Adaptive Noise Canceling Applied to Sea Beam Sidelobe Interference Rejection

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Abstract—Sidelobe interference has been a source of difficulty in the study of seafloor acoustic backscattering properties based on Sea Beam acoustic records. The filtering scheme used in Sea Beam adversely affects the underlying acoustic return and may also lead to bathymetric artifacts. Adaptive noise canceling (ANC) offers the potential for sidelobe interference cancellation coupled with signal preservation, provided both amplitude and phase information are available. The joint-process deterministic least-squares lattice is the adaptive filter of choice because of its superior transient response in the presence of power discontinuities. A REVGEN simulation of the Sea Beam system provided support for the proposed filtering technique. A complex data acquisition system was designed and built to record the in-phase and quadrature component of Sea Beam returns. Initial ANC processing of these recorded Sea Beam data provided satisfactory sidelobe interference cancellation with no noticeable degradation of the actual bottom returns.

I. INTRODUCTION

IN THE LAST decade, the availability of the Sea Beam bathymetric survey system to the international scientific community has revolutionized the way in which seafloor surveys are conducted. This system combines a hull-mounted narrow beam echo sounder (NBES) with an echo processor (EP) to produce on-line a high-resolution contour map of a swath of seafloor, roughly 3/4 of the water depth in width, for each traverse of the ship. The echo sounder uses a cross-fanned-beam geometry whereby a 7 ms continuous-wave pulse of 12.158 kHz is transmitted on a beam 2.2° by 54°, and bottom echoes are received on 16 electronically steered beams, each 2° by 2.2° and spaced 2.2° apart athwartships (Fig. 1). The echo processor detects and digitizes the echoes received on the 16 beams and performs time and angle of arrival computations to determine depths and horizontal distances on each beam. These bathymetric data are then displayed in near real time as a contour map of the swath of seafloor surveyed. More detailed discussions of the Sea Beam system are available in the literature (11)-(3)).

Although Sea Beam is primarily a bottom mapping tool, its multi-narrow-beam configuration is also well suited for studying the acoustic backscattering characteristics of the seafloor. Previous work with the envelopes of acoustic bottom returns received by Sea Beam has shown that useful information can be gained about seafloor roughness [4]. However, inherent in the multibeam geometry is a sidelobe interference problem in which strong, near-specular echoes entering the main lobe of any one beam are also received through the sidelobes of all other beams (Fig. 2). The Sea Beam echo processor addresses this interference problem through a dynamic thresholding process operating on the detected acoustic envelope samples. A “sidelobe” threshold level is set 12 dB down from the peak amplitude found in the 16 beams at each digitization cycle. Data points falling below this threshold are simply disregarded. Such a filtering scheme, combined with a bottom-tracking algorithm, works well for contour-mapping purposes, although in some instances it is responsible for bathymetric artifacts [3]. However, when bottom return and sidelobe interference overlap, this type of filtering severely degrades the underlying backscattering returns, thus inhibiting the process of extracting additional information, beyond bathymetry, from the Sea Beam acoustic signals. For example, the angular dependence of the backscattered energy may be an important indicator of the seafloor characteristics. Unless a more advanced method of sidelobe interference cancellation is applied, the estimation of this function from Sea Beam data will be incomplete at best [4].

A possible remedy for the Sea Beam sidelobe interference problem is offered by adaptive noise canceling (ANC). The set of circumstances giving rise to the ANC concept as a special case of the general Wiener filtering solution is illustrated in Fig. 3. The primary channel consists of the signal s corrupted by a form of additive noise n0, and the reference channel consists of a process n1 related in some unknown way to the primary noise. The key requirement is that the signal be uncorrelated to both the primary noise and the reference process. Solving the filtering problem in this setting is equivalent to producing the best minimum mean squared error (MMSE) estimate of the primary noise process. The ANC output, obtained by subtracting this estimate from the primary input, will consist of the signal component plus a residual error term. Detailed analysis based on a more specific ANC model and examples of practical applications of this technique are given by Widrow [5].

The same mechanism responsible for creating the Sea Beam sidelobe interference offers the potential for its removal through ANC. Each near-specular beam is a natural reference channel, which can be used to operate sequentially on the remaining 15 beams. Here, the sidelobe interference constitutes the primary noise n0. It is expected to be highly correlated with the main lobe return of one near-specular beam which represents the reference noise process n1. On the other
hand, this return is uncorrelated with the primary backscattered return received through the main lobe of all other beams. Thus, the basic ANC requirement is met and one may expect the adaptive algorithm to cancel the sidelobe interference from the primary channel by compensating for the differences in spatial transfer function between the two channels. An estimate of the main lobe backscattered return, representing the "signal" component $s$, will be produced at the filter output.

