FINAL REPORT

Improved Military Noise Monitoring System

ESTCP Project WP-201117

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Edward T. Nykaza
Engineer Research and Development Center

Jeffrey Allanach
Applied Physical Sciences Corporation

Jeffrey Vipperman
University of Pittsburgh

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Dr. Edward T. Nykaza
Mr. Jeffrey Allanach
Dr. Jeffrey Vipperman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army, Engineer Research and Development Center
2902 Newmark Dr.
Champaign, IL 61822

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14. ABSTRACT
The Bearing and Amplitude Measurement and Analysis System (BAMAS) is a network of advanced noise monitors designed for detection, localization, and classification of military blast and aircraft noise. Military blast noise is predominately characterized by impulses created by explosions, impacts, and large caliber artillery. These loud, low frequency, and short-duration acoustic pulses negatively affect residential communities near military installations and often result in lawsuits and training curfews/restrictions. The BAMAS system is intended to be used by Noise Managers at DoD installations to monitor noise emissions by quantifying the magnitude, frequency, location, and time of exceedingly loud noise events to ensure compliance with local noise limits, restrictions, and to make short/long term testing and training decisions based on measured acoustic noise levels. To achieve this goal, BAMAS noise monitors have been designed for remote, free standing operation and feature low-power data recorders for real-time signal analysis with continuous, low data-rate connectivity to a base station computer. BAMAS noise monitors feature a Type 1 microphone for accurate sound pressure measurements as well as a microphone array to facilitate wind mitigation and sound directional of arrival estimation. This project successfully demonstrated the autonomy and reliability of a large network of BAMAS noise monitors over the course of a one-year remote deployment at two US Army installations. In order to report noise emission data collected at these installations, they will remain anonymous and shall simply be referred to as Site A and Site B. Data collected at both demonstration sites helped facilitate validation of the systems' improved blast detection/classification and wind noise rejection capabilities. During the 12 month on-site data collection effort, BAMAS noise monitors were demonstrated to be actively monitoring 97% of the time while operating on solar power, while reporting >95% of military noise events exceeding its operating threshold and successfully rejecting >99.99% of wind events during periods of high wind. As part of this project, a website tool was developed to provide Noise Managers with improved access to real-time and historical noise data.

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List of Acronyms

ALEQ – A-weighted equivalent sound level

ANN - Artificial Neural Network

Apeak – A-weighted peak level

APS - Applied Physical Sciences Corp.

ASEL – A-weighted sound exposure level

BAMAS - Impulse Noise Bearing and Amplitude Measurement and Analysis System

CERL - Construction Engineering Research Lab

CF - Compact Flash

CHPPM - U.S. Army Center for Health Promotion and Preventive Medicine

CLEQ – C-weighted equivalent sound level

Cpeak – C-weighted peak level

CSEL - C-weighted sound exposure level

DNWG - DoD Noise Working Group

DNL - Day-Night Average Sound Level

DOA - Direction-of-arrival

DoD - Department of Defense

EA - Environmental Assessment

EIS - Environmental Impact Statement

EOL - End-Of-Life

ERDC - Engineer Research and Development Center

ESTCP - Environmental Security Technology Certification Program

FAT - Factory Acceptance Testing

FN - False Negative

FNR - False Negative Rate

FP - False Positive

FPR - False Positive Rate

Gen I – First generation binary noise classifier

Gen II – Second generation, 6-class noise classifier

GIS – Geographic Information System

GPS - Global Positioning System

GSA - General Services Administration

HMMWV - High Mobility Multipurpose Wheeled Vehicle

LAMAXfast – A-weighed maximum sound level with fast (125 ms) time constant

LAMAXslow – A-weighed maximum sound level with slow (1,000 ms) time constant)

Lc_{max} - C-weighted maximum sound level

LCMAXfast - C-weighted maximum sound level with fast (125 ms) time constant

LCMAXslow - C-weighted maximum sound level with slow (1,000 ms) time constant

Lc_{peak} - C-weighted peak (impulsive) sound level

L_{peak} - Z-weighted (flat) peak (impulsive) sound level

Lpk - Peak Sound Level

LZMAXfast - Z-weighted (flat) maximum sound level with fast (125 ms) time constant

LZMAXslow - Z-weighted (flat) maximum sound level with slow (1,000 ms) time constant

NEMA - National Electrical Manufacturers Association

NEPA - National Environmental Protection Act

RBF – Radial Basis Function

RF - Radio Frequency

ROC - Receiver Operating Characteristic

SD - Secure Digital

SEED - SERDP Exploratory Development

SERDP - Strategic Environmental Research and Development Program

SI - Sustainable Infrastructure

SIR – Signal-to-Interference Ratio

SLM - Sound Level Meter

SNR – Signal-to-Noise Ratio

SON - Statement of Need

SPL - Sound Pressure Level

SRP - Sustainable Range Program

TN - True Negative

TNR - True Negative Rate

TP - True Positive

TPR - True Positive Rate

TRL - Technology Readiness Level

UPitt - University of Pittsburgh

USACHPPM - US Army Center for Health Promotion and Preventative Medicine. It should be noted that USACHPPM is now under Public Health Command.

VPN - Virtual Private Network

Zpeak – Z-weighted (flat) peak level

ZSEL – Z-weighted (flat) sound exposure level

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Executive Summary

The Bearing and Amplitude Measurement and Analysis System (BAMAS) is a network of advanced noise monitors designed for detection, localization, and classification of military blast and aircraft noise. Military blast noise is predominately characterized by impulses created by explosions, impacts, and large caliber artillery. These loud, low frequency, and short-duration acoustic pulses negatively affect residential communities near military installations and often result in lawsuits and training curfews/restrictions. The BAMAS system is intended to be used by Noise Managers at DoD installations to monitor noise emissions by quantifying the magnitude, frequency, location, and time of exceedingly loud noise events to ensure compliance with local noise limits, restrictions, and to make short/long term testing and training decisions based on measured acoustic noise levels. To achieve this goal, BAMAS noise monitors have been designed for remote, free standing operation and feature low-power data recorders for real-time signal analysis with continuous, low data-rate connectivity to a base station computer. BAMAS noise monitors feature a Type 1 microphone for accurate sound pressure measurements as well as a microphone array to facilitate wind mitigation and sound directional of arrival estimation. This project successfully demonstrated the autonomy and reliability of a large network of BAMAS noise monitors over the course of a one-year remote deployment at two US Army installations. In order to report noise emission data collected at these installations, they will remain anonymous and shall simply be referred to as Site A and Site B. Data collected at both demonstration sites helped facilitate validation of the systems' improved blast detection/classification and wind noise rejection capabilities. During the 12 month on-site data collection effort, BAMAS noise monitors were demonstrated to be actively monitoring 97% of the time while operating on solar power, while reporting >95% of military noise events exceeding its operating threshold and successfully rejecting >99.99% of wind events during periods of high wind. As part of this project, a website tool was developed to provide Noise Managers with improved access to real-time and historical noise data.

1. Introduction

1.1. Background

Military testing and training noise (also known as blast noise) is a major issue for all DoD installations. There is a significant cost associated with noise; the Department of Defense spends millions of dollars annually in terms of NEPA assessments, damage claims, and lost and rescheduled training time. DoD has also spent large sums to close or relocate training facilities as a direct consequence of adverse community reaction to blast noise environments. Some of the multi-million dollar training ranges that have been closed and relocated over the past 15 years include: Camp Butner, NC; Ft. Sill, OK; Ft. Rucker, AL; Aberdeen Proving Ground, MD; Ft. Devens, MA; Ft. Belvoir, VA; Ft. AP Hill, VA; Ft. Ord, CA; Ft. Knox, KY; Ft. Benning, GA.

Military blast noise is a problem because the majority of the sound energy is concentrated in low frequencies between 10–100 Hz. These large wavelengths can travel long distances (i.e., 10s of kilometers) with minimal attenuation, though there is much variation in received levels due to the atmospheric conditions at the time of the blast noise event. For example, it has been shown experimentally that received peak levels from blast events can vary by as much as 50 decibels (dB) solely due to atmospheric conditions,[1,2] and that a large driver of community response to blast noise is due to the spatial and temporal variability of received blast events.[3] It has also been documented that noise can negatively affect residents of communities near installations, and complaints often result in lawsuits and training curfews/restrictions. For example, Fort Carson had a $3.2 million lawsuit filed against them by a developer in the late 1990's. The suit contended that Fort Carson's noise has taken away the developer's right to use the land as intended.[4] Combat readiness suffers as a result of such lawsuits. Training restrictions due to blast noise propagation hinder soldiers' ability to train to standard, jeopardizing readiness and survivability in actual combat situations.

Noise emanating from military installations is not a problem that will go away on its own, given current encroachment trends. The United States General Accounting Office reports that, "Urban growth near 80 percent of its (DoD) installations exceeds the national average."[5] The Senior Readiness Oversight Council (SROC) and DoD's Sustainable Ranges Initiative echoed this message in a report available on the SROC website. Noise pollution, which is already a prevalent encroachment challenge, will worsen as urban population centers continue to expand.[6] In a presentation given to the State-EPA Symposium in 2008, Major General Robert C. Dickerson, Commanding General, Marine Corps Installations East, states, "The impact of encroachment is broad, affecting our ability to execute realistic air, ground, and naval training across the nation, as well as beyond its borders."

Noise monitoring, in addition to better understanding of how humans and communities respond to military noise, is a key component to the solution to the military's noise problem. As noted by the chair of the Defense Noise Working Group (DNWG),

> *"Monitoring military noise is going to become a more important component of managing and assessing noise impacts at DoD installations, and therefore will be important for long-term sustainability of military mission capability. Installation and range managers need to have the capability to obtain real-time feedback of the noise generating activities emanating from their installations, so that they can make informed day-to-day and long term training decisions. While normally blast noise has been a major concern primarily for the Army, the other Services have a growing interest; the Air Force has identified blast noise as an issue as we establish ordnance ranges on our installations and the Navy is also dealing with ordnance noise issues at some of their bases."*

Noise monitoring, coupled with the latest data regarding human response to military noise findings, will also provide installations with tangible data with which to determine if noise complaints or damage claims are legitimate. This data is not currently available. In addition, historical noise records will provide decision makers with the information needed to decide whether a particular testing/training scenario (i.e., testing/training activity and location) always produces excessively loud noise or whether the recent loud events were due to anomalistic atmospheric conditions.

One of the biggest problems with current military noise monitoring systems, besides their cost, is that they do not accurately detect or classify military noises. They are plagued by wind noise, report an unacceptable amount of false positives, and do not record military noise events below a peak level of 118 dB.[7] Evidence of the current systems' inadequacies has been noted by the users of these systems (Pers. Comm. Kim Fillinger, Noise Manager at ATC-APG; Polly Gustafson, former Noise Manager at Ft. Benning, GA; and Dr. George Luz, former program manager at USACHPPM Operational Noise Program), and documented in the data collected from a large blast noise complaint study conducted by ERDC-CERL,[8] and data from SERDP projects: SI-1427, SI-1585, and SI-1436.

Applied Physical Sciences Corp. (APS, Groton, CT) and the University of Pittsburgh have developed an improved noise monitoring system, called BAMAS (the noise Bearing and Amplitude Measurement and Analysis System), for mitigating windborne and other sources of non-military noise. The system, which was developed with the support of SERDP, includes a collection of remote sensors capable of detecting, localizing, and classifying military noise events. The sensors are placed in an acoustic array and use real-time signal processing algorithms to estimate noise source locations. Mitigation of windborne and other non-military noise events is accomplished using cross-channel correlation analysis, beam-forming, and a military noise classifier developed by the University of Pittsburgh.[9]

1.2. Objective Of The Demonstration

The objective of this project was to demonstrate and validate the BAMAS noise monitoring system before military installations make a significant investment in this new technology for blast noise monitoring. In particular, the project was designed to ensure that the BAMAS system accurately detects and classifies military noises generated from testing and training activities, as well as properly reject non-military noise sources, a problem that has historically plagued other commercially available noise monitoring systems. In addition, the project would demonstrate that the monitoring system can cover a large area (i.e., greater than 1000 km^2) and can run continuously over long periods of time even amidst inclement weather conditions. Of particular interest to installation users (range managers, compliance officers, and decision makers) and proponents of this technology (i.e., DNWG, and PHC Operational Noise Group), the annual maintenance price and schedule was to be documented and the output from the system was to be recorded in a user-friendly format.

1.3. Regulatory Drivers

The Noise Pollution and Abatement Act of 1972 (also known as Noise Control Act) is a U.S. statute for regulating noise pollution with the intent of minimizing annoyance of noise to the general public. The U.S. Congress amended the Noise Control Act with the Quiet Communities Act of 1978 to provide for local and state noise-control programs and shifted the responsibility of noise control to the local and state governments.

In response to noise legislations, DoD Instruction 4715.13 “DoD Noise Program” establishes policy for establishing and maintaining a coordinated DoD Noise Program, and chartered the Defense Noise Working Group (DNWG) to advise the DoD regarding noise impacts. The DNWG recognized a need for real-time noise monitoring and assessment technologies.

Army Regulation 200-1 “Environmental Protection and Enhancement” establishes Army policy for 1) evaluating and documenting the impact of noise produced by ongoing Army activities, 2) monitor, record, archive and address operational noise complaints, 3) manage operational noise issues and community relations to sustain testing and training capabilities.

Army Regulation 350-19 “Sustainable Range Program” establishes Army policy for 1) maximizing accessibility of ranges and training lands by minimizing restrictions brought about by encroachment, and 2) establishing standard operating procedures for range operations that include monitoring and addressing operational noise-related complaints.

Army Regulation 210-21 “Army Ranges and Land Program” establishes Army policy for installations to establish proactive community noise awareness programs that are factual and informative.

The Army Environmental Requirements and Technology Assessments (AERTA) set forth the Army’s research requirements for critical environmental technologies for accomplishing the Army’s mission while minimizing impact to the environment. The AERTA documents noise concerns that have caused installations to relocate training, restrict operations, limit time of day for training, reduce charge size and close ranges. Army Commands adversely impacted by noise issues include AMC, NGB, USAR, USAREUR, MDW, USARPAC, TRADOC, and FORSCOM. The Army requires cost-effective technologies to predict, assess, and mitigate noise impacts that result in reductions in training throughput on ranges. Scientifically and legally defensible community noise impact criteria are needed to guide installation noise management decisions.

2. Demonstration Technology

2.1. Technology Description

The noise Bearing and Amplitude Measurement and Analysis System (BAMAS) is a network of advanced noise monitors designed to detect, localize, and classify sound for military, industrial, and aircraft applications. Developed specifically for remote and unattended operation in harsh outdoor environments, BAMAS noise monitors (Figure 2-1) provide significant capabilities beyond commercial systems that are based solely on conventional sound level meter (SLM) recorders. This includes:

- *Blast Noise Localization*: BAMAS noise monitors measure sound direction-of-arrival (DOA) using a tetrahedral microphone array. The DOA, which is defined as the direction (in degrees relative to True North) that sound waves propagate, is particularly useful to determine where the sound originated. For military applications, DOA is used to determine the location of muzzle blast and/or impact.

- *Wind Trigger Rejection*: Continuous and unattended monitoring for noise in remote areas presents a unique set of challenges that most noise monitors are not adequately designed to deal with. Typical outdoor noise monitors leverage conventional SLMs, which are not specifically designed or suitable for continuous outdoor use. One of the major problems with SLM-based noise monitors is their susceptibility to mistaking wind noise for actual noise events, and reporting these as real data. These false recordings are commonly referred to as wind triggers. Wind triggers can overwhelm the user with thousands of false positive records, making accurate assessment of military noise levels challenging if not impossible. BAMAS noise monitors leverage algorithms that analyze each unique noise record to determine if it is blast, aircraft, vehicle or wind noise. Recorded events determined to be wind noise are simply filtered out, leaving only the noise records of interest. BAMAS noise monitors have been demonstrated to have a very high wind trigger rejection rate.


Figure 2-1. BAMAS Noise Monitor

- *Online Web Tool*: The BAMAS system user interface is a website hosted by a base station computer. The website may be used to display the time, location, bearing, and sound level of blast noise recordings using an interactive satellite map and sortable table. All recordings can be displayed, replayed, and downloaded. All data presented on the website may be exported to Google Earth as a *.kml file and Excel as a *.csv file. Additionally, users may query the health status of each noise monitor, including the result of self-tests and the measurement of system voltages to affirm that the system is functioning normally.

