A Fresh Look At 'Broadband' Passive Sonar Processing

Robert E. Zarnich
Program Executive Office for Undersea Warfare, Advanced Systems and Technology Office,
PEO(USW) ASTO
Passive Processing Project Officer
2531 Jefferson Davis Hwy
Arlington, VA 22242-5169
zarnichre@navsea.navy.mil

ABSTRACT

Traditional passive broadband sonar processing has been constructed by performing spatial decomposition (beamforming) followed by a temporal filter (Eckart weighting) structured to maximize deflection for signal present while minimizing deflection under noise only conditions. This processing, while approaching optimality in the stationary single signal-stationary noise case, is not well suited for clutter rich environments and spectrally diverse signal sets. Techniques such as the Smoothed Coherent Transform (SCOT) and the PHAse Transform (PHAT) as well as a new ad hoc construction referred to as Sub-band Peak Energy Detection or SPED are finding increased usage in modern sonar systems.

This paper discusses sources of the performance gains over traditional processing. A conclusion that 'Passive Broadband' is fundamentally a Direction of Arrival (DOA) estimation problem is developed from this analysis. Based on this conclusion higher resolution techniques including, Quadratic Spectral Capon and Spectral MUSIC are applied to generate a similar broadband output. A comparison of performance to the Navy’s current Broadband schemes against a common real data set is presented.

1. INTRODUCTION

The submarine is the primary platform from which the Navy conducts Anti-Submarine Warfare (ASW). In that capacity, and in general, the submarine’s greatest ally is stealth. Staying submerged and passively observing the acoustic radiated energy of the surrounding contacts is the preferred mode of operation for the submarine. The Sonar is the eyes of the submarine. In ASW operations in particular, a submarine engaging another submarine, there are no means other than the sonar to observe the target and surrounding area while remaining submerged and preserving stealth.

If the sonar is the eyes of the submarine, ‘Broadband’ is the peripheral vision. It provides what many refer to as ‘Situational Awareness’ and others refer to as ‘Context’. The Broadband display is one that is used by many operators from the Sonar Operator all the way up to the Commanding Officer. It is a display that provides a relative bearing versus time history of the contacts around the sensor. This is important information since it is the only display that immediately provides a reference of the presence of objects and information regarding their relative motion.

Since the introduction of digital sonars, there have been two approaches to broadband in use for over 20 years. They are a traditional square law, or energy detector process, and a split aperture cross correlator. In the past several years two techniques have extended these basic concepts and recently found use in the Navy’s latest Submarine Sonar development. Correlation processing was enhanced via a whitening process developed by Carter et.al. [1], the Smoothed Coherence Transform (SCOT). The energy detector was enhanced with a non-linear peak picking operation for each frequency band over azimuth prior to integration over frequency. This technique is named the Sub-band Peak Energy Detector (SPED) and was original developed by Hughes Aircraft Corporation in Fullerton CA. Although the later of these techniques is an ad hoc approach, upon further analysis one discovers that its roots are in a well researched field, Direction Finding (DF). Based on this discovery application of a basic direction finding technique, Quadratic Capon Spatial Spectral Estimation, (MPDR), to the power accumulation concept of SPED yield interesting results.

2. Passive Acoustic ‘Broadband’

In the functional capacity described here, it would be expected that all contacts would be presented on the display regardless of the type of contact. The azimuthal information is important for surfacing a submarine to periscope depth and therefore screening out fishing boats.
in favor of submarines may not have a desirable effect. Desired attributes of a Broadband Processor might be best defined as:

1) A summary of detectable contacts
2) Precise location in time and Azimuth
3) Intuitive Format
4) Detail not Clutter

For the purposes of this paper we will define Clutter as a contact the masks another otherwise detectable contact on the broadband display. Detail would be best described as high resolution.

