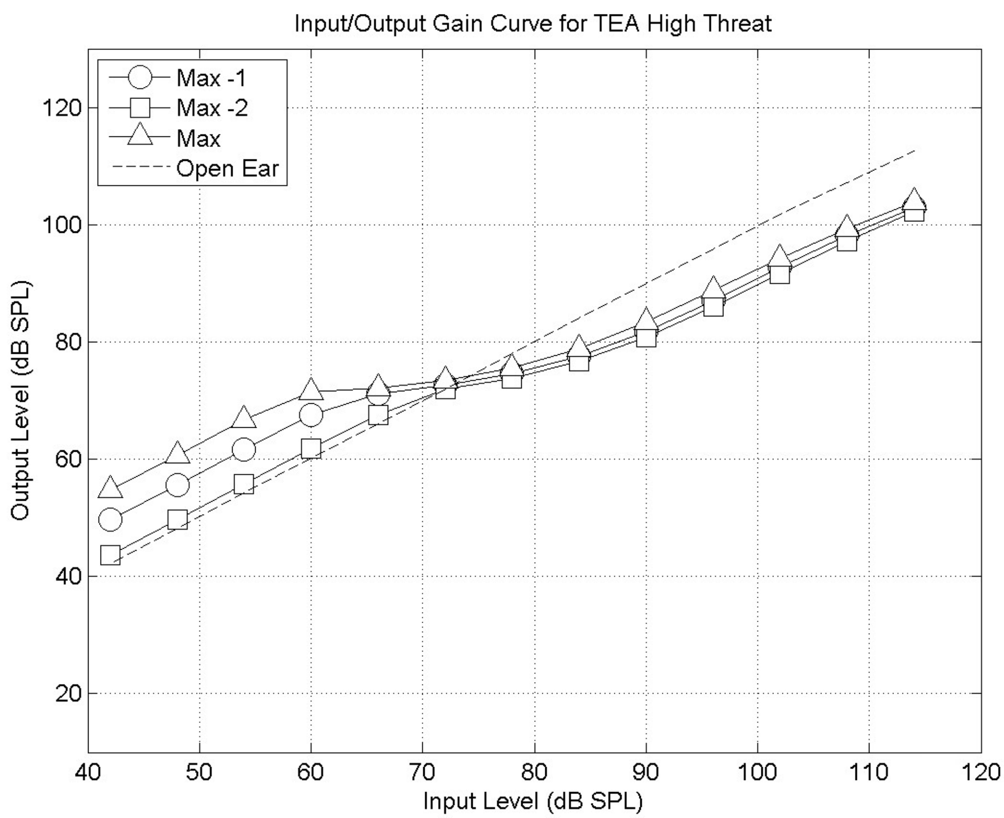

Figure 3. Input /Output gain curves for TEA HI Threat in hear-thru mode.

3.3 Continuous Noise Attenuation

Continuous noise attenuation performance measurements were collected with the TEA HI Threat headset alone and in combination with the Ops-Core Fast ACH (with and without the ARC HTH system). The measurements were conducted with the headsets in the "passive" (electronics off) condition using human subjects. All human subjects were compensated volunteers. There were ten male and ten female subjects, ranging in age from 18 to 34 years. All subjects were required to have a computer administered screening audiogram via Hughson-Westlake method, with behavioral hearing thresholds inside the normal hearing range; 25 dB hearing level (HL) or better from 125 Hz to 8000 Hz.

The facility used for this portion of the study was specifically built for the measurement of the sound attenuation properties of passive hearing protection devices. The chamber (Figure 4), its instrumentation, and measurement procedures were in accordance with the ANSI S12.6-2008[1]. This standard required measuring the occluded (with device in place) and unoccluded hearing threshold of human subjects using a von Békésy tracking procedure. The thresholds were measured two times for the unoccluded ear condition and two times for the occluded ear condition. The real-ear attenuation at threshold for each subject was computed at each octave frequency, 125 to 8000 Hz, by averaging the two trials (the difference between unoccluded and occluded ear hearing thresholds).

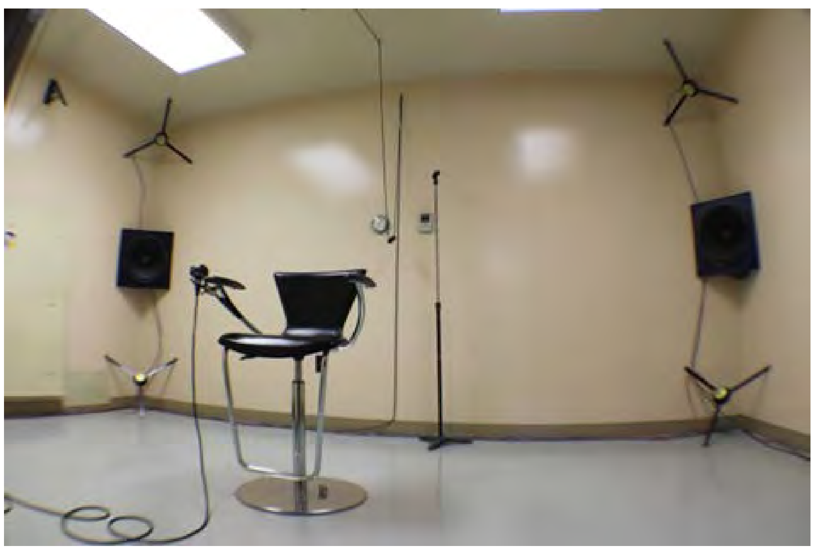

Figure 4. Facility used for measurement of continuous noise attenuation

Passive noise attenuation data were analyzed using the methods described in ANSI S12.68.[2] This ANSI standard detailed the methods for estimating the effective A-weighted SPL when hearing protectors were worn. The octave band method was the "gold standard" method for estimating a users' noise exposure. This method required both the noise spectra per octave band and the attenuation data per octave band. Mean and standard deviation (SD) noise attenuation data were calculated across subjects at each octave band frequency. A single Noise Reduction Rating (NRR) was also calculated for mean minus 1 and mean minus 2 standard deviations, Table 1. Figure 5 displays a graphical representation of the attenuation results at each measured frequency (mean minus 2 SD). Similar results were found when comparing the noise attenuation performance of the headset with and without the helmet. The attenuation results for all three configurations ranged from approximately 13 dB in the low frequencies and increased gradually to a maximum of 43 dB in the high frequencies.

Table 1. Passive mean and standard deviation noise attenuation for all configurations, electronics off and the calculated NRR (mean minus 1 and 2 SD)

Device		Frequency (Hz)							NRR	
		125	250	500	1000	2000	4000	8000	Mean – 1SD	Mean – 2SD
TEA HI Threat	Mean	13	16	22	29	30	34	39		
	SD	5	2	3	1	2	3	4	22	19
TEA HI Threat w/ Ops-Core Fast Helmet	Mean	14	16	24	30	29	38	43		
	SD	4	3	3	3	3	4	3	22	19
TEA HI Threat w/ Ops-Core & ARC System	Mean	15	17	22	30	28	37	41		
	SD	6	4	4	3	3	3	5	21	17

