WIDEBAND ACTIVE SIGNAL PROCESSOR PERFORMANCE IN THE PRESENCE OF MULTIPATH

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ABSTRACT

The wide band signal processor is recognised for its good range resolution, which is useful for extracting target detail and lowering the reverberation level. Such a processor can be realised simply by utilising a short pulse transmission and detecting the envelope or by using a cross correlator, where the range resolution is determined by the reciprocal of the bandwidth of the signal transmitted. The advantage of the cross correlator is that the pulse length of the signal transmitted can be chosen quite independently to achieve the required detection performance against a noise background. A further advantage, not so widely appreciated, is the ability to reduce echo fading, arising from multipath, by an equivalent diversity receiver action inherent in the correlator itself.

Practical measurements on a calibrated point target have demonstrated this improved echo stability which confers an improved probability of target detection. What was also discovered was an enhancement in reverberation level over that achieved by a simple short pulse receiver with identical range resolution which, in turn, means improved false alarm statistics. To improve the understanding of the correlator in this extra role, computer modelling was undertaken to see how well results could be matched to practice. Modelling results have shown good agreement with practice, enabling a much better appreciation of the correlator operation in terms of signal parameters and relevant environmental properties.

1. INTRODUCTION

An active sonar system has two major sources of background interference to contend with: namely noise and reverberation. Noise is relatively straightforward to counteract using an increase in signal energy and integration techniques. Reverberation, on the other hand, consists of an extremely large number of minute target echoes and, on this basis, because of the target like character, it is perhaps not surprising that reverberation can be a difficult background to counteract. In this case, for the wideband signal processor, the acoustic beamwidth or angular resolution, determined by the size of the transducer array, and the range resolution, determined by the transmission bandwidth, are used to spatially filter out the wanted echo from the unwanted scatterers.

Obviously, depending on the size of the wanted target reflector, a reduction in resolved patch size of the reverberating scatterers surrounding the target improves the target to reverberation ratio.

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1.1 The effect of Multipath and the use of Diversity Reception

A further phenomenon that can have a serious effect on signal processor detection performance is multipath, whereby inter-echo-element interference causes further fluctuation over and above that due to noise and reverberation. Obviously an effect that produces further degradation of echo stability must be included in detection performance analysis, because of the serious repercussions it has on estimates of probability of detection and false alarm.

A standard technique, employed to reduce the effects of multipath and consequent echo fading, is diversity operation. Such operation can be achieved in space, frequency, or time or some combination of these dimensions; the essential point being to provide separate signals in these dimensions to the point where their statistics become independent. Depending on the number of diversity signals present, so an average value of the signal levels or perhaps an optimum selection of one of them will yield a signal level capable of exceeding a threshold and giving the required probability of detection and false alarm.

It is of interest to note at this point that the correlation receiver could well be associated with a diversity receiver action [1] because it produces an output only when all the input signal has been interrogated and the signal has components separated in both time and frequency.

Having emphasised the importance of multipath and echo fading on probability of detection, and described the possible diversity receiver action of the cross correlator signal processor, there is a need to study these effects in more detail.

2. EXPERIMENTAL STUDY

When conducting signal-processing trials at sea, received target echoes have been found to fluctuate to a high degree from ping-to-ping. The full impact of this effect was demonstrated some thirty years ago when an attempt was made to measure the implementation loss of a new correlator by comparing its performance with the equivalent short pulse receiver under strictly reverberation-limited, shallow water conditions. By using the same bandwidth of transmission for the two systems, the range resolution was the same and thus the performance against reverberation should have been the same. Thus any shortcomings observed in correlator performance could then be attributed to implementation loss.

It was therefore surprising to observe that the only way of maintaining continuity of detected echoes was by virtually full time use of the correlator. It was this observation that prompted a more detailed study into fading and echo fluctuations and the effect on the correlator performance.

To this end an experiment was set up [1,2] to record amplitude fluctuations from a calibrated single highlight target under good signal to background noise conditions for both a correlation receiver and the equivalent short pulse receiver acting as a benchmark. The reverberation levels from both types of receiver were also monitored. Practical data was gathered over a period of several years in different locations.

2.1 Experimental Configuration

The experimental configuration is shown in figure 1.

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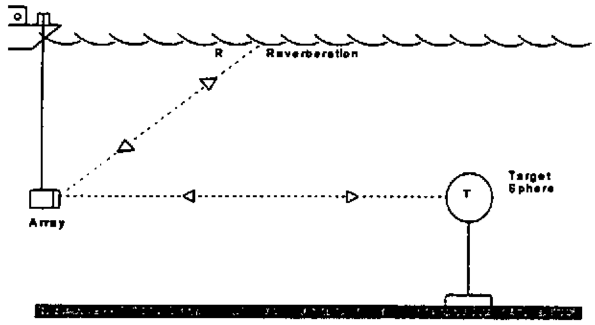
Figure 1: Experimental set-up



A sonar array equipped with training gear was suspended at about mid-water depth and signals from the array fed up the cable to monitoring/recording equipment on board the vessel.

