CENTURION –
A Total Port Maritime Surveillance Concept

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Mr. Bick has more than 40 years of professional engineering experience and has provided technical leadership and major contributions in the formulation of concepts and designs related to Undersea Warfare (USW) systems for the US Navy. Technical focus areas include undersea acoustics, USW mission analysis and sonar system design, acoustic transmit and receive array design, and advanced acoustic signal and data processing.

His technical accomplishments include:

- Invented and architected sonar designs for several major US defense contractors
- Authored and presented technical papers for the Journal of the Acoustical Society of America and Undersea Defence Technology, National Defense Industrial Association, Institute of Electrical and Electronics Engineers/Oceanic Engineering Society (IEEE/OES) Homeland Security, IEEE Oceans, and Society of American Military Engineers Homeland Security conferences.
- Two sonar patents; “Bow dome sonar”, “Sonar system”

Mr. Bick earned a Masters of Science degree in Electrical Engineering from Northeastern University, and a Bachelor of Science degree in Electrical Engineering from Purdue University.

Abstract

This paper summarizes the latest Navigation Systems Division (NSD) developments from the phase two spiral development of a US Navy sponsored total Port Maritime Surveillance System. Multiple harbor bottom acoustic arrays using fiber optic sensor array technology developed by NSD are the primary underwater sensors used to address the underwater threat and to complement the non-acoustic surface sensors to provide a total waterborne threat surveillance capability.

The latest developments include: (1) Creating system architecture for a stand-alone port surveillance system or an underwater surveillance subsystem (2) Creating a new acoustic and signal processing concept (3) Exploring a new approach to provide real time signal processing and (4) Processing acoustic array data in real time.

The testing results show that a passive acoustic tripwire concept using harbor bottom arrays implemented with Fiber Optic Acoustic System (FOAS) technology together with advanced real time signal and data processing can detect and track underwater threats including SCUBA divers.

Introduction

In the aftermath of the USS Cole and 9/11 incidents, the US Navy and Coast Guard are developing deployable and fixed surveillance capabilities that can be utilized to protect commercial and military vessels while at sea, at anchorage, or berthed in port in US and foreign waters. These surveillance capabilities are being deployed in the form of ship protection systems and harbor security systems.

Traditionally these types of systems have utilized sensors including radar, cameras, and the Automatic Identification System (AIS) for detection, tracking, classification, and identification of potential threats. However, these sensors present challenges in terms of deployment logistics, line of sight limitations, detection of small, hard to detect or fast moving surface targets, and detection of subsurface targets such as swimmers and swimmer delivery vehicles.

In particular, the detection of divers has been a challenge for both active sonars that transmit sound energy and receive target echoes and for passive sonars that only receive target radiated sound energy. Present diver detection systems use high frequency (50-100 kHz) active sonars. Reverberation limits the performance and range of the active detection of these monostatic high frequency sonars. This is similar to radar performance when it is limited by clutter. Solid “gap-free” coverage of the water column by active sonar search is difficult. It is even more difficult for shallow water bathymetry when there are natural scattering boundaries such as the surface, harbor bottom, and harbor entrances.

SCUBA divers’ low acoustic signature levels make passive detection difficult and substantial processing gain is required to allow detection at the required ranges. In particular, closed circuit or “rebreather” SCUBA gear radiates acoustic signatures well below ambient noise.

Centurion offers a Maritime Force Protection and Harbor Surveillance system development that is targeted against both surface and underwater threats. A Centurion test bed was established at the Naval Base Ventura County (NBVC), Port Hueneme, California, a military and commercial port of modest size and traffic.

The development of a passive acoustic threat detection, tracking, and classification capability was of particular interest to the Navy. Harbor bottom acoustic arrays using FOAS technology were designed, fabricated, and installed at the entrance to Port Hueneme to implement an “acoustic tripwire” to detect, track, and identify potential waterborne threats.

FOAS technology was chosen because of its light weight and the substantial flexibility it provides in placing its processing elements all electronics away from the sensors. The processing electronics can be located in a dry environment onboard a ship or ashore. In-water tests and data gathering enabled the development of an advanced signal processing concept and a practical real time processing implementation.

Centurion Architecture

Figure 1 illustrates the main functional components and data transfer that form the Centurion architecture.

The sensor types that were chosen for a total surveillance capability are acoustic sensors, radars, optical sensors, and an Automatic Identification System (AIS).

To address the underwater threat, two acoustic sensor types are considered; (1) a harbor bottom passive tripwire and (2) water column acoustic sensors.

The harbor bottom passive tripwire consists of line arrays of acoustic hydrophones that are laid on the harbor bottom, usually along straight lines.

The three water column acoustic sensor types are: (1) high frequency active monostatic sonars (2) a high frequency bistatic receiver which operates with an active soundhead and (3) high frequency passive sonars.

Each unique sensor type has its own processor which provides detection and tracking functions and a display ready data transfer capability.

The processor of a commercial off-the-shelf (COTS) sensor may produce unique data. The common interface converts the unique data from the sensor into a common data structure used by the Sensor Fusion Processor and Contact Manager.