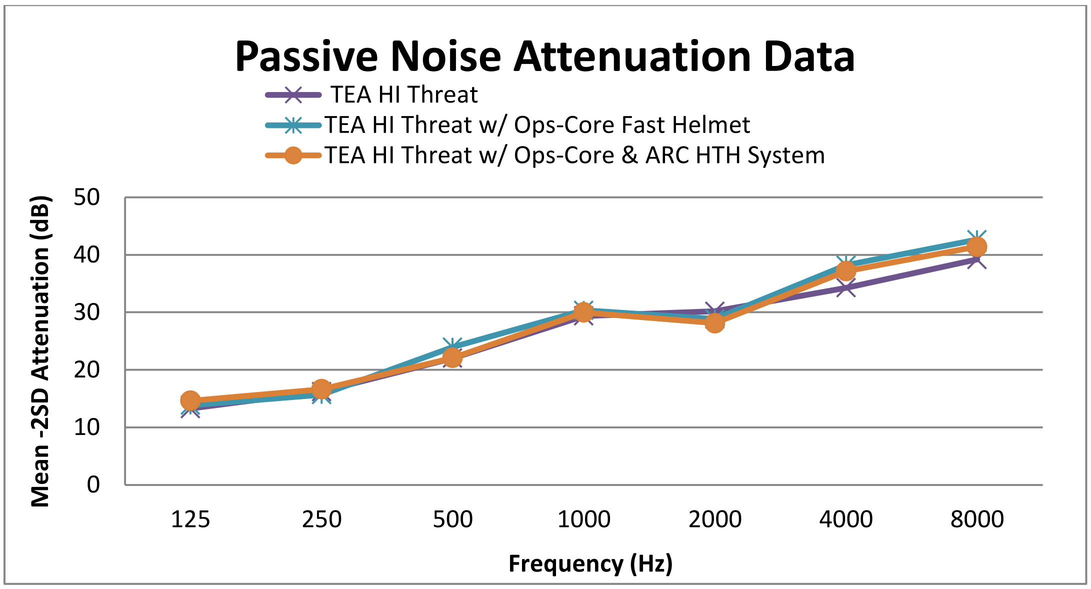

Figure 5. Passive mean-2SD noise attenuation for all configurations, electronics off

It was not always possible to calculate the effective A-weighted level under the hearing protector using the octave band method due to the lack of detailed noise data for all noise environments. Two other methods were described in ANSI S12.68: Noise Level Reduction Statistics, Graphical (NRS_G) and Noise Level Reduction Statistics for use with A-Weighting (NRS_A). NRS_G and NRS_A were calculated for all configurations and displayed in the Tables 2-4 and Figures 6-11.

The NRS_G rating required knowledge of both the C- and A-weighted noise levels, and used this additional information about the noise spectrum to more precisely estimate the range of protection provided. For example, if the C-weighted noise was measured at 100 dB and the A-weighted noise was measured at 94 dB then the difference between the two weighting levels would be 6. Therefore, the range of protection provided by the hearing protector could be found in Tables 2-4 and Figures 6-8 where B = 6. For these configurations, when the noise would be dominated by low frequency content (B = a high number) the level of protection ranged from 12-18 dB. However, when there was very little low frequency content (B = a low number) the level of protect ranged from 27-32 dB. NRS_A was appropriate for unpredictable noise environments that may vary widely as was the case with many military operations. However, if one was considering a noise environment that was relatively constant (e.g., dominated by low frequencies such as an aircraft or other vehicles), then NRS_G should have been used to calculate more accurate attenuation performance values.

Table 2. NRS_G results for TEA HI Threat, electronics off

NRS_G table	$B = L_C - L_A$	-1	2	6	13
Protection	x = 20%	31.9	26.5	22.4	18.3
Performance	x = 80%	29.0	23.0	18.1	12.0

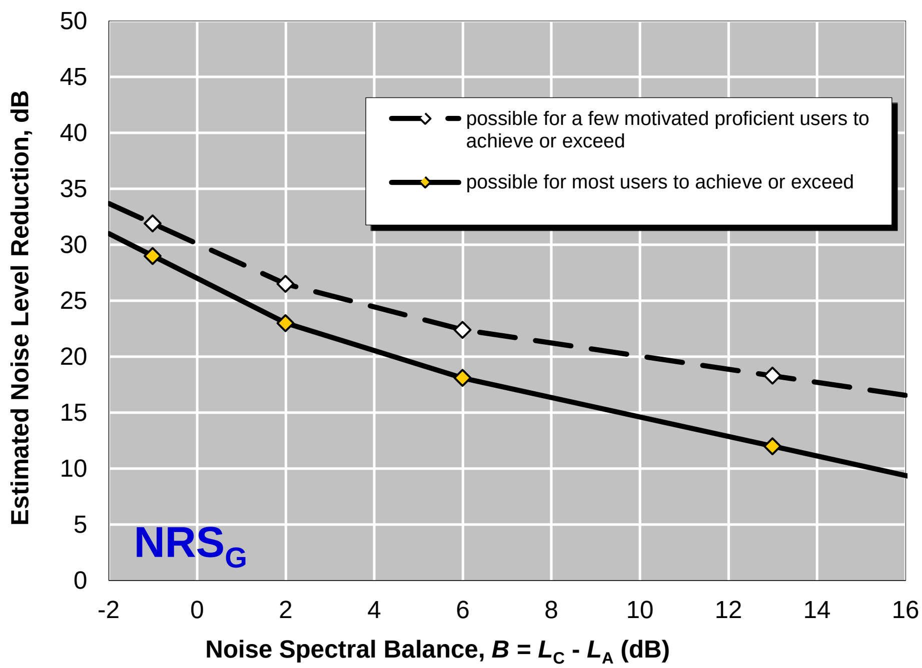

Figure 6. NRS_G results for TEA HI Threat, electronics off

Table 3. NRS_G results for TEA HI Threat w/ Ops-Core Fast Helmet, electronics off

NRS_G table	$B = L_C - L_A$	-1	2	6	13
Protection	x = 20%	32.8	27.2	22.7	18.3
Performance	x = 80%	28.5	23.3	18.5	12.8

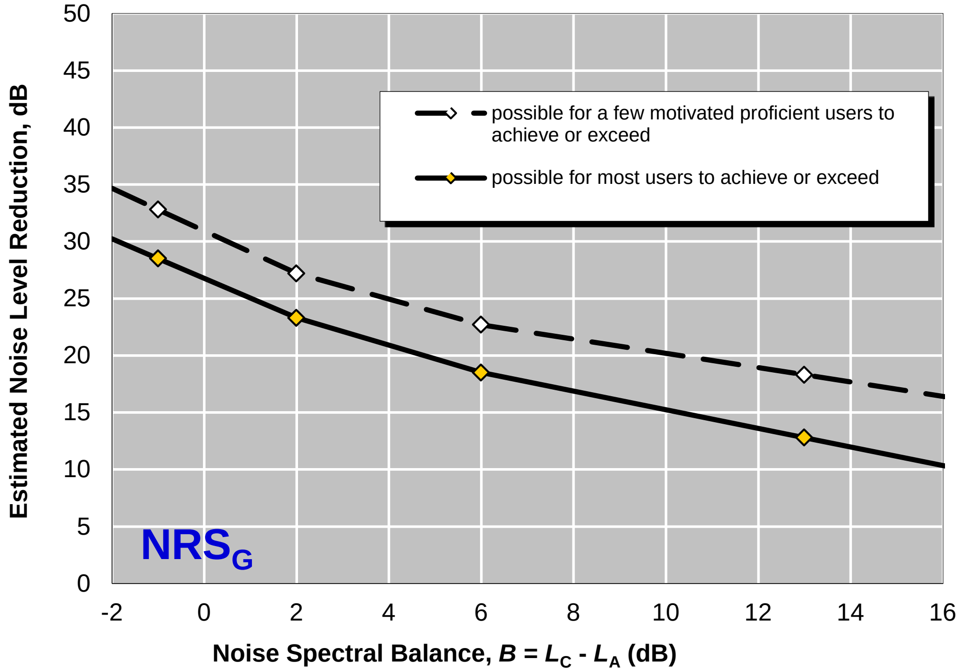

Figure 7. NRS$_G$ results for TEA HI Threat w/ Ops-Core Fast Helmet, electronics off

Table 4. NRS$_G$ results for TEA HI Threat w/ Ops-Core & ARC System, electronics off

NRS$_G$ table	$B = L_C - L_A$	-1	2	6	13
Protection	x = 20%	32.8	27.9	23.9	20.1
Performance	x = 80%	27.5	22.2	17.8	12.2

