
TITLE	Environmentally Adaptive Noise Estimation for Active Sonar
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1 Problem statement

The estimation of background noise statistics is fundamental to the automated processing and visualisation of sonar data. The distribution of noise in sonar data is highly variable, both in the spatial and temporal domains. Sonar data invariably contain a number of signals of interest (some of these may be broadband signals), which often represent a significant percentage of the available data. The overall aim of sonar data analysis is to separate the signals of interest from background noise and other environmental effects. To achieve this, a threshold value is chosen and only those signal components which exceed the threshold are preserved. The choice of threshold is critical; if the threshold is too high, weak but important signals might be discarded; if the threshold is too low, noise is likely to remain in the data, making further data processing more difficult.

Thus there is a need to develop adaptive techniques for estimating optimal thresholds for real-time sonar data processing, based on statistical analysis of the background noise distribution. There is continued interest, both in industry and the MoD, in environmentally adaptive sonar systems, since much of the background noise observed in sonar data can be linked to features in the environment. Another area of current interest is in the impact of active sonar systems on marine mammals. The hope is that improved analysis of sonar data will enable the use of less powerful signals, resulting in more environmentally friendly systems.

2 Background

Active sonar uses a sound transmitter and one or more receivers. A pulse of sound, called a *ping*, is transmitted into the water, and receiver(s) listen for reflections (echoes) of the pulse. When active sonar is used, scattering occurs from small objects in the sea as well as from the bottom and surface, creating an effect called reverberation. This can be a major source of interference, and can increase the probability of false alarm. Several hydrophones are used to measure bearing. By applying an appropriate time delay to the time series data for each hydrophone, a beam can be formed in a particular direction.

The target signal, if present, together with noise are first passed through a signal processing algorithm; typically this includes a matched filter for an FM pulse. FM pulses produce amplitude data in range and bearing, with good resolution in range. This gives highly structured echo returns and these may allow the possibility of resolving the different paths taken by the sound through the water. These include reflections from the sea surface and

bottom. The propagation of the sound through the water will be affected by the speed of sound profile, which in turn is affected by the depth and temperature of the sea water through which the sound is travelling. For paths reflecting from the sea surface and bottom, the effect on the received echoes can be significant. After the signal processing algorithm is applied, the data is normalised to remove long-term trends, and a detection algorithm, typically thresholding, is applied. The detections are then clustered. Parameters are calculated for each of the clusters, and non-target-like clusters are removed using a cluster shape recognition algorithm. The cluster positions are then passed to a tracking algorithm.

The estimation of the background noise statistics is fundamental to both the automated processing of sonar data and the visualisation of the sonar data by the operator. Sonar data background noise is generally highly variable in both amplitude and in the parent distribution, and such variation occurs in both the spatial and temporal domains. In addition, there are likely to be a number of signals of interest in the observed time series data.

3 Noise estimation

In active sonar, the time series under investigation is the output of a matched filter, obtained as the cross-correlation of the received echo with a copy of the reference signal (ping). A peak in the matched filter output indicates a high correlation between the received echo and the reference signal in the corresponding range cell, and thus suggests the presence of a reflecting object. The fundamental objectives are to simultaneously maximise the probability of detection (PD) and minimise the probability of false alarm (PFA).

To isolate peaks we apply a *threshold* to the matched filter output – only points above the threshold value are retained. The choice of threshold is critical: if the threshold is too high, small but important features might be discarded, while if the threshold is too low, too much noise will remain in the data, making further data processing more difficult. To compute a useful threshold, we must estimate the statistical properties of the underlying noise distribution, for example its mean, variance, skewness and kurtosis. We are also interested in computing confidence intervals for such estimates.