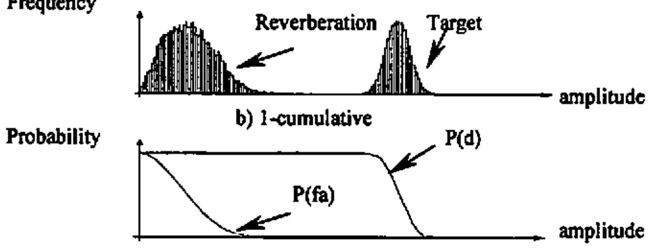
A calibrated target sphere was located at a range where its echo stood well above any noise and reverberation background so that any variations in echo amplitude were primarily due to conditions in the propagation path. Similarly the surface reverberation, at a closer range, was of sufficient amplitude to represent the effects of the propagation path on reverberation.

Two types of signal were used: A short pulse and a long pulse with a frequency sweep, both having the same centre frequency and bandwidth.

The two types of signal were transmitted alternately with sufficient time between each transmission for the associated reverberation to have died away. This approach enabled the comparison between processors to be unaffected by changes in propagation conditions as the experiment progressed.

The outputs of each processor were sampled in turn at points where the maximum amplitude of reverberation and target echo occurred. By sampling the amplitude of reverberation and the target over several hundred pings as an ensemble technique, stable histograms as shown in figure 2 were built up.

Figure 2: Histograms and Cumulative plots of target and reverberation

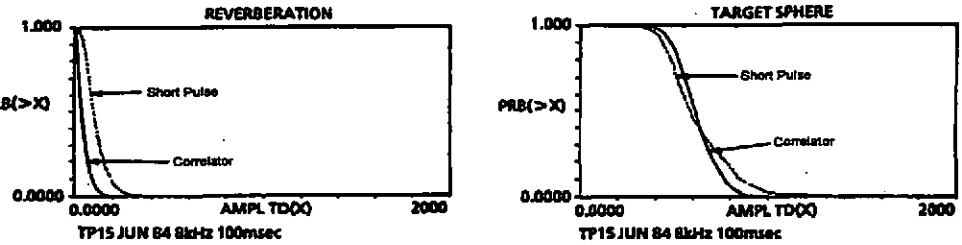


The histograms, approximating to probability density distributions, were then converted to 1-cumulative probability distributions as shown in figure 2.b. The 1-cumulative histogram provides a means of assessing performance against reverberation because the probabilities of detection P (d) and false alarm P(fa) can be read off.

2.2 Analysed Results

A typical example of analysed results comparing the correlator with the short pulse receiver are shown in figure 3 where the mean level of the echo from the target sphere has been adjusted to be the same for each processor on the basis of their identical range resolution. In figure 3 it can be seen that both target and reverberation distributions are tighter for the correlator and thus not only is target echo stability improved but a bonus of an enhanced reverberation performance is obtained.

Figure 3: 1-cumulative histograms for chirp and short pulse

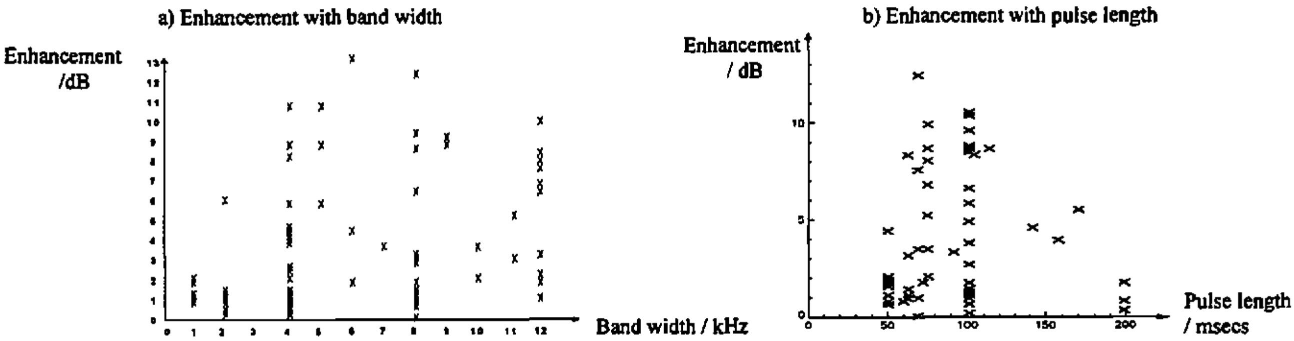


2.3 Reverberation performance enhancement

A wide range of results has been obtained in areas with water depth varying from the order of 15 metres to 50 metres. What must be emphasised at this point is that the multipath effects observed can not be associated with reflections from either the sea surface or seabed. Indeed multipath appears to occur in the so-called direct path and thus water depth is not a critical parameter. Hence a large number of results can all be grouped together.