The Sensor Fusion Processor receives the information from the different sensors, correlates all sensors contacts, and provides track management and automated rule-based decisions about whether a target is or isn’t a potential threat. For a potential threat, an alert is sounded on the situation display, and relevant potential threat information is transferred to the Command, Control, Communication, Computers, Intelligence (C4I) system. In addition, the track manager continuously updates the situation display

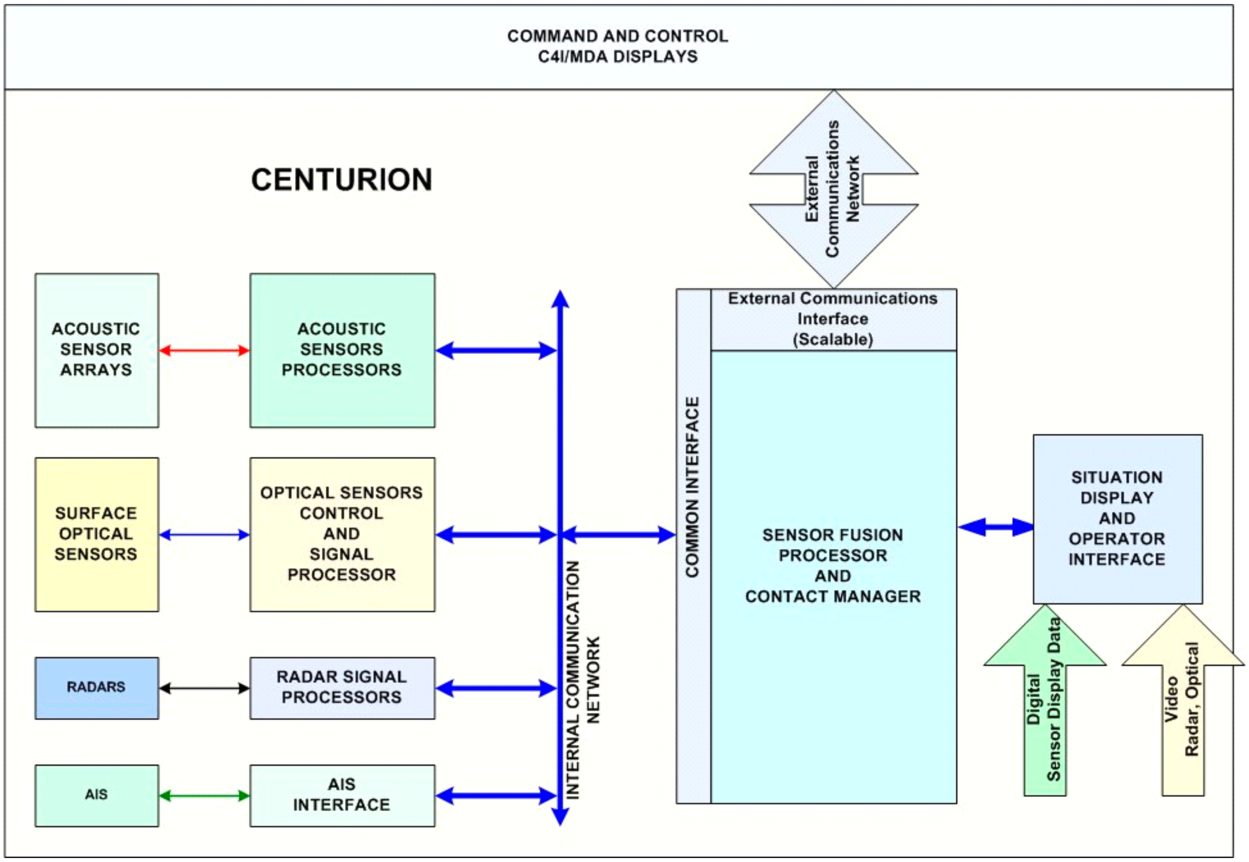


Figure 1. Centurion Architecture

with its most current contact information so contact symbols may be overlaid onto the situation display. The situation display for a harbor or port consists of an electronic nautical chart which is used as the background for the display layer.

The Situation Display and Operator Interface can be either a single operator workstation configured specifically for the waterborne threat surveillance function, or an existing C4I and Maritime Domain Awareness console. The operational goal is to provide an unattended capability, where the console is mainly used for routine watch checks and operator evaluation when on threat alert.

Centurion is highly scalable. It can be deployed as a minimal standalone system or used as a subsystem which will interface with existing port defense systems.

As shown the Centurion architecture integrates both the subsurface acoustic sensors and the surface non-acoustic sensors, provides contact data to command and control networks, and provides display ready contact data to the local situation display. The primary functions of Centurion are a common sensor data interface, fusion and correlation of multi-sensor contact data, a Command and Control system interface, and a situation display interface.

The Integrated Combat Management System (ICMS) shown in Figure 2 provides a low risk implementation of these functions. Northrop Grumman has used ICMS successfully on several shipboard combat systems including the Littoral Combat Ship (LCS).

FOAS Technology Fundamentals

The fiber optic acoustic sensors for the harbor bottom arrays use a Michelson interferometer configuration shown in Figure 3. A single optical coupler both splits and recombines the light. The incoming acoustic pressure causes the optical fiber, which is wound around a compliant (or flexible) mandrel that forms the sensing arm, to deflect proportionally to the acoustic pressure and to change the optical path length to produce a carrier phase shift ($\Delta\Phi_{SIG}$). The reference arm consists of optical fiber wound around a non-compliant mandrel. The interferometer input is a carrier signal resulting from a direct frequency modulation of the optical source.

