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SKUNKWORKS HANDS-ON PROGRAM (SHOP) MISSION ONE PROJECT REPORT: AN EARLY WARNING MISSILE DETECTION SYSTEM

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13. ABSTRACT (Maximum 200 words)
On 3 June 2002, Naval Surface Warfare Center, Dahlgren Division (NSWCDD) initiated the Skunkworks Hands-On Program (SHOP) Mission One training opportunity. The purpose of this newly developed and ongoing effort is to provide recently hired (less than two years) scientists and engineers an opportunity to gain hands-on experience in designing, developing, and testing a system. Novel concepts were developed based on the mission statement. A selected concept was designed and constructed to realize the final product. The team, comprised of eight scientists and engineers (at least one from each department at NSWCDD), was assembled and given the task of developing a proof-of-concept system to be completed in six months that would satisfy the following mission objective:

"Utilize the SHOP rapid prototyping process to design, develop, and demonstrate a system that is capable of providing timely detection and identification of hostile Anti-Ship Cruise Missiles (ASCMs) and their associated platforms with the warship in Emission Control (EMCON) Alpha."

EMCON Alpha describes an operating condition that requires cessation of any on-ship electromagnetic (EM) emission. For completeness, the team produced all required technical documentation for the overall system. The team also briefed a uniquely selected NSWCDD review panel at a Concept Review (CR), Preliminary Design Review (PDR), and a Mission Readiness Review (MRR).

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FOREWORD

As part of an ongoing professional development program, a team of eight recently hired scientists and engineers from each of Dahlgren's technical departments was tasked to develop a proof-of-concept system within six months utilizing the Skunkworks Hands-On Program (SHOP) rapid prototyping process. They were asked to design, develop, and demonstrate a system capable of providing timely detection and identification of hostile Anti-Ship Cruise Missiles (ASCMs) and their associated platforms with the warship in Emission Control (EMCON) Alpha. EMCON Alpha describes an operating condition that requires cessation of any on-ship electromagnetic (EM) emission.

In the successful completion of this task, the team produced all required technical documentation for the overall system and briefed a uniquely selected NSWCDD review panel at a Concept Review (CR), Preliminary Design Review (PDR), and a Mission Readiness Review (MRR).

Approved by:

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ABSTRACT

Naval Surface Warfare Center, Dahlgren Division (NSWCDD) initiated the Skunkworks Hands-On Program (SHOP) Mission One training opportunity on 3 June 2002. The purpose of this newly developed and ongoing effort is to provide recently hired (less than two years) scientists and engineers an opportunity to gain hands-on experience in designing, developing, and testing a system. Novel concepts were developed based on the mission statement. A selected concept was designed and constructed to realize the final product. The team, comprising eight scientists and engineers (at least one from each department at NSWCDD), was assembled and given the task of developing a proof-of-concept system to be completed in six months that would satisfy the following mission objective:

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1. INTRODUCTION

The SHOP Mission One can be defined as a training project that allows the members to design, develop, and test a specific product based on fulfilling the customer's stated need while concurrently learning the NSWCDD systems engineering process. The project mentors emphasized that if the team did not have a fully functional system at the end of the SHOP program, then their collective endeavor would still be successful if the NSWCDD systems engineering process was experienced by all team members.

The team learned about the process through hands-on experience. First, several solutions were researched and developed that met the mission objective; then findings presented to the review panel at a CR. The design selected at the CR was further developed to satisfy the requirements derived from the mission statement. This design was presented to the review board at the PD—at which point the panel judged whether or not the preliminary system was ready for development.

Once the system was developed and tested in the laboratory, an MRR was held allowing the review panel to decide whether the system was ready for real-world testing. The team faced many technical and interpersonal challenges throughout the mission. This report focuses on the developed system and overall design process. The accepted protocols that the SHOP Mission One team employed throughout the different stages of this training project will also be discussed. Although significantly impacting good teaming, the details of group dynamics in this mission remain beyond the scope of this discussion.

The mentors of the mission identified a minimum set of goals to be accomplished or experienced within the duration of the project timeframe as follows.

1. Learn how to collect and apply available intelligence data.
2. Experience how the Navy derives mission needs and/or system requirements.

3. Gain insight into obtaining a Fleet perspective on warfighting needs and incorporating that information into system requirements.
4. Understand anti-ship threats.
5. Become knowledgeable about ship EM environments.
6. Experience the correct combination of mature system engineering practices with accelerated development techniques.
7. Apply scientific and technological knowledge to formulate practical system solutions.
8. Experience analyzing, tracking, and managing project risk.
9. Experience the integration of a variety of complex hardware and software technologies to form a well-engineered system solution.

These goals and others were achieved. The team selected a design approach commonly referred to as Developer-Defined in lieu of others considered, including Object-Oriented and Military Standard.

2. CONCEPT DEVELOPMENT

The ASCM is typically launched from a blue-water sea-going or airborne platform beyond the visual horizon to avoid platform detection. Land-based launches were considered for operations in littoral water. All common means of missile-emitted energy detection were analyzed. Consistently, interviewed parties representing the Navy's need of early warning ASCM detection reinforced the requirement for timely detection. The team's focus, with all conceptual developments, attempted to realize a solution that provided as much time as possible before missile impact—thus giving the ship the maximum amount of time to respond with a threat deterrent or missile destruction. Detections occurring as early as launch-phase were investigated. The proposed system required an output that positively identified the missile type and supplied an angle-of-arrival (AOA) while producing minimal false alerts. Five main areas were identified with six total concepts investigated and reported by the eight-member team.

3. CONCEPT REVIEW

The team members began to brainstorm and research in an out-of-the-box mode. Several proposals were formulated in meeting the mission statement. All design concepts were then presented to the review panel, which selected the design for further development. The potential design candidates presented were as follows:

1. Infrared Detection
   i. Combination Staring, Scanning System
   ii. Fly Eye Staring System
2. Acoustic Detection
3. Ultraviolet Detection
4. Electronic Support Measures (ESM)
   i. Wideband Channelized Digital Signal Processing (DSP) Receiver
   ii. Side-lobe Comparison with Jitter Analysis Receiver
5. Artificial Neural Networks (ANN)

At the conclusion of the concept review, the panel selected the Wideband Channelized DSP Receiver in conjunction with an ANN system to be used for missile detection and identification. At that point, all other methods presented by the team were dismissed, although a modified approach to AOA determination with amplitude side-lobe comparison was retained. After completing several trade studies, an instantaneous bandwidth of 50-MHz was determined to be adequate to demonstrate the system concept. The team started working on solving the very difficult task of developing the chosen system. Eventually, the team decided the best way to design and develop the system was to divide the system into four main subsystems and divide itself into four subteams that would each focus on a particular subsystem.

