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Improved noise tolerance for sonar applications in critical environments

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Abstract *– Sonar systems are a key element in Harbor Security applications. One of the major challenges in their utilization is the presence of high levels of noise and clutter. In this paper, we analyze the distribution of errors in the time-delay estimation for a sonar system using a train of pulses and show that a robust fusion of echoes from multiple pings can greatly improve its resilience to noise. As a result, an increased range of operation can be achieved in applications to extremely noisy environments such as harbors, ports and costal facilities.*

Keywords *– sonar, accuracy, detection, noise tolerance*

I. INTRODUCTION

One of the biggest challenges in Harbor Security is the ability to continuously monitor a large area in the presence of constantly changing environmental conditions. Specialized sonar systems are being successfully developed for this purpose. However, the ability of sonar to detect objects is strongly influenced by the operating signal-to-noise ratio (SNR). As sound amplitude decays very fast in water this sensitivity reduces the effective sonar range. It is well known that the range accuracy decays for increasing levels of noise until a breakpoint is reached after which accuracy deteriorates by several orders of magnitude. We present a robust fusion of time-delay estimates from multiple pings that significantly reduces the SNR corresponding to the accuracy breakpoint. We analyze the signal-to-noise breakpoint, studying the probability of choosing the correct peak from the noisy cross-correlation function with a method similar to the one in [1], where the threshold effect was related to the existence of highly probable outliers far from the true time-delay value. This will enable us to extend the result to the case of multiple pings without a priori knowledge on the time-delay itself. This approach is different from that used in previous work on the multiple pings and single echo case [2, 5], where the multiple echoes for a single object are obtained artificially via multiple receivers and a unique ping. In fact, the bounds found in [2, 5] are valid only if the noise at the different receivers is totally uncorrelated or if the distance between transducer and receiver is constant, both conditions difficult to realize in practice. The proposed fusion of multiple pings has the potential of improving the resilience to noise of a sonar system, hence, increasing its potential range of operation and its applicability to extremely noisy environments such as harbors, ports and costal facilities.

II. METHODOLOGY

We developed a set of Monte Carlo simulations using a cosine packet. We first analyzed the histograms of the errors in the delay estimate of the ideal receiver for different SNR's (figure 1). For high SNR (≥20dB) all the errors are small and follow the Woodward equation that corresponds to values within the central bin in figure 1a. As the level of the noise increases, large errors in the estimates appear. The errors are uniformly distributed over the entire a-priori window, and the relative ratio between the correct estimates (central bin) and the level of the uniform distribution decreases with SNR (figures 1b, 1c, and 1d). However, even for high levels of noise the central peak is significantly larger that the rest of the distribution.

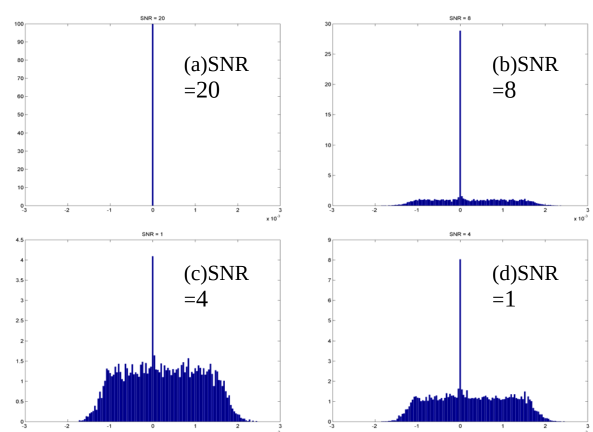

Figure 1 – Histograms of the errors in the delay estimate in a Monte Carlo simulation for different SNR's. For high SNR (≥20dB) all the errors are small and follow the Woodward equation that corresponds to values within the central bin in figure (a). As the level of the noise increases, large errors in the estimates appear. The errors are uniformly distributed over the entire a-priori window, and the relative ratio between the correct estimates (central bin) and the level of the uniform distribution decreases with SNR, see figures (b), (c), and (d). However, even for high levels of noise the central peak is significantly larger that the rest of the distribution.

Figure 2a shows the performance of ideal receiver for a single ping. For high SNR the accuracy follows the Woodward equation corresponding to a coherent ideal as expected from the theory of optimal receivers. The performance breaks for low SNR around 17 dB. Figures 2b, 2c and 2d show the analysis of the accuracy breakpoint for different number of pings, 10, 50 and 100 respectively.