BAMAS noise monitors (Figure 2-2) are comprised of a data recorder, tetrahedral microphone array, environmental enclosure, cellular data modem, anemometer, real-time signal processing software, and optional solar panel. Software installed on the data recorder provides enhanced detection, localization, and classification of military noise signals, and rejection of false positives generated by wind noise. BAMAS noise monitors transfer sound recordings, triggered by excessively loud noise, wirelessly to a base station computer using a broadband cellular data connection. Noise data received from each noise monitor is archived in an SQL database and posted on a local website for user access and analysis.

BAMAS noise monitors record one second sound clips of noise events exceeding the system operating threshold which by default is set to 95 dB re. 20μPa (this threshold may be adjusted higher if necessary). Each noise event is processed to measure its sound pressure level (SPL), DOA, propagation speed, and its signal type. This is particularly useful for determining which firing point or training area caused the noise event. BAMAS noise monitors report the unweighted peak SPL (Lpeak) by default. This is measured using a precision Type 1 microphone. Onboard software is used to filter out noise events triggered by excessive wind and unwanted sounds (cars, motorcycles, biological). The noise monitor uses several criteria to determine whether or not to save and report the noise file to the base station. The monitors will report if (1) the unweighted peak sound pressure level (Lpeak) exceeds 95 dB re. 20μPa, (2) the measured sound wave propagation is consistent with the speed of sound (~340m/s), and (3) the onboard classifier identifies the sound to be military blast noise, aircraft noise, or small arms fire. The second and third criteria are specifically used to filter out unwanted noise events triggered by wind conditions and nearby roadways (cars, motorcycles, etc.).

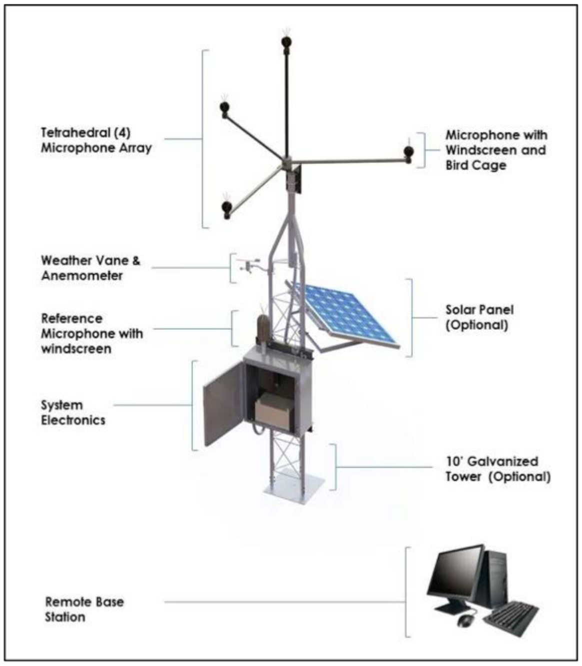

Figure 2-2. BAMAS noise monitor is comprised of tetrahedral microphone array, Type 1 outdoor microphone, an electronics enclosure with low power data recorder, and weather vane with anemometer. The version shown here is configured with several options including solar panel and 10ft-galvanized tower. The BAMAS base station computer is a Linux PC that receives data from multiple remote noise monitors, stores that data in a central database, and provides access to that data from a specially designed website.

All BAMAS systems have the following components (Figure 2-3):

- Tetrahedral microphone array with protective windscreens.
- Type 1 microphone with environmental enclosure and windscreen allowing for precision measurement of sound pressure level.
- Electronics enclosure, providing resource security and environmental protection for:
    - BAMAS data recorder, which contains noise detection and recognition software.

- o 3G cellular modem with VPN connectivity for secure real-time system reporting – the modem features low power consumption, drawing 1.2W when idle and 3.4W at peak.
- o 12V 100Ah deep cycle battery backup providing system sustainability– in the event of a power interruption, this battery is capable of powering the system for over 5 days from a full charge.

- Noise classification software. This software will identify recorded files as blasts, aircraft noise, small arms, or other.
- Anemometer to report local wind characteristics.
- (Optional) AC/DC converter for installations where 120V AC power is readily available.
- (Optional) Solar panel and controller for very remote and/or standalone installations.
- (Optional) 10’ galvanized steel tower for permanent installations (shown to left).
- (Optional) 10’ stainless steel tripod for semi-permanent installations (shown to right).

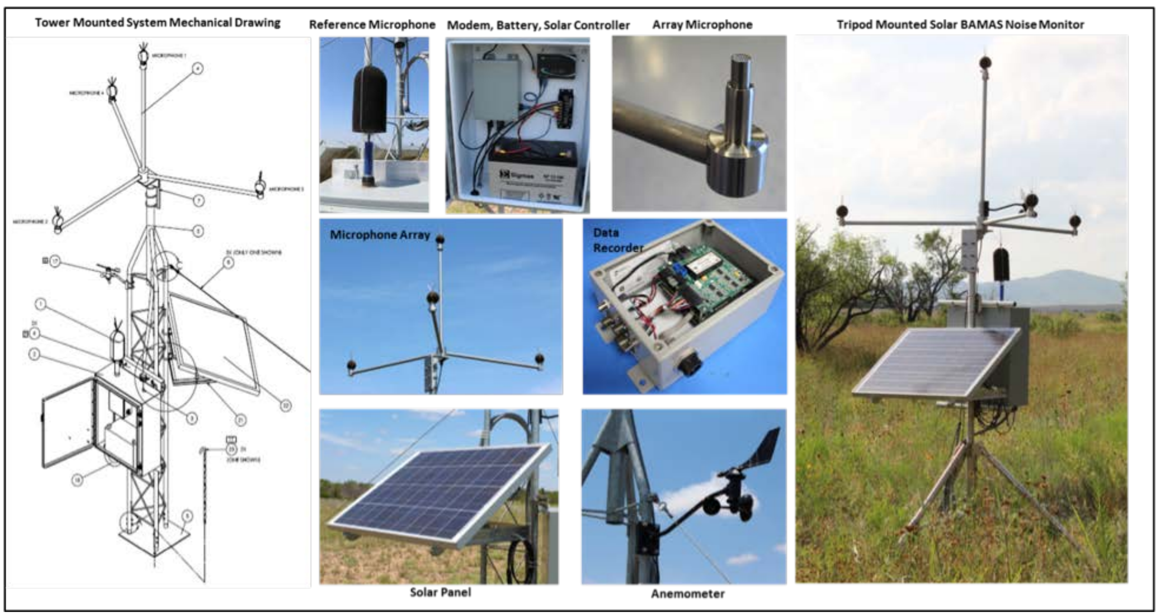

Figure 2-3. BAMAS noise monitor system components

BAMAS noise monitors work as a network (Figure 2-4). Each monitor records sound from its microphone array continuously and temporarily stores “noise events” which exceed the system threshold to a local disk. Noise recordings are then processed by onboard detection software designed by APS and classification software designed by the University of Pittsburgh. This software functions to determine if the sound is a valid military noise event. Sound recordings identified as one of several classes including blast, aircraft, small arms, jet, or vehicle are saved to disk and then uploaded to a network database. Given noise monitors are typically deployed in remote areas, noise recordings are sent wirelessly using a 3G/4G cellular modem. Data from all the noise monitors is stored on the base station computer which hosts the network database and the BAMAS web-based user interface. All cellular connections are established using a virtual private network (VPN).

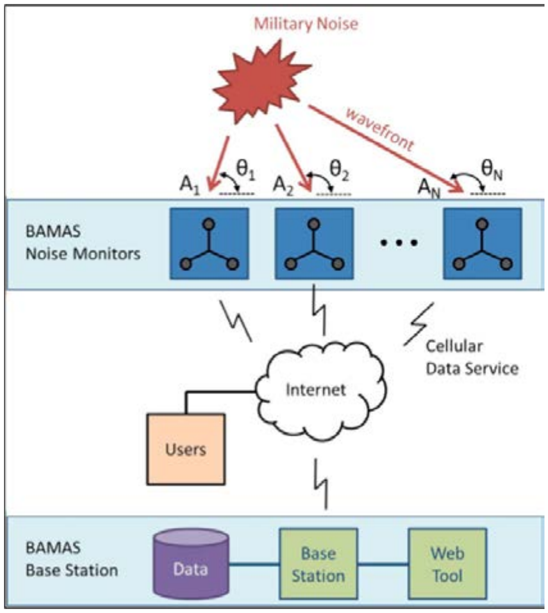

Figure 2-4. BAMAS communications network

A key feature of the BAMAS system is the integrated University of Pittsburgh blast noise classifier. The noise classifier can discern between wind and various acoustic sources, including blasts, small arms, aircraft, vehicles and thunder. The classifier is based on an artificial neural network (ANN) that uses signal features (e.g., kurtosis, crest factor, spectral slope, sound exposure level, etc.) from the detected event and outputs impulse prediction for the type of noise recorded. This feature was validated as part of the project as described in Section 6.6.

2.2. Technology Development

2.2.1. Prior Research And Development

Research and development of the BAMAS system technology was conducted under several different SERDP projects led by APS and the University of Pittsburgh and is described in detail in the final reports for those projects (i.e., SI-1427, SI-1585, and SI-1436).

Table 2-1. Summary of Project SI-1427.

Summary of Project SI-1427
The objective of this project was to develop a military noise monitoring system that provides improved noise measurement capabilities and is more reliable than existing systems. Specific technical objectives achieved during the two phases of work included: (1) Development of a microphone array and low power computer platform for measuring, recording, and processing low frequency military noise events, (2) Development of signal processing algorithms for rejecting windborne false positive noise events and localization of military impulse noise sources, (3) Development of base station software for monitoring and controlling the remote noise monitors, (4) Development of a website and database. The website, hosted by the base station computer, allows users to visualize the time, location, bearing, and peak level of the noise events archived by the system. Moreover, the location and bearing of each noise event can be displayed in Google Earth. (3) Preliminary field testing of 2 prototype noise monitors at Marine Corps Base Camp Lejeune (MCBCL) in North Carolina.

Table 2-2. Summary of Projects SI-1436 and SI-1585.

Summary of Projects SI-1436 and SI-1585
The purpose of these projects was to develop improved noise classification algorithms that can reject wind noise (a large source of false positives). The specific aims of SI-1436 were: (1) Develop a high-fidelity waveform library by measuring various types of military ordnance (and wind and aircraft) in the field. (2) Develop a set of signal metrics that can be used for classification. (3) Develop, train, and evaluate a noise classifier based upon artificial neural networks The specific aims of SI-1585 were: 1. Expand the measured waveform library started in SI-1436. 2. Continue refinements of the noise classifier developed in SI-1436. 3. Establish the hardware requirements of the algorithms. 4. Develop a real-time laboratory demonstration of the classifier. 5. Develop and demonstrate a prototype classifier system at a military base.

2.2.2. Research And Development As Part Of This Project

The main objective of this project is to demonstrate and validate the BAMAS system, thus the majority of research and development was performed prior to this effort. However, there were several initiatives taken to mature the BAMAS technology to satisfy end-users, including:

(1) several modifications to the noise monitor design to permit easy installation and improve reliability in remote areas (Section 2.2.2.1)
(2) a complete redesign of the BAMAS website to promote user-friendliness and improve visualization of noise data (Section 2.2.2.2)

(3) several improvements to the UPitt military noise classification software to provide improved, wider recognition of sound (Section 2.2.2.3)

2.2.2.1. BAMAS Noise Monitor Design Modifications

Several improvements were made to the BAMAS noise monitors as part of this project (Figure 2-5). This included the development of a solar-powered version of the noise monitor as well as providing the option of selecting one of several corrosion resistant mounting platforms. The tower and tripod configurations promote ease of installation and allow microphone arrays to have unobstructed exposure to noise. The ability to opt for a solar powered BAMAS noise monitor is advantageous for noise monitoring in remote locations where AC power is either unavailable or cost-prohibitive to install. Legacy components that carried over to the current system generation, such as microphones and cable harnesses, were reviewed and modified to simplify field replacement and maximize durability. This includes encapsulating cable terminations with urethane to prevent water and dirt intrusion. The modifications promote ease of maintenance and system longevity through the simplification of replacing components exposed to possible corrosive environments.

Figure 2-5. BAMAS noise monitor design modifications. The SERDP prototype system (left) was designed to mount to telephone poles. The latest design (middle and right) allows for improved flexibility with installation.

2.2.2.2. BAMAS User Interface

The BAMAS website (Figure 2-6) is a powerful and user friendly tool that is capable of providing real-time system-wide noise monitor feedback as well as detailed historical data referencing. The website was designed using HTML5, making it mobile device friendly, and has been tested in all major web-browsers, as well as with iPhone®, iPad®, and Android OS devices.

The website is used to retrieve historical (and real-time) data from a network of BAMAS noise monitors. Noise event data can be displayed one of three ways: (1) graphically using a GIS map; (2) by date/time using a dynamic and sortable table - event details are tabulated providing event date/time, receiving noise monitor, peak sound pressure level, event type, and the bearing/elevation from the receiving unit; and (3) graphically by rendering a plot of the noise pressure signature. For users who would like to have access to data without a web connection, or desire to post process data, event data tables are downloadable as CSV files for use in Excel, and event maps can be downloaded as KML files to view in Google Earth.

Analysis of historical data is possible by configuring start and end date/hour times on the dynamic calendar. Additionally, users can select data displays by individual noise monitors, and event types. Live Mode allows users to monitor event activity in real-time. Activating Live Mode displays all events from all units for the last half hour, while automatically updating and displaying new events.

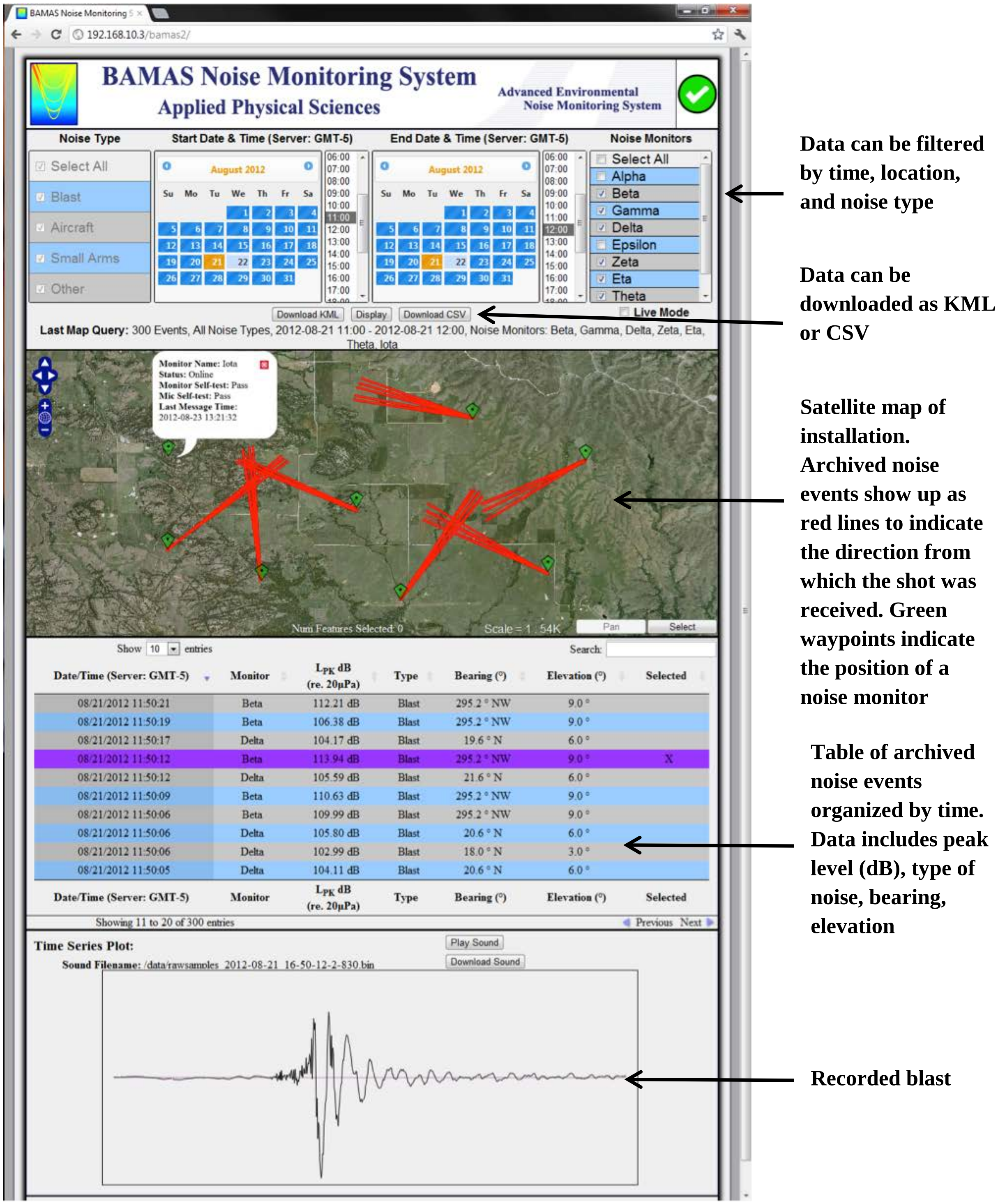

Figure 2-6. BAMAS website.