The two independent transmission parameters used by the cross correlator are bandwidth and pulse length, and it is convenient to display reverberation performance enhancement in terms of these two parameters. Taking bandwidth first, enhanced performance for a range of bandwidths is shown in figure 4.a.

Figure 4: Performance enhancement against a) bandwidth and b) pulse length



It can be seen that considerable variation occurs at each bandwidth and is dependent primarily on the particular environmental conditions of the site and time of day. There does not appear to be any real optimum bandwidth and the reduced performance at bandwidths below 4 kHz could well be simply due to the limited number of samples taken.

Considering pulse length next, as shown in figure 4.b, there does seem to be some dependence on pulse length although results above 100 mseconds are somewhat limited in number. It is probable that environmental propagation instabilities giving rise to excess phase distortion could contribute to a degradation in correlator performance at the larger pulse lengths. Further comments on the importance or otherwise of pulse length will appear later.

Finally, as far a reverberation enhancement is concerned, it is interesting to see whether the enhancement could in any way be related to a possible diversity receiver action provided by the

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correlator. Occasionally, during the trials, it was observed that multipath conditions were such that the short pulse echo became elongated as successive delayed returns effectively added to the pulse length creating a much higher reverberation level. In this case, an apparent enhancement in correlator reverberation performance was actually due to short pulse degradation and these results, although relevant to overall performance, obviously should not be included in a study concerned with investigating possible causes of *improved* correlator performance. Thus a few sets of acoustic data were selected where there were no discernible, misleading phenomena occurring, such as echo elongation but did include a useful range of reverberation enhancement values.

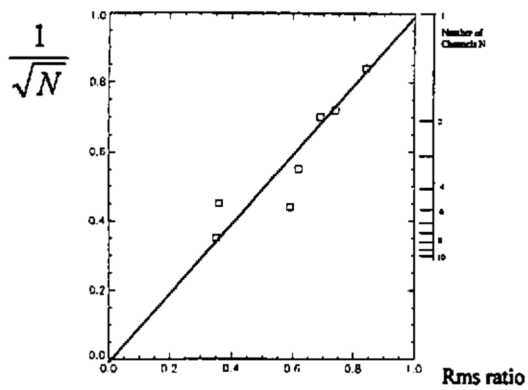
To assess possible diversity receiver action and its effect on reverberation performance, practical reverberation data associated with each result under investigation was considered as occupying the equivalent tapped delay line section of the correlator [2] and the number of taps with zero auto-correlation values was evaluated [5]. This number would then indicate the number of taps or channels where the statistics was independent and hence the number of equivalent diversity channels. In [5] the following relationship has been derived.

$$\text{RMS ratio} = \frac{\text{rms reverberation level from correlator}}{\text{rms reverberation level from short pulse}} \equiv \frac{\text{N channel diversity}}{\text{single channel}} = \frac{1}{\sqrt{1+(N-1)k}} = \frac{1}{\sqrt{N}}$$

because k has been measured as ≈ 1.

The values of $1/\sqrt{N}$ are plotted against the rms ratios in figure 5 and demonstrates that a $1/\sqrt{N}$ effect or diversity receiver action is taking place. It is interesting to include a scale of the number of effective diversity channels as shown on the right hand side of fig 5.

Figure 5: $1/\sqrt{N}$ plotted against rms ratio



3. MODELLING THE EXPERIMENT

The equipment configuration and the aims of the experiment were outlined in section 2.2. What was unknown at the time of the experiments was the degree of multipath and amplitude variation in the propagation path, although spectral and auto-correlation measurements of returning waveforms provided useful clues to some of the questions. Thus, with a large amount of information gathered over the years, it was felt that it might be possible to model the underwater environment and the operation of the signal processors used in such a way that matching of the practical results by the

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model would provide a more detailed insight into the interaction between specific multipath and propagation conditions, and the improved performance of the correlator.

3.1 Possible environmental conditions affecting target echo stability and reverberation level

Observed echo fluctuations or fading could arise from instabilities in the underwater propagation path and target position. The propagation path could be subject to **multipath interference**, which in turn could give rise to amplitude and phase fluctuations of an echo. In addition, a **variable propagation loss** arising from, for example, the changes in the ratio of forward to back scattered sound along the propagation path, could provide further amplitude variations. Phase variations in the propagation path could arise from changes in the speed of sound along the path and fluctuations in target position could also give rise to phase variations but for a tethered sphere the effect should be small and independent of the orientation of the target.

Reverberation levels should also be affected by **multipath interference** and possible further effects could arise from the **motion** and **lifetime** of the scatterers involved.