The organization consisted of the following:

1. Radome and associated Environmental Control Unit (ECU)
2. Antenna and Radio Frequency (RF) Front-End System
3. Digital Signal Processing Receiver (DSPR)
4. Central Processor (CP)

With four subteams working on a specific task, a technical lead was chosen for each design center to improve organization and maintain the line of communications with all eight members of the total team. The responsibility of the technical lead was to hold weekly meetings and open the daily war room conferences for discussions, solutions, suggestions, and updates for each of the four subsystems. The selection of the technical lead was purely based on his or her experience in the particular subsystem subject area. Each technical lead was then responsible for communicating any design changes or design problems to the project coordinator and other leads. The project coordinator would make sure that all subsystems were focused on the same overall design plan and facilitate design change communication between the groups. This was done to prevent the most common source of failure in a project that contains several subgroups: lack of communication. The project coordinator was also responsible for ensuring all subteams possessed the resources and tools necessary to complete their specific tasks. For that reason, a standard operating procedure was established, with the project coordinator becoming a liaison between procurement personnel and the design center leads.

Research and design began and continued through to the PDR, although time did not permit entire system-level software simulation. The team moved expeditiously, executing hardware and software design, assembly, and testing. Subteam and collective team schedules were forecast with an effort to effectively and efficiently coordinate all work and maintain forward progress. Realizing that the whole team had accepted a significant task, the collective view became to do whatever it would take to get the job done.

3.1 Radome and Environmental Control Unit

The radome and ECU system was a combination of an enclosure and temperature control system used to protect the antenna and RF circuitry from moisture and harsh temperatures. The ECU was designed to maintain the necessary temperature within the enclosure to a predefined range considering the thermal load applied. Although this subsystem was originally combined with the antenna and front end, the ECU and radome presented a significant workload and emphasis deserving classification as a separate design and development center within the team.

3.2 Antenna and RF Front-End System

This subsystem functioned to capture RF pulses within a specific band and down-convert the signals, translating from the gigahertz to the megahertz frequency range to accommodate a reasonable sampling rate. Faithful reproduction of intelligence (modulation and pulse) data with minimal distortion was an essential requirement that was additionally realized. A major design task entailed filtering out-of-band signals while realizing a sensitivity figure that satisfied the requirements for distant timely detection.

The required front-end sensitivity to detect a radar-seeking missile just appearing over the radar horizon was calculated using the Friis power transmission formula and 4/3 Earth's radius. Accounting for transmission line losses and RF chain device losses, an initial estimate of –69 dBm was determined as the minimum discernable signal (MDS) required. Further studies using the Advanced Refractive Effects Prediction System (AREPS) concluded that, on average, an MDS of –73 dBm would be required to detect an over-the-horizon appearance of an ASCM.

The envisioned subsystem function included signal capture using pyramidal horns with blanking/attenuation controlled by a pre-trigger blanking signal from the AN/SLA-10 via the Central Processor, or controlled directly by an operator. The AN/SLA-10 monitors all of the ship's EM transmissions and generates pre-trigger-of-transmit blanking signals that are distributed and interfaced to receivers onboard the ship. Receiver front ends are blanked or muted to reduce electromagnetic interference (EMI) reception. A PIN diode switch would attenuate the input signal as required to eliminate reception of ownship RF emissions.

The desired seeker signal required band limiting and amplification. Down-conversion or frequency translation of the radar pulses facilitated processing of high frequency (HF) to very high frequency (VHF) signals, 1 to 51 MHz. Further amplification of the down-converted signal was required to meet sensitivity requirements. An anti-aliasing crossover-distortion filter with a low-pass response prevented violation of the Nyquist sampling theorem in the DSPR. Three duplicate front-end channels were required.

3.3 Digital Signal Processing Receiver

The main functionality of the DSPR subsystem was to digitize the captured down-converted RF signals and process the data for pulse parameter extraction. The DSPR was also responsible for grouping the extracted parameters into a pulse descriptive word (PDW) and transmitting the information to the Central Processor. The data transfer was completed using Ethernet and the TCP/IP protocol.

Tasks for the development of the DSPR consisted of the following: Review threat data specifications to determine required subsystem specifications; research signal processing techniques that could be used to obtain frequency, time, and number of emitter information; develop and analyze the code for each of the signal processing techniques; research available data transfer protocols between DSPR and CP; and finally, research hardware components that could be used for the development of the DSPR subsystem.

3.4 Central Processor

The function of the Central Processor was to identify the type of emitter(s) described in the PDWs received from the DSPR. A derived need of the identifying function was to distinguish between PDWs related to one threat from PDWs of another threat. Finally, it was the CP's responsibility to display all information on current threats to the user.

An artificial neural network was proposed as the tool to perform the emitter identification functionality. A freeware

ANN, the Stuttgart Neural Network Simulator [1], was acquired to investigate the feasibility of this option.

4. THE PRELIMINARY DESIGN REVIEW

This section describes the design process, risk mitigation, and overall experience for each of the subsystems that occurred between the concept design review and preliminary design review.

4.1 Radome and Environmental Control Unit

The radome and environmental control unit design gained momentum after the concept review in which a concept was selected for the team to research and develop. The initial design took into account that the fully realized system would exist aboard a ship and, therefore, the radome's physical design would be as a semi-spherical dome to house the antenna and other systems. Adhering to the expected radome environment, a set of requirements was produced addressing both the shipboard operating environment and the mission statement.

Risks were identified with the design of the radome. Prior to the PDR, the radome was to be a custom design provided by a radome manufacturer according to dimension and frequency specifications. Also requirements arose from the Antenna and RF Front-End System in regard to cooling and therefore drove the need for an environmental control unit. Yet, while this was a critical area to the prototype system, emphasis at this point was devoted to the acquisition of a radome. This acquisition had a lead-time of 30 to 60 days after the receipt of an order. This was a risk that would have caused a slip in the schedule because no ordering could be done prior to the PDR even though there was a pending MRR taking place within only 30 days. Another risk was attributed to whether the manufacturer could find a mold fitting the design requirements. A mold could not be located, so a custom one had to be fabricated in order to build the radome. The original price quote for the radome fell between $2,000 and $3,000. With the need to build a mold, the price escalated to approximately $7,500-$8,500, well beyond our budget for the radome. The alternative that was decided prior to the MRR entailed building the radome ourselves. The risks included getting the materials to build the radome and also the learning curve involved in the construction. We also chose to change the radome's original design from a semi-spherical dome to that of a rectangular box to simplify its manufacture. So after assessing different materials and issues raised regarding refractive properties, we selected Lexan™ as the best radome material that would meet the requirements derived from the mission statement.

4.2 Antenna and RF Front-End System

Tasked to capture, band-limit, amplify, and down-convert received microwave pulses to the very high frequency (VHF) band, trade studies were conducted and decisions made using engineering judgment as to the best type of front end configuration and the best choice of components. Of particular interest was the trade study performed to determine configuration and type of the antenna system. The chosen antenna required independence of frequency with respect to antenna pattern. The standard gain (20 dB) pyramidal horn was chosen to best prove the concept considering the observed 50-MHz bandwidth. Working closely with the DSPR group, an array of 3 horns arranged along a circular segment with pattern crossover occurring at the 3 dB down points was chosen. The DSPR group determined that a crude AOA algorithm could be implemented in MatLab™ code using a minimum of three horns.