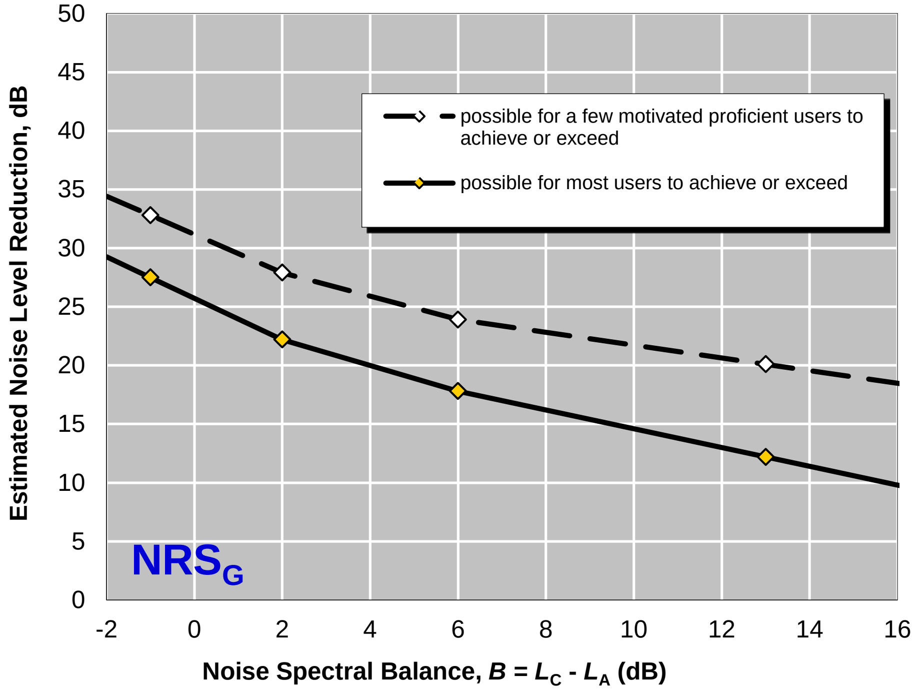

Figure 8. NRS_G results for TEA HI Threat w/ Ops-Core & ARC System, electronics off

NRS_A was the simplest method and could be used by subtracting the value from the measured A−weighted noise level to estimate the level of sound at the ear under the hearing protector. This method offered several advantages over the well-known NRR. The NRR was developed to be subtracted from the C-weighted noise exposure, with a 7-dB adjustment that must be applied prior to subtracting it from A-weighted exposure values. C-weighted exposure values were often not known, and therefore the rating for subtraction from A-weighted exposures with the NRS_A eliminated these problems with the NRR. Another advantage of the NRS_A was that it calculated two levels of protection to indicate the range of performance that was achieved (Figures 9-11). As was previously discussed, there were no significant differences in attenuation results for the three configurations that were measured. The NRS_A values for these devices ranged from approximately 22 dB of attenuation on the lower end (80%) to approximately 30 dB of attenuation on the higher end (20%). This range reflected both the variation across the subjects in the test panel providing insight into how hard/easy the device may have been to fit, as well as variation in noise level reduction with the noise spectrum in which the device was used.[14] The majority of users (80%) could achieve the performance specified by the lower value in the range, with only the most motivated proficient users (20%) able to achieve the higher value. A narrow range indicated the hearing protection device provided a more stable and predictable level of protection. When the methods described in ANSI S12.68 (octave band method, NRS_G, and NRS_A) were not used, the use of the NRR (mean-2SD) was acceptable with the application of appropriate deratings.

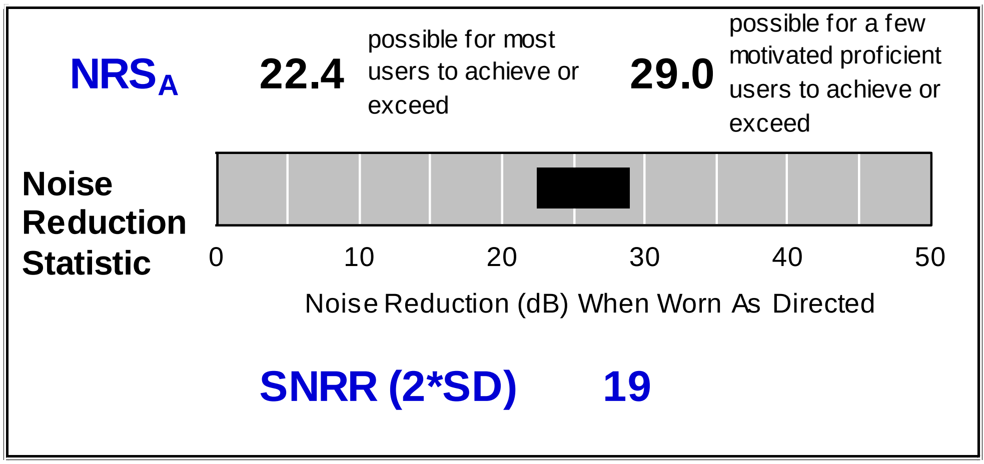

Figure 9. NRS_A results for TEA HI Threat, electronics off

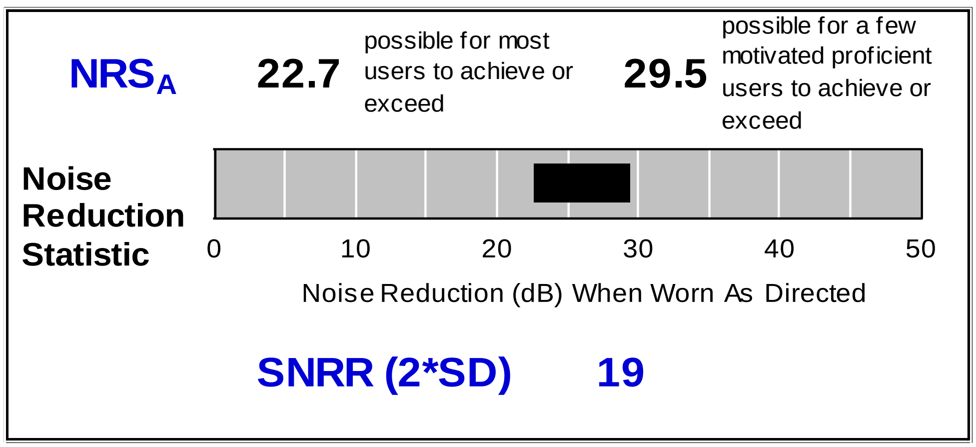

Figure 10. NRS_A results for TEA HI Threat w/ Ops-Core Fast Helmet, electronics off

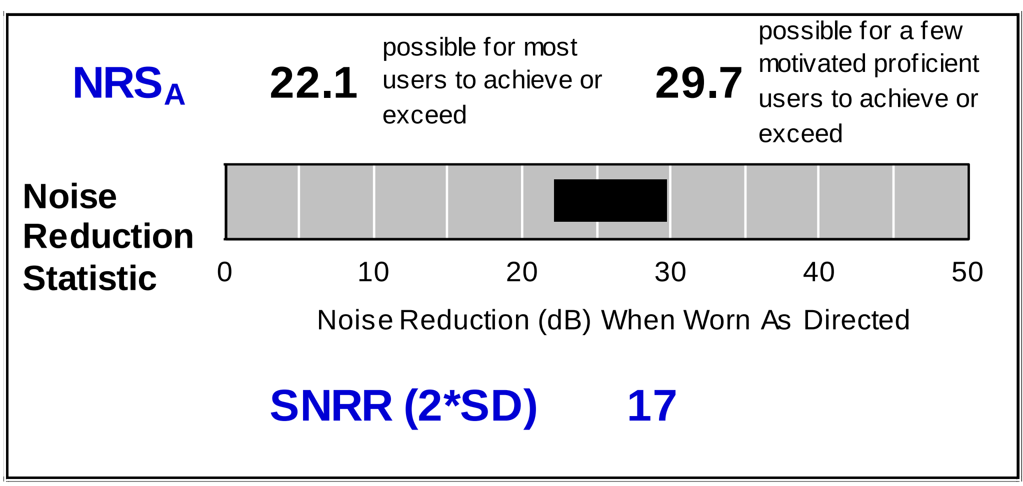

Figure 11. NRS_A results for TEA HI Threat w/ Ops-Core & ARC System, electronics off

3.4 Impulsive Noise Attenuation

Impulsive noise insertion loss/attenuation data was collected for the TEA HI Threat with and without Oakley® SI Ballistic M Frame spectacles Versions 2.0 and 3.0 and the Oakley® SI Ballistic Goggles (Figure 12). These additional test configurations were added to assess the impact of wearing vision protection in combination with the hearing protectors.

a. b. c.