3.2 Modelling of sonar pulses and received echo

A simple model of the short pulse and chirp were created to simulate the pulses used in practice.

The received target echoes from such pulses was modelled by introducing possible amplitude distortion, phase distortion, and multipath effects arising from the environment.

The short pulse echo was then subject to the derivation of the envelope followed by a modicum of integration, in contrast to the chirp echo, which was subject to the cross-correlation integral followed by the derivation of the envelope. In the time scale of a listening interval each output pulse looks remarkably similar and it is only when expanded that the typical sin(x)/x envelope of the correlated chirp becomes apparent.

3.2.1 Amplitude distortion

Taking the effects of a variable propagation loss first, the received target echoes were subjected to a random amplitude modulation or fluctuation.

100 variations of each pulse were generated to observe the effects of the fluctuation frequency, and it was seen that increasing the frequency of fluctuation has the effect of reducing the standard deviation of the chirp distribution, but has little effect on the short pulse. This is due to the correlator 'smoothing out' the fluctuations by averaging during the pulse length. This effect was noted in practice as can be seen in figure 3.

Pure amplitude distortion alone is not expected as there has always been evidence of multipath present during in-water experiments. Thus further consideration of amplitude distortion will be left until multipath is studied.

3.2.2 Phase distortion

Phase distortion can be thought of as a stretching and/or compressing of the waveform during the pulse length arising from fluctuations in the speed of sound in the propagation path. Note that the target used in the experiment was nominally stationary and thus phase distortion due to it's movement is likely to be very small.

Pulses were generated to observe the effects of phase fluctuation frequency and spread.

The short pulse is not affected by phase distortion alone, because the echo strength is only dependent on the envelope which is calculated using amplitude information alone. The chirp, on the other hand,

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is affected because the correlation process uses phase information, and the output amplitude is reduced as the phase distortion is increased.

During practical trials, severe correlator output degradation was never seen. This implies that there is a limit to how much phase distortion a chirp encounters by being reflected off a stationary target sphere. It is possible this excessive amount of phase distortion could apply to surface scatterers, which could be moving rapidly or oscillating, or the pulse could be influenced by the rapidly varying temperatures and eddying currents at the surface.

Hence only a small amount of phase distortion was considered for target echo modelling.

3.2.3 Multipath

As stated in section 1 the underwater environment is subject to multipath. It is likely that these paths are different in effective length, either due to multiple refractions from inhomogenities in the water or variations in velocity gradient along the path, and hence a pulse transmitted from the array could return from the target with two (or more) echoes, each at slightly different times. This difference in times will be referred to as an *offset*.

As an initial step in multipath simulation, a two path model was adopted for simplicity ***and was subsequently found to be adequate.***

The system was modelled by generating two pulses, one starting at time *zero* and the next at time *offset*, and summing them. The chirp pulses were summed prior to correlation. In this manner, the echo strength of the return is dependant upon the offset used.

In practice, the offset is likely to fluctuate about a mean and the rate of fluctuation becomes an important parameter.

For very slow fluctuation rates, where the amplitude of the chirp input to the correlator is essentially constant over the pulse duration, there will be no difference between the target echo statistics for the correlator and short pulse. This is known as flat fading. When the offset fluctuation rate increases, such that there are many cycles of undulation during the chirp pulse length, then the correlator output represents an average value of the fluctuating input whilst the short pulse output still represents the full extent of the amplitude fluctuations. It is then that the improved target echo stability of the correlator output becomes evident as shown in figure 3.

3.2.4 Variation of chirp pulse length

The effectiveness of this averaging process must depend on the rate of amplitude fluctuation and the pulse duration so that the population of amplitude samples is sufficient to yield a good average. During the experiment, a range of pulse lengths was tested, ranging from 50 to 200 msecs.

It is the rate of fluctuation within a given pulse length that is the important parameter and the fluctuation rate times pulse length product (T.f) represents a performance product. Such a product is demonstrated in figure 6, where improvements in target echo stability for the correlator over the short pulse are represented by the ratio of standard deviations which are seen to reduce to 0.1 by the time T.f reaches 50. Thus for a given fluctuation rate produced by the environment a value for T can be chosen to achieve a given target stability improvement.