Summaries of the identified interface requirements were as follows. The radome and antenna mount and ECU interface requirements addressed antenna array and structural support with trainability requirements, environmental requirements, electronic enclosure mounting, alignment of cable penetrations, and radome window thickness, density, and homogeneity. DSPR interface requirements defined the selected 50-ohm coaxial cable and connection, the expected front-end voltage level output, and the considerations to determine the best quantization operating point.

A trade study was conducted to determine the least costly method to implement the three identical band-pass filters. A two-cavity resonant filter using a shunt inductive discontinuity was designed and implemented with simple WR-90 aluminum waveguide material. Industry standard SMA connectors were used for launch/receive probes in the cavities. Shape perturbation in the rectangular cavity was employed to provide a frequency tuning/coupling adjustment [2]. The cost of machining and materials was found to be minimal compared to purchasing commercially off-the-shelf (COTS) devices, and this was in keeping with the mission vision of allowing the design engineer to gain experience in systems engineering, even at the component-assembly level.

A similar trade study was performed concerning the required low noise amplifier (LNA). In this case, the design was accomplished in-house while out-sourcing fabrication at a reasonable cost: far below the cost of COTS units. The fabrication house provided an assembled, unconditionally stable LNA with 20 dB of gain housed in a sturdy die-cast aluminum enclosure. Although the two common-source high-electron-mobility-field-effect transistor (HEMFET) stages required both negative and positive biasing power supplies, the rectified output a 555 Timer integrated circuit (IC) was used in the bias design to supply the negative potential on the gate of the NE3210S01 HEMFET. Thus, only a single, direct current (DC) power supply was required for bias to the front-end electronics. In keeping with the "hands-on" emphasis of the SHOP mission, the cost of design and fabrication man-hours was not weighted the same as other factors in either trade consideration. The experience gained held a higher priority in this unique environment.

The capability of local filter design and fabrication became even more useful when a narrow band-pass filter was required to filter spurious injection heterodynes amplified by the original local oscillator's broadband traveling wave tube amplifier. The mission team was forced to use all locally available equipment to reduce cost. The injection heterodynes produced artifacts in the down-converted output of the mixer. The flexibility of independence from commercial venders facilitated a quick response to the problem that otherwise would have interrupted progress with a long delay to procure the required filter.

Although the mixer and intermediate frequency amplifier could have been designed in-house, research of COTS units showed that device specifications would be best met by purchasing the units designed and manufactured by industry experts in their respective concentrations with optimized designs. The Marki M20218SA was chosen to provide robust, high third-order intercept characteristics. The Analog Devices AD8367 500-MHz Linear-in-dB, 45-dB Voltage Gain Amplifier (VGA) with Automatic Gain Control (AGC) Detector integrated circuit was selected to amplify the down-converted VHF signal with negative feedback for front-end overload protection. With a characteristic input/output impedance of 200 ohms, a purely resistive impedance matching network was designed and implemented for a 50-ohm impedance match within the subsystem. At input levels of –30 dBm and greater, the output was clamped to an approximate 0.5 Vpp output level with minimal distortion. The wideband Ditom Microwave D3I8016 Ferrite Isolators provided optimum nonreflective channel operation with interfaces to the Marki mixers.

Although originally planned as a hardware filter, the low-pass filter was implemented in software using a discrete infinite impulse response (IIR) design to be loaded in the DSPR. The filter was custom-designed using the Butterworth analog prototype for a maximally flat response [3] [5].

4.3 Digital Signal Processing Receiver

The DSPR subsystem was the limiting factor for the overall system design. This subsystem not only digitized the captured RF signals, it also performed pulse detection and pulse parameter extraction on the digital data. At the proposed sampling frequency, a tremendous amount of data would be generated. In order to process this data in real time, DSP processors integrated with high-speed Analog-to-Digital Converters (ADCs) were necessary. Not only would the team have to learn how to program such devices (steep learning curve), they would have to integrate them to make sure all operations occurred at the appropriate time. In addition, the floating-point operations per second (FLOPS) requirement for the processor(s) was not known since the algorithms for pulse detection and pulse parameter extraction were still in the developmental stage. It became apparent to the DSPR team that the DSPR proof-of-concept subsystem could not be constrained to the real-time requirement of the mission.

The DSPR team proposed a non-real-time solution by using a 2.2-GHz Dual Processor PC and installing three high-speed sampling ADC PCI boards with onboard memory capability. This setup would provide the system with 10 seconds of capture time and the flexibility of changing the sampling frequency if necessary. The proposed system provided the appropriate level of hands-on hardware experience that would allow adequate time to research, analyze, and further develop the intelligence of the DSPR subsystem.

The SHOP mentors felt that waiving the real-time requirement for the DSPR subsystem required the approval of the review panel. As a result, the DSPR team generated a subsystem trade study document to formally present the problem that the team was facing in meeting the real-time requirement. This document presented three DSPR subsystem designs and listed the advantages and disadvantages as well as a schedule of completion for each of the designs. After reviewing the document, the review panel felt that holding the DSPR subsystem to real-time operation would jeopardize the completion of the overall system. The review panel decided to waive the real-time requirement for the DSPR subsystem. The team strongly felt that waiting until the PDR to resolve the real-time issue cost the DSPR team valuable time in the development of the final DSPR subsystem.

The DSPR team envisioned utilizing spectrum analysis techniques as the signal-processing tool for both pulse detection and pulse parameter extraction (i.e., Fast Fourier Transform (FFT), Short-Time Fourier Transform, and Wavelets). The team went through a lengthy process of simulation and data analysis to ensure that accurate PDWs would be generated using this method. Data analysis indicated that the accuracy in the PDW parameters could be achieved if at least a 25% of data overlap could be maintained between successive FFT windows [4]. At the proposed sampling frequency of 105 MHz, real-time operation would require a more extensive and elaborate subsystem design. In addition, the bandwidth requirements for a full-scale system would result in a bulky and expensive system. The DSPR team researched other signal processing techniques that would not only provide feasibility in achieving real-time requirements but would provide ease for expandability. As a result, both time and frequency domain analyses were implemented for the generation of a PDW.

Time-domain analysis was used for the detection of a pulse and for pulse parameter extraction (time-of-arrival, pulse-width, pulse-amplitude, and angle-of-arrival). Frequency domain analysis was used to extract pulse frequency information; furthermore, it was researched as a possible discriminating tool for simultaneous pulse intercepts. Initial results were positive but the algorithm for detecting simultaneous pulses was not incorporated in the final code due to time and schedule constraints.

The main focus in developing the algorithms was to make the subsystem robust to the strong electromagnetic interference that is often encountered onboard ships. The final design implemented narrow channels (much less than GHz bandwidth) that significantly reduced the noise in the data. Frequency selection filters as well as autocorrelation techniques were also researched in improving the signal-to-noise ratio (SNR) of the algorithms. The latter techniques were not incorporated in the final algorithms due to schedule constraints. The development of algorithms that fully address the EMI problem is beyond the scope of this project and paper.

4.4 Central Processor

The team used object-oriented programming strategies to develop a software architecture that would implement the required functions. The complete design was documented using the Unified Modeling Language. This design included four main objects and their associated public and private interfaces.