Figure 12. Oakley eye wear a. Version 2.0 spectacles b. Version 3.0 spectacles c. Ballistic goggles

Impulsive insertion loss/noise attenuation performance measurements of the TEA HI Threat in various configurations when exposed to acoustic blast (impulsive noise) with high peak pressure levels were conducted. Impulsive peak insertion loss (IPIL) data was calculated at multiple peak noise levels ranging from 170 dB to 195 dB sound pressure level (SPL). Devices were measured in the passive (electronics off) mode.

IPIL (i.e., reduction in peak pressure of the impulsive noise) measurements were conducted to determine the effect an acoustic blast may have on the auditory system of the user. Four acoustic test fixtures (ATFs) were used simultaneously in these measurements to allow for the evaluation of different hearing protectors at one time. The ATFs were ISL-1 type heads equipped with ¼" microphones in the ear canals. Each ATF was fit with a hearing protector and was exposed to acoustic blasts. IPIL data was calculated at 170, 185, and 195 dB peak levels. The measurements were collected in accordance with ANSI S12.42-2010[2] Methods for the Measurement of Insertion Loss of Hearing Protection Devices in Continuous or Impulsive Noise using Microphone-In-Real-Ear or Acoustic Test Fixture Procedures. ANSI S12.42 required a measurement at 130 dB SPL and 150 dB SPL; however, measurements were conducted at 185 and 195 dB SPL, which was more typical of a blast that a user may be exposed to in a military setting.

The measurements were conducted on the test range of the French-German Research Institute of St. Louis (ISL) situated in Baldersheim, France. The test area being used for the measurements was equipped in a way to allow the detonation of an equivalent of

300g of C4™ explosive. Using this mass of explosive it was possible to initiate a shockwave with a peak pressure level of up to 195 dB SPL and an A-duration of about 1.5 ms. An A-duration of an impulsive signal was the time interval between impulse onset and the first crossing with the baseline.

A ¼" microphone or slender probe (tapered pencil gauge) was used to measure the free-field pressure wave according to the International Test Operations Procedures (ITOP) 4-2-822, Electronic Measurement of Airblast Overpressure and Impulsive Noise.[14] Figure 13 shows the placement of the ATFs during the blast measurements. For each blast, the sound pressure level at 9 transducers was recorded. This included 8 signals from the ATFs, each equipped with two microphones and pre-amplifiers (one for each "ear drum") and 1 signal from the free-field pressure transducer (slender probe). Daily microphone calibrations were completed with a B&K 4226 calibrator at 125 Hz with a level of 114 dB.

Figure 13. Placement of ATFs and free-field pressure transducer

Pressure measurements were recorded using 16-bit digital recorders at a sampling rate of 100 kHz. In order to visualize the movements of the hearing protectors, high-speed video (minimum speed of 10,000 frames per second) was recorded of the ATFs right ear at 195 dB SPL for each headset configuration.

Initially, an unoccluded ear measurement (no hearing protector) was conducted to calculate the free-field to ear canal transfer function using a 150 dB SPL nominal peak noise level with an A-duration of 2 ms, Figure 14. The Transfer Function of the Open Ear (TFOE) was used to calculate the IPIL for each fit of the hearing protectors.

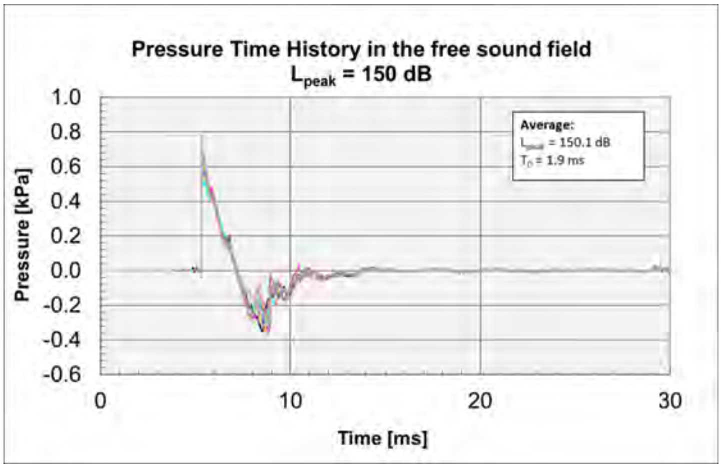

Figure 14. Pressure-time history of the impulses generated for the determination of the TFOE

For the calculation of the Insertion Loss (IL), the TFOE was calculated for all 1/3 octave-bands centered between 25 and 16 kHz. The TFOEs were used to calculate the IPIL; the complex transfer function with a resolution of 6.1 Hz has been calculated. Mean TFOE for left and right ears separately are graphed in Figure 15.

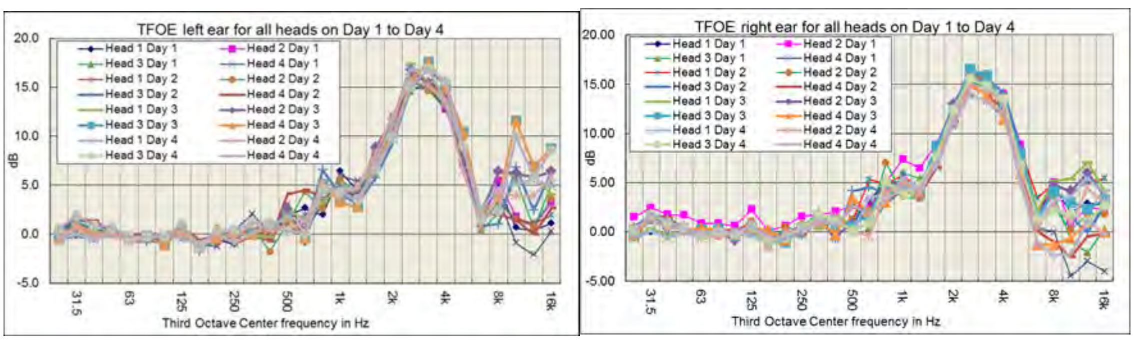

Figure 15. Mean TFOE for each head, each day, left and right ear

After the determination of the TFOE, the measurements were completed with the different hearing protectors in place. Each hearing protector was measured five times at each peak noise level; each time, the hearing protector was removed and refitted or replaced by a hearing protector of the same type.

The impulsive (blast) waves were generated by explosives. Figure 16 shows a schematic of the set-up. The type and the mass of explosive as well as the distance between the explosive and the ATF determined the peak noise level and the A-duration of the generated signal, Table 5. Figure 17 shows an example of the pressure time history and sound spectrum for a 170 dB SPL noise level.

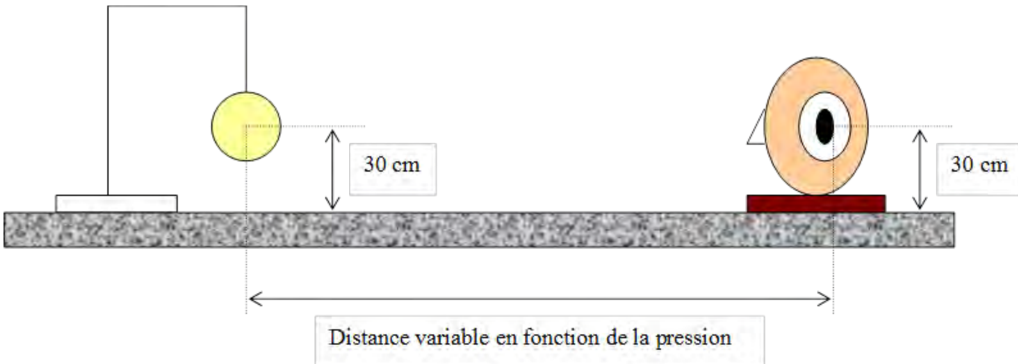

Figure 16. Schematic of the set-up of the explosive charge for the creation of a shock wave

Table 5. Type and mass of explosive and distance between ATF and explosive for different peak pressure levels and A-durations

Peak Noise Level (dB SPL)	Explosive Type	Mass (g)	Distance from ATF (m)	Measured Average A-Duration (ms)	Measured Average Peak Noise Level (dB SPL)
170	Primer (RDX 95/5)	35	6.5	2.3	170.8 (0.991 psi)
185	C4	130	3.4	2.2	184.6 (4.85 psi)
195	C4	300	2.2	1.7	195.9 (17.82 psi)