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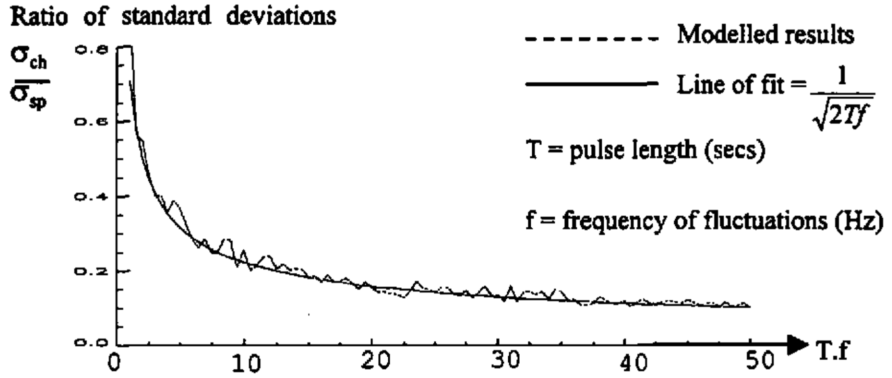
Figure 6: Effectiveness of correlator averaging



There will however be a limit to the maximum value of T and hence target echo stability improvement, depending on the magnitude of offset fluctuations (phase instabilities) in the medium and the resultant degradation of the correlator performance.

3.2.5 Variation of signal bandwidth

In addition to observing the effect of chirp pulse length, variations in signal bandwidth were included in the experiment. A range of bandwidths from 1 kHz to 16 kHz were selected and it therefore becomes necessary to include the effect of signal bandwidth in the model.

Again, 100 pings were generated and the previous parameter variations applied for the range of bandwidths. The effect of changes in bandwidth on the single high-light target response was found to be negligible.

3.3 Modelling Reverberation

As described in section 2, in addition to the measured target data the experiment included the gathering of reverberation data. To model reverberation there is a need to postulate possible mechanisms involved.

3.3.1 Scatterer description and construction of reverberation waveforms

Reverberation consists of the return from a myriad of scatterers in, for example, the sea surface. Due to the nature of the surface, the scatterers may be fast moving, oscillating, or have a short life span. Although the nature of a scatterer is somewhat different to a stable target, the same techniques can be applied to model them. For example, a moving or oscillating scatterer can be modelled by including phase distortion, and a short life span can be represented by amplitude distortion such that the amplitude of some of the pulse is zero. Bandwidth and pulse length can also be modelled using the same techniques as the target.

So by representing scatterers as a large number of distorted, tiny targets randomly distributed in time, a model of reverberation can be constructed. For the chirp, the model of reverberation is passed through a correlator, followed by an envelope detector whereas the short pulse reverberation has only to be passed through an envelope detector before it is analysed. The analysis involves producing histograms of the modulus of the envelope, and deriving the ratio of reverberation levels that was termed a reverberation enhancement in section 2 and its derivation now forms the aim of the modelling.

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3.3.2 The multipath model of reverberation

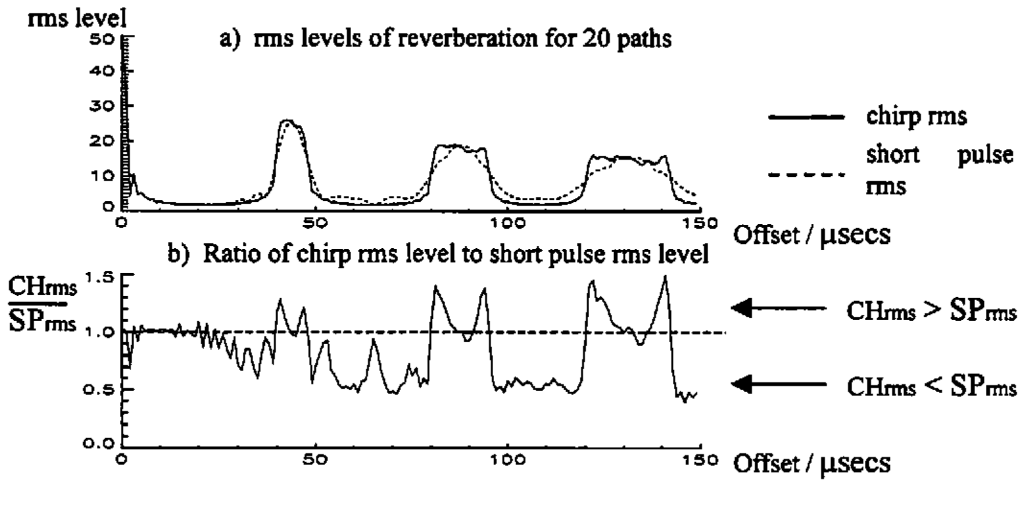
Random distortions such as those described in section 3.2 can be applied to a scatterer such that, if considered as a single target, the resulting amplitude distributions are markedly different for the correlator and the short pulse receiver. When each population of scatterers has been used to construct a reverberation waveform the resulting amplitude distributions for the two types of receiver have become virtually identical. Thus, unless a considerable fraction of the scatterer echo is removed as in the lifetime treatment, scatterer distortion has little or no effect on the reverberation characteristics. This implies that inter-scatterer interference, occurring as the reverberation waveform is produced, vastly outweighs individual scatterer distortion. Likewise, interference from a two path model for multipath (adequate for the target model) is also overwhelmed by the scatterer interference. It is therefore necessary to increase the number of paths to adequately represent reverberation in a multipath environment. If this becomes the case, the averaging or diversity receiver action of the correlator could then appear.