The proposed architecture of the Central Processor consisted of these four main objects:

- PDW Receiver
- Threat Correlator
- Display
- User Interface

A client-server model was proposed to provide the interface between the DSPR and the CP. The responsibility of the PDW Receiver was to host connections to the DSPR(s) and receive PDWs from these connections. The original design called for an iterative, connectionless server receiving PDWs from the DSPR(s). It was not known at that time how many computers the DSPR team would use to satisfy their requirements. Additionally, the PDW Receiver needed to convert data acquired from the local area network into PDW objects for the Threat Correlator (TC).

The Threat Correlator's requirements were to correlate PDWs into groups generated by unique threats and to identify the threat(s) based on the characteristics of the PDWs. In order to perform the identification, the TC contained the artificial neural network. A derived requirement was the need to calculate the pulse repetition frequency and scan rate to reduce the risk of false alarms. Since all known threats were contained within the TC, it assumed the responsibility for performing these calculations. To prevent the depletion of resources, the TC also performed its own removal of old data. Finally, the TC kept track of when information updates should be sent to the Display.

The role of the Display was to present all known threat information to the user in a usable manner. The team set a threshold requirement of using simple text in a tabular format. If the schedule permitted, work would then be done to implement the Display using a graphical user interface.

The User Interface was required to maintain the current operation state of the Central Processor. The capability to start operation, stop operation, log data, and enter debugging mode were all derived requirements of a functional CP. The User Interface provided the user the means to change all of these modes in an intuitive manner.

Trade studies determined that the Linux operating system (OS) provided a stable operating platform, minimal operating system overhead latency, and a good programming environment. In these studies, OS stability, OS overhead latency, programmer familiarity, available development tools, cost, and OS acquisition delay were all factors that were examined. Windows 2000 was also considered.

Trade studies were also done to determine which Ethernet protocol, UDP or TCP, would best implement the interface with the DSPR. Speed was more important than dropping a few PDWs, so UDP was selected to reduce transmission overhead. Furthermore, the connection management properties of TCP were deemed unnecessary because there would only be one Ethernet switch between the computers, so it was unlikely that packets would get lost.

The ability and accuracy of an artificial neural network to perform identification of emitters was tested and documented for presentation at the PDR. A simulation was created to demonstrate the SNNS's capabilities to the panel. In this simulation, data reflecting what the CP team expected to receive was used so the simulation would be as realistic as possible. In addition, a database-lookup approach was selected as a backup plan in the event that the neural network could not be integrated or failed to perform within our specified design.

4.5 SHOP Shelter

A shelter was necessary to contain the system equipment providing protection from a potentially harsh environment. The original vision suggested that a field test would be conducted in Puerto Rico, and plans were made accordingly. The team was instructed to develop requirements and specifications for the shelter. Based upon those specifications, a unit would be supplied.

5. THE MISSION READINESS REVIEW

This section describes the design process, problem mitigations, and overall experience for each of the subsystems that occurred between the preliminary design review and the mission readiness review. In this design phase, power budgets were formulated by each respective design center/group with the cumulative power requirement appropriately tracked by the shelter team. Isolation transformers were procured to protect noise-sensitive subsystems.

5.1 Radome and Environmental Control Unit

Once the PDR was conducted, further research needed to be devoted to the concept of controlling the environment within the radome (directly proportional to the temperature conditions of the testing site). The ECU was developed incorporating the use of a BASIC Stamp Micro-controller (BSM), temperature thermostat sensor, and Peltier Junction devices. The antenna and subsystems were specified to be at a certain temperature level while operating in the test environment. So the ECU's job is to provide cooling or heating (if needed) of the antenna and subsystems and the area within the radome. The ECU performs these tasks by incorporating a thermostat temperature sensor connected to a serial port to the BSM. The temperature readings are gathered and sent to the controller where a software program evaluates the readings and determines if they exceed or fall below pre-set cooling or heating parameters. Our ECU software program has been set to allow cooling if the temperature reading exceeds 0°C or heating if the reading falls below –5°C. No heating or cooling occurs for any reading within the threshold. Once the BSM software makes the evaluation, a signal is sent out, to relays connected to Peltier Junctions, that initiates the corresponding heating or cooling requirement.

The risks associated with the elements in the ECU ranged from low to medium. Peltier Junctions are solid-state applications with no moving parts or chemical fluids. For applications involving relatively steady state cooling where DC power is being applied to the junction on a more-or-less continuous and uniform basis, a Peltier junction's reliability is extremely high. The mean time between failures (MTBFs) for a Peltier device exceeded 200,000 hours (22.8 years) and the acquisition lead-time was only 4 days. There was relatively no learning curve in using the Peltier junctions and they cost approximately $23 each. Similarly, the temperature sensor was purchased off-the-shelf with relatively no learning curve for application installation and an acquisition lead-time of only 1 day. The BSM was also purchased from a vendor. There was a small learning curve in developing code to perform the heating and cooling functionality. Yet, the acquisition lead-time was only 3 days with a product cost of $159.

The radome and ECU subsystems were designed to satisfy the requirement of protecting the antenna and other electrical systems while maintaining a controlled temperature environment. The objectives were met within the budget and the time allotted.

5.2 Antenna and RF Front-End System

The top-down process of engineering design was employed to develop subsystem specifications within the antenna and RF Front End. Beginning with the system requirements, specifications were developed for each device in the front-end cascade. Each specification was traceable up and down the continuum of hierarchy through seamless interfaces between devices. The industry standard transmission line impedance of 50 ohms was chosen to consistently interface all microwave and RF devices reducing reflection losses. Unidirectional isolators prevented remixing of microwave signals at the mixer interfaces. The goal that the front-end designer maintained was to ensure all specifications were met nominally or marginally exceeded, with a continuously traceable connection throughout the complete system specification hierarchy while realizing a robust system.

With one engineer completing design, assembly, and testing of the entire subsystem, a carefully planned and formulated schedule of subsystem fabrication guaranteed milestone and cumulative success. Parallel work on each part with a daily time-share among the multiplicity of subtasks made progress easier to attain. Using the multitasking scheme, similar to multitasking software architecture, efficiency was maximized. Interfacing subsystem leaders worked closely to clearly define and implement interface requirements. All interface conflicts were resolved. While awaiting parts delivery for other components of the subsystem, the plan expected all resources for at least one component would be available, a common industry process called "just-in-time procurement." A daily routine of parts tracking and modifications to the assembly plan and schedule was employed, particularly when parts did not arrive as expected. Flexibility and tenacity became the key coping mechanisms to realize desired goals.

Much of the time in this phase of the project was spent researching venders to purchase parts, creating parts lists, obtaining paper price and availability quotations as required by the procurement process, and tracking orders. Although much effort was made to reduce the parts count, the RF Front-End System contained the largest number of procured piece parts. Some unnecessary delays were experienced in the parts procurement process as 2.5 weeks passed after parts list submission before procurement began. Order tracking became an essential daily routine to meet deadlines and realize the finished product.