II. THE LEAST-SQUARES LATTICE FILTER

In ANC applications reported to date, the least mean squares (LMS) filter [5] has been almost exclusively used as the central adaptive processor. Joint-process filters of the lattice type have been known to possess significant operational advantages over the direct tapped-delay-line (TDL) implementations, such as the LMS, in adaptive channel equalization and frequency-tracking situations [6], [7]. It has recently been
shown [8] that the lattice advantages extend to the noise-canceling configuration. The "exact," deterministic least-squares lattice (LSL) [9] in particular was found to be superior to both the LMS and lattice filters of the gradient type during abrupt changes in the signal statistics. Because of the transient nature of the sidelobe interference "ridge," the LSL (Fig. 4) was chosen for the current application. The lattice parameters $k_i^+$ and $k_i^-$ are known as the reflection or partial correlation coefficients. The $e_i(n)$ and $r_i(n)$ are the $i$th order forward and backward prediction error sequences, respectively. The $r_i(n)$ constitute an orthogonal basis for the reference process $x(n)$ and are weighted by the cross-channel coefficients $k_i^q$ to produce an estimate of the primary process $d(n)$. The parameter $\alpha_{LSL}$, bounded by [0, 1], controls the time constant of the filter's exponentially decaying memory. Large values of $\alpha_{LSL}$ imply short time constants (i.e., fast adaptation).

The scalar, complex, joint-process, exponentially weighted "prewindowed" LSL algorithm is summarized as follows:

Initialization ($i = 0, 1, \cdots, p$)

\[
\begin{align*}
E_i^e(-1) &= e_{LSL}, \quad e_{LSL} = 0.001 \quad \text{and} \quad i \neq p \\
\Delta_i(-1) &= 0, \quad i \neq 0 \\
\gamma_{i-1}(-1) &= 0, \quad i \neq p \\
k_i^q(i-1) &= 0.
\end{align*}
\]  

Time update ($n \geq 0$)

\[
\begin{align*}
e_0(n) &= r_0(n) = x(n) \\
E_i^e(n) &= E_i^e(n) - (1 - \alpha_{LSL})E_i^e(n-1) + |x(n)|^2 \\
\gamma_{i-1}(n) &= 0 \\
e_i^d(n) &= e_i(n) + k_i^q(n)r_{i-1}(n-1), \quad i \neq p
\end{align*}
\]

Order update ($i = 0, 1, \cdots, p$)

\[
\begin{align*}
\Delta_i(n) &= (1 - \alpha_{LSL})\Delta_i(n-1) - \frac{e_{i-1}(n)r_{i-1}^*(n-1)}{1 - \gamma_{i-2}(n-1)} \\
k_i^q(n) &= \Delta_i^q(n)/E_i^e(n-1), \quad i \neq 0 \\
k_i^p(n) &= \Delta_i(n)/E_i^e(n-1), \quad i \neq 0 \\
e_i(n) &= e_{i-1}(n) + k_i^q(n)r_{i-1}(n-1), \quad i \neq p \\
r_i(n) &= r_{i-1}(n-1) + k_i^p(n)e_{i-1}(n), \quad i \neq p \\
E_i^e(n) &= E_i^e(n-1) - |\Delta_i(n)|^2/E_i^e(n-1), \quad i \neq 0 \\
E_i^f(n) &= E_i^e(n-1) - (1 - \alpha_{LSL})\Delta_i^f(n-1) - \frac{e_{i-1}(n)r_{i-1}^*(n)}{1 - \gamma_{i-1}(n)} \\
\gamma_{i-1}(n) &= \gamma_{i-2}(n) + |r_{i-1}(n)|^2/E_i^e(n-1), \quad i \neq 0 \\
\Delta_i^q(n) &= (1 - \alpha_{LSL})\Delta_i^q(n-1) - \frac{e_{i-1}(n)r_{i-1}^*(n)}{1 - \gamma_{i-1}(n)}
\end{align*}
\]