2.1 Traditional Energy Detection Based Broadband

Figure (1) outlines the general approach to the second-generation passive broadband. It is referred to as second generation since the first generation broadband was processed on an analog system and this approach was subsequently realized on a digital system, hence second generation. Beamforming is either conventional or adaptive. (Although in the first and fielded submarine sonars it was a conventional time delay and sum approach.) The beams are steered such that the beams overlap at approximately their half power. Spectral Weighting is comprised of time to frequency transformation, magnitude squaring, and a weight chosen as prescribed in Eckart [2]. Spatial Normalization is a split window normalizer. This process scales measured spatial power value to a normalized distribution expected by the requantization process. The Non-Linear Requantization maps the power values to a reduced dynamic range while retaining a marking density on the display that is sensitive to levels above expected noise while not being over driven by strong signals. The mapping is chosen based on empirical historic data.

This processing as discussed in [2] and other classic works is developed for single signal detection, of known spectral content, in the presence of a known noise field. Unfortunately the noise field is neither fixed in time or in space over any large time interval. Based on experience and empirical data the presumption that the signal and noise spectra is known and fixed is not well founded. To realize this consider the earlier observations that observing surface craft is equally as important under different operating conditions as detecting and tracking submarines during ASW operations. Therefore, although the process is developed as an optimal one, it is ill posed for the requirements of a Broadband Processor as outlined in 2.0.

2.2 Current Broadband

In the past decade with the advances in computing resources available to implement sonars more elaborate schemes have been formulated and two have found success. The SCOT whitened split aperture correlator and the SPED algorithms as discussed earlier are two of those. Both of these algorithms have matured through application on various arrays over a variety of frequency bands. The correlation based broadband provides best overall performance during periods of physical non-stationarity such as that seen during own ship turns. SPED provides support for detecting contacts whose broadband signature may not be at minimum detectable levels but contains significant power in temporally narrow spectral components. In this way the two techniques are complementary since the whitening component of the correlation process eliminates these narrow contributions, and the necessary spatial-temporal normalization for proper operation of SPED is difficult during the periods which lack physical stationarity.

2.2.1 Correlation Based Broadband

Figure(2) provides an outline to a generalized correlation based broadband. Of interest is the striking common ground to direction finding. The aperture is separated into two equal sub-apertures. In the current system a beam level adaptive beamformer with 7 degrees of freedom, with a unity gain constraint, a soft mainlobe pattern constraint, diagonal loading, and a weight norm adjustment is employed. Beams are formed with overlap on the order of the 1 dB down intersection. The SCOT whitening algorithm is used [1], and beams with common steering directions are cross correlated with a lead, lag, and no common azimuth delay terms. The resulting correlation scan is up-sampled to smooth the displayed scan and a similar quantization process used.
MacDonald and Schultheiss [3] showed that a split aperture cross-correlation processor was an optimal method for direction finding with broadband contacts under a limited set of conditions. This is an important observation when researching enhanced broadband processing.

2.2.2 Peak Energy Detection

Figure(3) provides an outline to the generalized SPED processing concept. The beamforming has the same characteristics as the beamformer discussed in 2.2.1 however the entire aperture is used. The second stage, Normalization and Peak Picking, de-trends the data across frequency. Sea noise has power greatest at lower frequencies, decreases on the order of 8-10 dB per octave over 1-10 Hz, flattens out over the 10-100 region and decreases 5-6 dB per octave over the 100-100 kHz region for deep-water spectra. Deep water and other noise measurements are discussed in detail in Urick [4] and Burdic [5] along with many others. The de-trending is to prevent any particularly loud band from dominating the accumulated power. The peak picking operation is done over azimuth for each frequency. The maximum number of observable peaks in any given scan is given by the simple expression in equation (1). This is due to the polynomial behavior of the array manifold vector \( v_s \) when evaluating the spatial spectrum. Recall:

\[
V_s = e^{-j2\pi \frac{d}{\lambda_s} \cos(\theta_s)}
\]

and \( d \) is an \( N \times 1 \) vector with the values of the position of the element along the axis of the array, \( \lambda_s \) is the wavelength of the signal of interest, and \( \theta_s \) is the angle of the signal path intersection with the axis of the array as measured from the forward end of the array. When considering the outer product of the sampled data and the steering vector the spatial spectrum has a limited number of modes. The number of wavelengths over the aperture dictates the possible number of observable peaks defined in equation (1).