Channel devices were mounted in drilled, die-cast aluminum enclosures with input/output I/O ports marked using dry transfer alphanumeric characters. Bulkhead connectors were appropriately chosen to provide input/output passage through the enclosures. Microwave devices were electrically connected using RG-402 Type coaxial cable with appropriate SMA- and N-Type male and female connector terminations. Coaxial shield material failures occurred because of stress applied by moments developed at coaxial shield/connector solder welds. Repositioning and resizing of the cable lengths eliminated the shield breakages. The VHF devices were coupled using RG-213 coaxial cable terminated with N-Type connectors.

Because the team was uncertain as to the platform on which the system would be tested, semi-flexible Heliax® Type coaxial cable connected the local oscillator mounted in the shelter operating at 8.999 GHz to the mixer LO inputs via a 20-dB amplifier and 3-way power divider. Approximately 8-dBm of signal loss occurred in the Heliax® transmission cable. The trade in this case was to allow complete portability of the antenna array and front end with the least weight while providing a significant degree of freedom concerning the adaptability of the radome base-plate mounting.

Five separate engineering change requests (ECRs) were submitted for approval and applied in the front-end subsystem. Semiconductor amplitude limiters were initially to be installed at the output of each antenna in every channel to prevent possible damage to the LNAs. Research showed that the amplitude limiters using nonlinear diode devices generated spurious signals within the antenna in the presence of high-level, near-field signals. Anticipating out-of-band ownship interfering signals, an engineering change was submitted and approved to include another band pass filter cascaded before and after the limiters. This ECR (Number One) was made obsolete by ECR Number Five, which eliminated the solid-state limiters from the design because of the long lead time to obtain the devices and fact that system testing was no longer planned to be carried out in a normally hostile electromagnetic interference environment. Also, the attenuators with pretrigger blanking inputs were unnecessary and were not implemented for the same reason.

ECR Number Two dealt with implementation of the AD8367 amplifier. ECR Number Three outlined the need to implement an anti-aliasing filter with discrete design due to a very narrow transition band in the low pass response characteristic. The MatLab™ mathematics software package was employed to assist with efficient design algorithm development and filter response simulation.

An analog Butterworth prototype was applied to design an IIR maximally flat filter [5]. With the constraint to prevent alias crossover distortion, the filter approached the ideal low-pass model with a narrow transition band while realizing the required pass-band and stop-band magnitude response. The bilinear transformation filter design procedure, implemented for simulation in MatLab™, demonstrated both the transform application usefulness and interactive convenience in realizing a low-order transfer function with desired frequency response and minimized throughput delay. The filter was designed during a Discrete Signal Processing graduate course that was conducted by the University of Virginia. The objectives learned in this course proved to be essential in developing such a difficult process in the time available.

A filter yielding near-ideal response was required and realized to operate with a maximum 1.5-dB down response of 51 MHz as constrained by the fixed 105-MHz sampling rate in the DSPR. This sampling rate was increased just days before the MRR and system field-test because of contractor default in delivery and specifications as discussed below. An alternate system was chosen by the DSPR team resulting in changes to interface requirements.

Initially, the resonant cavity band-pass filters employed conductive epoxy to bond the Amphenol 901-9758 SMA connector launch/receive probes to the WR-90 aluminum surfaces. The connector probes could best be centered in their respective penetrating holes with a custom-made alignment jig if using epoxy. Although the manufacturer's specifications indicated that the epoxy strength was sufficient, strain yielded to material failure with the fractured bonds completely severing the waveguide body from the connector. ECR Number Four described the use of 2-56 x 1/8 inch screws to secure the connectors to the aluminum surfaces. New waveguide bodies were machined with the appropriate mounting holes.

Quality assurance testing was completed on all devices as they were received or completed. Component-level specifications were verified. As the channel assemblies were completed, operational functionality was tested and performance test results were noted. The front-end designer submitted the antenna and front end to the DSPR team to apply objective subsystem level tests simultaneously facilitating real signal testing for the receiver and unbiased analysis of subsystem performance.

A notable outcome of component testing was the realization of a slightly wider than desired bandwidth established at 1 dB down from unity gain in the output of the band-pass filters. The bandwidth measured 73 MHz with center frequency at 9.025 GHz using a network analyzer. The target bandwidth of 50 MHz was not realized because the inductive brass posts forming the shunt discontinuity were only available in industry standard sizes. The post diameter dominantly affected the filter bandwidth with an intermediate diameter size necessary to realize the slightly narrower desired bandwidth. Additionally, the filter skirt slope of –12 dB/100-MHz could have been made steeper by cascading an additional dual cavity filter of the same design. Filter insertion-loss associated with the 73-MHz bandwidth was also compromised with a 4-dB loss in lieu of a 1-dB loss realized with an experimental unit exhibiting a 30-MHz bandwidth with much steeper skirts. This extremely narrow bandwidth (with respect to the radar X-band center frequency) was the result of installing the next larger standard diameter brass post. In retrospect, brass posts with the required diameter could have been machined.

An additional stage of low noise gain would have been required if additional band-pass filtering were implemented. The trade in this case would have been to force the DSPR to analyze the noise floor measured at –69 dBm using separate test instrumentation. Sophisticated algorithms to do such were considered beyond the scope of this mission. Additional front-end gain would have extended the MDS beyond the noise floor. Material nonavailability prevented target component-level specification realization in this case, but the band-pass filters were considered sufficient for use in the front end considering the additional filtering accomplished by the discrete low-pass filter.

Two days before the scheduled MRR, the traveling wave tube amplifier used to amplify the local oscillator (LO) mixer signal input failed with internal arching. The front-end designer identified a black-box amplifier that operated in the correct frequency range to amplify the 8.999-GHz signal. Specifications for the mechanically sealed Avantek APT-18646 amplifier-unit were not available. Hewlett Packard acquired the original equipment manufacturer. Gain and power specifications were determined by burn-in testing. Eventually, a source of the specifications was uncovered and the amplifier specifications were verified with the burn-in test outcome after returning from field testing.

The MRR board required that appropriate steps be taken to attain a high probability of LO reliability before permission to proceed would be granted. A 48-hour amplifier burn-in test was completed suggesting a high level of confidence that the replacement would operate without failure when taken to the field for the scheduled system test. Implementing the solid-state solution, the LO output suffered the loss of 5-dBm with the mixer injection level decreased to 19 dBm in lieu of the designed 24 dBm because of gain limitations in the APT-18646. This loss significantly affected the MDS capability of the front end during field test, although all signals transmitted during the test were successfully detected. The front-end design proved to be robust in sensitivity.

Safety was considered paramount in the antenna and RF front-end design. Test procedures included instructions on safe operation of test equipment, both indoors and outdoors. Safe microwave exposure limits were researched, documented, and communicated. The level of microwave power transmitted during indoor and outdoor testing remained far below exposure limits. The simple rule remained to avoid staring directly into the transmitting pyramidal horn.