Monitoring the health of a network of BAMAS Noise Monitors may be accomplished using the health monitor utility built into the website (Figure 2-7). This utility allows users to verify that the monitors have sufficient power and have passed their built-in tests. The data shown below is for a network of nine solar powered BAMAS noise monitors installed at Site A. At the time this picture was taken, all monitors were "Online" which indicates there were no detected issues with the hardware or software. As we will discuss later, the reliability of these noise monitors over the course of the one-year experiment proved to be excellent.

Health Monitor:

Show 10 entries Search:

Id	Monitor Name	Status	Self-test	Mic. Self-test	Battery Voltage	Logic Voltage	Array Mic. Voltage	Ref. Mic. Voltage	Last Heard Time (Server: GMT-5)
1	Alpha	Online	Pass	Pass	13.547	3.286	8.987	11.843	2012-10-19 14:48:19
2	Beta	Online	Pass	Pass	13.477	3.269	8.955	11.189	2012-10-19 14:49:23
3	Gamma	Online	Pass	Pass	13.524	3.291	8.999	11.743	2012-10-19 14:49:54
4	Delta	Online	Pass	Pass	13.513	3.283	8.979	11.508	2012-10-19 14:50:00
5	Epsilon	Online	Pass	Pass	13.641	3.298	9.018	11.417	2012-10-19 14:49:29
6	Zeta	Online	Pass	Pass	13.681	3.297	9.014	11.353	2012-10-19 14:48:53
7	Eta	Online	Pass	Pass	13.606	3.274	8.949	11.555	2012-10-19 14:49:15
8	Theta	Online	Pass	Pass	13.606	3.285	8.983	11.551	2012-10-19 14:49:20
9	Iota	Online	Pass	Pass	13.631	3.287	8.986	11.377	2012-10-19 14:48:37
Id	Monitor Name	Status	Self-test	Mic. Self-test	Battery Voltage	Logic Voltage	Array Mic. Voltage	Ref. Mic. Voltage	Last Heard Time (Server: GMT-5)

Showing 1 to 9 of 9 entries Previous Next

Website: Applied Physical Sciences, 2012

Figure 2-7. BAMAS Health Monitor Utility is built-in to the website.

2.2.2.3. Military Noise Classifier

The primary goal for the classification work was to increase the number of recognized classes of noise from two (referred to as the "Gen I" classifier) to six (referred to as the "Gen II" classifier): blast, small arms, fixed and rotary wing aircraft, vehicle, wind, and electronic. During the course of the research, the latter category was dropped and thunder was added in its place – electronic noise appeared to be specific to one prototype unit. At the same time, performance was to be maintained at greater than or equal to 90% accuracy. The work done in this effort involved manually classifying thousands of new waveforms collected by the active BAMAS units under typical operating conditions, so that data could be used for the training and analysis of the Gen II classifier. Misclassifications were closely examined to determine the cause and classifying algorithms were improved where possible. The goal was to create a classifier that is sufficiently general such that is does not require site-specific training. This was achieved by training with data from one or more libraries (SERDP library, SI-1436, SI-1585) and libraries from BAMAS units at three different military bases. As expected, using all available data from all sites was found to produce a satisfactory general classifier that worked for all data from all bases. Using the data from Site A or Site B also produced a classifier with higher accuracy, since a large quantity of "real-world" data was obtained from these sites. Another goal was to compare and contrast the binary classification accuracy of the recently rediscovered "CHPPM Criteria,"[10] to that of the UPitt classifier. The CHPPM Criteria metrics (Lcmax, Lcpeak, Lzpeak, CSEL) were included in the development of the Gen II Classifier. Effects of SNR and wind speed on classification performance were also examined. UPitt was also responsible for validating the operation of the classifier.

2.3. Advantages And Limitations Of The Technology

The BAMAS technology was compared to 21 commercially available environmental and military noise-monitoring systems manufactured by Cirrus Environmental (UK), Cassella (UK), Rion (Japan), Norsonic (Norway), Larson and Davis (US), Bruel and Kjaer (Denmark), NoiseMeters (US), Databuoy (US), Safety Dynamics (US), SST (US), Microflown Avisa (Netherlands), Raytheon BBN Technologies (US), Alliant TechSystems (US), Ducommun Miltec (US), Army Research Laboratory (US), and SARA (US). The following noise monitor specifications were compared: model type, dynamic range, frequency range, frequency weighting, time weighting, measurement metrics, data storage, weather measurement, communication options, calibration, power consumption, battery backup, operating temperature, relative humidity, software, and algorithms.

The advantages and disadvantages of the BAMAS system are noted below. In general, it is very difficult to compare noise-monitoring systems as many of them are specifically designed to monitor a particular noise source. For example, none of the environmental noise monitors available are able to capture and classify military noise sources. In addition, the military noise monitors that are available, many of which were not available at the beginning of this research, are designed for battlefield acoustic’s applications and not easily adapted to an environmental (military) noise monitoring applications where the source is often several kilometers away from the noise monitor.

2.3.1. Advantages

- ***Wind Trigger Rejection:*** the BAMAS stands alone in terms of being able to effectively reject windborne noise triggers. Wind noise can generate hundreds (and sometimes thousands) of false positives each day, the presence of which makes analysis of military noise metrics impractical. Other commercial systems do not have software for wind noise mitigation and thus are less effective for assessing impulse noise created by military testing and training activities. In addition to providing better quality data, the wind noise rejection software allows these noise monitors to run with a very low detection threshold. BAMAS noise monitors are typically initialized with a 95 dB threshold as compared to other commercially available blast noise monitors, which generally range from 110-115 dB – as much as 20 dB lower. For these systems, a lower detection threshold would significantly increase the number of wind triggers, but this is not the case for the BAMAS system. With a lower detection threshold, the BAMAS noise monitors can detect blast noise at significantly greater distances than other systems; thus, fewer BAMAS noise monitors are required to cover a particular area. This feature was validated as part of this project as described in Section 6.1.

- ***Real-time Noise Assessment:*** BAMAS noise monitors record and analyze any sound that exceeds its operating threshold (95 dB) in real-time. Sound events identified as military noise (or aircraft) are queued and passed to the Base Station computer over the 3G cellular network and subsequently deleted from the data recorders once transfer confirmation is received. Confirmed military noise events appear on the BAMAS website near real-time. A small number of commercially available monitors also provide real-time feedback, but often have a much higher trigger threshold.

- ***Noise Classification:*** The BAMAS system's software employs a military noise classification algorithm designed by the University of Pittsburgh. This algorithm can effectively identify recorded noise as Blast, Small Arms fire, Jet Aircraft Noise, Truck/Car/Propeller Aircraft Vehicle Noise, Thunder, and Wind. This feature was validated as part of the project as described in Section 6.2 and Section 6.6. By including wind as a class of noise that the algorithm is trained to detect, a second line of wind rejection is provided for BAMAS. The software could be expanded to include additional categories of noise (with retraining). Foremost, the classifier greatly reduces the amount of time and effort for range management, since events are already classified. Other noise monitor systems require range managers to listen to each recorded event to identify the source manually.

- ***Noise Localization:*** Military bases generally have many (>20) firing points and impact areas spread out over a large area (>100 sq. miles) of land. BAMAS noise monitors use a 4-channel microphone array, unlike most other commercial systems that only use a single microphone. Data collected through this array is processed to reject windborne noise and to estimate the direction the noise was received from. Noise direction finding enables noise managers to assess which firing points (or training locations) may be generating excessively loud noise. Without noise direction finding, it can be difficult if not impossible to determine which firing point may be causing a community noise problem. This feature was validated as part of this project as described in Section 6.4.

- ***Flexible Design:*** BAMAS noise monitors are available in several options including solar and AC powered versions. Additionally, the noise monitors can be mounted on small, semi-permanent metal towers and mobile tripods, both of which are easily installed.

- ***Standalone Noise Monitoring:*** The BAMAS system uses a cellular data network to connect each remote monitor to a base station computer. Noise monitors may be installed anywhere provided cellular coverage is available. This feature, combined with solar power capabilities, eliminates the need for existing infrastructure such as telephone lines, communication towers, or fire towers to be present. This feature was validated as part of the project as described in Section 6.5.

- ***System Reliability:*** BAMAS noise monitors have been deployed and operational for several years (since September 2010) at Site B with minimal maintenance and without need for replacement components. Deep cycle batteries are trickle charged as part of all system designs, and provide backup power in the event of power outages. Noise data recorded during lapses in cellular communication are queued for transfer on the data recorder until connectivity is restored. This feature was validated as part of the project as described in Section 6.5.

- ***Remote System Health Monitoring:*** The BAMAS base station software continuously monitors the health and status of the remote noise monitors. This software has the ability to send emails to a specified address when any BAMAS noise monitor drops off the network. Other commercial systems with base stations utilize similar technology, but the system designed by APS automatically notifies the user when certain events and/or failures occur. This feature was discussed in Section 2.1.

- ***Website:*** The BAMAS system user interface is a website hosted by the base station computer. The website may be used to display the time, location, bearing, and sound level of blast noise recordings using an interactive satellite map and sortable table. All recordings can be displayed, replayed, and downloaded. All data presented on the website may be exported to Google Earth as a *.kml file and Excel as a *.csv file. Additionally, users may query the health status of each noise monitor via the website, including monitors' results of self-tests and measurements of system voltages. While this is a great improvement over existing installation noise monitoring systems, may of the other commercially available noise monitoring systems also provide web-based visualization options.

2.3.2. Limitations

- ***Concurrent noise sources***: Military noise originating from two or more geographically distributed sources that are received by the monitor simultaneously (within the same 1 second sampling window) will be archived as a single event or will confuse the software causing it to be rejected. This is, however, a problem that all of the current noise monitoring systems face and an active area of research.

- ***Sampling Frequency:*** BAMAS noise monitors were developed for military blast noise monitoring, which consists of low frequency, short duration sound. The system uses a 5 kHz sampling rate which allows for small file sizes, manageable data transfers and robust lower-cost hardware. This sample rate limits accurate observation of high frequency and/or longer duration signals, but because blast noise occurs at very low frequencies and duration as previously mentioned, the sampling rate is sufficient for use in this circumstance. It should be noted that BAMAS can be reconfigured for a higher sampling rate with minor hardware and software modifications; however, in its current configuration, BAMAS does not presently support measurement of frequencies exceeding 2.5 kHz.

- ***Cellular Coverage:*** As described in Technology Description, BAMAS monitors rely on commercial cellular coverage for the transfer of data from noise monitors to the base station. This limits their use to locations that have adequate cellular coverage.

- ***Noise Classifier:*** The classifier is not 100% accurate, but misclassifications are typically spurious (i.e. most blasts from a training exercise would be classified as blasts). If unsure, the user can listen to the waveform of the event to validate its source. Acoustic events mixed with windborne noise can be difficult to accurately classify (may be classified as one or the other). However, in typical testing conditions, wind often masks acoustic events, making it difficult in practice whether to hand classify uncertain waveforms in the library as wind triggers or noise events. No distinction is currently made between vehicles and propeller aircraft (both are considered the "vehicle" class). If the classifier is exposed to a noise source for which it is not specifically trained, it will classify it as the closest known noise source. Adding additional noise classes would require additional training of the classifier, but necessary software updates of the classifier in BAMAS can be done remotely.

- ***Congruence with SERDP 1546:*** A limitation of the current BAMAS system is that the noise monitors do not currently output the noise metrics over the durations that were found to have the best correlation with the way communities respond to noise (i.e., C-weighted Sound Exposure Level (CSEL) over a duration of 3-6 seconds). In addition, the use of the unweighted peak level over a 1-second duration – the metric the BAMAS monitor currently outputs – does not capture all of the acoustical energy present in the signal making the outputted peak levels prone to spurious errors. For example, an ad hoc analysis that looked at the unweighted peak blast noise levels reported by the CERL and BAMAS monitors found good agreement on average (i.e., 0.6 dB), but high variance (i.e., standard deviation of 6 dB). The high variance is likely due to the different lengths in the signal duration recorded by the two monitoring systems (i.e., the CERL monitor recorded 6 seconds of signal whereas the BAMAS monitor recorded 1 second of signal). With these limitations exposed, it is also important to explain that there was good reason for originally designing the BAMAS monitor to output the unweighted peak level. At the time of its design unweighted peak level was the standard metric used to assess the risk of receiving blast noise complaints and the duration of 1-second was designed to cut down on the amount of data sent over the cellular network to the base station. Lastly, while making the changes from outputting an unweighted peak level over a duration of 1-

second to a CSEL over 3-6 seconds is not trivial and beyond the scope of this demonstration, it is something that the manufacturer is seriously considering. This change can be accomplished by a remote software update and does not require any hardware modifications, thus is not a fundamental limitation of the BAMAS technology.

- ***Cost:*** While many of the proponents of this technology (e.g., military installations and Defense Noise Working Group) find the cost of the BAMAS monitors to be a limitation, it is important to note that the BAMAS system has been competitively priced. Full details of the BAMAS cost schedule is given in Section 7.1. The BAMAS monitors, with a cost of roughly $40K per node, fit within the range of other commercially available systems. The average cost of other commercially available systems is on the order of $25K +/- 15K. However, it is also important to note that the other systems are not well suited to monitor military installation noise. That being said, the current costs of the BAMAS could limit the number of installations that are willing to invest in the technology.

3. Performance Objectives

The purpose of the project is to demonstrate an improved noise monitoring technology operating autonomously over an extended period of time. In doing so, a set of performance objectives was established (Table 3-1) at the beginning of the project as a means to define what improvement really means. For each objective we list the success criteria along with the results from our yearlong data collection effort – for each objective, we reference the section where a detailed discussion of the results is presented. The BAMAS noise monitors met or exceeded all of the performance objectives listed.

Table 3-1. Performance Objectives.

Performance Objective	Success Criteria	Results	Section
System autonomy and reliability	BAMAS noise monitors shall be actively monitoring for **>90%** of the time and in all weather conditions	BAMAS noise monitors were actively monitoring for **>97%** of the time in all weather conditions	6.5
Improved rejection of wind noise and other spurious non-acoustic signals	BAMAS noise monitors shall reject **>95%** of sound recordings initiated by wind noise or other spurious non-acoustic signals	BAMAS noise monitors were observed to have a false alarm rate of 10^{-5} during periods of high winds. This means the rejection rate was **>99.9%**	6.1
Improved detection of military blast noise	BAMAS noise monitors shall detect, record, and report **>95%** of military noise events exceeding threshold as compared with CERL system.	BAMAS noise monitors exhibited the capability to report **>95%** of military noise events exceeding its operating threshold in non-severe weather.	6.2
Improved noise classification	BAMAS noise monitors shall classify all recorded sounds with **>90%** accuracy	More noise classes were added to the classifier, while at the same time improving accuracy. Accuracy is > 90% and as high as 92.9%.	6.6
Comparison with existing noise monitor	BAMAS noise monitors shall report fewer false noise recordings than the existing commercial noise monitor	BAMAS noise monitors successfully reported fewer false alarms than the SLM during the Phase 1 Test, despite the 115 dB threshold on the SLM device.	6.3
Microphone calibration	The software calibration mode is demonstrated to adjust the sensitivity	The software calibration utility allows users to reset microphone sensitivity by plugging directly into the data recorder, or over the VPN	6.7
Blast noise localization	Users are able to determine where the blast noise originated from using the localization result (bearing only) overlaid on a map	Users are able to effectively determine an approximate blast noise source location by use of the embedded map on the BAMAS website. Under ideal conditions, BAMAS accurately localized sound DOA within a standard deviation of 4.9°	6.4
Ease of use	Users find the software easy to use and beneficial for managing and/or assessing noise levels caused by military testing and training activities	The BAMAS web interface allows network monitoring and data extraction for any user. The suite of combined features can perform tasks that previously required multiple interfaces and thorough knowledge of system metrics.	6.8

4. Site/Platform Description

4.1. Test Platforms/Facilities

Data to support the evaluation of system performance was collected at two US Army installations over the course of 1 year. These installations will be referred to as Demonstration Site A and Site B.