The method of modelling is similar to the two path case described in section 3.2.3, except that instead of the original path having a second path with a time delay of *offset*, there are more paths, each with time delays of *offset(n)* to the previous one, where *n* is the number of multipaths and offset(n) is a random or constant time delay between paths. **Initially a constant time between paths is considered, which helps to clarify the issues being presented. Finally fluctuations in offset and lifetime are introduced.** By varying *n* it was found that practical, observed values of reverberation enhancement could be modelled using values of *n* between 20 and 50. The next step was to observe the effects of varying the offset time in the model to produce what might be termed an *rms diagram*.

The figure 7 shows the effect on rms levels of offsets in the range 0 to 150 μsecs for 20 paths. The bandwidth for the reverberation generated is set at 4 kHz.

The rms levels of reverberation can be read off from figure 7.a and the difference in rms levels, represented as an **rms ratio**, is shown in 7.b.

Figure 7: Rms levels of reverberation for multipath offsets and 20 paths



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The trace below the dotted line in fig. 7.b shows regions where the chirp reverberation is lower than the short pulse. This trace could suggest a suitable range of offsets to model the difference in rms values seen in practice.

As the number of paths increases, regions where the chirp performs better than the short pulse become more pronounced, giving rms ratios of as little as 0.3 for 50 paths (note that an rms ratio of 0.3 corresponds to a drop in reverberation level of 10 dB. This can be seen to happen in the experimental results illustrated in figures 4.a & 4.b).

There are also regions where the rms ratio is greater than 1.0, inferring that the chirp's performance is worse than the short pulse. As this is rarely seen, lifetime effects could also be present, which would lower the rms ratio, or perhaps some factor of the environment causes an offset which is stable and happens to lie in the favourable region of the diagrams. Not enough is known at present about the environment to comment further.

3.3.3 Pulse elongation

The presence of pulse elongation was introduced in section 2.3. To see whether this multipath model provides evidence of pulse elongation, it is helpful to generate an auto-correlation of the reverberation. As examples, auto-correlations of chirp and short pulse reverberation for two separate runs are calculated, one with a high rms ratio (short pulse performs better than the chirp) and the other with a low rms ratio (chirp performs better than the short pulse).

Figure 8.a shows the 1-cumulative histogram of the reverberation envelope where the short pulse performs better than the correlator. The parameters used to create the reverberation were 20 paths, each with an offset of 45 μsecs. Figure 8.a.ii) & 8.a.iii) illustrate the auto-correlation waveforms, with the expected zero at 250 μsecs (1/B, B=4 kHz) missing (i.e. both elongated). This condition can be associated with an rms ratio of the order of 1 or above as shown in figure 7.b.