5.3 Digital Signal Processing Receiver

At the PDR, the team proposed two possible DSPR subsystem designs. One design was the system described in section 3.3 of this report. The second design consisted of a Sun-Server with Dual 900-MHz processors and three ADC PCI-Boards. The latter system would have the capability of capturing 10 seconds of data and storing it on RAM in real-time. At this point the data could either be backed up in SCSI drives (sized to allow a total of 86 10-second captures) or could be processed directly from RAM. In addition, each ADC board had one Xilinx FPGA Chip (1 million system gate). The combination of the Xilinx FPGA, the real-time operating system (Solaris), and the high-bandwidth system bus architecture provided the team with a platform that could achieve real-time operation if the pulse detection code could be incorporated in the FPGA and the additional code translated into C code. This second system was a COTS solution from SensorCom Inc. It was a backup system in case manufacturer's lead-time on the ADCs for system 1 could not be negotiated within 4 weeks. SensorCom Inc. had promised a 15-day turnaround after receipt of order for the system.

All manufacture lead times for ADCs were in the range of 8-10 weeks; as a result, the team decided to go with the off-the-shelf solution proposed by SensorCom. The proposed delivery date of the system was 15 November 2002, and SensorCom delivered the system 3 weeks late on 9 December 2002. When the system was received, the DSPR team started an acceptance test and on 11 December 2002 concluded that the system did not meet several required specifications. The team contacted SensorCom and an agreement was reached for the company to remedy the problems as soon as possible. The company failed to meet the deadline and on 16 December 2002 the contract was canceled. The team decided to implement the original DSPR design that was proposed at the CDR—a combination of a digital storage oscilloscope (DSO) and personal computer for the processor. On the day that the contract was canceled, the team was able to locate an available DSO. Immediate work began to translate the captured DSO data to a format that could be read and processed by MatLab™. On 17 December 2002 the DSPR team had successfully completed the DSPR subsystem and started the process of subsystem testing.

The hardware that was needed to develop the DSPR system was expensive; as a result, the DSPR subsystem had a high price tag. For ten seconds of data capture capability, System I had a cost of $66K and System II had a cost of $84K. Even if the computer for System I had been assembled in-house, the price would have still been considerably more than any of the other subsystems ($62K). In the end, the vendor default was seen as something positive since the DSPR concept had been proved without incurring a cost.

The pulse detection and pulse parameter extraction algorithms were completed by mid-November. Generated MatLab™ pulse scenarios were then used to fully test the capability of the algorithms. MatLab™ algorithms for transmittal of the PDW via Transmission Control Protocol (TCP) were implemented in the algorithm on 24 November 2002. On 25 November 2002, the DSPR and CP subsystem had initial contact. Initial contact with the RF Front End did not occur until 18 December 2002. On 19 December 2002, we had the initial integration run between the RF Front End and Central Processor subsystems.

The DSPR subsystem has an overall sensitivity of 3.5 dB. (The signal has to be 3.5 dB greater than the noise for accurate extraction of pulse parameters.) It can also detect two emitters 100% of the time if emitter signals are separated in time by 160 nanoseconds,

$$Time = 2*N*(sampling\ frequency)^{-1} \qquad (1)$$

In Equation (1), N corresponds to the number of data samples that are analyzed as a group; this analysis determines whether a pulse is present in the data (N=20; sampling frequency=50MHz). The minimum signal separation that would result in only one PDW generation for two distinct pulses is 80 nanoseconds.

Although the current DSPR algorithm is not able to detect temporal-simultaneous pulses, it can detect spatial-simultaneous emissions if temporal separation between emitter pulses is between 80-160 nanoseconds, with 100% detection of two emitters at 160 nanoseconds or greater. This was the reason the DSPR was able to accurately generate two distinct PDWs when tested with the preprocessed simultaneous emitter signal that was recorded at Patuxent River Naval Base.

A total of five ECRs relating to the DSPR were submitted to the mentor. ECR Number Two addressed the change in the algorithm to incorporate both time and frequency domain analysis. The remainder of the ECRs (one, three, four, and five) addressed the changes that came about in the DSPR subsystem as a result of contractor default.

5.4 Central Processor

After the PDR, the Central Processor team researched powerful computers and decided to assemble their own, rather than order a COTS computer from a standard manufacturer such as Dell™. This decision was both schedule and budget-based. The team had learned that, when ordering items less than $2500, delivery would take a day or two; however, when ordering was in excess of $2500, another level of review of the order was required and thus more time before parts delivery. Desiring to minimize this time, the decision was made to assemble the computer from parts ordered. Total parts cost was $3400. Within two weeks of order submissions, all parts were received and the Central Processor was built. Immediately thereafter, RedHat 7.3 was installed to verify all parts were working properly.

The team concluded that it would pose unnecessary risk to abandon the SNNS in favor of the MatLab™ Neural Network toolbox within the allotted schedule. The SNNS had performed well in the realistic simulation for the PDR. Furthermore, the SNNS had an interface that was well understood by this point.

Next, all Central Processor sub-objects were assigned to a team member for implementation. A schedule was made for each object's completion so integration testing could be coordinated.

Changes to the interface specifications were negotiated after initial contact was made between the two subsystems on 25 November 2002. It was discovered that MatLab™ used the same number of bits to represent all numbers transmitted as it does for the largest number. Therefore, all data type optimizations were discarded from the PDW structure, and the team agreed that all numbers within a PDW would be 32-bit integers. In addition, the team decided to use TCP rather than UDP because TCP was faster. Research had shown that TCP was actually 33% faster for our application. The team believed that the Nagle Algorithm would only be a factor if the bandwidth of the transport medium were heavily taxed. The preliminary estimate of 1.5 MB/second was well below the realistic estimate of 10 MB/second bandwidth using a 100 Base-T Ethernet network. The assumption that the Nagle Algorithm would hinder the program's performance, due to windowing and buffering of data, was proven wrong when tested. Simple programs that sent data between two machines, at realistic rates for the problem, were implemented in C code and differed only in the use of TCP and UDP. Data collected from this field test showed that TCP transferred data across our network 33% faster than UDP.

It was also necessary to make changes to the PDW Receiver. In addition to changing from the UDP to the TCP protocol, the PDW Receiver changed to a multi-threaded concurrent server instead of the previously designed iterative server. The Data Receiver ECR documented the need to dynamically reestablish connections with the DSPR. This was much easier to implement using the concurrent model than the iterative. Additionally, this change improved performance because the CP effectively used four processors. This is because the team built the CP using two 2.6-GHz Xeon processors capable of HyperThreading™.

Due to the changes within the DSPR subsystem resulting from the vendor default and the cascading changes in the threat specifications, the neural network had to be retrained to identify the redefined threats. In order to reprogram and retrain the neural network, an entirely new set of training data had to be generated to match the updated threat specifications. The software doing statistical analysis of the incoming PDWs also had to be heavily modified. The algorithms had to be modified to deal with far less data than had originally been envisioned as being available.

It was found during the implementation phase that the software would be capable of processing many more PDWs than would realistically be produced. Therefore, the Redundant Data Destroyer (RDD) served no purpose and unnecessarily complicated the interface between the PDW Receiver and the Threat Correlator. The RDD ECR documented the removal of the RDD and simplification of its associated interface.