Because targets are often large (relative to the wavelength of the transmitted pulse) and irregularly shaped, a single target is likely to produce a cluster of peaks in the matched filter output. A suitable *cluster analysis* algorithm is therefore used to identify clusters. Clusters are then passed to a shape recognition (classification) system, to decide whether or not a given cluster in the matched filter output corresponds to a target. As well as choosing suitable detection thresholds, we propose that estimates of the noise statistics could be used to improve the cluster analysis and classification steps. For example, it could be that a certain noise distribution produces clusters of a certain type with certain regularity – such clusters might be called *artefacts* of the noise distribution. If the noise distribution is known or accurately estimated, a statistical method of reducing the false alarm rate while retaining the same probability of detection can be developed. To our knowledge, a classification scheme based on noise parameters, especially ones that estimate and adapt to the propagation conditions in the local environment, is a novel approach in sonar data analysis. Another possible area of research would be to investigate whether the estimated noise parameters can be used to estimate the probability of false alarm.

While we are interested in estimating the noise distribution over a single transmission, correlations between both adjacent beams (spatial correlation) and successive time series (corresponding to successive pings) should also influence the noise estimation process. In particular, certain features of the marine environment will persist across a number of transmission cycles. Thus we are interested to see whether environmental models can be used to improve the noise estimation process. For example, we could use ray-tracing algorithms to predict the multi-path, and hence predict the corruption of a point source due to the environment (this will introduce correlation into both the signal and noise, and hence influence the noise distribution). Furthermore, the fact that sound travels slowly in water means that only a small number of previous transmissions (pings) are likely to be relevant at any given time. It is also possible that the noise distribution could vary significantly from one transmission to the next – this is in addition to the noise being non-stationary as a function of range.

Difference methods

Let $z_t = s_t + r_t$ represent the data where z_t is the observation sequence, s_t is the signal of interest and r_t is the noise sequence. We define $\gamma_t(k)$ to be the *difference product*

$$\gamma_t(k) = (z_t - z_{t-k})(z_t - z_{t-2k})$$

and $\Gamma_W(k)$ to be the sample mean of the $\gamma_t(k)$ over the window $W = [t_{\min}, t_{\max}]$,

$$\Gamma_W(k) = \frac{1}{|W|} \sum_{t \in W} \gamma_t(k)$$

If the signal s_t is smooth and the sampling frequency is sufficient to ensure that s_t is approximately linear over the interval $[t - 2k, t]$, it can be shown that

$$\Gamma_W(k) \approx \langle r_t^2 \rangle_W - \langle r_t r_{t-2k} \rangle_W + 2k^2 \langle s_t'^2 \rangle_W - 3k^3 \langle s_t' s_t'' \rangle$$

where $\langle \cdot \rangle_W$ represents a sample mean taken over the window W while s_t' and s_t'' are respectively the first and second derivative of the signal at time t . If the noise distribution is not (approximately) stationary over W , the sample mean $\langle r_t^2 \rangle_W$ can be thought of as the ‘average’ second moment of the noise distribution over the window.

Let k_{\min} be the smallest k for which $\mathcal{E}(r_t r_{t-2k}) = 0$, i.e. k_{\min} is the location of the first zero of the noise autocorrelation function ($k_{\min} = 1$ for white noise), and let k_{\max} be the largest k for which $s_t - s_{t-2k} \approx 2k s_t'$, i.e. k_{\max} is the point at which the approximate linearity of the signal breaks down. If $k_{\min} < k_{\max}$ then

$$\Gamma_W(k) \approx \langle r_t^2 \rangle_W + 2k^2 \langle s_t'^2 \rangle_W \quad \text{for} \quad k_{\min} \leq k \leq k_{\max}$$

Thus $\Gamma_W(k)$ scales linearly with k^2 in the interval $[k_{\min}, k_{\max}]$, with constant term equal to the sample moment $\langle r_t^2 \rangle_W$ computed over the window W . In practice, the interval $[k_{\min}, k_{\max}]$ is chosen by identifying an approximately linear region in the plot of $\Gamma_W(k)$ against k^2 . Simple linear regression can then be used to estimate the limit of $\Gamma_W(k)$ as $k \rightarrow 0$, which provides an estimate for $\langle r_t^2 \rangle_W$. In essence, we attempt to eliminate the signal s_t from the observation sequence z_t , by exploiting its local linearity to estimate the limit of the difference product $\gamma_t(k)$ as the signal differences $|s_t - s_{t-k}|$ and $|s_t - s_{t-2k}|$ decrease (approach zero). The sample moments $\langle r_t^3 \rangle_W$ and $\langle r_t^4 \rangle_W$ of the noise distribution can be estimated similarly, using 3-fold and 4-fold difference products respectively:

$$\begin{aligned} \gamma_t^{(3)}(k) &= (z_t - z_{t-k})(z_t - z_{t-2k})(z_t - z_{t-3k}) \\ \gamma_t^{(4)}(k) &= (z_t - z_{t-k})(z_t - z_{t-2k})(z_t - z_{t-3k})(z_t - z_{t-4k}) \end{aligned}$$

The success of this approach depends on a number of very favourable conditions. One aim of the research project is to see whether these ideas can be extended to overcome some of the difficulties encountered in sonar data analysis. Principal among these is that the signal of interest is a cluster of peaks rather than a smoothly varying sequence, so alternative methods of eliminating the signal before estimating noise parameters must be investigated. Furthermore, the noise distribution is highly variable across the time series, with short ranges dominated by reverberation and long ranges dominated by ambient noise (sea-bed clutter can appear at almost any range). We remark that for non-stationary noise, the choice of window size is critical. If the window is too small, there are insufficient data to compute reliable estimates of the distribution parameters, particularly the higher order statistics. If the window is too large then the noise distribution might itself vary considerably over the window.

4 Study Scheme

In the first year, it will be necessary for the student to develop a good understanding of modern techniques in statistical signal processing and data analysis, including cluster analysis, multiresolution analysis, Hidden Markov

Models, methods for fitting statistical distributions to data, and a number of classification and other machine learning algorithms. The student will also need to become familiar with the current techniques for normalisation and detection in active sonar. This will require a review of the literature and implementation of some of the more popular normalisation techniques. These techniques can then be applied to simulated data and to real data, or data whose statistics are calculated from real data. Thales can provide either real data or the information to generate realistic data.

For the remaining two years, the student will develop techniques that can improve current techniques for normalisation and detection in active sonar. It will be necessary to have algorithms that can work in either noise limited or reverberation limited environments and which can provide information to downstream algorithms about the type of environment. The data used for the normalisation need not be restricted to data collected from just one ping, and data from previous pings can be used to estimate parameters or choose an appropriate algorithm for the environment. Geographic information about the local environment e.g. from a database, may also be used. The use of this information could make the algorithms applicable in shallow water or coastal regions where active sonar often performs poorly due to the high reverberation level.

It is proposed to investigate these topics by the adaptive estimation of noise parameters. One approach is to extend the differences methods outlined above. The effects of the environment on this model are of interest, particularly the temporal variations that could be observed. For active sonar much of the clutter observed in noise could be related to seabed features hence spatial coherence in the estimation of the parameters defining the distribution to which the data may belong could also be exploited. The model may be different for each environment, for example in deep and shallow water. Change points from one model to another may therefore need to be identified.

The recent introduction of wide band processing for FM pulses has enabled processing to be carried out on a several different frequency sub-bands. The study should also lead to the development of algorithms that can improve detection within each sub-band, and across sub-bands. If a sub-band processing strategy is adopted then traditionally the noise estimation process would be applied independently to each sub-band. Since the behaviour of the attenuation of the transmission could obey a reasonably well understood frequency dependent attenuation law, we could exploit such prior knowledge and estimate the noise statistics using information from across all sub-bands.

Any algorithms developed for this study should be tested with real data, which can be analysed by the student when he/she is at a Thales site.

5 Benefits To Thales Underwater Systems

The development of better normalisation and detection algorithms in active sonar will enable Thales to detect lower SNR targets, and have more information about the noise environment in which the signal is being detected. This will enable cluster shape recognition and tracking algorithms to be modified to better track targets in different noise environments.

6 Requirements

The nature of the research topic and the analysis of restricted data supplied by Thales will require that only UK nationals be considered.