Figure 8: 1-cumulatives and auto-correlations of modelled reverberation

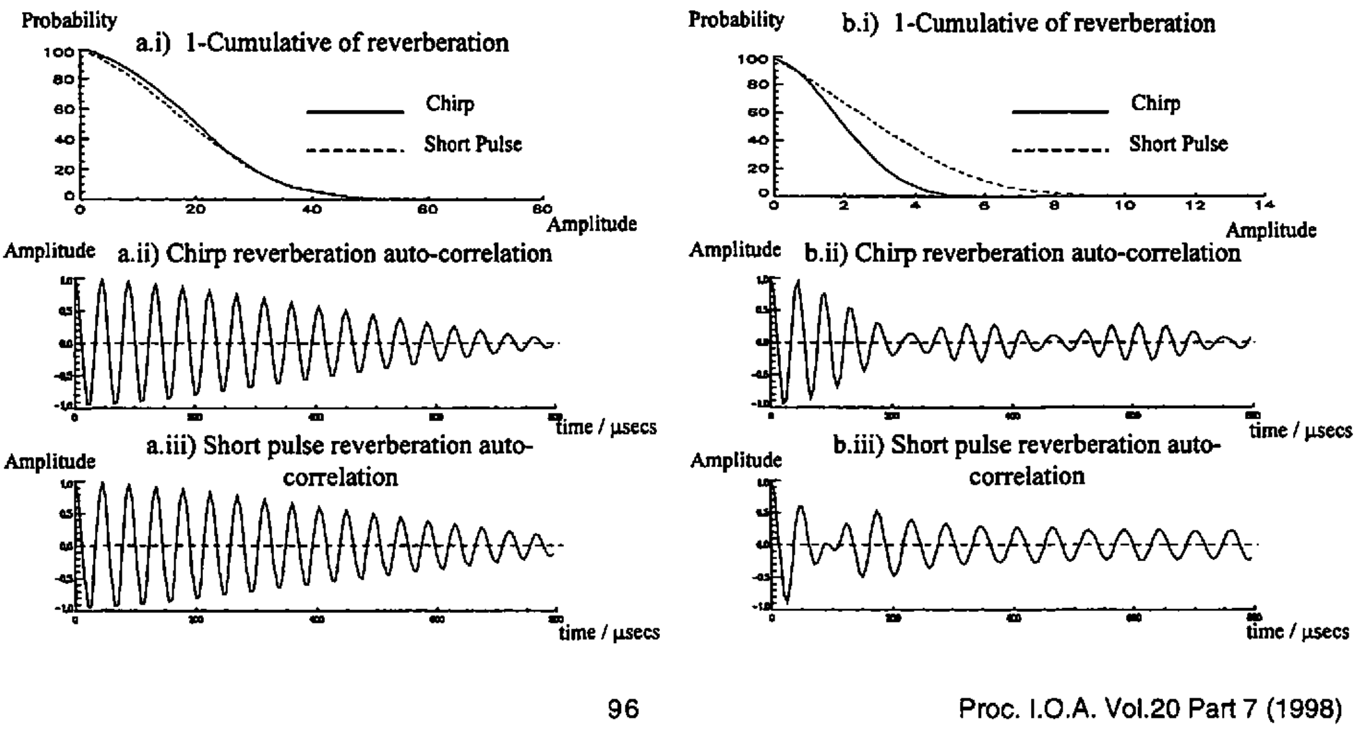

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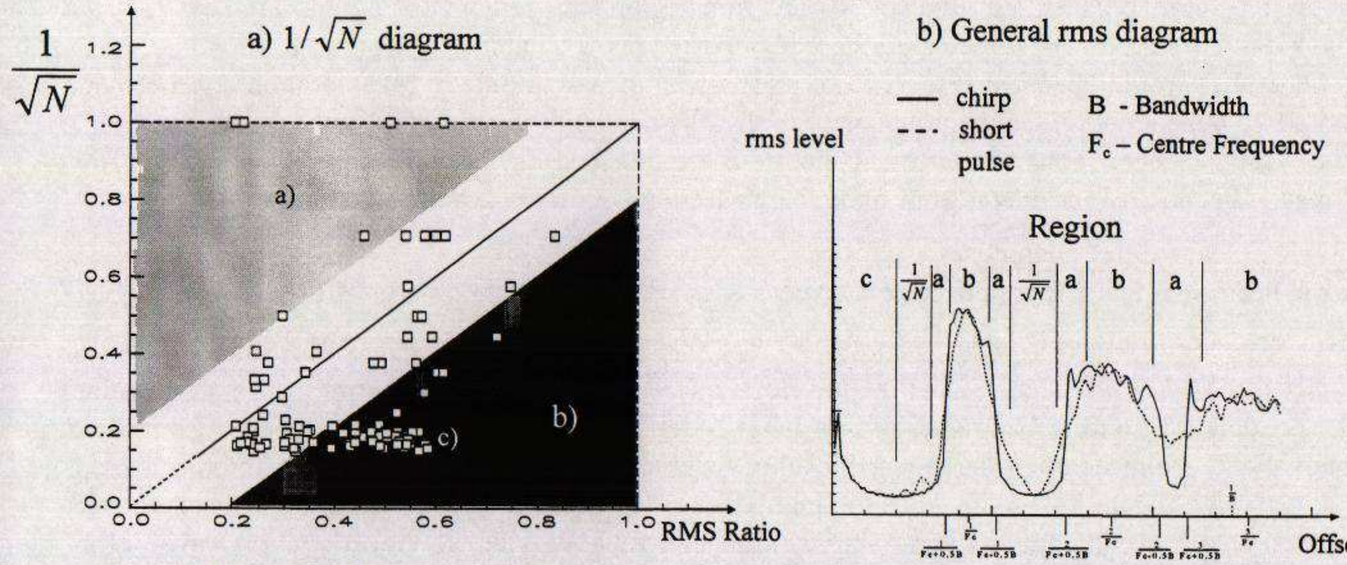
Figure 8.b shows the 1-cumulative histogram of the reverberation envelope where the correlator performs better than the short pulse. The parameters used to create this reverberation were 20 paths, each with an offset of 75 μsecs. In this case, the first zero in the chirp auto-correlation waveform shown in figure 8.b.ii) is close to the expected 250 μsecs whereas the short pulse auto-correlation is obviously elongated. This indicates that pulse elongation is occurring for the short pulse only, giving rise to higher reverberation for the short pulse which produces an rms ratio of 0.66 in this case.