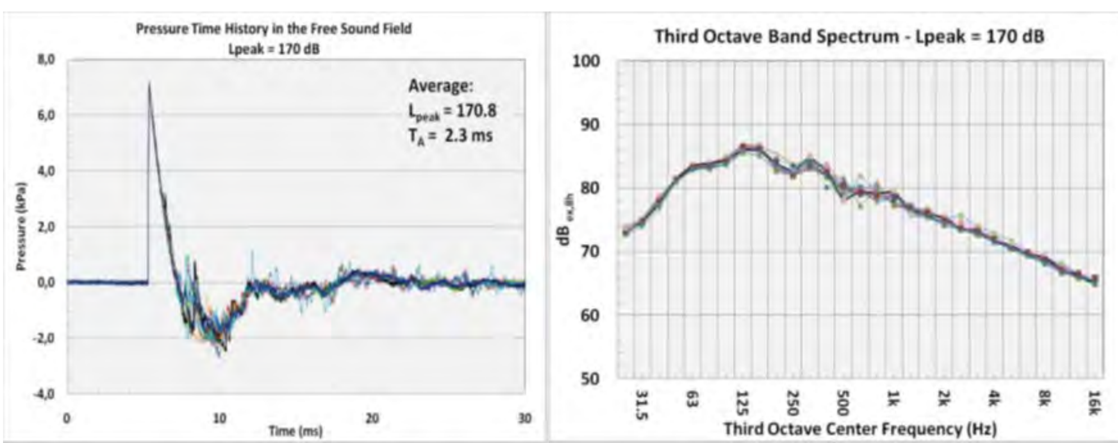

Figure 17. Pressure time history and 1/3 octave band spectrum for the 170 dB SPL noise level

The insertion loss for each ear and each peak pressure level were recorded. Table 6 lists the average IPIL for each device powered off at 170, 185, and 195 dB. The data is displayed in Figure 18 for all configurations. The level of protection for all the measured configurations ranged from 15 dB during a 170 dB SPL impulse to 30 dB during a 195 dB SPL impulse. The IPIL response was not linear for all the configurations. The difference in IPIL data for the same device at the different peak pressure levels illustrated the need for measurements at various sound levels for an accurate understanding of the impulsive noise protection characteristics. For this data set, one of the device configurations had a consistent response with similar IPIL levels at all three sound levels, while the other device configurations generally provided more attenuation at higher sound levels than lower ones.

Table 6. Average Impulsive Peak Insertion Loss (IPIL) data from blast measurements

Hearing Protector	170 dB SPL	185 dB SPL	195 dB SPL
TEA HI Threat Over Head	27.2	28.4	29.4
TEA HI Threat Over Head w/ Oakley 3.0	18.4	21.4	30.6
TEA HI Threat Behind Head	22.2	23.7	26.9
TEA HI Threat w/ Ops-Core Helmet	23.4	24.9	28.4
TEA HI Threat w/ Ops-Core & Oakley 3.0	15.2	20.9	28.9
TEA HI Threat w/ Ops-Core & Oakley 2.0	17.8	21.4	29.0
TEA HI Threat w/ Ops-Core & ARC	29	23.2	28.4

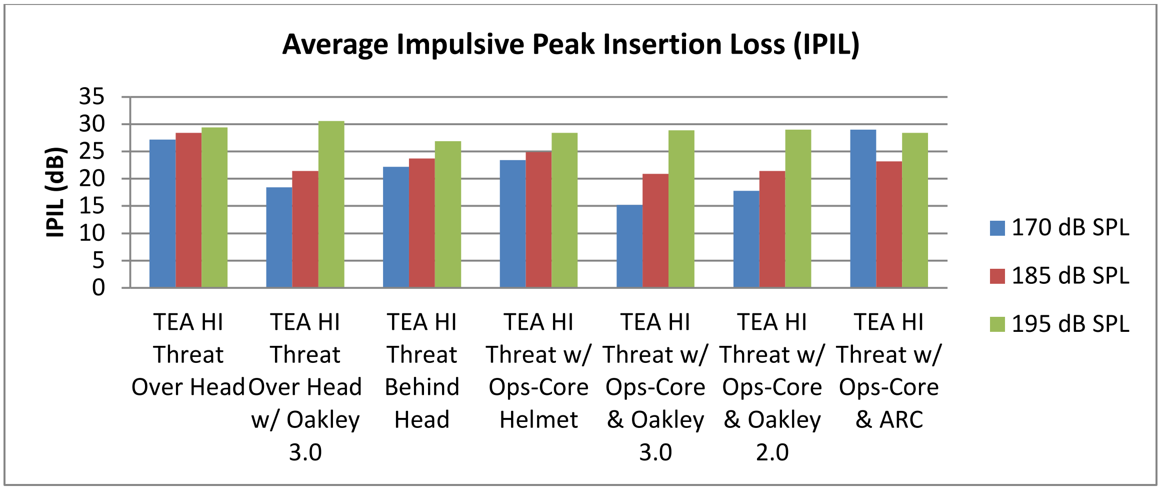

Figure 18. Average Impulsive Peak Insertion Loss (IPIL) data from blast measurements

3.5 Auditory Localization

Localization response measurements were collected for 8 paid volunteer subjects; 4 male and 4 female subjects ranging from 18 to 32 years of age. All subjects had bilateral hearing threshold levels less than or equal to 15 dB from 125 to 8000 Hz and were a subset of the subjects who completed the noise attenuation measurements.

All measurements were collected in ALF (Figure 19) at WPAFB. The aluminum-frame geodesic sphere was 14 feet in diameter with 4.5 inch loudspeakers equipped with four light-emitting diodes (LEDs) located at each of the 277 vertices on its inside surface. The ALF apparatus was housed within an anechoic chamber. The subject stood on a platform in the center of the sphere. The location of the platform had the potential to distort the signals from the speakers located directly below the subject, therefore only 237 loudspeakers, evenly distributed, above -45° elevation, were used in this study. The distance between speakers ranged roughly between 8° and 15°.

Figure 19. Auditory Localization Facility (ALF) at WPAFB

Subjects registered their responses with an Intersense IS-900 tracking system (Figure 20). The IS-900 used inertial-ultrasonic hybrid tracking technology to provide precise position and orientation information. The tracking system includes a head tracker coupled with a response wand. The head tracker was mounted on the subjects' head to provide tracking data on the X, Y, and Z coordinate location of the head, as well as the yaw, pitch and roll during the duration of each trial. The head tracker also assisted the subject in aligning his/her head to the 0° azimuth, 0° elevation speaker location to begin each trial. The response wand was equipped with a joystick and five buttons which could be programmed for various purposes depending on the task. For this study, the subjects were required to press a single button while pointing the wand at their desired response location.

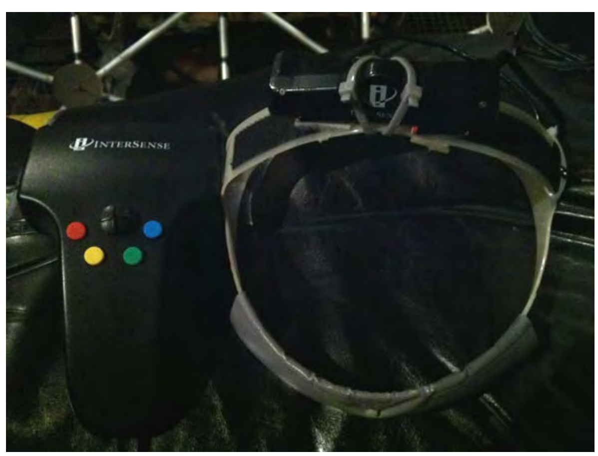

Figure 20. Intersense IS-900 tracking system

The stimuli were presented to the subjects in two different conditions. In one condition, the stimulus was a 250-ms burst of broadband (200 Hz - 16 kHz) pink noise. This duration was chosen in order to reduce the possibility that a subject would initiate a head movement during the stimulus presentation. Such a movement would provide dynamic localization cues, which would result in improved performance. In addition many real world sounds encountered by the user were likely to be short duration (e.g. weapons fire, explosions). In another condition, a broadband (200 Hz - 16 kHz) pink noise was presented continuously until a localization response was made. This allowed subjects to make use of dynamic localization cues and move their heads during stimulus presentation to orient to the sound.