Demonstration Site A: Nine (9) BAMAS noise monitors were installed at Demonstration Site A and were set to collect noise data from April 4, 2012 until June 18, 2013. The noise monitors were installed along the perimeter of the installation – to form a network between the military installation and the adjacent community – with a spacing of 0.5-2 miles (Figure 5-1). During this time, the 9 units observed nearly 33 million triggers. A trigger is defined as any sound event which exceeds the system operating threshold (95 dB) causing the noise monitor to temporarily record, analyze, and then make a decision whether the data is valid – specifically whether it is a blast, aircraft, vehicle, thunder, or wind event. On windy days, the number of triggers will increase significantly. However, the noise monitor is required to filter out these disturbances. The climate at installation Site A is generally hot, dry, and arid. During the summer, temperatures are consistently above 90ºF with regular strong winds. Other seasons see periods of rain and wind, with average highs in winter reaching into the fifties, and lows dropping below freezing. Overall, the installation averages close to 250 sunny days per year.

Demonstration Site B: Five (5) BAMAS noise monitors were installed at Demonstration Site B and were set to collect data beginning in mid-2010, with a system upgrade occurring in June 2011 and near continuous data collection for the next year. Noise monitor units are dispersed amongst several towns surrounding the site, and are spaced several miles apart. The climate at installation Site B is variable. During the summer, the climate is hot, but more humid than Site A, with significantly lower average wind speeds. During winter seasons, the average temperature remains at or below freezing and the average snowfall for the region is greater than 70 inches annually. Overall, the installation averages approximately 150 sunny days per year, and over 150 days that see slight precipitation.

4.2. Present Operations

The BAMAS noise monitor network at Site A is being relocated to a facility with a greater need for noise monitoring, while the network at Site B will remain in place for continued operation.

4.3. Site Related Permits And Regulations

There were no required permits for this demonstration; however this work was coordinated with the participating installations.

5. Test Design

To evaluate the performance objectives of the project, the BAMAS technology demonstration was divided into two phases. The first phase was a 1 week on-site dem/val exercise at Site A where the performers observed live-fire events and compared data collected by human observers with data recorded by the BAMAS monitors. The second phase was a large-scale, long-term (1 year) data collection at Sites A and B.

5.1. Phase One: Onsite Demonstration & Validation

During the week of June 18, 2012 all team members assembled at the BAMAS Demonstration Site A (Figure 5-1) to coordinate with range personnel and observe artillery training operations with a variety of noise monitoring equipment. The primary focus of the exercise was to collect data for the evaluation and validation of the following performance objectives:

- Improved rejection of wind noise and other spurious non-acoustic signals (6.1)
- Improved detection of military blast noise (6.2)
- Comparison with existing noise monitors (6.3)
- Blast noise localization (6.4)

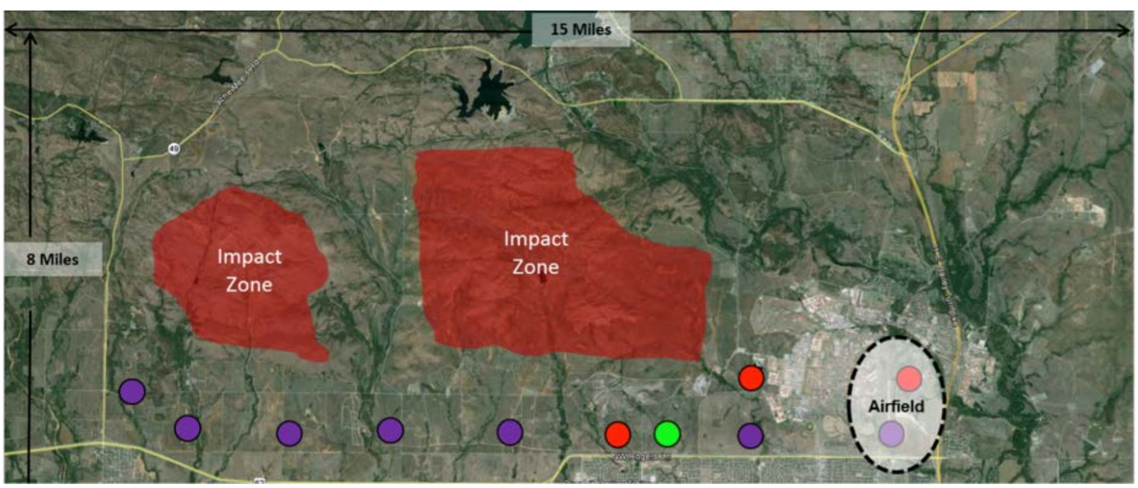

Figure 5-1. BAMAS Site A Phase 1 Test Setup.

The test equipment consisted of:

- 9 Active BAMAS Noise Monitors (Figure 5-1: Purple and Red dots) operating at a 95 dB detection threshold.
- 3 laboratory-grade noise monitors collocated with BAMAS Units Alpha, Zeta and Iota (Figure 5-1: Red dots) operating at a 100 dB detection threshold. These systems were built by CERL, therefore are herein referred to as CERL noise monitors, for another

SERDP project and were leveraged for this project to corroborate data collected by the BAMAS noise monitors.

- 3-5 commercially available noise monitors (Larson Davis model 870) collocated with BAMAS monitors operating at a 100 dB detection threshold.
- 1 commercially available SLM located within 100 yards of active artillery units (Figure 5-1: Green dot) operating at a 115 dB detection threshold.

Teams were distributed at the locations where CERL and BAMAS Noise monitors were collocated, and hand notated blast and impact times and apparent direction of origin. Data collection was performed on June 19 and June 21, 2012 in variable weather conditions. June 19 was very windy with an average wind speed 15-20 MPH and with gusts above 30 MPH. Thunderstorms passed through the region at various times of the day (Figure 5-2). The observation period on June 19 lasted from 09h00 until 16h00. June 21 was calm with occasional steady winds between 5 and 10 miles an hour (Figure 5-3). The observation period on June 21 lasted from 09h00 until 14h00. Both days saw live fire military activities from a nearby firing point; however June 21 was noted to be approximately 3 times more active than June 19 by human observers.

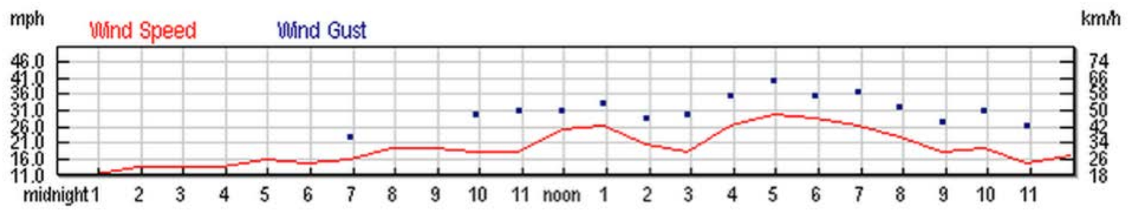

Figure 5-2. Site A Wind - June 19, 2012 (Source wunderground.com).

Figure 5-3. Site A Wind - June 21, 2012 (Source wunderground.com).

5.2. Large-Scale Data Collection And Validation

BAMAS noise monitors at Site A were installed on June 18, 2012 and deactivated one year later. Over this period, they were calibrated 3 times, received moderate software upgrades in conjunction with validation efforts, and received an upgraded Gen II classifier from the University of Pittsburgh. Microphone calibrations were performed onsite by CERL team members, software modifications were performed remotely over the VPN, and all validations were done remotely with data downloaded from the network Base Station. System deployment remained the same as the layout used during the Phase 1 onsite test. Data accumulated at Sites A and B during Phase 2 were used to validate of the following performance objectives:

- System Autonomy And Reliability (6.5)
- Improved Noise Classification (6.6)
- Microphone Calibration (6.7)
- Ease Of Use (6.8)

6. Performance Assessment

A significant amount of data has been used in the evaluation of system performance. Over the one-year demonstration period, BAMAS noise monitors at Site A archived over 33 million triggers while reporting only 450,000 (1.4%) of those as noise recordings. That is, 450,000 noise events exceeded 95 dB and were classified as either military blast, aircraft, or small arms fire. This implies 98.6% of sound events were filtered out prior to being reported to the user. As described earlier, a trigger is defined as any sound event that exceeds the system detection threshold. Triggers can be caused by real noise from aircraft, vehicles, biologics, artillery or even transient pressure disturbances caused by wind and weather. Each trigger is temporarily recorded by the noise monitor and then analyzed using wind detection and classification algorithms developed by APS and the University of Pittsburgh. Triggers that pass specific criteria are permanently saved to the unit's memory to be transferred to the Base Station over the cellular network. In addition to saving each noise event to disk, every noise monitor archives specific information about each trigger so it can be determined after-the-fact why a particular noise event was filtered out. This includes the date and time, the peak SPL from each microphone, the calculated bearing and horizontal elevation to the source, the anemometer wind speed and direction, and several detection/classification metrics.

Data collected during the Phase 1 test included human notations of the event time and the apparent event type (generally blast, impact, small arms/machine gun, and thunder), as well as the data collected from the commercial devices described in Section 5.1. The commercially available noise monitors indicated the event time and peak SPL, as well as the custom blast classifier results, while the SLM recorded the event time, peak SPL and a 3 second recording of the event. CERL noise monitors reported event time and multiple noise metrics including peak SPL and classifier results, along with human notations of classification accuracy.

Additional BAMAS data is available for the Phase 2 validation, collected from noise monitor status updates set at approximately 2-minute intervals and saved to the Base Station in a month-long file. These status updates record the noise monitor node name, date and time, wind speed and direction, system battery voltage, and internal (data recorder) temperature. Half-hour interval updates report additional noise monitor system logic voltages. Data from both phases was used in assessments as applicable.

6.1. Improved Rejection Of Wind Noise

Success Criteria: BAMAS noise monitors shall reject >95% of sound recordings initiated by wind noise or other spurious non-acoustic signals.

Data: As previously noted, commercial noise monitors are typically plagued by wind and other sources of non-military noise, and as a result commonly increase the noise monitor detection threshold to deal with this issue. However, this is not a good solution given that increasing the trigger threshold can result in missed detections of important noise events. The BAMAS microphone array allows the system to mitigate wind noise, and therefore can also accommodate a low detection threshold – improving the system's overall capabilities.

On June 19, 2012, during the demonstration/validation exercise observation period, BAMAS noise monitors collocated with commercially available noise monitors archived 86,093 triggers (Table 6-1) using a detection threshold of 95 dB. As a reminder, triggers are noise events that cross the systems detection threshold, while recordings are noise events that both exceeded the detection threshold and were identified by onboard classification algorithms as military noise events. Recorded noise events that were caused by wind are defined as false alarms. Our success criterion states that the number of false alarms should be less than 5%. Over the course of that day's exercise, the 5 BAMAS noise monitors at Site A listed in Table 6-1 (named Alpha, Zeta, Gamma, Eta, and Iota) archived 86,093 triggers with only one recorded event containing wind. This gives a probability of false alarm of approximately 10^{-5} or a rejection rate of >99.99% - which exceeds our success criteria for wind noise rejection. During this same time, the COTS noise monitors (collocated with the BAMAS noise monitors) archived 18,844 noise recordings (Table 6-2) using a detection threshold of 100 dB. These noise monitors were equipped with a blast classifier, previously designed by CERL in coordination with the University of Pittsburgh. This classifier reported that 56 of the events recorded by the device were blast events. The CERL noise monitors essentially have no ability to reject wind. A further comparison and analysis of the comparison between the BAMAS and COTS noise monitors is given in Section 6.3.

Table 6-1. BAMAS Wind Activity - Phase 1 Test – June 19, 2012.

BAMAS - June 19, 2012 - 9AM to 4PM	Alpha	Zeta	Gamma	Eta	Iota
Total Triggers	3334	17803	18948	23523	22485
Recorded Wind Events	0	0	0	1	0
Probability of False Alarm	0	0	0	0.000043	0
Average P_{fa} For 7 Hour Observation Period	1 in 86,000				

Table 6-2. COTS Noise Monitor Wind Activity - Phase 1 Test – June 19, 2012.

COTS Noise Monitor - 100 dB threshold - Tuesday June 19, 2012	Alpha	Zeta	Gamma	Eta	Iota
Total Triggers	3235	7221	1546	3152	3690
CERL Blast Classifier Acceptances	45	7	0	3	1
CERL Classified Non-Blast Events	3190	7214	1546	3149	3689
Probability of False Alarm	0.986089	0.99903	1	0.999048	0.99973
Average P_{fa} For 7 Hour Observation Period	0.997028				

An analysis of the BAMAS system's wind rejection capability was also performed using Phase 2 data. Table 6-3 shows that almost 33 million triggers were archived by BAMAS noise monitors at Site A during the yearlong validation period, with over 450,000 events recorded. This indicates that only 1.4% of those were identified by our software as relevant military noise. Of those 450,000 noise recordings, about one third (~150,000) were classified as military blast events. This means that less than 0.5% of noise actually detected by the noise monitors was related to military training exercises involving large caliber guns. The remaining two thirds of those noise recordings (~300,000) were classified as Jet Aircraft, Small Arms, Vehicle, or Thunder.

Table 6-3. BAMAS Observed Blast Events by Calendar Year.

Year	2012	2013	Total
Active Months	8	6	14
Total Triggers Archived by BAMAS noise monitors	17,095,595	15,858,188	32,953,783
Events Recorded by BAMAS noise monitors	256,381	200,438	456,819
Classified Blasts	81,590	84,246	165,836

Given that there was a large volume of data collected each day, it was possible to assess how the BAMAS monitor performed during periods of high wind. For this analysis we looked at the windiest days of the year to determine how many noise events were falsely recorded and how many were rejected. On those windy days we expect to see a lot of rejected triggers. Historical weather data was taken from NOAA weather station located at a municipal airport close to Site A, and was sorted by the maximum average daily wind speed. Data from the BAMAS noise monitors on these days was compiled and analyzed to produce Table 6-4. The data shown here reveal several findings. First, noise monitors can be overwhelmed with hundreds of thousands of wind triggers in a single day. As an example, on April 18th of 2013 when the mean daily wind speed was 25mph, the 9 BAMAS noise monitors at Site A archived 679,410 wind triggers. That is over 20 hrs. of continuous wind noise exceeding 95 dB in a 24 hr. period. Second, the BAMAS noise monitors are able to filter out >99% of those wind triggers.

Table 6-4. BAMAS activities during the 25 windiest days of observation sorted by mean daily wind speed.