\[
\text{Peaks} = \left( N \ast \frac{f_{\text{signal}}}{f_{\text{design}}} \right) - 1 \quad (1)
\]

Peak picking identifies the beam and therefore steering angle closest to the true direction of arrival. Fine Bearing Interpolation is done to register the peak in a azimuth grid finer than the one used to create the original beam set. Assuming approximately linear beam power versus azimuth, since beams are highly overlapped, a direction of arrival (DOA) is estimated from the powers of the highest beam and the two adjacent beams and the cell in the grid closest to the DOA estimate is retained as best estimate. Accumulation over frequency is a summing operation. In the current implementation there are two modes. The first retains only the presence of the peak, meaning a one is placed in the cell. This mode is referred to as ‘Clutter Suppress’. The second places the power estimate in the cell in a fashion consistent with traditional energy detection. Both modes are summed over frequency to create a scan in time. Spatial Normalization is similar to that discussed in 2.1 as is the quantization process. The display is then rendered and updated for various integration intervals.

2.3 Observations on Current Techniques.

These techniques were developed through extensive use of real data from fixed and moving arrays. They have proven quite successful. None of the techniques incorporate a frequency-weighting scheme other than the cut off edges. In current implementations there are multiple bands running concurrently. In both methods a common theme of increased precision of DOA estimation exists. The whitened correlation process is optimal under limited conditions for broadband as discussed in [3]. A beam scan peak pick is also optimal for narrowband under limited conditions as discussed in [5]. As alluded to in section 2.0, resolution and acuity are the key elements in making the broadband processing successful when the temporal filtering is an all pass filter.
Since the essence of these processes appears to be the ability to perform direction finding combined with novel approaches to accumulate and summarize the contacts in an intuitive display format it begs the question, what would better Direction Finding provide?

3.0 Direction Finding Based Broadband

Figure(4) represents a general approach to exploit a DF processor followed by a power accumulation scheme modeled after SPED. Van Trees [6] details various approaches to doing the Covariance Estimation as well as the Direction Finding. The classic MVDR result when working with an unknown covariance becomes Minimum Power Distortionless Response (MPDR) and can be used as a direction finding technique. When one evaluates the reciprocal of the quadratic product of steering vector and the inverted Covariance Estimate versus scan bearing, $\theta_{\text{scan}}$, equation (2), the value is proportional to power with a scaling factor of $\frac{1}{N^2}$. This then corresponds to a spatial spectral estimate for the sample period over which the covariance, $R_x$, is estimated. When only the Noise Sub-Space eigenvectors are used the familiar MUSIC algorithm results, however the value is no longer proportional to power.

\[
\text{Power}(\theta) \propto \frac{1}{v^H(\theta)R_x^{-1}v(\theta)}
\]  

(2)

In the form presented [6] refers to this as a member of the Quadratic Spectral Algorithms, specifically the Quadratic Spectral Capon Algorithm. The algorithm estimates the DOA’s as those which maximize $\text{Power}(\theta_{\text{scan}})$. One could choose to invoke a threshold if screening against a minimum SNR. Similarly MUSIC retains the values which maximize the expression for the noise sub-space. The Accumulation over frequency, Spatial Normalization, and Quantization and Display will follow similarly from the SPED outline in 2.2.1

3.1 Prototype DF Based Broadband Implementation

The goal was to construct a DF based approach to Broadband to enhance overall performance while retaining the ability to process through own-ship maneuvers with the capability of the correlator and retain the sensitivity to strong narrowband contacts as in SPED. The design must support the update intervals required of a tactical system. This really means that we can’t simply integrate over any period of our choice since information must be updated frequently to be relevant. Initially, integration periods for $R_x$ were chosen consistent with the integration periods used for the current SPED process. The processing was done on a 48 element linear array. Specific bands of interest and resolutions would make this discussion classified and are omitted.