The test configurations were the Ops-Core helmet only, TEA HI Threat alone, TEA HI Threat with the Ops-Core helmet, and a control configuration labeled as "Open," meaning the subject would run the task without a device (unoccluded ear). The experiment was coded and executed using the MATLAB programming language by Mathworks™. For each condition the subject fit him/herself with the appropriate device according to the directions provided by the manufacturer. The fit was verified by the experimenter, the hear-thru mode was activated, and the unity gain was set. The experimenter then directed the subject from the control room, where the fitting took place, into ALF. Once inside the sphere, the standing subject was raised or lowered by adjusting the height of the platform to ensure the subject's head was in the center of the sphere.

To start each trial the subject aligned his/her head to a loudspeaker located directly in front of them (0° azimuth, 0° elevation) and pressed a button on the response wand. A stimulus was presented randomly from one of the 237 speakers in the sphere. The stimulus was either a 250 ms burst of pink noise or a presentation of continuous pink noise. The subject would then locate and select the target speaker by pointing at it with the wand and clicking the response button to enter his/her selection. The LEDs on the speakers were tracked to the wand's movement so the subject could verify the location of his/her response. After a response was recorded, the LEDs of the target speaker were activated to give the subject feedback on his/her performance.

Each of the 8 subjects completed 320 trials in the burst noise condition and 64 trials under the continuous noise condition for each device configuration and one control condition in which no device was worn. The ratio was weighted 5:1 for burst to continuous because the short bursts more accurately represented sounds a user would encounter in a real world environment. Both burst and continuous stimuli could be presented in a single block of trials. All stimuli were presented at 65dB.

Two metrics of particular interest were percentage of angular errors > 45˚, and percentage of front-back reversals. Both of these metrics were obtained from the same data set. Angular error was the difference between the actual target location and the subject's response location as measured by the distance between the two points along the surface of the sphere. The rationale behind including this measurement was its operational relevance. In general, we assume that if an operator's attention can be directed to within

45°, he/she would then be able to use other sensory information, especially vision, to acquire the target. Subject data was collected with an “open” ear configuration (unoccluded ear) in order to serve as a reference point for determining how wearing a hearing protection and communication device affects localization. Table 7 and Figure 21 show the percentage of mean angular errors that were > 45º with each device configuration for the burst and continuous noise conditions. Subjects had errors > 45° 1.4% of the time in the burst noise condition and 0.4% in the continuous noise condition when no device was worn. The data demonstrated that localization performance was degraded when the TEA HI Threat headset was worn with or without a helmet. However, the addition of the Ops-Core helmet alone had no negative effect on localization performance.

Table 7. Percentage of mean angular errors > 45˚ for burst and continuous noise conditions

Hearing Protector	Burst (%)	Continuous (%)
Open	1.4	0.4
Ops-Core Helmet	1.8	0.8
TEA HI Threat	37.1	12.1
TEA HI Threat w/ Ops-Core Fast Helmet	44.6	25.2

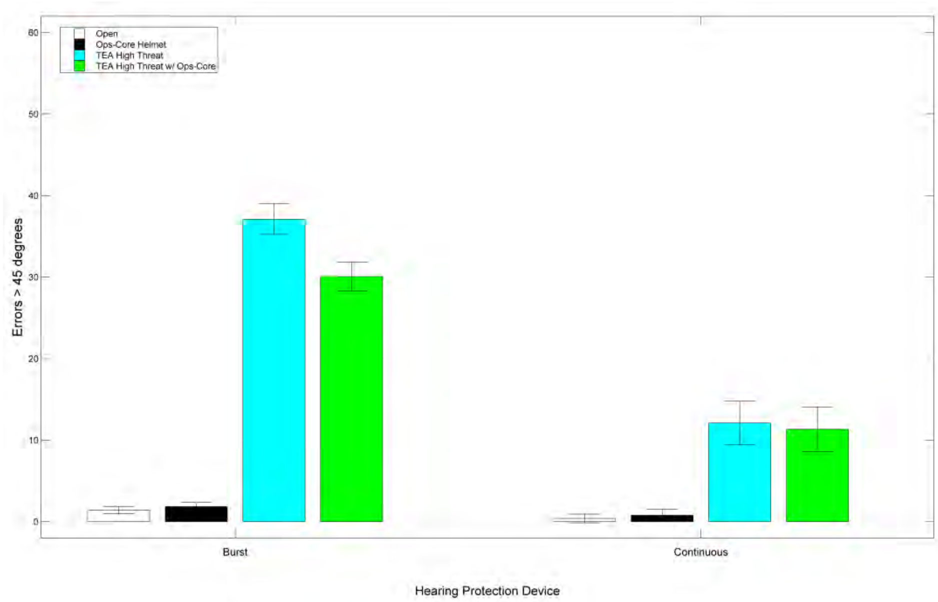

Figure 21. Percentage of mean angular errors > 45˚ for burst and continuous noise conditions

Front-back reversals occurred when a subject was unable to determine whether a sound was in front of them or behind them. The front-back reversal percentages were compiled from the same measurement as the errors > 45°; these metrics were two different ways to interpret the same data set. The percentage of front-back reversals is displayed in Table 8 and Figure 22. In the open (unoccluded) ear configuration the subjects had front-back reversals 3.9% of the time in the burst noise condition and 1.0% in the continuous noise condition. The data demonstrated that localization performance was degraded when the TEA HI threat was worn with and without the helmet in the burst noise condition. The percentage of front-back reversals for the continuous noise condition more closely matched the open (unoccluded) ear data with a range of 0.6% to 2.3%.

Table 8. Percentage of front-back reversals for the burst and continuous noise conditions

Hearing Protector	Burst (%)	Continuous (%)
Open	3.9	1
Ops-Core Helmet	5.1	0.6
TEA HI Threat	24.6	2.3
TEA HI Threat w/ Ops-Core Fast Helmet	16.4	1.2

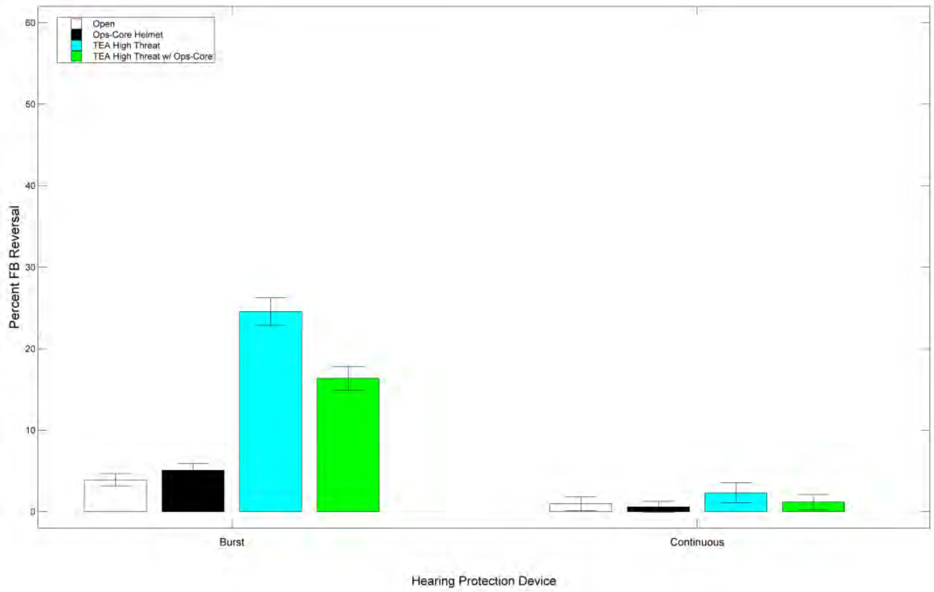

Figure 22. Percentage of front-back reversals for the burst and continuous noise conditions

3.6 Aurally Guided Visual Search

Data were collected in an aurally guided visual search task using the same eight subjects that participated in localization measurements. All measurements were collected in ALF at WPAFB. The facility design and setup, as well as the subject fitting procedure and setup procedure once inside facility, are described in detail in the localization section above.