Rank	Date	Mean Daily Wind Speed (MPH)	Max Daily Wind Speed (MPH)	Max Daily Wind Speed (MPH)	Event Averaged Mean Wind Speed* (MPH)	Number BAMAS Rejected Triggers	Percentage BAMAS Rejected Triggers	Number BAMAS Accepted Events	Percentage BAMAS Accepted Events
1	5-Mar-13	27	38	37.8	11.8	395,488	(99.06%)	3,743	(0.94%)
2	18-Apr-13	25	36	34.2	11.9	679,410	(99.41%)	4,029	(0.59%)
3	25-Dec-12	24	37	37	12.4	576,260	(100.00%)	4	(0.00%)
4	23-Apr-13	24	36	34.2	12.3	551,058	(99.89%)	586	(0.11%)
5	10-Apr-13	23	37	36	8.5	562,417	(99.72%)	1,596	(0.28%)
6	9-Apr-13	22	39	34.2	12.2	379,713	(99.86%)	522	(0.14%)
7	20-Dec-12	21	32	33.4	11.4	449,299	(99.95%)	219	(0.05%)
8	12-Jan-13	19	32	28.2	11	463,833	(100.00%)	4	(0.00%)
9	14-Apr-12	19	30	26.4	8.1	415,417	(99.97%)	106	(0.03%)
10	2-Apr-13	19	26	28.8	10.7	399,669	(99.48%)	2,084	(0.52%)
11	20-Jun-12	19	25	24.6	7.3	242,689	(99.55%)	1,090	(0.45%)
12	29-May-13	18	40	46.8	9.1	306,760	(99.85%)	453	(0.15%)
13	22-Mar-13	18	30	27	10.8	190,588	(99.28%)	1,384	(0.72%)
14	31-May-12	18	30	26.4	9.9	121,949	(99.13%)	1,070	(0.87%)
15	25-Feb-13	18	29	27	11	602,145	(99.03%)	5,906	(0.97%)
16	27-May-13	18	28	28.8	7.6	294,099	(99.99%)	26	(0.01%)
17	26-Oct-12	18	25	24.6	9.9	295,146	(99.49%)	1,526	(0.51%)
18	24-Mar-13	18	24	27	10.9	427,497	(99.75%)	1,051	(0.25%)
19	4-Mar-13	17	45	41.4	14.6	208,056	(99.37%)	1,318	(0.63%)
20	19-Jun-12	17	30	28.2	7.9	299,552	(99.73%)	799	(0.27%)
21	10-Mar-13	17	28	32.4	10.5	310,520	(99.62%)	1,179	(0.38%)
22	15-Apr-12	17	26	31.7	9.6	275,850	(99.95%)	146	(0.05%)
23	7-May-12	17	25	21.1	10	225,437	(99.86%)	320	(0.14%)
24	19-May-12	17	25	24.6	7.7	206,767	(99.88%)	256	(0.12%)
25	26-Feb-13	17	24	25.2	10.5	185,060	(99.54%)	850	(0.46%)

To further validate the improved rejection of wind noise, Figure 6-1 was assembled using data collected during a several month period of Phase 2 testing. The number of rejections made by individual BAMAS noise monitors was calculated on an hourly basis, and plotted on a log scale against the maximum wind speed occurring during that period of detection – with the understanding that there should be a strong correlation between the number of hourly rejections and the wind speed during that hour. A 91.85% correlation was measured between the maximum hourly wind speed and the number of hourly rejections. This implies that the BAMAS noise monitors reject more noise events as the hourly wind speed increases. It is important to note that when the wind speed reaches 25mph, the number of wind triggers rejections reaches a limit. To be clear, the BAMAS noise monitors analyze 1-second periods of sound thus the maximum number of files analyzed in a 1-hour period is 3600. On days when the wind speed approaches 25 mph, the number of rejected wind triggers approaches 3600, which implies that the noise monitor is constantly rejecting noise events.

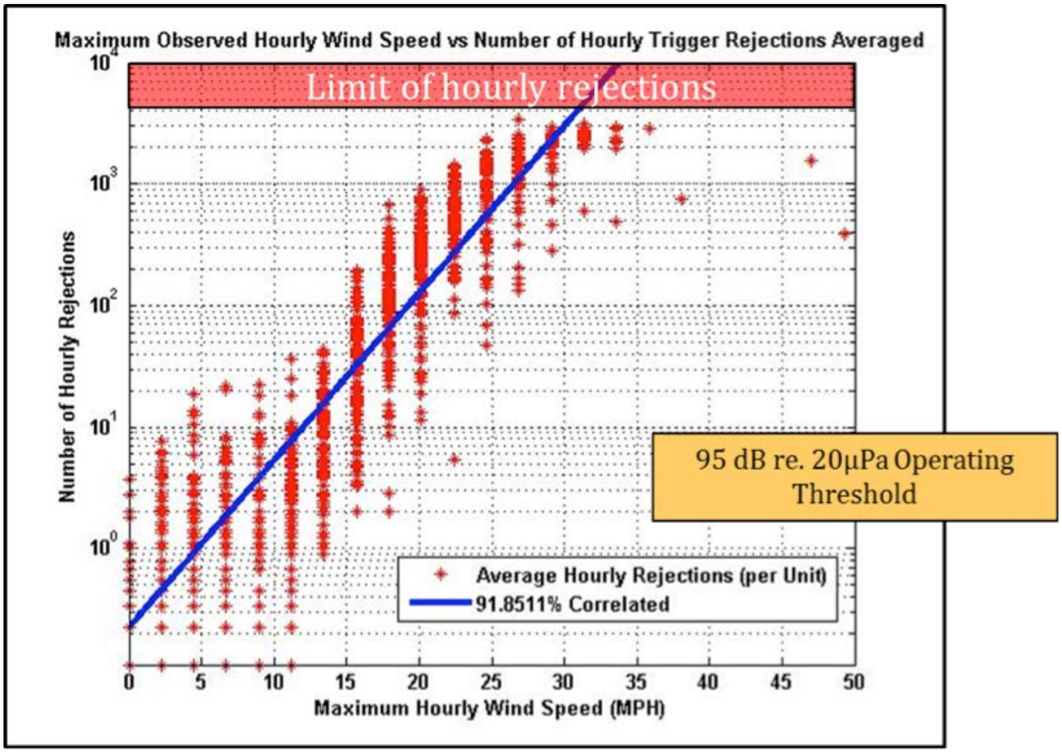

Figure 6-1. BAMAS hourly rejections correlated with maximum hourly wind speed.

Summary of Results: The BAMAS noise monitoring systems were successful in rejecting unwanted wind noise through the use of a microphone array and the wind rejection algorithm. During the Phase 1 testing, the false alarm rate was determined to be 10^{-5} over the course of a day of extreme winds. Long term evaluation of wind triggers show that BAMAS noise monitors tend to reject large amounts of activity during extended periods of high wind and that the number of rejections are highly correlated with the observed wind speed. Analysis of both short and long term data sets indicates that the BAMAS wind trigger rejection rate exceeds 99%.

6.2. Improved Detection Of Military Blast Noise

Success Criteria: BAMAS noise monitors shall detect, record, and report >95% of military noise events exceeding threshold as compared with CERL system.

Data: During the demonstration/validation exercise on June 21, 2012 – data was collected from 3 collocated CERL and BAMAS noise monitors (locations indicated on the map as Alpha, Zeta, and Iota). Research staff listened to (i.e., human classified) the CERL noise monitor data so that the detection accuracy could be established and a unit-to-unit comparison could be made. It is important to note that BAMAS noise monitors were configured with a 95 dB threshold, whereas the CERL monitors were set to record events exceeding 100 dB. This implies that the BAMAS noise monitors should record more noise events since its detection threshold is 5 dB lower. Data from both systems is shown in Figure 6-2. Note that the red stars (CERL recordings) are nearly perfectly overlapping with black circles (BAMAS recordings), suggesting that both systems recorded the same events and similar acoustic levels. A further comparison of acoustic levels captured by both units is given in Section 6.3.

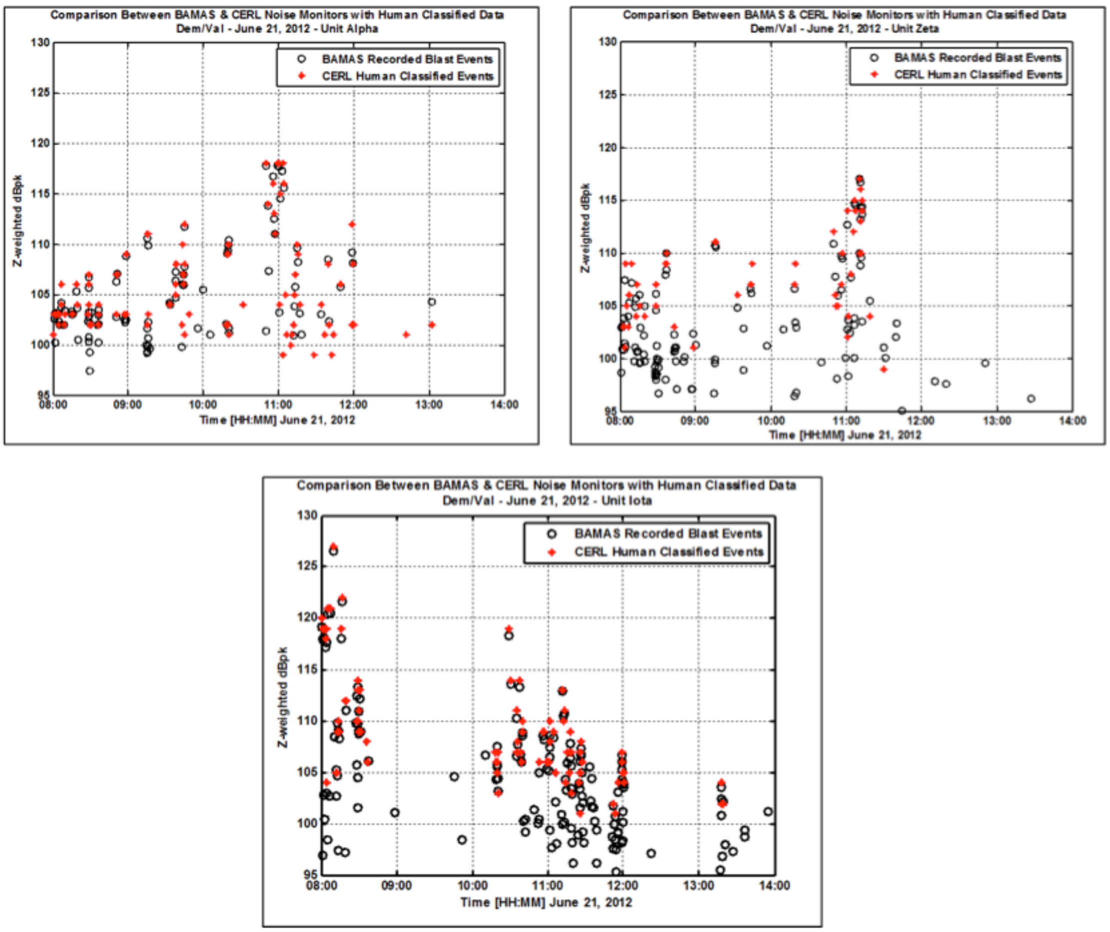

Figure 6-2. Comparison between BAMAS & CERL Noise Monitors from Phase 1 Testing. Unit Alpha (Top Left), Unit Zeta (Top Right), Unit Iota (Bottom).

The events displayed in Figure 6-2 were matched by hand comparing the blast times and peak sound pressure levels. The total number of matching noise events is shown in Table 6-5. The table shows that the BAMAS monitors did manage to meet the desired criteria, with one of the noise monitors reporting 96% of military noise as compared with the CERL systems; however two of the systems fell slightly short of the 95% goal – specifically noise events recorded by monitors at location Alpha had a 79% match and 94% at location Iota. This slight mismatch is likely accounted for by the difference of equipment and setup of the two systems. For example, the CERL noise monitoring system uses different array microphones and geometry. It was located closer to the ground, and had a higher sample rate. These subtle variations likely make up the small percentage of events that do not match. It is important to note that the BAMAS noise monitors reported more noise events by virtue of its lower detection threshold. For example, at location Zeta the BAMAS noise monitor recorded 119 events whereas the CERL monitor recorded only 51. Even with this detection threshold difference, it was found that both systems missed several events above 105 dB. Several noise events exceeding 105 dB reported by the BAMAS system were not reported by the CERL system and the opposite was also true.

Table 6-5. CERL and BAMAS Noise Monitor Observations - June 21, 2012.

Unit	Alpha	Zeta	Iota
CERL Human Classified Blasts	98	51	81
BAMAS Accepted and UPitt Classified Blasts	99	119	151
Matched CERL and BAMAS/UPitt Blasts	77	49	76
% BAMAS Events Matching CERL	79%	96%	94%

Effective military noise monitoring systems should be capable of rejecting unwanted noise while detecting desired noise events, without significant performance compromise. This is important because, as previously mentioned, training happens in all conditions for military preparedness. Here we demonstrate that BAMAS noise monitors have the capabiltiy to perform in all weather conditions. Figure 6-3 shows actual data collected during Phase 2, wherein a daylong training exercise occurs on a day with high winds (5-15 MPH). The figure shows mutiple plots from that day; 1) Windspeed 2) Peak Sound Pressure Level 3) Sound Bearing (DOA) - with rejected events displayed in red and accepted events indicated in black. Reading these plots togther, we see that during the morning the BAMAS noise monitor was reporting blast noise from two different directions: North (0°) and North-West (300°). In this case the noise monitor was likely detecting both the muzzle blast and the impact/detonation. The received level from these blast events ranged from 100 to 105 dB and the wind speed was very low. At 1200, wind speeds quickly increased to 5-15MPH and BAMAS monitor began to reject many thousands of triggers, which is identified by the many red dots and seemlingly random bearing estimates. Although the BAMAS monitor was rejecting a lot of wind noise, it continued to correctly report blast noise events through 1530. This can be seen by looking at the bearing of the reported blast events. The bearing remains the same before and after 1200 when the wind picked up, and illustrates the effectiveness of the classificaiton algorithms running onboard the BAMAS noise monitors; they were able to filter out unwanted wind noise without sacraficing its detection performance.

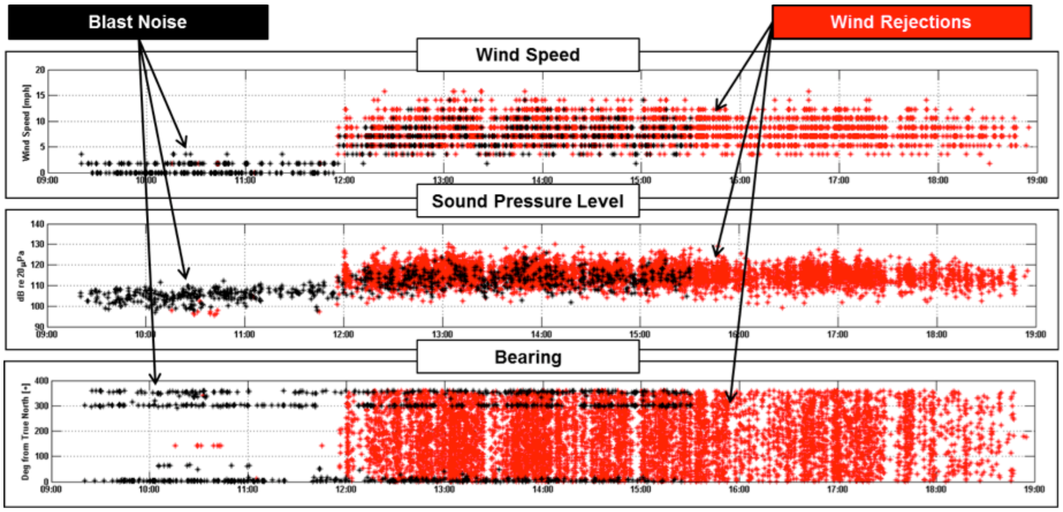

Figure 6-3. BAMAS blast detection amongst wind activity.

Since we have observed that BAMAS noise monitors are capable of discerning desired events amidst undesired noise, it is useful to quantify these detection capabilities. An additonal analysis was perfomed by using simulation to determine the BAMAS algortihm detection rate of signals (i.e. blasts) amongst interference (i.e. wind). Randomly selected wind files were scaled against the peak SPL of randomly selected blasts, creating a known signal to interference ratio (SIR). Figure 6-4 shows the results of the original BAMAS algorithm in red, where an event has a probability of detection (P_D) of 0.5 at an SIR of 10 dB. To be clear, this means that 50% of blasts with peak SPL 10 dB louder than ambient noise would be detected. Based on the results of this analysis it was determined that the algorithm could be improved – meaning that we could increase the probability of detection for the same interference level. Several revisions were made to our code and Figure 6-4 depicts the results of the final simulation with the improved algorithm represented in blue. Here the original algorithm was run along side the improved version for the exact same wind and blast file combinations; an improvement in the detection is obseved at all levels of SIR. For example, we were able to increase the probability of detection to 65% at an SIR of 10 dB. Moreover, at 20 dB we were able to increase it by 18% (from 81% to 99%).