Additional ECRs were submitted and approved regarding the functions performed by the Threat Correlator. The original design called for many objects to reside at the same level in the hierarchy of objects contained by the Threat Correlator. Implementation showed that this greatly hindered the speed at which data could be moved within the Threat Correlator. The Pulse Associator and Threat Manager ECRs documented the needs to have some objects contained within other objects, rather than all objects being separate. In this manner, the data that the affected objects needed to access was immediately accessible to the moved objects. This removed a level of interfacing and improved performance.

The final ECR involved adding a Screen object to the design. It was discovered that the thread handling the display of information to the user and the thread handling the user interface could be writing to the screen at the same time. The library used for displaying text on the screen was not hardened for multithreaded use. Thus, it was necessary to add another Thread_Mutex_Guard object to the design for providing mutually exclusive access to the functions that displayed information on the screen [6].

When all objects had been implemented, unit testing of the Central Processor began. As with most projects, the results were not perfect on the first try. Data was extracted and analyzed from multiple points within the subsystem until it correctly identified and reported all six threats. At this point, as part of integration testing, the 17 signals, with which we were to be presented at our new testing site in Patuxent River Naval Station, were run through our system as a further test. Once these signals were received and identified correctly, we then performed verification testing to ensure that, in all cases, our testing was accurate.

5.5 SHOP Shelter

Originally, the shelter was to be provided according to specifications through on-base resources. A requirements list was generated specifying the appropriate number and size of equipment racks, safety equipment, and power and heating and cooling requirements. This list was submitted in mid October so that those building our shelter would have time to acquire needed hardware and integrate it into the physical shelter. In mid November the team was notified that the shelter would have to be created from within the team.

After querying other members of the team for their power needs, the appropriate racks were ordered, and design began on the power system for the shelter. Various departments were contacted on site at NSWC Dahlgren to arrange for a heating and cooling system to be installed and for the shelter to be repaired and patched.

Each other subsystem was contacted, and in accordance with each power budget specified, it was determined that 50 amps at 120 volts was required to be provided by the shelter. A power panel was designed and wired to provide this level of current. Also installed was a line isolator to ensure that, if powered via a generator, clean power would be available. Lighting and rack systems were then installed. At this point, the overall system had changed significantly; it was too late to reliably order new mounting equipment, and so alternative mounting methods were developed and employed successfully. As our needs had changed, fifty amps became excessive. As a result, the shelter was overbuilt and able to supply two and a half times the power actually needed. In addition, spare racks were available for equipment that was no longer needed. The shelter remains with the SHOP program as a capital asset, ready to serve future missions if needed.

6. TESTING AT PATUXENT RIVER NAVAL BASE

Upon completion of the design, documentation, and MRR, the team members prepared for a live field test of the ASCM warning system as shown in Figure 1. A list of seventeen signal scenarios was prepared and disguised with false names representative of missile characteristics from the

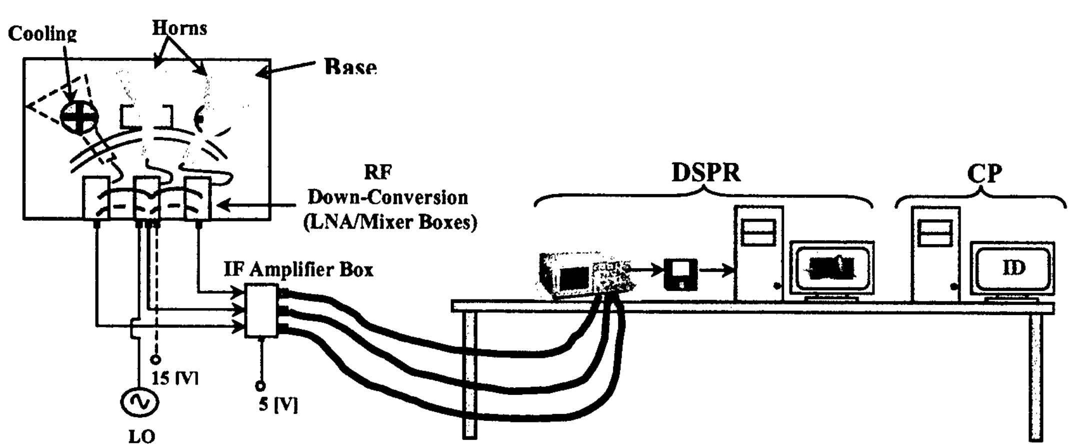


Figure 1. SHOP Mission #1 System

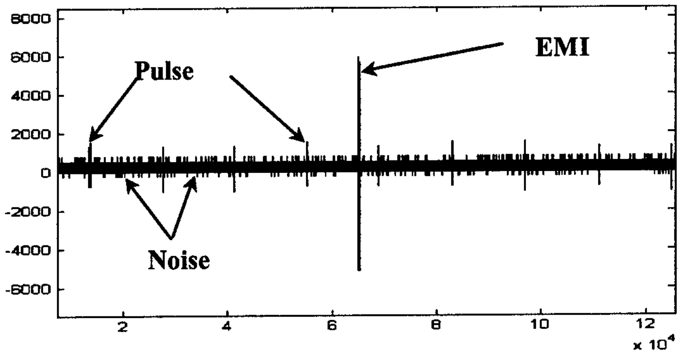


Figure 2. Test Signal 10 (Day 2)

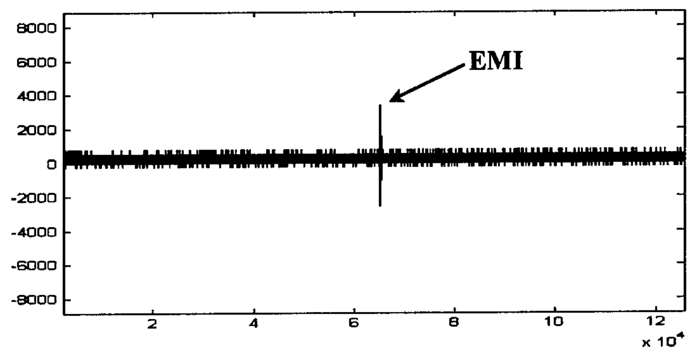
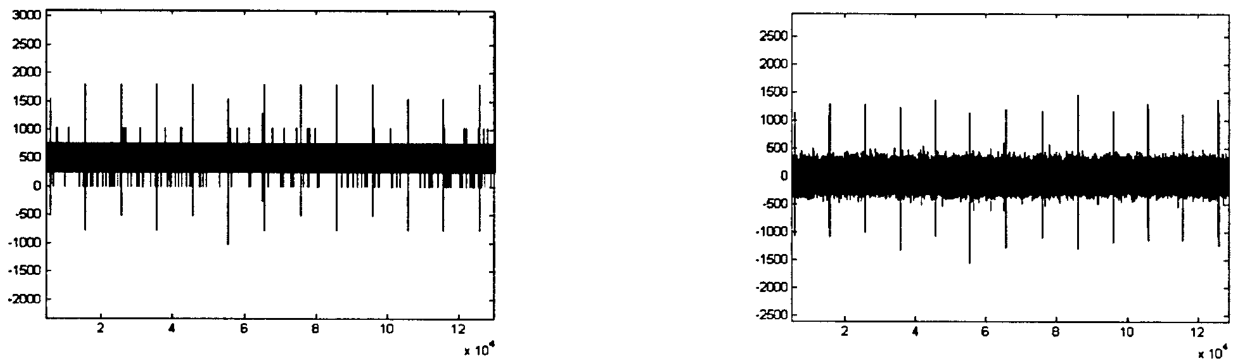