The blue line describes the optimal accuracy that can be achieved using cross-correlation from multiple pings. Its breaking point represents the optimal breaking point that could have been achieved using stationary sonar and target, and that could be predicted by using the Barankin bound as in [6, 9]. This breaking point however is not attainable, as it relies on careful registration of returns from different pings. Such careful registration can only be done if the distance between object to target is kept constant, or if it is known for each ping in advance. It can be seen that robust fusion of multiple pings based on the mode (light blue, and magenta lines) improves noise resiliency while retaining close to optimal achievable accuracy under multiple pings. In general there is no significant improvement in the resiliency to noise when a simple mean of the observations is used due the strong contamination of the distribution from outliers (red lines).

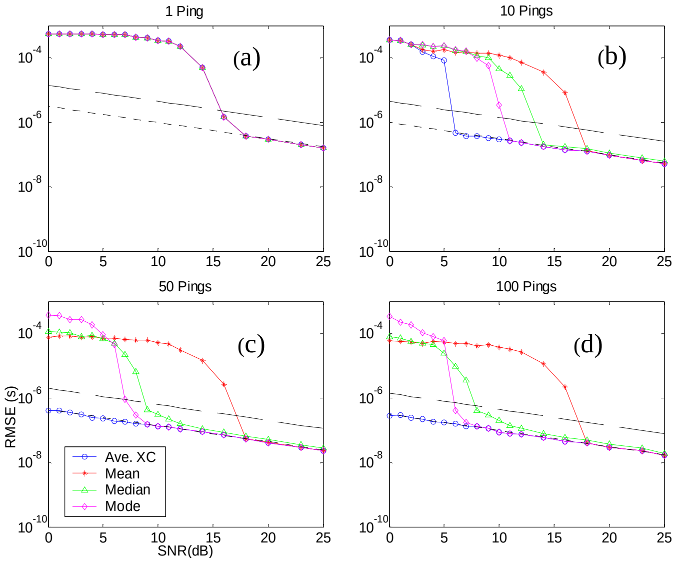

Figure 2 – RMSE as a function of SNR and number of pings – 1, 10, 50 and 100 respectively – for the Cosine Packet. Notice how the SNR breakpoint for the average of multiple pings (red line) does not decrease with the number of pings.

Figure 3 shows a summary of the results for different methods. The breakpoint for the averaged cross-correlation function (blue squares) follows the ideal curve obtained by reducing the level of the noise (solid blue line) as described above. The breakpoint of the estimate obtained from the mean does not substantially change as the number of pings in increased. A more robust statistics such as the median improves the resiliency to noise as the number of pings increases (green triangles). The best results are obtained by using the mode of the estimates from the multiple pings (magenta diamonds).

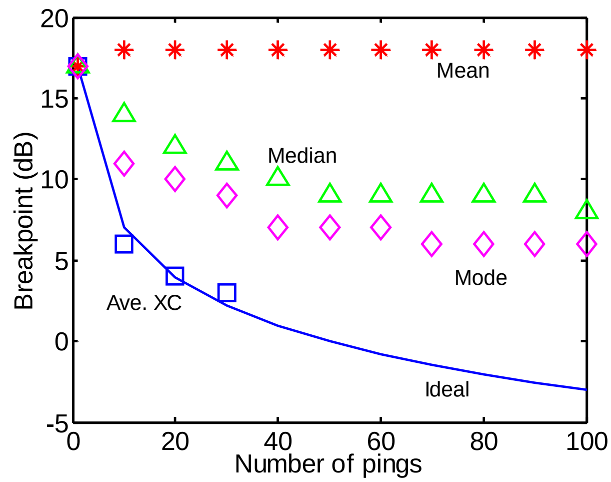

Figure 3 – Breakpoint in dB as a function of number of pings for different methods. The solid line corresponds to the ideal case of noise reduction by averaging the echoes.

III. CONCLUSIONS

We have shown that multiple pings are useful for improving the accuracy and in particular the resilience of time-delay estimation to background noise. In particular a robust statistics such as the mode of the distribution of echo delays which is obtained from multiple pings, significantly decreases the signal-to-noise ratio breakpoint. We have further shown that the mean of this distribution has the same breakpoint as a single ping, thus not contributing at all to the resilience to noise.

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