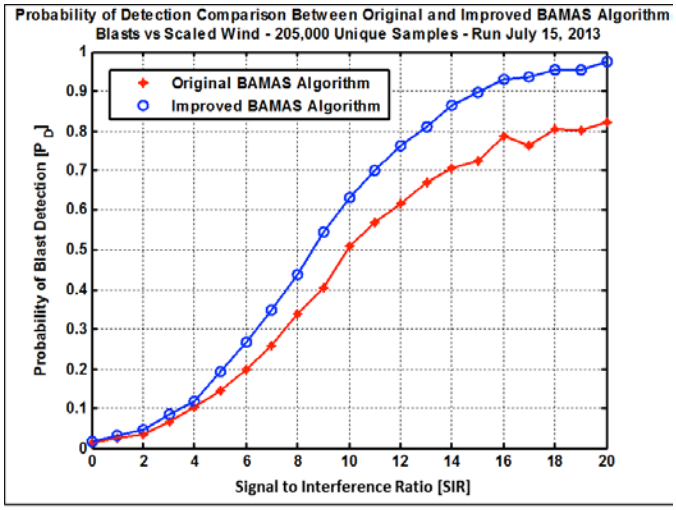

Figure 6-4. BAMAS probability of detection simulation.

Results: The BAMAS noise monitors demonstrated the capability to detect, record, and report >95% of military noise events exceeding threshold as compared with the CERL system, however did not meet this performance objective at all co-located observation points. BAMAS was able to repeatedly detect blast events during periods of wind, proving the effectiveness of the wind rejection capabilities in conjunction with blast detection capabilities. Results of a simulation that scaled wind against blast peak SPLs showed that improvements could be made to the BAMAS blast detection software; the improved algorithm demonstrated a better probability of detection than the original for the same signal to interference ratios.

6.3. Comparison With Existing Noise Monitors

Predetermined Success Criteria: BAMAS noise monitors shall report fewer false noise recordings than existing commercial noise monitors.

Data: During Phase 1 testing, commercially available noise monitors were set up collocated with BAMAS systems, as described in Section 5. The results of the systems' respective recordings are provided in Table 6-1 and Table 6-2 in Section 6.1. From these tables we see that during a daylong observation with high winds, BAMAS noise monitors accepted 1 wind event out of 86,093 triggers during the onsite testing exercise. The collocated COTS noise monitors recorded 18,844 triggers – 18,788 (99.7%) of which were determined to be non-blast by the retrofitted classifier. This means that the BAMAS systems demonstrate a substantial improvement in false noise rejection when compared with the COTS system. Additionally, the SLM setup at the firing point and configured with a threshold trigger of 115 dB recorded 105 events. While post processing these files by human classification, 5 events were determined to be wind, as they contained no blast content. This shows that a high detection threshold is not a suitable substitute for the BAMAS wind rejection capabilities.

Results: Despite the higher detection threshold and shorter operation period, the COTS sound level meter recorded more false positive events than the BAMAS noise monitors during high winds. Use of the CERL classifier on the COTS noise monitors to provide an indication of the quantity of blast versus non-blast reports that can be expected from the COTS device; BAMAS noise monitors can be expected to report significantly less false reports than these existing commercial noise monitors.

6.4. Blast Noise Localization

Success Criteria (Qualitative): Users are able to determine where the blast noise originated from using the bearing localization result overlaid on a map.

Results: To meet the established qualitative performance objective, users should be able determine the approximate location of where the noise event was produced as it relates to specific firing locations. Figure 6-5 shows an example of how website users can resolve the general DOA of noise events. Visual correlation with local firing point embedded in the map allows users to determine the approximate source location by using the red lines which indicate the DOA of a particular noise event. Overlapping lines from two or more noise monitors provides an estimate of the triangulated position of the noise source location. Figure 6-5 demonstrates a case where two noise monitors have detected the same event and the overlapping lines correctly indicates the location of approximate location of the noise source.

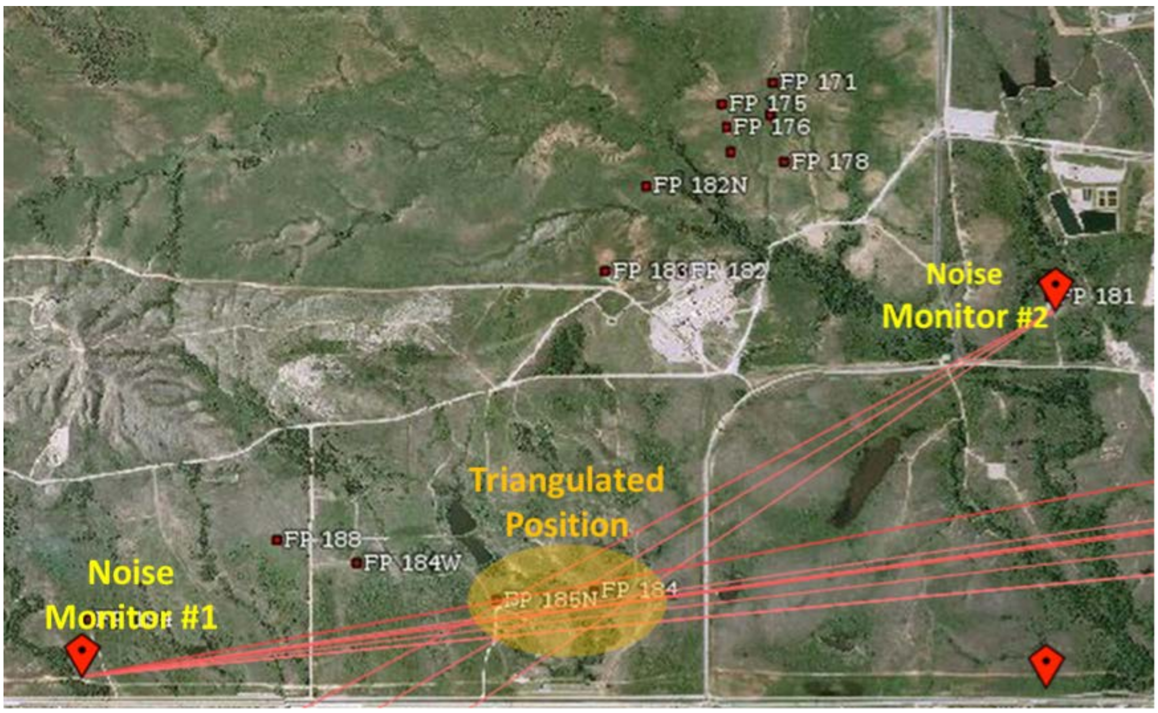

Figure 6-5. BAMAS blast noise localization using website integrated map.

Despite being beyond the scope of this task, quantitative data was also investigated. On June 21 during the demonstration/validation exercise at Site A, noise monitor Beta, affixed to a mobile tripod, was placed one kilometer North Northwest of the artillery firing point (Figure 6-6). One hundred thirteen noise events were recorded and their bearing estimates compared to ground truth.

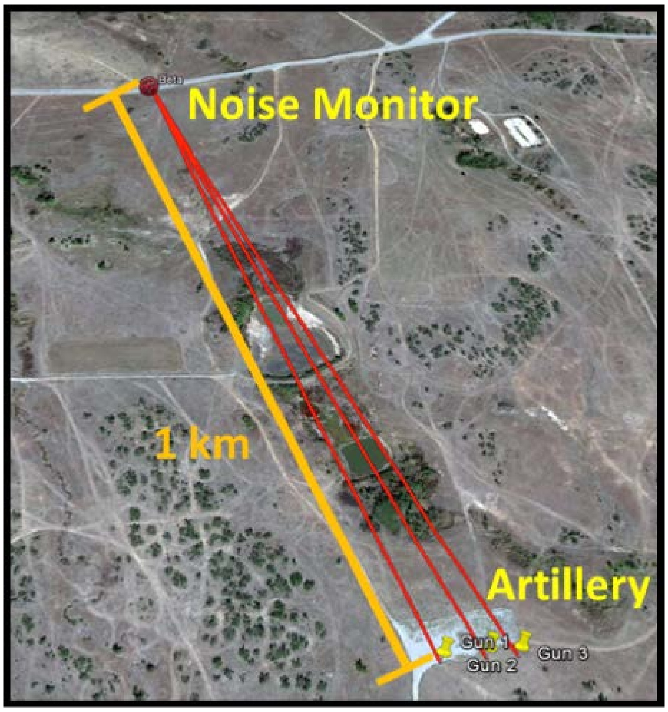

Figure 6-6. BAMAS blast noise localization during Phase 1 testing.

The actual bearings (based on GPS measurements) from noise monitor Beta to the three artillery guns points were calculated as:

Table 6-6. Artillery Source Relative Locations during Phase 1 Testing.

Gun Number	Angle
1	157.1˚
2	155.5˚
3	153.4˚

A histogram of the measured bearing of those 113 noise recordings is shown in Figure 6-7. The bearing has a mean of 151.4˚ with a standard deviation of 4.9˚. This differs from the actual bearings in Table 6-6 by only 3.6 ˚. This small bearing offset is caused by imperfect orientation of the microphone arrays with respect to True North. The standard of deviation, which is a better measure of bearing accuracy, is relatively small. For example, if the noise monitor is 1 mile from the noise source this would amount to a cross-range error of only 422ft.

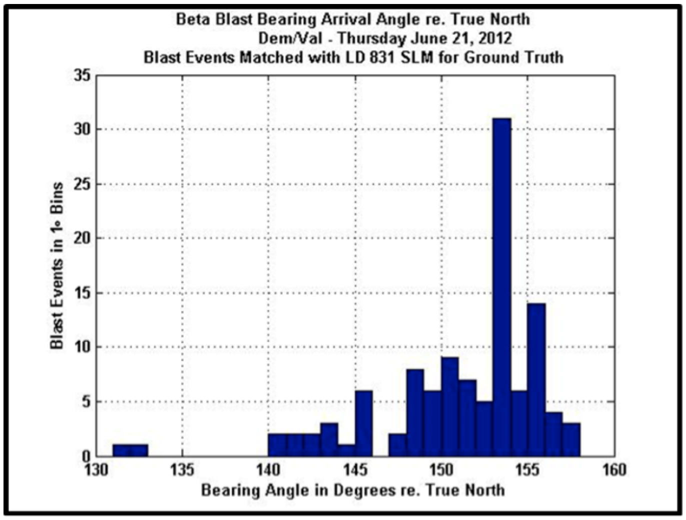

Figure 6-7. BAMAS artillery localization histogram from Phase 1 testing.

6.5. System Autonomy And Reliability

Success Criteria: BAMAS noise monitors shall be actively monitoring for 90% of the time in all weather conditions

Data: Each noise monitor is configured to send out "heartbeats" at approximately two-minute intervals so that the Base Station monitoring software can verify unit activity. This amounts to 700 heartbeats each day. Should a unit fail to send out 7 consecutive heartbeats, the base station will generate a notification email – alerting users to the system's inactivity. The information sent with these heartbeats is saved in a monthly status log file, separate from the log file containing data collected by the noise monitor. Using the status log, it is possible to determine individual unit and overall network uptime.

During the Phase 2 yearlong data collection at Site A, system uptime was observed to be 91.04% when accounting for the standard rate of 700 heartbeats per monitor per day. While this exceeds our success criteria, it does not account for cellular outages and several multi-day periods when the noise monitors were being serviced – therefore the system's reliability is actually much better than 91.04%. Moreover, this measure fails to account for periodic outages caused by software upgrades and non-BAMAS algorithm based data collections that occurred during this year period. Accounting for these unavoidable outages, we determined the BAMAS noise-monitoring network at Site A was operational and activity monitoring 97.54% of the time. It is important to note that a single BAMAS monitor went offline close to the end of the testing period. APS spent some time troubleshooting this noise monitor however are unable to identify a fix. It appears that cycling the power does restore the noise monitor however we were unable to determine the cause. With this small exception, all the other noise monitors have proven to be very reliable. To that end, the 5 noise monitors at Site B have been fully operational since 2010 with only temporary outages caused by down power lines.

Figure 6-8 and Figure 6-9 show examples of the data that is collected from the units – one can see that on December 25, 2012, BAMAS units only charged a moderate amount – due to lack of sun caused by a storm that day. Using all of the collected status data during Phase 2 testing, it is possible to observe that throughout the entire noise monitor network no unit battery voltages dropped below 11.65V, as reported by the noise monitors themselves. Battery voltages were noted as dropping below 12V an average of only 9 times for each noise monitor.

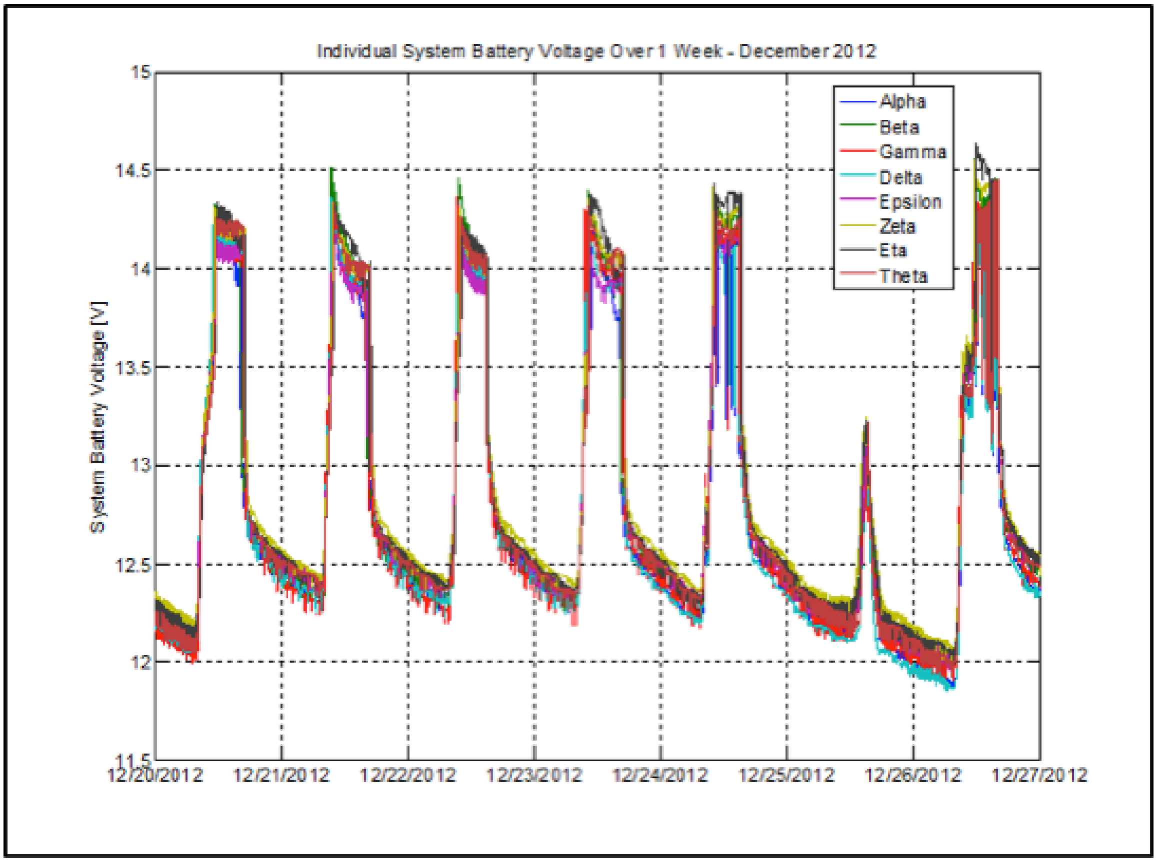

Figure 6-8. BAMAS Status Data Reporting – System Battery Voltage.