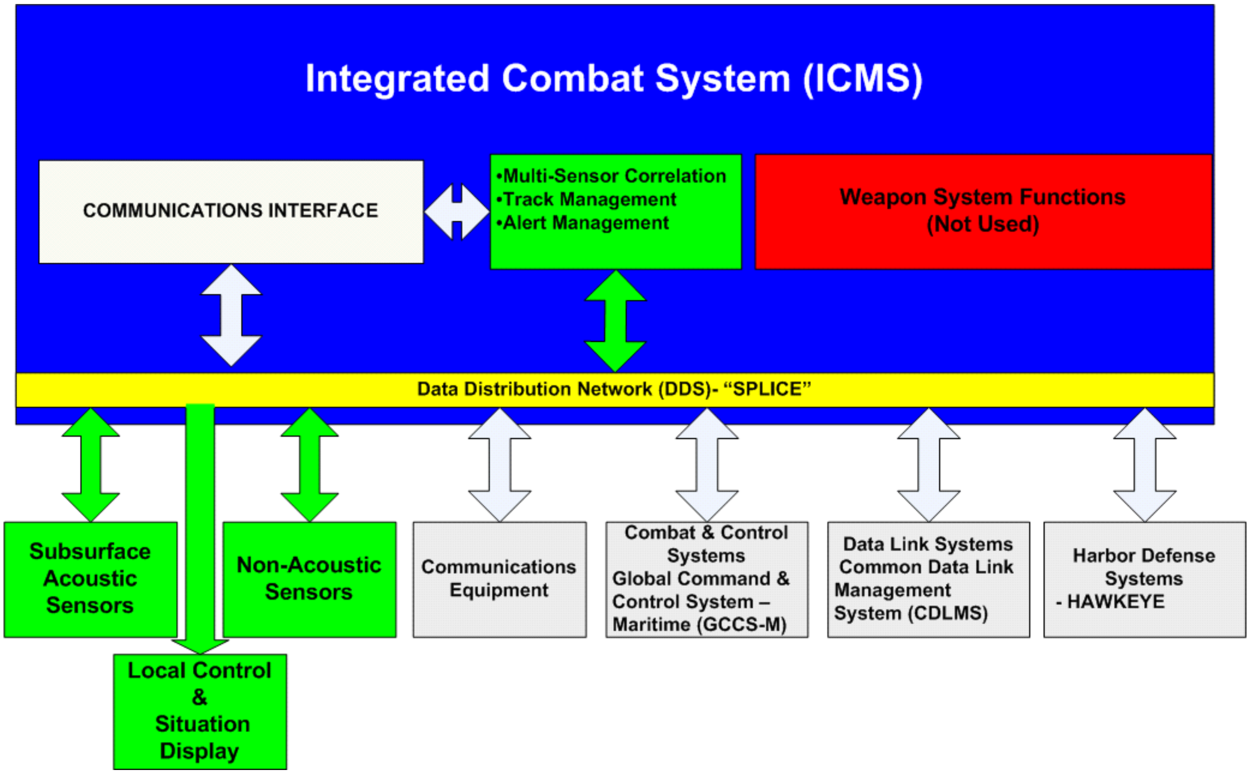


Figure 2. ICMS Implementation

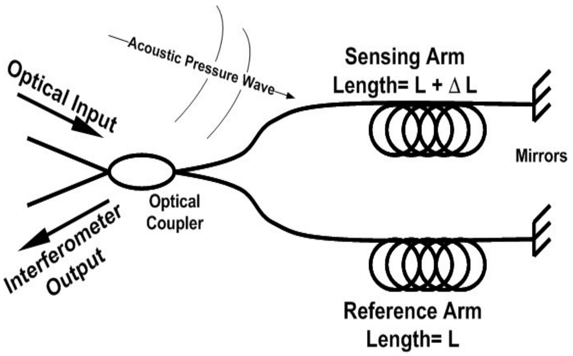


Figure 3. Fiber Optic Michelson Interferometer

The output of the interferometer is:

$$I = I_{\mathrm{DC}} + I_{\mathrm{AC}}\, cos(\Delta\Phi\,),$$

where

I is the total light carrier intensity,

I_{DC} is the DC intensity component

I_{AC} is the AC intensity component, and

$\Delta\Phi$ is the total phase shift between the reference and the sensor arms

The total phase shift is a combination of the modulating carrier phase shift ($\Delta\Phi_{\mathrm{M}}$) and the sensor arm acoustic signal induced phase shift ($\Delta\Phi_{\mathrm{SIG}}$):

$$\Delta\Phi = \Delta\Phi_{\mathrm{M}} + \Delta\Phi_{\mathrm{SIG}}$$

$$\Delta\Phi_{\mathrm{M}} = \beta\, sin(\,\omega_{\mathrm{M}}\, t\,),$$

where

$\beta = 2\pi\,\eta\,\Delta L\, A\,/\,c,$

$\eta =$ index of refraction

ΔL is physical path difference between the sensing and reference arms, and

A is the peak amplitude of the modulating carrier of radian frequency ω_M

$$\Delta\Phi_{SIG} = \frac{2\pi\,\eta\, L\xi\varepsilon}{\lambda}$$

where

L is the fiber length wound on the sensing mandrel,

ξ is a correction factor for the strain-optic effect

ε is the strain in the fiber, and

λ is the light wavelength

The output of the interferometer is a modulated carrier signal intensity expressed as:

$$I = I_{\mathrm{DC}} + I_{AC}\; cos(\,\beta\, sin\,\omega_M\, t + \Delta\Phi_{\mathrm{SIG}}\,)$$

The odd harmonics of the carrier signal are amplitude modulated by the sine of the signal induced carrier phase ($\Delta\Phi_{\mathrm{SIG}}$). The even harmonics are modulated by the cosine of the signal induced carrier phase. The acoustic signal is recovered as the arctangent of the sine and cosine components. The optical interferometric hydrophone responsivity (or sensitivity) is expressed as total phase shift per unit pressure (in radians/micro Pascal).