Figure 3. Test Signal 4: No data was captured, except for the strong interferer. (Day 2)

available threat data. These signal scenarios were called into the emission center at the Patuxent River Naval Base, Atlantic Test Ranges, Electronic Warfare and Emitter Site (Pax River) and programmed into the emitters before the team's arrival. The team members packed up the equipment in the shelter and traveled to the Chesapeake Bay coast. There they set up the system on the shore of the Chesapeake Bay about 6 miles from the emission site. Once the system was connected and calibrated, the naval base staff began emitting the test signals one by one using a two-way radio to communicate between the site and the tower. The last in the series of tests was specially designed to test the limits of the design with two missile emitters simultaneously synthesized.

The first day of testing proved successful as the SHOP system accurately detected 11 of 14 missiles. Due to the design, the system could not capture certain circular scan signals since the DSPR required manual triggering by an operator, although the signals were detected. On day two, the system again proved successful at processing captured signals, however, the capture percentage was less than experienced on day one. Even when the signal was captured, the system had a difficult time in generating accurate PDWs because of a strong near-band interfering signal. As a result of another test being run for electronic warfare aircraft the evening of our first day, which cut short the scheduled test time, all antennas associated with the test were not repositioned to allow the system to receive the requested signals. In addition, the Pax River emissions site had not reset all of their transmitters to the required specification, thus causing several signals to be resent. The combination of these two conditions, along with our artificially shortened test time, forced a time pressure that heightened the possibility of human error. This did not allow for the required manual threshold evaluation and filtering necessary to accurately detect all signals. Several other aircraft were in the area and speculated to be the source of interference. Figure 2 shows captured data illustrating the noise floor and a strong interference signal, which caused problems with the pulse detection algorithm. Figure 3 shows captured data indicating the pulse signal was missed completely and only the strong interference signal was recorded.



4a.

4b.

Figure 4. Day-2 Data
a. Test 15 as captured and processed at the test range
b. Data after being preprocessed by a Low-Pass Filter and Band-Limiting Filter]

A DC offset was noted in some captured signals on day two with a mean temperature 10° below the previous day. The team speculated that the offset came about due to the effects of the extreme cold on the equipment, since the offset decreased as testing proceeded. The highest temperature on day two rose to only 17° F.

After researching the probable source of failure after returning to NAVSEA Dahlgren, the team found that the specified operating temperature (+10° C to +50° C) of the Tektronix TDS 744 DSO had been significantly violated. Due to a last-minute scurry to find a viable alternative for a digital receiver to record signal data, this detail was overlooked. Further inquiries indicated that a signal path calibration that conditions the DSO internal vertical amplifiers for operating temperatures below 5° C was available in the software library of the DSO. Had the signal path calibration routine been run before, and between tests on day two, the DC offset would have been eliminated.

A minor source of noise was identified as being produced by the fluorescent lighting in the shelter. The magnitude of effect was dependent on the physical location of coaxial cables feeding the DSO. Tests conducted after returning to NSWC Dahlgren confirmed a direct correlation. This source was an extremely small (micro-volt magnitude) signal and completely alternating current observed at approximately 1 MHz.

Additionally, the designed IIR discrete filter was not loaded in the DSPR [5]; hence, it was not used during live testing. Figure 4 illustrates how discrete filtering would have helped in the detection of a pulse and in the extraction of its parameters.

During the final test, a special signal designed to simulate two simultaneous incoming missiles was transmitted. The SHOP system could not accurately provide a detection due to the presence of EMI and the DSO DC offset. The recorded test scenario was later preprocessed at NSWCDD with low-pass and band-limiting discrete filters to eliminate the interference. The system was then able to provide accurate detection and identification of the two threat emitters. The experience serves to emphasize the importance of incorporating EMI robustness in any future Navy Electronic Support EW System design.

Overall, the field test conducted at Patuxent River Naval Base was considered an overwhelming success in many ways. The new scientists and engineers were exposed to the process of organizing and executing a live test of a developed system. The members also experienced hands-on training and insight into the problems one may have to deal with at live events. The team also enjoyed the success of capturing and processing a majority of the test signals, keeping in mind that this was the first exposure of the system to live emissions. All signals were detected by the system, with only limited difficulty in processing some signals. With no formal assignment of duties, the field test demonstrated an example of cooperative, harmonious teaming, with each member vigilantly seeking to serve and assist.

7. CONCLUSION

Beginning with the mission statement to detect and classify hostile ASCM emitters, the SHOP team sought to provide a novel solution to the need of the Fleet, our customer. Intelligence data was reviewed, system requirements were defined, and much effort was invested in thoroughly understanding the threat. The team adopted a developer-defined philosophy of system design with a top-down, specification-traceable approach. Mature engineering practices with accelerated development techniques were exemplified by eliminating the time to create a system software model and simulate the entire system before proceeding to hardware assembly. Design team members maintained a clear view of the common goal and communicated clearly and regularly to achieve success. Team members mitigated problems one at a time with focus. Procurement and acquisition protocols were exercised significantly. At the mission midpoint, the team asserted the tenacity to finish successfully. Products of the mission beyond the working rapid prototype system (hardware and software) included system specifications, trade studies, engineering drawings, test plans and procedures, and briefing packages.

Beyond the SHOP mentors, centers of technical excellence and expertise were consulted if required. By applying scientific and practical knowledge, a solution to the given challenge was formulated and executed. Analyzing, tracking, and managing project risk were keys to maintain progress throughout the mission. Technical leaders constantly reviewed design progress to look for flaws that would interrupt realization of a fully functional integrated system. The integration of complex hardware and software subsystems posed a serious challenge that was met with patience, maturity, diligence, and good engineering judgment. Many observers noted that the SHOP Mission One team gained the experience in these few months that normally takes many years to obtain. The team got the job done, and each member's experiences will contribute to future successes at NSWC Dahlgren. This inaugural SHOP Mission provided great insight, both for the junior scientist and engineer at NSWC Dahlgren (with better skills for real-world problem solving) and the SHOP mentors (with greater wisdom for executing future missions).

Possible system improvements include cascading additional filter sections for steeper band-pass filter skirts in the front end, inclusion of discrete filtering in the receiver, algorithms to detect very low level signals at or close to the noise floor, and expanded bandwidth by employing multichannels and novel antennas. Further questions may be addressed by contacting the SHOP Mission One members using the contact information found below.

8. SHOP TEAM MEMBERS

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John J. Griffith (B32) BS/CS

8.5 SHOP Shelter

Britt D. Burton (K71) BS/Phys

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