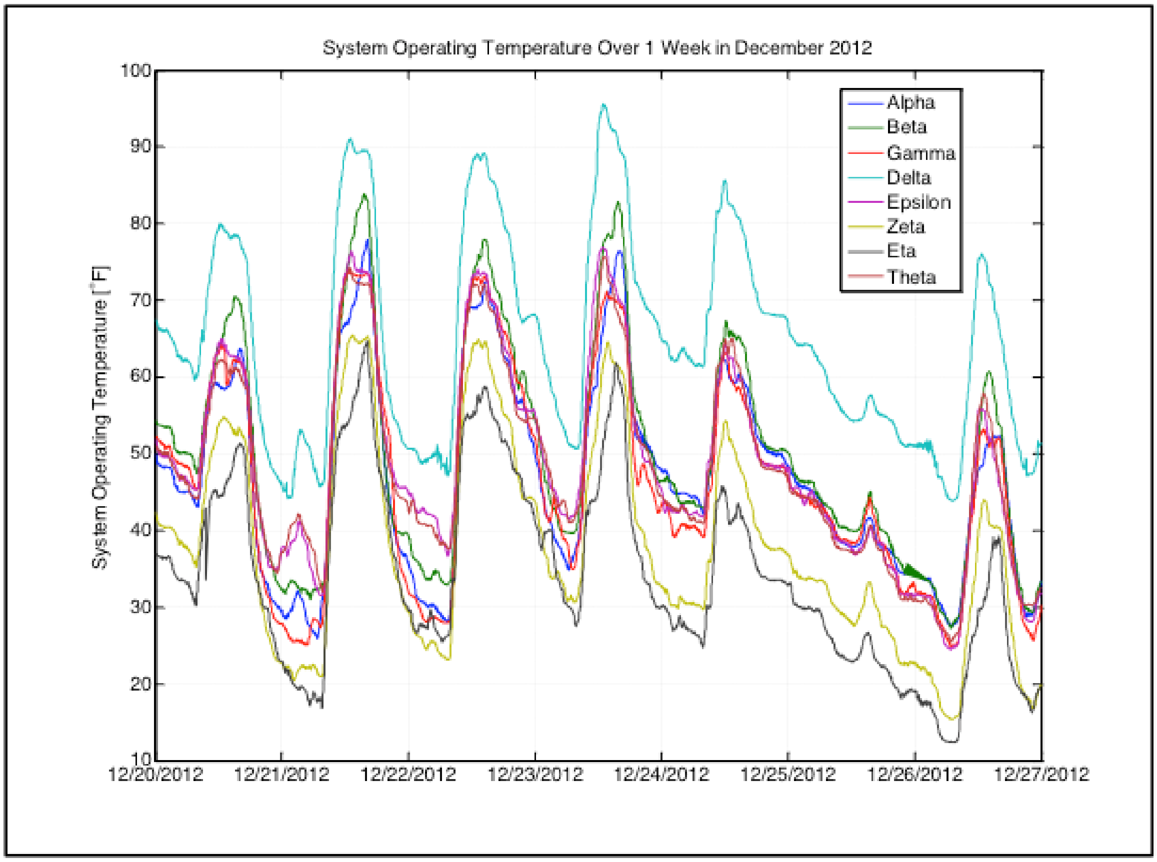

Figure 6-9. BAMAS Status Data Reporting – System Operating Temperature.

Results: A comparison of expected daily heartbeats to those that were reported over the course of a year showed that the BAMAS noise monitors were actively monitoring for 91.04% of the time, exceeding the requirement of 90%. Excluding some of the routine maintenance that was performed (to upgrade software for example) and cellular outages (which are unavoidable), the system reliability is actually 94.54%. The solar powered noise monitors experienced no outages due to loss of power, demonstrating the robust nature of the deep cycle battery and solar panel combination, coupled with the low power draw of the system.

6.6. Improved Noise Classification

Success Criteria: BAMAS noise monitors shall classify all recorded sounds with >90% accuracy

Background: A small amount of research and development went into the improvement and expansion of the first generation (Gen I) classifier developed by the University of Pittsburgh (UPitt) during the preceding SERDP efforts (SERDP 1436, SERDP 1585). The Gen I classifier is a binary classifier, which classifies recorded signals as either a blast or non-blast using four signal metrics.[9] The Gen I binary classifier was initially improved (accuracy > 95%), in collaboration with CERL, by including an additional 19 signal metrics,[11] and later expanded (Gen II) to include the classification of six additional noise sources: blast, wind, machine gun, vehicle/propeller aircraft ("vehicle"), jet aircraft ("aircraft"), and thunder.

The Gen II classifier, like the original Gen I classifier, was built using an artificial neural network (ANN) and 25 signal metrics: the 4 Gen I signal metrics (i.e., kurtosis, crest factor, spectral slope and weighted squared error), the 15 metrics used to improve the Gen I classifier (i.e., Apeak, Cpeak, Zpeak, LAMAX fast, LCMAX fast, LZMAX fast, LAMAX slow, LCMAX slow, LZMAX slow, ASEL, CSEL, ZSEL, ALEQ, CLEQ, and ZLEQ), and new metrics identified in this effort (i.e., the centroids of the autospectra, and peak counters), which captured the frequency content and repetitive nature of some of the signals of interest.

Results: The Gen II classifier was trained and tested using the source libraries listed in Table 6-7, which included 47,464 human classified noise sources collected during the preceding SERDP and current ESTCP projects. As was done during the development of the Gen I classifier, human subjects classified recorded noise sources via listening to the recorded signal and visualizing both the time series and frequency spectra. When the Gen II classifier was tested the overall accuracy (total correctly classified/total classified) was 92.9%, which met the original criteria of >90%.

Table 6-7. Collected Noise Samples by Type From All Sources.

	Blast	Wind	Machine Gun	Aircraft	Vehicle	Thunder
Wind Library	0	10,103	0	0	0	0
SERDP	278	566	0	110	0	0
Base A	4,848	129	51	5,501	1,498	3,684
Base B	6,016	385	1,259	448	3,589	221
Base C	3,619	1,737	649	945	1,742	86
Total	14,761	12,920	1,959	7,004	6,829	3,991

Metric economization was also performed using Forward Sequential Selection (FSS) method to reduce the number of metrics from 25 to something more computationally efficient. It was found that with the top 8 metrics an overall accuracy of 90% could be achieved. Table 6-8 contains the confusion matrix for the final, reduced classifier. The columns are the targets and the rows are the predictions. The diagonal represents correctly classified waveforms and the overall accuracy is given at the bottom right corner. The binary classification accuracies (e.g. blast/not blast (96.2% accuracy), wind/not wind (97.57% accuracy), etc.) are also given in separate confusion matrices below the main truth table. Reducing the number of metrics used from 25 to 8 greatly improved computation time. Although more complex, the Gen II classifier could still be implemented on a single (but faster) microprocessor, as was done with original Gen I classifier.

Table 6-8. Final confusion matrix for economized ANN.

blast	wind	mach	air craft	vehicle	thunder	
13911	203	174	3	65	557	6.72%
274	12303	11	7	204	11	3.96%
137	5	1503	22	94	59	17.42%
7	12	49	2971	434	28	15.14%
64	335	93	571	9018	393	13.90%
318	92	170	27	310	2962	23.64%
5.44%	5.00%	24.85%	17.50%	10.93%	26.13%	90.02%

Blast

13911	1002	94.56%
800	31684	96.93%
3.07%	5.44%	96.20%

Air Craft

2971	530	82.50%
630	43266	98.79%
1.21%	17.50%	97.55%

Rubric

#TP	#FP	%TP
#FN	#TN	%TN
%FP	%FN	%OV AC

Wind

12303	507	95.00%
647	33940	98.53%
1.47%	5.00%	97.57%

Vehicle

9018	1456	89.07%
1107	35816	96.09%
3.91%	10.93%	94.59%

Machine Gun

1503	317	75.15%
497	45080	99.30%
0.70%	24.85%	98.28%

Thunder

2962	917	73.87%
1048	42470	97.89%
2.11%	26.13%	95.85%

In addition to testing the overall accuracy of the classifier, a small study was conducted to assess the variation between three human subjects to ensure that there was minimal human classification error. This was found to be the case. For this study, two students with minimal training (naïve listeners) and one with experience (expert listener) listened to the same 1,000 randomly chosen waveforms divided equally among the six noise classes. High agreement was found between all subjects (Table 6-8), with exception to thunder, which only had 95% agreement. It was found that the naïve listeners sometimes confused blast noise with thunder.

Table 6-9. Agreement in Hand Classifications For Three Different Users.

Blast	Wind	Machine Gun	Aircraft	Vehicle	Thunder
98%	100%	100%	98%	98%	95%

An analysis of the effects of wind speed and signal to noise ratio (SNR) on classification performance was also conducted. This analysis randomly mixed 2,000 pure wind and 2,000 pure blast waveforms to achieve SNRs ranging between -20 and 40 dB. Here, the SNR was defined as the ratio of the mean squared pressure of the blast signal to the mean squared pressure of the wind noise signal over a 1-second duration. The accuracies of the classifiers are given in Figure

6-10. With higher SNR, the number of blast classifications increases, while the incorrect classification of other sources decreases. Table 6-10 shows the blast classification accuracy in particular for the economized (FSS) and full ANN for various SNRs. Blast detection performance was found to degrade somewhat for low (0 dB) SNR conditions, but improves greatly for modest (10 dB) SNR levels.

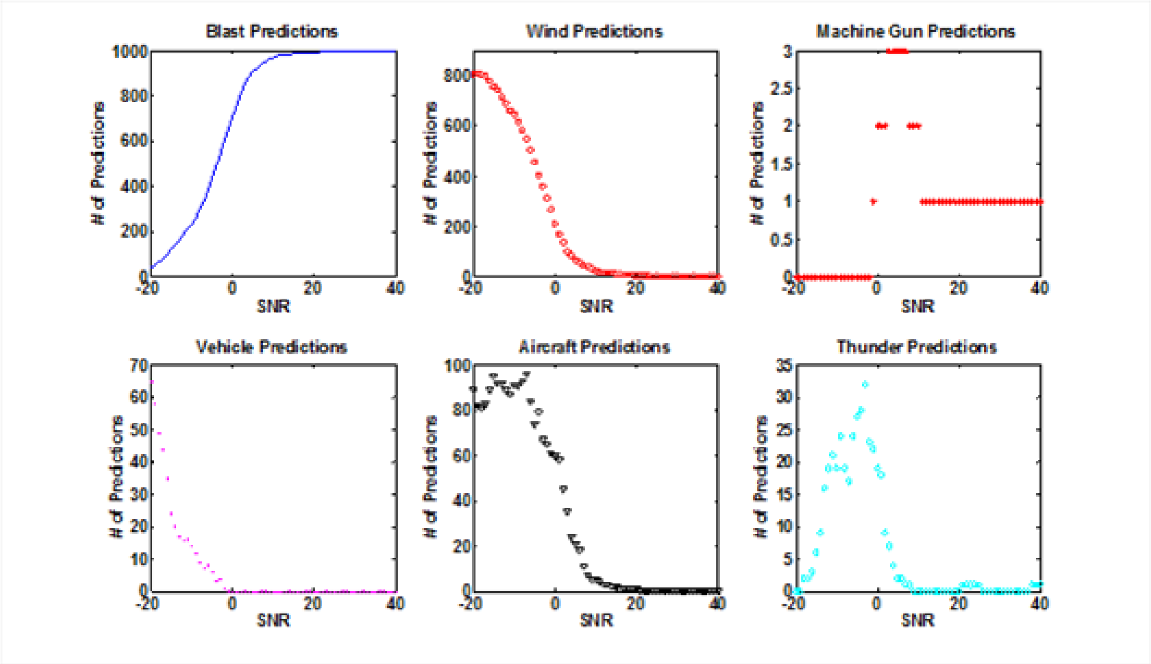

Figure 6-10. Classification accuracy for various SNRs with an economized ANN.

Table 6-10. Comparison of Blast Classification Accuracy for Economized (FSS) and Full ANN for various SNRs.

SNR	0 dB	10 dB	40 dB
FSS ANN Blast Accuracy	73.2%	97.5%	99.9%
Full ANN Blast Accuracy	95.5%	96.0%	99.9%

6.7. Microphone Calibration

Success Criteria (Qualitative): The software calibration mode is demonstrated to adjust the sensitivity.

Data: CERL team members made use of the BAMAS Calibration Utility (Figure 6-11) to calibrate all BAMAS noise monitors at Site A, and values were tracked as in Table 6-11. After an 8-month period and a third calibration, the sensitivity values for each microphone were analyzed and average values were determined as shown in Table 6-12.

Table 6-11. BAMAS Microphone Calibration Tracking for Unit Alpha.

Mic.	Factory Calibration 4/12	11-Sep	19-Dec	(FAT-Sept)	(Sept-Dec)	Mean Difference	Variance Difference	Overall Drift
1	-130.10	-130.40	-130.10	0.30	-0.30	**0.00**	**0.180**	0.00
2	-130.47	-130.61	-129.65	0.14	-0.96	**-0.41**	**0.605**	-0.82
3	-130.65	-130.72	-130.60	0.07	-0.12	**-0.03**	**0.018**	-0.05
4	-130.26	-130.78	-130.89	0.52	0.11	**0.31**	**0.084**	0.63
5	-120.25	-120.71	-120.53	0.46	-0.18	**0.14**	**0.205**	0.28

Additional data for the other noise monitors is available in the Appendix.

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Table 6-12. Changes in BAMAS Microphone Sensitivity.

Changes in BAMAS Microphone Sensitivity	Microphone Mean Drift	Variance Between All Microphones
Array Microphones	-0.035 dB	0.164 dB
Reference Microphone	0.766 dB	0.102 dB

It is notable that the Type 1 reference microphones experienced the largest shift in sensitivity. Due to the sophistication of these microphones, they can be cleaned onsite or returned the manufacturer for cleaning and calibration. The array microphones are relatively low cost, sealed microphones and showed very little overall sensitivity drift. These microphones are expected to last for several years before requiring replacement– as already observed at test Site B.

Results: The microphone calibration software, as seen in Figure 6-11, has been used to successfully calibrating all BAMAS units by users with minor training. The tool allows users to log into a system remotely through the cellular modems while connected to the VPN, or on-site by connecting directly to the data recorder Ethernet port and modifying their PC IPv4subnet. The tool can also be used to view sound levels, thus allowing users to verify the operation of each individual microphone.

A calibration document has been compiled for use by APS technicians, and calibration utility install packages can be compiled for individual installations that wish to perform calibration on their own units without APS support. This allows for customers to establish a more thorough knowledge of the system components and operation, and supports system maintenance to be performed at any desired frequency.

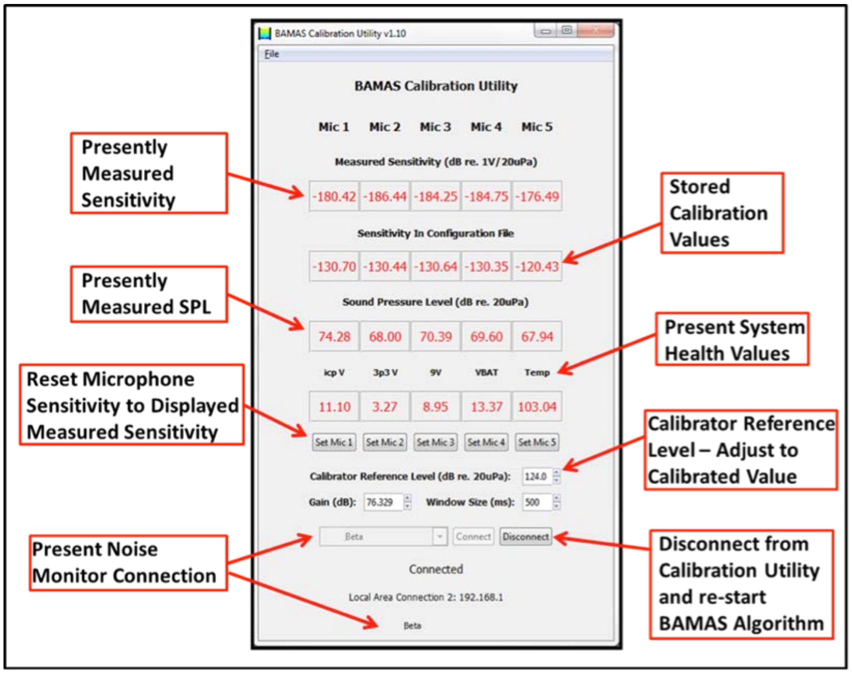

Figure 6-11. BAMAS Calibration Utility.

6.8. Ease Of Use

Success Criteria (Qualitative): Users find the software easy to use and beneficial for managing and/or assessing noise levels cause by military testing and training activities.

Results: The original BAMAS web site was designed as a tool that would allow users to securely view event date & time, observing noise monitor, and peak SPL while permitting them to view and listen to event waveforms, and download events, CSV files and mapping files. The functionality of this existing design was fairly limited and the interface not easy to use. Revisions were performed to the BAMAS noise monitor web interface, and the current interface can be seen in Figure 2-6. This website integrates many new features requested of users, in particular the ability to download the data into Excel and Google Maps. All noise data presented on the website is dynamically linked between the satellite map and the spreadsheet. This allows users to sort the data in any fashion they require to assess their noise footprint. For example, the user can sort the data in the table by maximum amplitude, by location, by time, and so on. Additional features, such as the noise monitor health utility and live mode were added to the web interface, facilitating real-time network monitoring for any remote users.