Multiple fiber optic sensors in an acoustic array are time division multiplexed (TDM) as illustrated in Figure 4. Delay coils are incorporated between each ladder rung to ensure that individual sensor pulses do not overlap at the output.

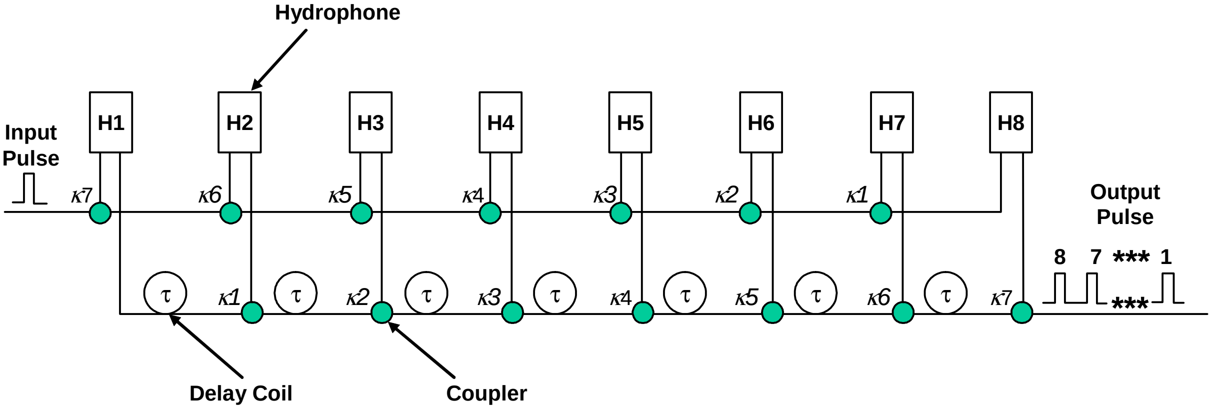


Figure 4. Time Division Multiplexing of Fiber Optic

An interrogation pulse "samples" the hydrophones at a repetition rate which impacts both fidelity of the recovered signal and maximum signal handling capability. The fringe rate sets a lower bound for the interrogation rate. The fringe rate is the rate at which changes in the carrier phase between interrogation samples exceeds π radians, which is also called a phase excession. A phase excession presents an ambiguity and discontinuity in the demodulated signal. The interrogation repetition rate is usually at least five times the Nyquist rate used for sampling the recovered acoustic signal.

Acoustic and Signal Processing Concept for an Acoustic Tripwire

The total acoustic tripwire array laydown shown in Figure 5 consists of two 48-hydrophone arrays which stretch across the harbor entrance.

The search perimeter, 350 m x 400 m, shown in Figure 6 is the area enclosed for which a matched-field beamformer and detector is presently implemented for quiet underwater threat detection and tracking.

Each array has 2-symmetric split apertures as shown in Figure 7 to enable spatial correlation processing. A design program has been developed to optimize the broadband array gain-bandwidth product for a particular harbor entrance. The aperture design uses a non-uniform spacing, a fixed hydrophone count per array, 2-line arrays, and a desired angle from the harbor entrance axis. The resulting hydrophone spacing and density function for a half-aperture, the Bick density, effects an array gain (or Directivity Index (DI) which is similar to that achieved by a Taylor weighting density function as shown in Figure 8.

Figure 5. FOAS Harbor Bottom Array Tripwire

Figure 6. Matched-field Search Area

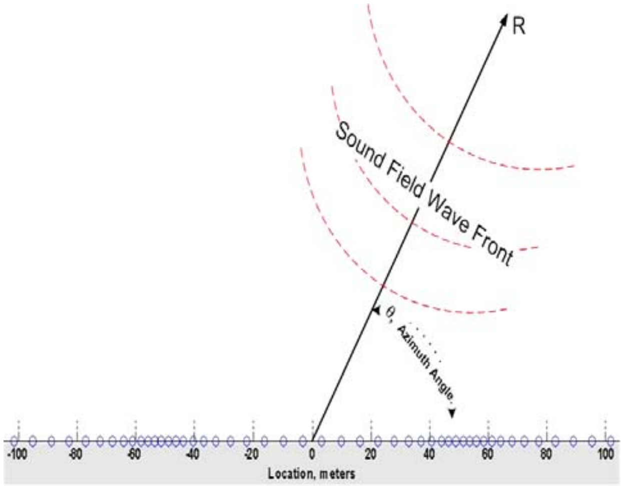


Figure 7. Array Aperture and Beamforming Geometry

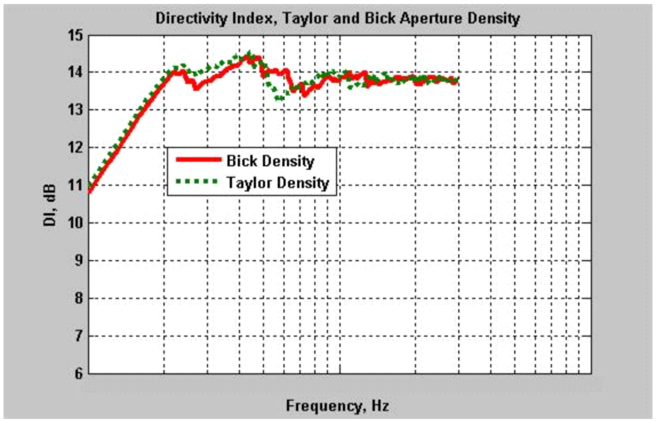


Figure 8. Broadband Array Gain Effected by Aperture Design

The broadband DI versus frequency plot assumes a perfect coherent signal gain. However, for the large apertures used for beamforming (adding spatial samples coherently), the sound field is complex and both range and bearing dependent.