The feasibility of the proposed ANC procedure was tested through a computer simulation involving REVGEN (REVerberation GEnerator) [10], a high-fidelity sonar simulation program developed at the Applied Physics Laboratory (APL) of the University of Washington. REVGEN is a direct software implementation of the point-scattering model of reverberation. Returns from a large number of discrete scatterers, distributed randomly through the volume and the boundaries, are summed coherently at each receiver to obtain a synthetic reverberation time series. The REVGEN output consists of the complex-basebanded reverberation signal. Scattering layers, platform trajectories, attenuation and reflection losses, arbitrary multiple transmitting and receiving beam patterns, and transmitted signal type can be specified through appropriate REVGEN parameters. We have used REVGEN to perform a realistic simulation of the Sea Beam system in which all known system parameters, including beam patterns, have been preserved [11]. A total of four receiving beams was deemed sufficient for the purposes of the test and a flat seafloor was assumed. The synthetic Sea Beam data show ample evidence of the sidelobe interference problem (Fig. 5(a)). Next, the three outer beams were processed through the joint-process LSL filter, with the down-looking beam serving as the reference channel. As shown in Fig. 5(b), the sidelobe interference is effectively removed with no evidence of distortion in the remaining signals.

In order to make possible the application of this technique on acoustic data obtained from the Sea Beam system, a data acquisition system capable of recording the entire complex acoustic signal was designed and built at the Marine Physical Laboratory (MPL) of the Scripps Institution of Oceanography (SIO).

A. Complex Acoustic Data Acquisition System

The acoustic data acquisition system is designed to operate in parallel with the Sea Beam system without interfering with its normal bathymetric function. This parallel system is built around a DEC LSI-11/73 processor with 2 megabytes of memory [12]. It is fully transportable and has been used
successfully aboard three different ships equipped with Sea Beam: SIO's R/V Thomas Washington, the French oceanographic vessel Jean Charcot, and the R/V Atlantis II of the Woods Hole Oceanographic Institution.

As seen in Fig. 6, coupling between the acoustic data acquisition system and Sea Beam is done in the NBES for the 12.158 kHz clock signal, in the EP for signals from the 16 preformed beams and the sonar key, and from the gyroscope junction box for roll signals. To minimize interference between the two systems, all these signals are either capacitively coupled or taken in as high-impedance differential inputs. Because the Sea Beam system transmits a 7 ms pulse of 12.158 kHz, the resulting bottom-echo signals are essentially band-limited so that quadrature sampling can be used. This requires a minimum of hardware provided one uses a sampling frequency which is an integer submultiple of the carrier frequency. As shown in Fig. 7, the signals taken at the output of the beamformer go through a bandpass filter and are multiplied by a digital time-varying gain (TVG) to compensate for acoustic transmission losses through the water column. At the next stage, two sets of 16 sample-and-holds are used to perform the quadrature sampling. The first set is triggered by a clock pulse at 12.158 kHz, and the second set is triggered by the 90° phase-delayed version of this pulse. This method ensures simultaneous sampling of all 16 channels for each phase component. The outputs of the sample-and-holds are
then low-pass filtered in a band 250 Hz wide and sampled at 1/12th of the reference frequency, yielding 16 pairs of in-phase (I) and quadrature (Q) components of the original beamformed acoustic signals.

At present the data acquisition software is configured to digitize and record the I and Q components of Sea Beam's 16 beams at a rate of approximately 1 kHz per channel (32 channels). A 33rd channel is dedicated to roll signals and is sampled in sequence at the same 1 kHz rate for ease of operation of the analog-to-digital converter. These data are recorded on standard 9-track 2400 ft magnetic tapes at 3200 BPI. Depending on the length of the digitization window, typically 0.8 s for water depths to 2000 m and 1.4 s beyond, a tape holds between 900 and 1400 pings.

This data acquisition system was tested for the first time in December 1985 aboard the R/V Thomas Washington during a cruise across the equatorial Pacific and subsequently used in June 1986 aboard the R/V Jean Charcot during a survey in the northeastern Pacific. In the following, we present data samples from both cruises.

B. Processing Results

As a first step, segments of recorded complex Sea Beam data were subjected to a series of validation tests. Periodograms were produced which showed a consistent spectral behavior, with a signal bandwidth of the order of an inverse pulse length. No signs of aliasing were evident. The I and Q channels for each beam were uncorrelated and the phase displayed a uniform random behavior. Nonzero beam to beam correlation was solely due to sidelobe interference components. In all, the tests showed the signals to be valid complex reverberation records, indicating that the quadrature sampling scheme is functioning properly [12].