At the center of each speaker in ALF was a cluster of four LEDs. Subjects were tasked to complete an aurally guided visual search task where they identified a visual target in the presence of 50 visual distracters at randomly selected positions around the sphere. For this task, the target stimulus was a cluster of LEDs in which either two or four LEDs were illuminated. The distracter stimuli were clusters of LEDs with either one or three illuminated LEDs. In addition, a 250 ms burst of broadband (200 Hz - 16 kHz) pink noise was played from the speaker at the target location at a predetermined sound level. The time required for the subject to find and identify the target was measured as a function of the noise-burst SPL with the communication device, with the "Open" configuration (unoccluded ear) as a reference.

To start each trial the subject aligned his/her head with a designated loudspeaker located directly in front of them (defined as 0° azimuth, 0° elevation) and pressed the trigger button on the underside of the response wand. At this point, 50 distracter stimuli were illuminated along with the one target stimulus. The subjects' task was to quickly locate the target stimulus and identify whether two or four LEDs were illuminated at the target location by pressing a response button on the top of the ALF response wand. If two LEDs were illuminated on the target speaker the subject would respond by pressing either the red or yellow button. If four LEDs were illuminated on the target speaker the subject would respond by pressing either the blue or green button (Figure 20). After the subject recorded his/her response, he/she would realign to the front speaker to begin the next trial.

The configurations were the TEA HI Threat and a control condition labeled as "Open," meaning the subject would run the task without a hearing protector (unoccluded ear). Each of the eight subjects completed 180 trials per configuration, with 60 trials at three different sound levels. In addition, each subject completed 60 trails in an unoccluded visual only condition. This condition was added to create a worst case scenario situation where the subject was given no auditory cue and forced to visually search for the target. Levels were selected that spanned a range from quiet to easily audible (not to exceed 85 dB SPL at the eardrum).

Previous results from our lab have shown a large reduction in the time it took to acquire a visual target when a sound that was easily detectable and localizable was played from the target location, relative to a visual search with no aural guide. A reference point for the visual only search was added to Figure 23. The subjects averaged a response time of 12.2 seconds to find the target when no aural guide was provided. The average response times for the TEA HI Threat are presented in Table 9 and Figure 23. Donning the TEA HI Threat resulted in increased search times across all sound levels in comparison to the open (unoccluded) ear condition. The subjects took approximately 6 more seconds to find the target when wearing a device with the 15 dB SPL aural guide and approximately 3 seconds more with the 40 and 70 dB SPL aural guide.

Table 9. Average response time (seconds)

	Target Level (dB SPL)		
Hearing Protector	**15**	**40**	**70**
Open	4	1.5	1.5
TEA HI Threat	10.2	4.6	4.4

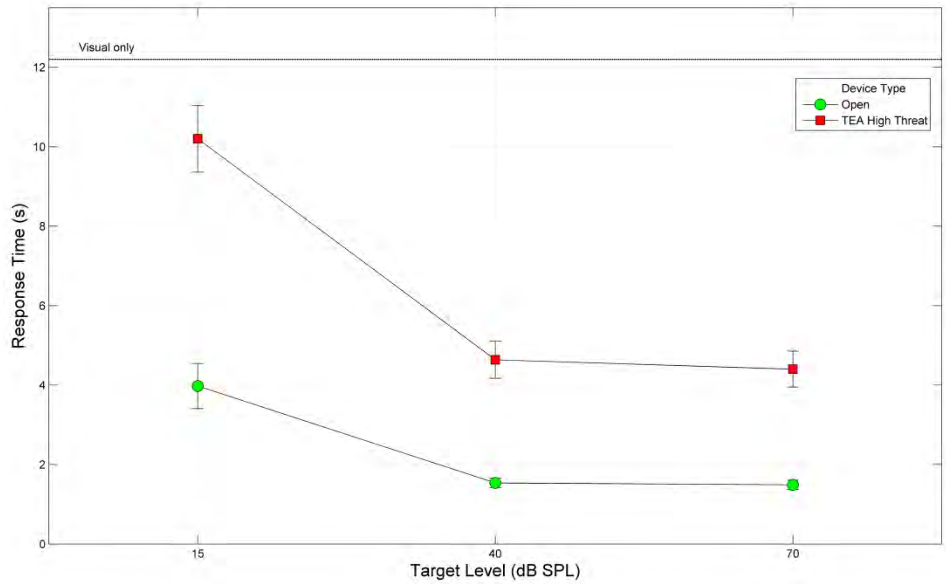

Figure 23. Average response time (seconds)

3.7 Speech Intelligibility

The AFRL VOice Communication Research and Evaluation System (VOCRES) facility was used to measure speech intelligibility performance with the TEA HI Threat headset. VOCRES was designed to evaluate voice communication effectiveness in operationally-realistic acoustic environments. The facility consisted of a programmable, high-power sound system housed in a large reverberant chamber, capable of generating high-level (130 dB SPL) noise emulating acoustic environments in operational situations. Ten operator workstations were positioned in the facility (Figure 24), each equipped with a touch-screen display and communication system capable of replicating end-to-end military communication chains (i.e., intercoms, oxygen systems, headsets, microphones, and helmets). In this way, full communication systems, as well as individual system components, could be measured under operational conditions to determine the impact these systems might have on speech intelligibility and communication effectiveness.

Figure 24. AFRL's VOCRES facility used to measure speech intelligibility performance

Participants were monitored by the experimenter using a closed-circuit camera and an audio monitoring system. Verbal instructions regarding experimental procedures were provided to participants. Speech stimuli were presented by live talker. Cueing of target words for the talker and recording of listener responses were both accomplished via a custom MatLab 7.0 application. A laptop computer with a graphical user interface (GUI) was utilized for subject responses. The talker and listeners had individual computers at their respective work stations.

Measurements were conducted in accordance with ANSI S3.2[4] with the exception of the number of subjects. A limited number of assets reduced the number of subjects from five talkers and five listeners to four talkers and four listeners. The Modified Rhyme Test (MRT) was selected for the test material. The MRT consisted of 50 six-word lists of rhyming monosyllabic English words. Measurements for the devices were collected in 65, 85, and 105 dB overall sound pressure level (OASPL). The talker and listeners were in the same noise environment. The goal was to quantify the ability of trained listeners to correctly identify target words transmitted by a trained talker using the combination of Multi-Band Intra/Inter Team Radio (MBITR) and the TEA HI Threat headsets.

For data collection, each presentation of a MRT list consisted of one talker position and three listener positions. The talker position rotated throughout the measurement conditions until a full set of data comprising four talkers and four listeners was collected. Each talker completed three MRT lists in each noise condition. During the experimental task, the talker was presented with the stimulus on the computer screen ("You will mark MRT word, please"). The talker then communicated the phrase to the three listeners via the MBITR radio and headset combination. Listeners selected the word heard by using a pen to click on the correct word from a list of six words on the laptop screen. Responses were recorded and an average score was calculated. An example of the MRT format for the talker and listener stations is provided in Figure 25.

Number 1, you will mark **WENT** please.
Number 2, you will mark **HOLD** please.
Number 3, you will mark **PAT** please.
.
.
.

1.

Went	Sent	Bent
Dent	Tent	Rent

2.

Sold	Cold	Told
Fold	Hold	Gold

3.