To illustrate this, Figure 9 shows the coherent signal gain for the 24-hydrophone half aperture versus azimuthal bearing angle for a near-field target using a far-field beamformer. The ideal gain is 27.6 ($20 \log_{10} 24$) dB. Figure 10 illustrates the ideal gain is achieved when the beamformer uses steering vectors that are matched to the pressure vector for a given range bearing location. Figure 11 zooms in on the one degree steering angle target discrimination that is implemented with the matched-field beamformer. Similarly, Figure 12 illustrates the range discrimination using 4 meter range discrimination for the matched-field beamformer.

The beamformer and broadband detection approach is based on maximizing the Processing Gain (PG), which includes both the spatial gain from the beamformer and the temporal gain from the detection processing. The PG sets the passive sonar's figure-of-merit and coupled with propagation loss, it establishes the maximum range for threat detection. Tripwire warning time for decision making and reaction time is established by the maximum detection and track range of the sensors and the inbound velocity of quiet acoustic targets.

Using a simple propagation loss model and the passive sonar equation, the required processing gain versus signal-to-noise ratio (SNR) at the target and maximum target detection ranges can be computed. The results are plotted in Figure 13. Overlaid on the plot is the ideal processing gain using the tripwire array design and processing parameters shown. The range of SNR's shown encompasses that expected for SCUBA divers. From this, detection ranges for the quietest threats would be expected to be measured in tens of meters, whereas detection ranges at the high end of the quiet threats would be measured in hundreds of meters. The surface waterborne threats from slow to fast, small boats, trawlers and shipping vessels all have significantly higher SNR's than the SNR range encompassed in Figure 13.

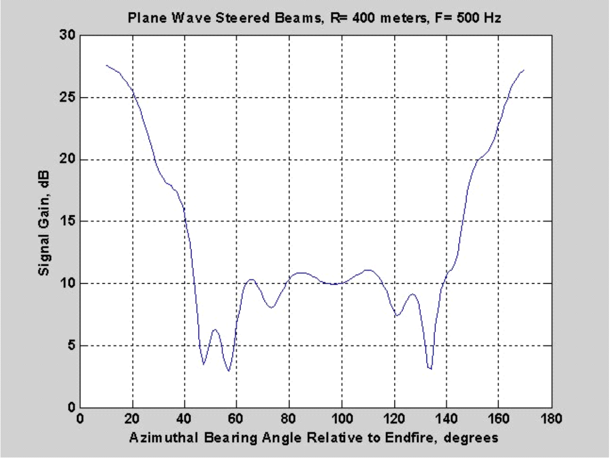


Figure 9. Signal Gain for Far-field Beamforming and a Near-Field Sound Source

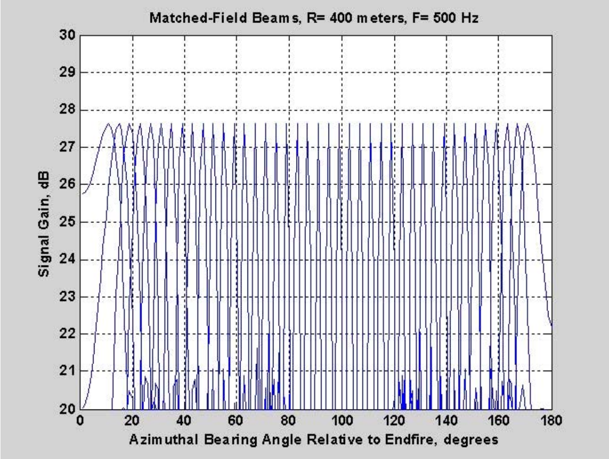


Figure 10. Signal Gain for Matched-field Beamforming, Fixed Range

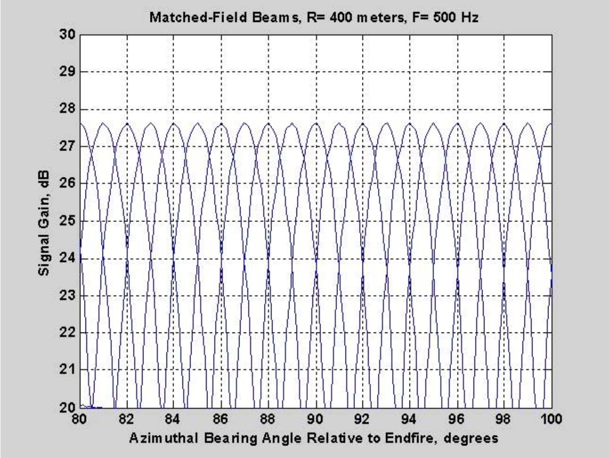


Figure 11. Signal Gain for Matched-field Beamforming, Fixed Range, Showing One Degree Resolution