3.1.1 Estimate the Covariance

The integration time, 5 seconds, chosen initially did not provided enough sample support to guarantee a positive definite estimate so diagonal loading was employed. As a good rule of thumb, [6] suggests that loading greater than the signal of interest and on the order of 10dB less than the loudest interferer provides robust performance. This was used as a starting point and through experimentation settled on in the prototype implementation. To do this $R_x$ is normalized by its trace divided by its rank. This leads to an expected value of the element variance of 1, to which -10dB times an identity matrix is added to the normalized $R_x$. The normalization term is retained as it is needed to estimate the true power along DOA estimates. Eventually an exponentiation time of 20 seconds was arrived at to provide robust performance.

3.1.2 Direction Finding

The Quadratic Spectral Capon (QSC) algorithm and MUSIC were both used. The number of steering directions, over which spatial power estimates were made, chosen was $10^4$. This was reduced by a factor of 2 however the visual effects on the display were not appealing so 481 directions were retained. Many attempts to choose a fixed number of degrees of freedom for MUSIC were made but the results were mixed. At times MUSIC appeared better than QSC but the goal was robust performance so QSC is recommended for this application.

Many effects plague the sub-space techniques such as correlated paths (Multi-Path) which are quite normal in undersea acoustics. Using AIC and MDL for model order estimation dynamically proved to provide poor performance. Since SNRs of targets of interest tend to be low these tests are not very effective. Until better techniques for model order estimation are available it
would appear sub-space approaches for DF would not be viable for problems where the model order is highly variable and signals of interest are small, such as this problem.

### 3.1.3 Accumulate Over Frequency

Both methods discussed in 2.2.2 were used. Almost uniformly the power summing method dominated the performance of the binary approach. This is the recommended method.

### 3.1.4 Spatial Normalization

Although the results indicate that some method of spatial normalization would improve performance, none was done in the interest of time. The normalization process only enhanced an already discernable contact but added a factor of about 15 to the execution time of the prototype algorithm.

### 3.1.5 Quantization and Display

The accumulated power was converted to ‘dB’, using $10\log$ of the spatial power estimate. MATLAB™ imagesc and image commands displays were used to render the results to image shown in 5.d.

### 3.4 Results

Figures (5.a), (5.b) and (5.c) are the SPED, SPED CS and Correlation Broadbands. Figure (5.d) is the 20 second averaged $R_x$ QSC algorithm with power accumulation. Of note is the maintenance of performance through turns, suppression of broadside array noise, and the overall sharpness of the traces. This is just one data set and many more have been used to test the concept. One can see quite clearly the improvement in overall performance in these graphics. The processing is also providing very precise location for some isolated narrowband components that are otherwise collected in weak traces on the SPED broadband.

### 4.0 CONCLUSIONS

Performance enhancements are available through improved Direction Finding based processing. This study indicates there still may be significant room for improvement however more research is required. Several areas to be pursued include the following. A capacity for better subspace estimation would allow a more robust employment of MUSIC as a DF technique for improved closely spaced contact resolution. Integration time extension during periods where the objects retain temporal stationarity, but lack physical (orientation) stationarity is an area which appears to have interesting implications. If longer integration times can be had without the smearing effects in the Covariance, contacts can be detected at reduced SNRs. Additionally resolution can be enhanced through reduced bearing variances, thereby reducing overlap of closely spaced traces on the display. Colorization schemes and other approaches could be exploited to improve the visual presentation as some were explored but are beyond the bounds of this paper.

### 4 REFERENCES


Figure 5.a SPED Clutter Suppress (SPED-CS)

Figure 5.b SCOT Correlation

Figure 5.c SPED Energy Detection

Figure 5.d 20 Second Rx DF Based Broadband