Pan	Pad	Pat
Path	Pack	Pass

Figure 25. Examples of the talker (left) and listener (right) ensembles

Speech intelligibility results were combined for all subjects per noise level and device configuration. The speech intelligibility scores for the TEA HI Threat headsets are presented in Table 10 and Figure 26. The scores ranged from approximately 65% correct in the highest noise environment to approximately 86% correct in the lowest noise environment. The subjects' scores were adjusted for guessing as described in ANSI S3.2[4] using the following formula.

$$Score = 2(R - \frac{W}{n-1})$$

Where:

Score	=	Percent Correct (Adjusted For Guessing)
R	=	Number Correct
W	=	Number Incorrect
n	=	6 (number of choices available to listener)

Table 10. Speech intelligibility scores

Noise Level (dB)	SI Score (%)
	TEA HI Threat Headset
65 dB	86.3
85dB	84.8
105 dB	64.9

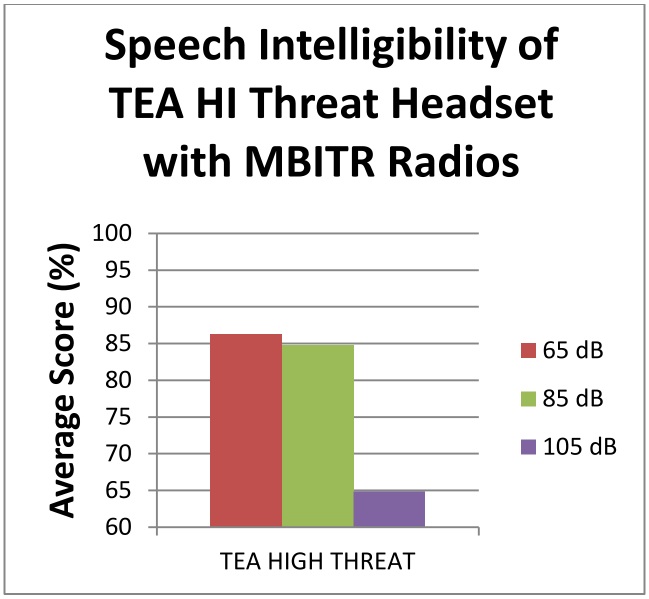

Figure 26. Speech Intelligibility Performance

4.0 DISCUSSION

All hearing protection and communication devices should be assessed in multiple ways to describe the performance of the device and the effects on an operator's ability to perform the mission. Subjective and objective measurements should be conducted to characterize a device's noise attenuation performance as well as any negative effect on situational awareness capabilities that may result. Noise attenuation in both continuous and impulsive noise environments, auditory localization capabilities, and speech intelligibility were all assessed for the devices in this study.

Selecting an Appropriate Device for the Mission

It was important to consider the environment of the end user, and to evaluate the pros and cons for each parameter independently and then jointly to form a trade space for an informed data based decision/selection. It was advisable to select the most important parameter relative to a mission for the initial selection matrix and then to consider other additional parameters when selecting a device. In general, there was normally a trade-off between attenuation (continuous and impulsive) and localization. One of the proposed benefits of using active devices was that they may have increased the user's situation awareness when compared to passive devices. However, the results of these measurements indicated that active hearing enhancement devices negatively impacted localization abilities when compared to the open (unoccluded) ear. The one major benefit of hearing protection devices like the TEA HI Threat over passive devices was that they allowed the user to communicate directly with other users across broadband wireless radio systems, intercom systems, etc. A score of 80% or greater would be considered acceptable for current military standards[15]. The TEA HI Threat met the requirement for 65 and 85 dBA noise conditions. However, it was not able to meet the requirement for the 105 dBA noise environment. This was a limitation of the device that should be considered when deciding what could be used based on specific requirements of a given mission.

Extra Configurations

The TEA HI Threat headset was commonly used in combination with other types of personal protective equipment (PPE). Eye protection was often achieved with the addition of spectacles or goggles to the warfighters' ensemble. The data collected during impulsive peak insertion loss measurements suggest that the addition of spectacles or goggles had the potential to negatively affect attenuation in an impulsive noise environment; present during both the 170 dB and 185 dB noise measurements, but not 195 dB (see Table 6 and Figure 18 above). The TEA HI Threat headset was also measured in combination with the Ops-Core Fast ACH during the impulsive noise and localization portions of the study. The addition of the helmet resulted in relatively small degradation when compared to the TEA HI Threat alone.

Device Fit and Design

Other considerations beyond the performance parameters measured in this study exist when assessing hearing protectors. Sizing and fit was one such consideration. With circumaural devices like the TEA HI Threat, sizing was typically less of a concern, especially when compared to the incredible variety of ear canal sizes and shapes that earplugs must accommodate. The headband of the TEA HI Threat was fully adjustable to fit many different widths and lengths of heads. It was also designed to be worn in combination with an ACH so it naturally integrated with the helmet currently in use by military ground operations.

5.0 CONCLUSIONS

Passive hearing protection devices could potentially provide high levels of attenuation in both continuous and impulsive noise environments. However, due to the level of noise attenuation, communications and situation awareness capabilities could be negatively affected. The TEA HI Threat headsets reduced the noise level in the ear when the user was exposed to continuous and/or impulsive noise. The devices also reduced important aural cues required to localize sounds essential to maintaining situational awareness. The active headsets may have amplified low level sounds, but the localization performance was degraded in comparison to the open (unoccluded) ear performance. The results from the speech intelligibility measurements for the TEA HI Threat headsets were acceptable in low to moderate noise environments, however, at 105 dB, the average scores did not meet current military standards.

When considering a hearing protection and communication device, consideration should be given to the prioritized requirements of the operational environment of the end user and the performance metrics of the device. The results of the hearing protector performance assessments may provide insight into new technologies and/or design criteria for the next generation of hearing protection and communication devices.

6.0 REFERENCES

1. ANSI/ASA S12.6, "American National Standard Methods for Measuring the Real Ear Attenuation of Hearing Protectors".
2. ANSI S12.42-2010, "American National Standard Methods for the Measurement of Insertion Loss of Hearing Protection Devices in Continuous or Impulsive Noise using Microphone-In-Real-Ear or Acoustic Test Fixture Procedures".
3. ANSI S12.68-2007, "American National Standard Methods of Estimating Effective A-Weighted Sound Pressure Levels When Hearing Protectors are Worn".
4. ANSI S3.2-2009 American National Standard Method for Measuring the Intelligibility of Speech over Communication Systems
5. Abel, S., Baudou, J., Bjorn, V., Buck, K., De Boodt, F., Drullman, R., Henry, P., James, S., McKinley, R.L., Sarafian, D., Van Der Veken, P., Hearing Protection - Needs, Technologies, and Performance, NATO RTO TG-147 Final Technical Report, April, 2010.
6. Brungart, D. S., Kordik, A. J., Simpson, B. D., & McKinley, R. L., Auditory localization in the horizontal plane with single and double hearing protection. *Aviation, Space, and Environmental Medicine, 74,* 937-946, 2003.
7. Bolia, R. S. & McKinley, R. L., The effects of hearing protectors on auditory localization: evidence from audio-visual target acquisition, *International Journal of Occupational Safety and Ergonomics*, Vol 6, No. 3, 309-319, 2000.
8. Bolia, R. S., D'Angelo, W. R, & McKinley, R. L., Aurally Aided Visual Search in Three-Dimensional Space, *Human Factors*, Vol 41, No. 4, 664-669, Dec 1999.
9. McKinley, R. L., & Bolia, R. S., The effects of hearing protectors on reaction times in audiovisual target acquisition. Proceedings of the 7th International Congress on Noise as a Public Health Problem, Sydney, Australia, pg 205208, 1998.
10. McKinley, R. L., D'Angelo, W. R., Nelson, W. T., Perrott, D. R., & Bolia, R. S., Three experiments in aurally aided visual search. *Journal of the Acoustical Society of America* 102:3139, 1997.
11. McKinley, R.L., D'Angelo, William R., Haas, Michael W., Perrot, David R., Nelson, W. Todd, Hettinger, Lawrence J., Brickman, Bart J., "An Initial Study of the Effects of 3-Dimensional Auditory Cueing on Visual Target Detection," *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting*, 119-123, October 1995.
12. Perrot, David R., Cisneros, McKinley, R. L., and D'Angelo, William R.,"Aurally Aided Detection and Identification of Visual Targets," *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting*, 104-108, October 1995.
13. International Test Operations Procedures (ITOP) 4-2-822, Electronic Measurement of Airblast Overpressure and Impulse Noise.
14. Council for Accreditation in Occupational Hearing Conservation, "Redefining the NRR", *The Newsletter of the Council for Accreditation in Occupational Hearing Conservation*, Volume 19: 2, 2007.
15. MIL-STD-1474E, "Department of Defense Design Criteria Standard Noise Limits", 15 April 2015.