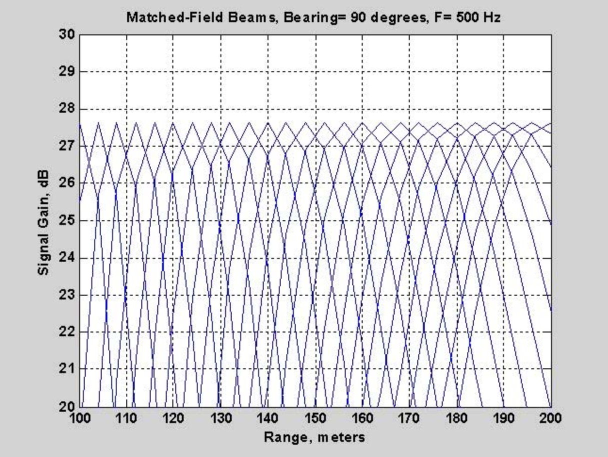


Figure 12. Signal Gain for Matched-field Beamforming, Fixed Bearing, Showing Four Meter Resolution

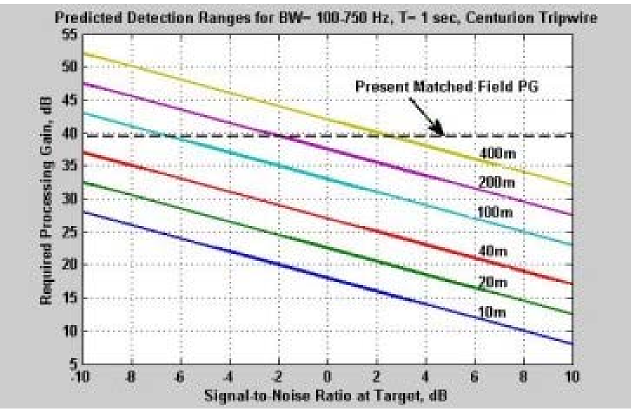


Figure 13. Required and Implemented Processing Gain versus Detection Range and Signal-to-Noise Ratio

Real Time Signal Processing Challenge and Implementation

The real time processing challenge relates to the processing resource requirements:

a. Processing load – the processing load is driven by the dimensionality required for matched-field beamforming; the number of subapertures, water column grid size and resolution, processing frequency band and frequency resolution, and number of hydrophones. To illustrate the magnitude of the processing load, the matched-field beamformer prototyped in MATLAB on a PC with a single CPU required 30 hours to process a 10 minute test data epoch.

b. Working random access memory (RAM) – For real time operation, all constants and variables needed for computation need to be in RAM or cache memory. The steering vectors including the real time program need to fit within total accessible memory.

The signal processing functions implemented in real time are illustrated in Figure 14. The major functional components are a frequency domain beamformer, concurrent far-field and near-field focusing, concurrent spatial split-aperture correlation and sum beam processing, and broadband detection processing.

The multi-threaded processing architecture used to execute and balance the processing operations with multiple processors is illustrated in Figure 15. The quad dual core server computer being used to implement the real time processing is illustrated in Figure 16.

Two performance compromises were made to execute the processing in real time:

a. The original frequency band was reduced by 4:1 and the frequency analysis resolution was reduced by 3:1.

b. The water column grid size which had an XY area of 350 x 400 meters at a 4 meter resolution originally allowed 3 depth layers but was reduced to 1 depth layer.