7. Cost Assessment

7.1. System Cost

APS has established a GSA schedule for sales of BAMAS noise monitor systems. The following table outlines the costs, with options noted for each individual unit (Table 7-1). A comparison of the cost of BAMAS system to other environmental and military noise monitors is discussed in Section 2.3. As previously noted (Section 2.3), the BAMAS monitors are competitively priced. They include a contemporary web interface that dynamically combines available data for immediate access from the users' web-enabled device of choice, with sound events localized on a map and current noise monitor health status. The validated wind rejection and blast detection capabilities, combined with the validated classification abilities of the noise monitors allows users to avoid wasting costly time when resolving noise issues, and eliminates the need for maintaining acousticians or noise specialists on staff. The remote administration capabilities of BAMAS allow for off-site operation, network monitoring and modification of noise monitor units by end users. Remote manufacturer support capabilities allow for offsite product assessment, eliminating the need for costly travel for minor troubleshooting efforts. The only caveat to this statement is if the cellular modems go off-line.

Table 7-1. BAMAS GSA schedule.

PRODUCT	Quantity	UOI	COMMERCIAL LIST PRICE*
BAMAS Noise Monitor, Solar powered, No Structure	1-5	Ea	$37,000.00
BAMAS Noise Monitor, AC powered, Fixed Tower	1-5	Ea	$40,400.00
BAMAS Noise Monitor, Solar powered, Fixed Tower	1-5	Ea	$40,500.00
BAMAS Noise Monitor, AC powered, Mobile Tripod	1-5	Ea	$39,000.00
BAMAS Noise Monitor, Solar powered, Mobile Tripod	1-5	Ea	$39,100.00
BAMAS Base Station Computer	1	Ea	$9,500.00

*All prices outlined above do not include site survey or installation costs.

7.2. Noise Monitor Coverage Area

Though BAMAS may have a higher per-unit cost than some commercially available noise monitors, there can be an overall noise monitor network cost savings due to the low detection threshold that the noise monitors feature. The real-noise detection feature of BAMAS, made possible by specially designed computer algorithms, allows for greater area coverage for blast noise monitoring at this lower detection threshold.

Expanding on the blast detection capabilities of BAMAS discussed Section 6.2, it is important to remember that blast noise is characterized by low frequency impulses which tend to have low atmospheric absorption during propagation. This means that the use of standard calculations for the spherical spreading of atmospheric acoustic noise will thereby be conservative estimates for blast monitoring applications. Slightly modifying standard spherical spreading models for sound attenuation by increasing losses over large distance doubling, a conservative determination was found for artillery firing. Using 180 dB source levels observed from towed Howitzer artillery guns, sound pressure levels of 115 dB were calculated at distances from the source up to 2.5 miles (4km), 100 dB at distances of 5 miles (8km) and 95 dB at distances of 7.5 miles (12km) or more (Figure 7-1).

Assuming a 95 dB receive level provides enough SNR at the noise monitor (which in our experience it does), this gives a single BAMAS noise monitor the advantage of monitoring approximately 175 square miles (452 km^2), while 100 dB threshold systems could cover approximately 75 square miles (200 km^2), and 115 dB threshold systems could cover approximately 20 square miles (50 km^2). Most COTS noise monitoring systems are set for 100-115 dB so as to reduce the chance of recording wind noise – thus the BAMAS noise monitors provide up to a 155 square mile advantage.

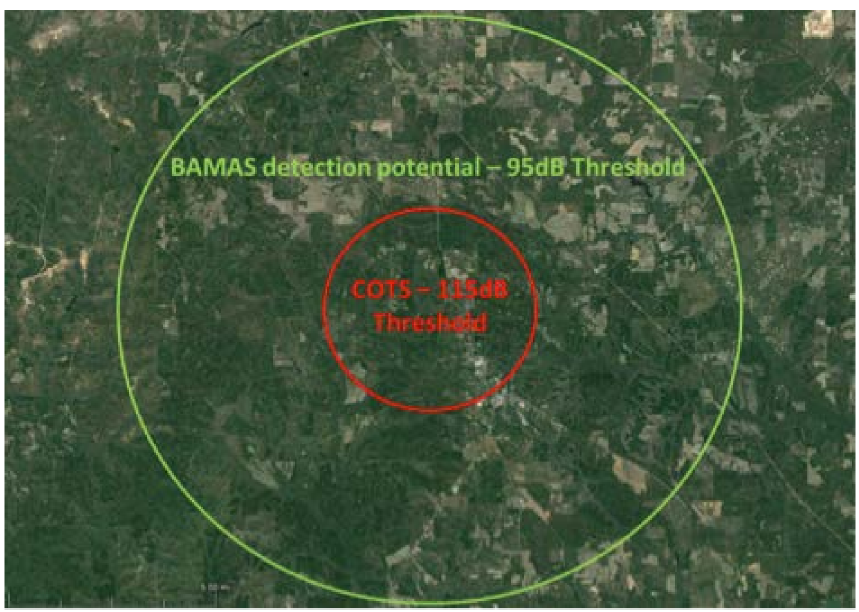

Figure 7-1. Comparison of potential noise monitoring area between BAMAS and a COTS noise monitor with a threshold of 115 dB.

Installations with noise problems wishing to maximize noise monitoring potential would likely require noise monitors to be installed at the base perimeter, such that they can observe sound levels of noises as they impact surrounding residential areas. Applying the same coverage characteristics as Figure 7-1, Figure 7-2 shows the coverage advantage of BAMAS versus COTS noise monitors with a 115 dB threshold; an overall reduction in the total number of required systems for effective region monitoring. This means that fewer BAMAS systems would be required to provide similar or better coverage than COTS units with higher detection thresholds, likely proving an overall cost advantage in procurement and maintenance.

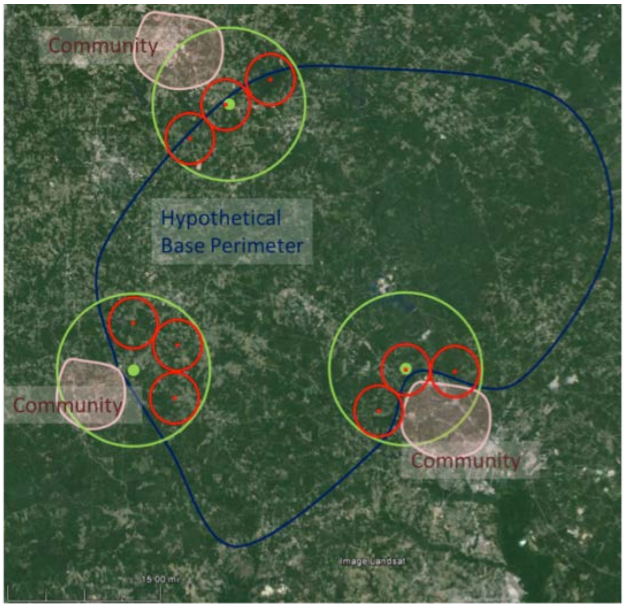

Figure 7-2. Hypothetical noise monitor coverage. BAMAS coverage (green circle) vs. COTS system (red circle).

This analysis can be corroborated by examining the actual blast detections heard by BAMAS units at installation Site A. Figure 7-3 shows that 17% of blasts detected by the BAMAS noise monitor network in 2012 at Site A were detected below a threshold of 100 dB, with an additional 32% of detections occurring below 105 dB. Noise monitors with detection thresholds above 105 dB would suffer a 49% reduction in observed blast events compared to BAMAS while noise monitors with detection thresholds above 115 dB would suffer a 92% reduction in observed blast events, assuming that 9 COTS noise monitors were distributed in the same manner as the BAMAS systems at Site A. This means that fewer BAMAS systems would be required to provide similar or better coverage than COTS units with higher detection thresholds, likely proving an overall cost advantage in procurement and maintenance.

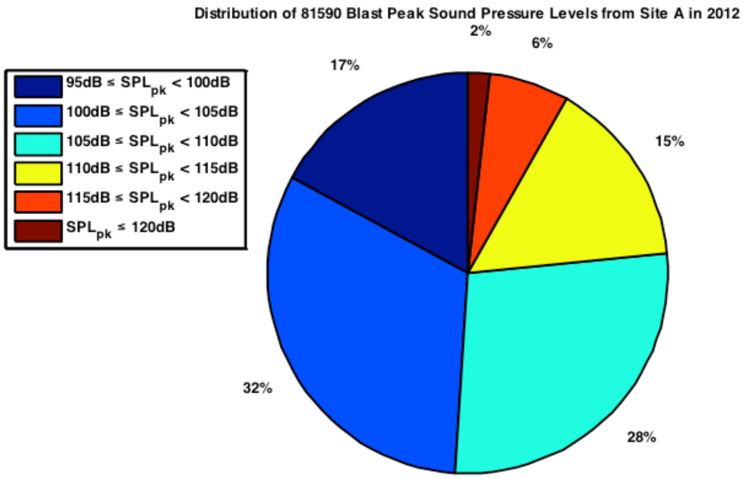

Figure 7-3. Peak blast sound pressure levels (dB) from Site A in 2012.

8. Implementation Issues

8.1. Stakeholders In Implementation

Eight of the noise monitors originally installed at Fort Sill have transitioned to Fort A.P. Hill in Virginia. The monitors were installed by CERL/ESTCP while reconfiguration of the software to support the new location was accomplished by Applied Physical Sciences (APS). APS continues to provide hosting for the website and base station associated with this system; end users have secure access without the need for a VPN or reconfiguration of their network firewall to all data through the BAMAS website. This website is accessible on all internet capable devices including smart phones, tablets, and computers. Please contact APS or CERL if you wish to view the data.

The Noise Monitors have been in operation for over three years and have required only minor repairs associated with their disassembly transport and reinstallation.

8.2. Procurement Issues – Ease Of Production/Scale Up Issues

APS does not foresee any procurement issues. The GSA schedule that has been constructed for unit purchasing reflects cost breaks for large-scale production of unit components.

8.3. Proprietary Or IP Issues Associated With Technology

There are no proprietary or IP issues associated with this technology.

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Appendices

A. Points Of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone E-mail	Role in Project
Dr. Ed Nykaza	ERDC-CERL 2902 Newmark Drive Champaign, IL 61822	217-373-4561 edward.t.nykaza@usace.army.mil	Government PI
Jeffrey Allanach	Applied Physical Sciences Corp. 475 Bridge Street, Suite 100 Groton, CT 06340	860-448-3253x105 jallanach@aphysci.com	Industry PI
Dr. Jeffrey Vipperman	University of Pittsburgh 3700 O'hara St. 636 Benedum Hall Pittsburgh, PA 15261	412-624-1643 jsv@pitt.edu	University PI
Bruce MacAllister	ERDC-CERL 2902 Newmark Drive Champaign, IL 61822	217-373-4439 bruce.a.macallister@usace.army.mil	Field Technician
Lynn Engelman	Chair of Defense Noise Working Group (DNWG)	703-692-9147 lynn.engelman@pentagon.af.mil	Stakeholder
Catherine Stewart	Program Manager Operational Noise Program USAPHC 5158 Blackhawk Rd APG, MD 21010	410-436-1031 Catherine.stewart@us.army.mil	Stakeholder

B. BAMAS Microphone Calibration Comparison

		Using LD CAL250114 dB@ 251.2 Hz	B&K Calibrator124 dB @ 250Hz						
	Mic.	Factory Calibration 4/12	11-Sep	19-Dec	(FAT-Sept)	(Sept-Dec)	Mean Difference AVG[(FAT-Sept)(Sept- Dec)]	Variance Difference VAR[(FAT-Sept)(Sept- Dec)]	Overall Drift (FAT-Dec)
Alpha	2	-130.47	-130.61	-129.65	0.14	-0.96	**-0.41**	**0.605**	-0.82
	3	-130.65	-130.72	-130.6	0.07	-0.12	**-0.03**	**0.018**	-0.05
	4	-130.26	-130.78	-130.89	0.52	0.11	**0.31**	**0.084**	0.63
	5	-120.25	-120.71	-120.53	0.46	-0.18	**0.14**	**0.205**	0.28
Beta	Mic.								
	1	-130.52	-130.7	-130.57	0.18	-0.13	**0.02**	**0.048**	0.05
	2	-130.21	-130.44	-129.89	0.23	-0.55	**-0.16**	**0.304**	-0.32
	3	-130.49	-130.64	-130.39	0.15	-0.25	**-0.05**	**0.08**	-0.1
	4	-130.34	-130.35	-130.29	0.01	-0.06	**-0.03**	**0.002**	-0.05
	5	-120.08	-120.43	-120.83	0.35	0.4	**0.38**	**0.001**	0.75
Gamma	Mic.								
	1	-130.57	-130.91	-130.46	0.34	-0.45	**0.05**	**0.312**	-0.11
	2	-130.23	-130.69	-130.02	0.46	-0.67	**0.1**	**0.638**	-0.21
	3	-129.98	-130.24	-129.35	0.26	-0.89	**0.31**	**0.661**	-0.63
	4	-130.45	-131.02	-130.74	0.57	-0.28	**0.15**	**0.361**	0.29
	5	-119.71	-120.15	-120.19	0.44	0.04	**0.24**	**0.08**	0.48
Delta	Mic.								
	1	-130.34	-130.72	-130.71	0.38	-0.01	**0.19**	**0.076**	0.37
	2	-130.73	-130.78	-130.76	0.05	-0.02	**0.02**	**0.002**	0.03
	3	-131.11	-131.39	-131.49	0.28	0.1	**0.19**	**0.016**	0.38
	4	-130.41	-130.6	-130.77	0.19	0.17	**0.18**	**0**	0.36
	5	-120.58	-121.01	-121.35	0.43	0.34	**0.38**	**0.004**	0.77
Epsilon	Mic.								
	1	-129.99	-130.36	-130.22	0.37	-0.14	**0.11**	**0.13**	0.23
	2	-129.6	-129.84	-129.04	0.24	-0.8	**0.28**	**0.541**	-0.56
	3	-130.49	-130.87	-130.7	0.38	-0.17	**0.1**	**0.151**	0.21
	4	-130.21	-130.73	-130.33	0.52	-0.4	**0.06**	**0.423**	0.12
	5	-121.14	-121.65	-121.99	0.51	0.34	**0.42**	**0.014**	0.85

Zeta	Mic.								
	1	-130.25	-130.45	-130.38	0.2	-0.07	**0.06**	**0.036**	0.13
	2	-130.14	-130.54	-129.78	0.4	-0.76	**0.18**	**0.673**	-0.36
	3	-130.78	-131.3	-131.09	0.52	-0.21	**0.16**	**0.266**	0.31
	4	-130.4	-130.73	-130.3	0.33	-0.43	**0.05**	**0.289**	-0.1
	5	-120.63	-121.17	-121.51	0.54	0.34	**0.44**	**0.02**	0.88
Eta	Mic.								
	1	-130.63	-130.87	-130.26	0.24	-0.61	**0.19**	**0.361**	-0.37
	2	-130.35	-130.78	-130.71	0.43	-0.07	**0.18**	**0.125**	0.36
	3	-130.25	-130.71	-130.26	0.46	-0.45	**0**	**0.414**	0.01
	4	-129.95	-130.47	-129.61	0.52	-0.86	**0.17**	**0.952**	-0.34
	5	-120.87	-121.29	-121.44	0.42	0.15	**0.28**	**0.036**	0.57
Theta	Mic.								
	1	-130.02	-130.19	-128.88	0.17	-1.31	**0.57**	**1.095**	-1.14
	2	-130.08	-130.51	-130.44	0.43	-0.07	**0.18**	**0.125**	0.36
	3	-130.11	-130.77	-130.67	0.66	-0.1	**0.28**	**0.289**	0.56
	4	-130.78	-131.11	-131	0.33	-0.11	**0.11**	**0.097**	0.22
	5	-120.04	-120.58	-120.93	0.54	0.35	**0.45**	**0.018**	0.89
Iota	Mic.								
	1	-130.34	-130.85	-130.59	0.51	-0.26	**0.13**	**0.296**	0.25
	2	-130.03	-130.56	-130.24	0.53	-0.32	**0.11**	**0.361**	0.21
	3	-129.72	-130.29	-129.14	0.57	-1.15	**0.29**	**1.479**	-0.58
	4	-129.88	-130.27	-129.28	0.39	-0.99	**0.3**	**0.952**	-0.6
	5	-119.9	-120.82	-121.32	0.92	0.5	**0.71**	**0.088**	1.42

Mean Drift (Array)	**-0.035**
Mean Drift (PCB)	**0.766**
Drift Variance (Array)	**0.164**