Following the validation tests, a large number of randomly selected Sea Beam records were inspected for evidence of sidelobe interference and were subjected to ANC. The interference structure was found to vary considerably between different seafloor regimes. The most common form arises when the seafloor is flat and highly reflective, in which case a single sidelobe interference ridge is observed well removed from the main scattered return in the outer beams but gradually merging with the seafloor return in the interior beams. The relative level of the interference varies with the reflectivity of the bottom. A typical record of this type is shown in Fig. 8(a). The filter output for $p = 2$ and $\alpha_{SL} = 0.002$ is shown in Fig. 8(a). Starboard beam 1 was used as the reference channel. It can be seen in Fig. 8(b) that the sidelobe interference spike is greatly suppressed but not completely eliminated. This is due to the fact that, owing to Sea Beam geometry, there are usually two neighboring near-specular beams. As a result, a second pass through the filter is often needed. The output of the second filter pass, this time with port beam 1 as the reference,
is shown in Fig. 8(c). The sidelobe is suppressed further, with no evidence of distortion in the remaining scattered returns.

When the seafloor has a complex structure, multiple near-specular reflections, resulting in multiple interference ridges, are possible. A case in point is the record shown in Fig. 9. Several strong near-specular returns result in multiple interference ridges. This type of interference requires a cascade of filter runs. In this case, a two-stage cascade LSL run was made which resulted in the cancellation of the two more prominent interference features. The usefulness of cascade processing is ultimately limited by the cumulative effect of the error introduced at each cancellation stage. Note that in Fig. 9, beam number 4 on starboard and beam number 2 on port are invalid due to hardware malfunction in the data acquisition system, and were not taken into account in the processing.

When relatively steep slopes exist on the flanks of the Sea Beam swath it is possible to have the sidelobe interference ridge overlap with the main scattered return, even in the outer beams. This is one of the most severe types of interference, as the sidelobe rejection method used in Sea Beam cannot differentiate between bottom return and sidelobe interference and indiscriminately eliminates both. One such record and the corresponding filter output are shown in Fig. 10. It appears the backscattering signal previously masked by the interference ridge is recovered, although it is not possible to assess the degree of distortion it may have suffered in the absence of "ground truth" information.

In order to offer some insight into the operation of the LSL filter, the "likelihood" parameter $\gamma$ has been plotted together with the primary, reference, and output channels for starboard beam 8 of the same record (Fig. 11). It can be shown ([9]) that $0 \leq \gamma \leq 1$. This parameter can be expected to be approximately zero except when the signal statistics undergo drastic changes, in which case it will approach unity. Note that in the LSL recursions, the "crosscorrelation" coefficients $k_{ij}$ are weighted by a gain factor equal to

$$\frac{1}{1 - \gamma_{i-1}}$$

Therefore, when $\gamma_{i-1}$ approaches 1 the algorithm will undergo fast, almost instantaneous, adaptation. It is the presence of this optimum gain factor that sets the LSL apart from suboptimum gradient approximations and results in its superior transient response. In Fig. 11(c), the likelihood parameter is shown to quickly approach unity as the sidelobe interference sets in. This fast transient response results in the elimination of the interference component from the filter output (Fig. 11(d)).

These examples are typical of a large number of cancellation runs performed on recorded complex Sea Beam data. Overall, filter performance was remarkably consistent. It appears that a low-order LSL filter ($p \leq 3$) is adequate for this application. The filter showed relatively little sensitivity to the choice of adaptation coefficient $\alpha_{LSL}$ in most cases. This is understandable because the onset of the specular return to a reference beam far outweighs any "memory" of past values. Another factor controlling filter memory is the initialization of its coefficients. Low initial power estimates coupled with a
relatively large $c_{LSL}$ often lead to filter instability. A robust initialization method must be devised before the cancellation technique can be safely applied on a large scale. Another concern in this regard is algorithm speed. We have programmed three different versions of the LSL, in Ratfor, C, and APAL, the native language of the FPS-5205 array processor. A substantial speedup factor was achieved with the array processor (approximately 15) over the original Ratfor version, making possible the efficient postprocessing of large segments of complex Sea Beam data. It currently takes approximately 30 s to process one 16-beam Sea Beam record. Finally, the surprising diversity of sidelobe interference types creates the need for potentially complex decisions regarding the choice of reference beams and the number of cancellation runs appropriate for each Sea Beam record. We are currently in the process of implementing such a decision-making scheme.

IV. SUMMARY

An adaptive noise canceling technique involving the joint-process deterministic least-squares lattice filter was for the first time applied to Sea Beam data recorded with a complex acoustic data acquisition system designed and built at MPL. The REVGEN simulation of Sea Beam proved highly realistic in predicting filter performance. Initial ANC processing results for recorded complex Sea Beam data indicate that the technique is effective in removing the sidelobe interference without degrading the underlying bottom return. This result also makes it possible to analyze the bottom returns received on individual beams of a multibeam sounder to extract information about the acoustic backscattering properties of the bottom.

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REFERENCES


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