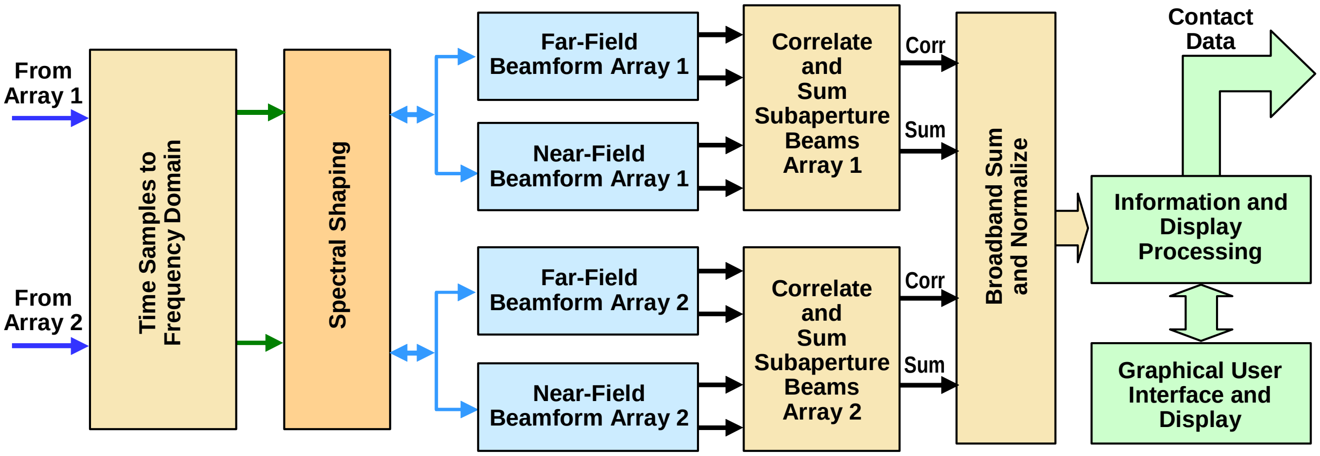


Figure 14. Acoustic Signal Processing Functions

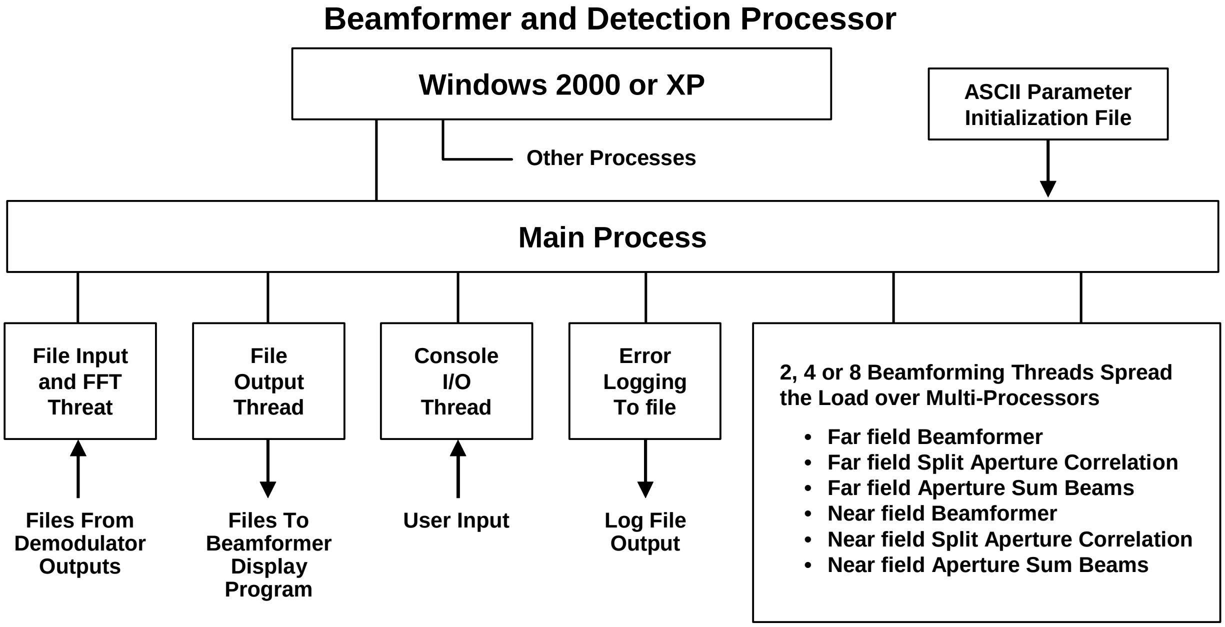


Figure 15. Real Time Software Architecture

Figure 16. Quad Dual Core server computer used for passive signal beamforming and detection processing

Test Results

Over 15 test scenarios were conducted between May and August of 2006, including slow diver delivery boats, go-fast boats, and divers. All recorded data was played back through the real time processor, and detection and tracking results were displayed on sonar evaluation displays. Clear threat detection and tracking was produced for all scenarios with the exception of the closed circuit diver. Although a clear track was not developed for the closed circuit diver (since the diver had a transient signature), several detection hits were observed.

Examples of an open circuit SCUBA diver scenario and a snapshot of the real time sonar displays are shown in Figure 17 and Figure 18. In Figure 18, the detection displays are shown on the leftmost panels. The top left panel is a Bearing versus Time display (BTR) for the far-field beamformer and the diver detection is not evident. The bottom left panel is the matched-field display of the XY cell detections. This snapshot clearly shows the diver being detected at approximately X=35 and Y=45. The right lower panel shows a track history leading up to this snapshot and older track points are faded out. Overlaid on the track plot is a solid line showing the true positional data. The top right panel is a narrowband classification display showing Frequency versus Azimuth (FRAZ), which does not show any narrowband signature components.

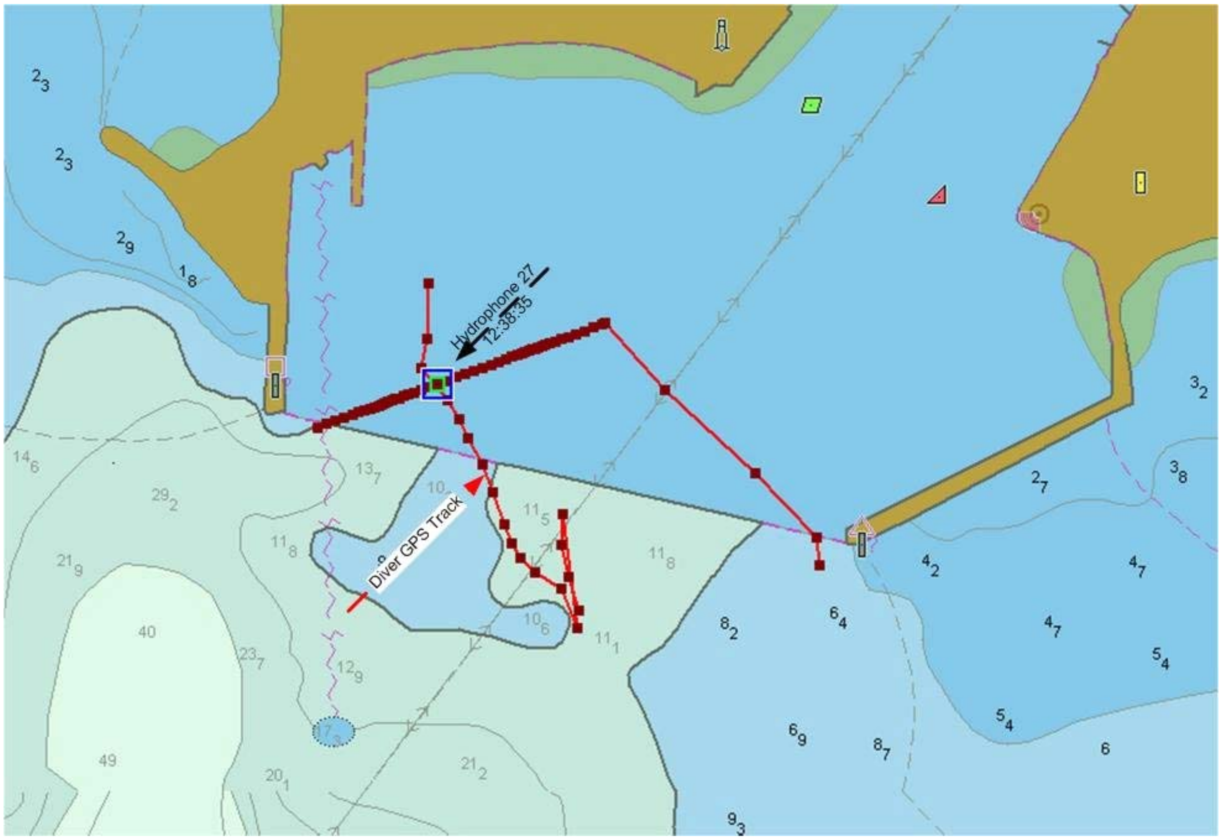
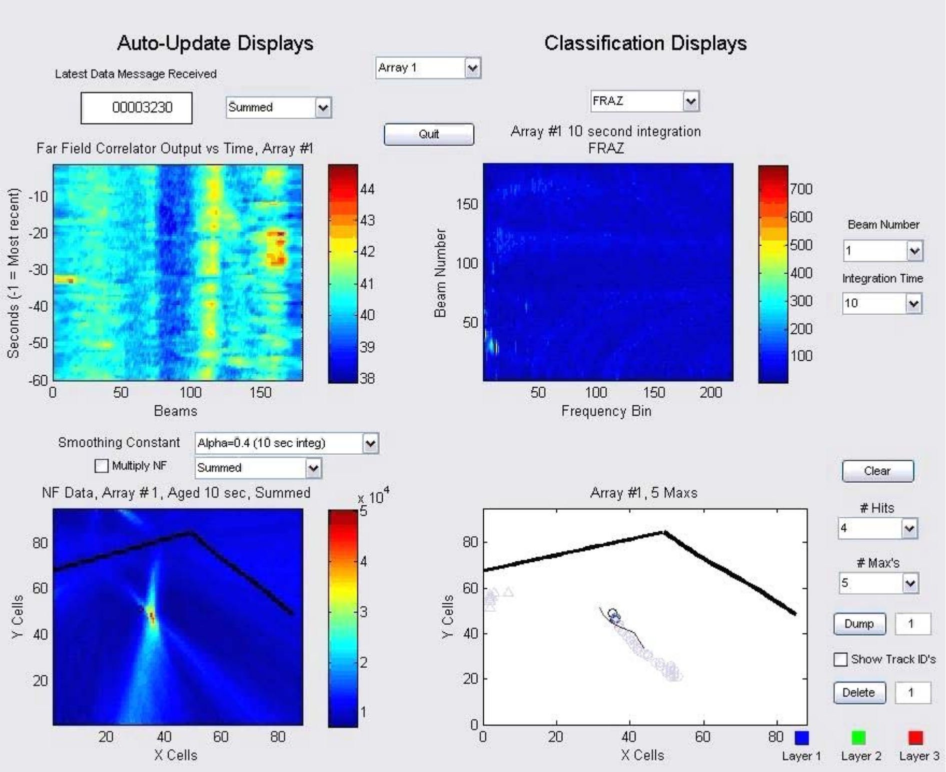


Figure 17. SCUBA Diver Scenario



Latest Data Message Received: 00003230

Array 1

Summed

FRAZ

Beam Number: 1

Integration Time: 10

Smoothing Constant: Alpha=0.4 (10 sec integ)

☐ Multiply NF

Summed

Hits: 4

Max's: 5

Dump: 1

☐ Show Track ID's

Delete: 1

Figure 18. Real Time Passive Sonar Evaluation Displays

Summary

The major results from the Centurion phase two developments are:

- Harbor bottom arrays were shown to passively detect and track low radar cross section surface craft ranging from slow boats to go-fast boats and underwater divers.
- An integrated sensor and C4I approach was defined to provide either a standalone Centurion surveillance system or a sensor system that could be seamlessly integrated with existing harbor surveillance systems such as the Northrop Grumman “HAWKEYE” Harbor Defense System.
- The high computational requirements of the advanced signal processing required for the passive harbor array sensor were shown to be consistent with COTS server computers capabilities.
- The installation of the lightweight FOAS harbor arrays was shown to be consistent with modest size vessels and diver support.

Strategic Programs & Business Development (SP&BD), Navigation Systems Division

One of the main functions of the SP&BD organization is to sustain NSD’s competitive advantage in all of its product lines by providing cutting edge technologies that supply entirely new capabilities to the marketplace and also enhance its current products.

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