3.4 Analysing reverberation auto-correlations for the 1/√N effect.

Having observed the modelled effects of pulse elongation, the next effect to be investigated using modelling is what has been termed the $1/\sqrt{N}$ effect in section 3.3.6, where N refers to the number of channels of an equivalent diversity receiver. To obtain the number of independent channels N as described in section 2.3, an auto-correlation function of the reverberation was calculated. To extract the number of independent channels in the auto-correlation function, the envelope of the modulus of the auto-correlation function was taken, and the number of the number of zeroes calculated.
One hundred reverberation sequences were generated with 25 paths and offsets in the range of 0 to 100, and their distributions and rms levels calculated. Auto-correlations of each reverberation sequence were generated and the number of zero crossings (N) were found. The graph of $1/\sqrt{N}$ was plotted against the rms ratios, which can be seen in figure 9.

Figure 9 : a) Graph of $1/\sqrt{N}$ plotted against rms ratios for reverberation & b) General rms diagram for multipath reverberation



The graph in 9.a is shown to be divided into three regions, namely a, b, & c. It is not easy to be precise in terms of the boundaries of each region but the conditions existing in each region can now be identified.

Region a) is associated with short pulse elongation, where low rms ratios occur simply due to the high reverberation level from the short pulse. An example of short pulse elongation is shown in figure 8.b with appropriate elongation of the auto-correlation function and increase in reverberation

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level for the short pulse. As the line representing the $1/\sqrt{N}$ or diversity effect is approached so the points represent a mixture of elongation and $1/\sqrt{N}$.

Region b) can be identified by an elongation of both chirp and short pulse auto-correlations as shown in figure 8.a and an N count larger than that associated with a $1/\sqrt{N}$ relationship alone. It is likely that some $1/\sqrt{N}$ effect is present where an rms ratio is seen to be favourable.

Region c) is again where N count is large, giving rise to a low value of $1/\sqrt{N}$ despite rms ratios up to 0.6. Most of the points are for offsets under 70 μsecs, and for offsets less than 25 μsecs multipath interference is small and N count is high accounting for the low $1/\sqrt{N}$ (approximately equal to 0.2) around which the points are clustered. As such points have not been seen in practice it is likely that offsets as low as 25 μsecs have not been experienced. The region where the $1/\sqrt{N}$ relationship or diversity reception is seen to hold is characterised by auto-correlation plots where the first minimum and subsequent minima occur at about 250 μsecs corresponding to the reciprocal of the 4 kHz bandwidth used. Regions a),b),c),& $1/\sqrt{N}$ can be usefully represented on the rms diagram in figure 9.b. To make the rms diagram more general offset times are represented in terms of the reciprocal of the centre frequency and bandwidth of the signals concerned.

3.5 Effect of bandwidth on multipath reverberation levels

The effect of bandwidth on the short pulse and correlator levels of reverberation under multipath conditions can be considered by referring to the rms diagram (figure 9.b). As the bandwidth B is increased it can be seen that, except for the first region, the remaining regions favouring $1/\sqrt{N}$ disappear. However, if F_c is increased these regions become available at the higher bandwidths.

In general, it would appear that there is no reason why the magnitude of reverberation enhancement should be dependent on bandwidth, except in that the bandwidth controls the availability of regions of diversity receiver action in terms of the offset experienced on the day of the experiments. This agrees with conclusions drawn from figure 4.a in section 2.3.

3.6 Effects of pulse length

It has been seen that, where the correlator possesses a lower reverberation level than the short pulse receiver under multipath conditions, it is due to a diversity receiver action or the $1/\sqrt{N}$ effect. To depict the $1/\sqrt{N}$ effect, zeroes of the envelope of the auto-correlation for multipath reverberation were counted for a range of values of rms ratio. N represents the number of zeroes in a given time interval and is a measure of the reduced level of reverberation from the correlator or, in other words, a lower value for the rms ratio. Thus the higher the N the better the reverberation enhancement and this can be achieved simply by increasing the time interval over which the reverberation waveform is processed. This time interval corresponds to the pulse length of the chirp signal. Hence improvements in reverberation enhancements would be expected with increases in pulse length. Such an effect is shown in figure 4.b of section 2.3 for the practical measurements followed by a decrease in enhancement at the higher pulse lengths. As all measurements were normalised with respect to the average target echo response, the decrease in performance could well be due to a degradation in correlator performance at the higher pulse lengths due to instabilities in the under water medium, such as offset fluctuations.

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3.7 Effect of multipath offset fluctuations & scatterer lifetime

To model the effect of multipath on reverberation satisfactorily it has been found necessary to introduce 20-50 paths with the offset time occurring in progressive steps. This step-like characteristic has been observed in practice [3,4] due to the presence of layers of uniform temperatures and salinity separated by thin high gradient interfaces. As the spacings between each path are unlikely to be exactly the same in reality, the concept of a fluctuating offset must be taken into account. This infers that a mean offset is specified for all paths, but each offset is subject to a small deviation from that mean.

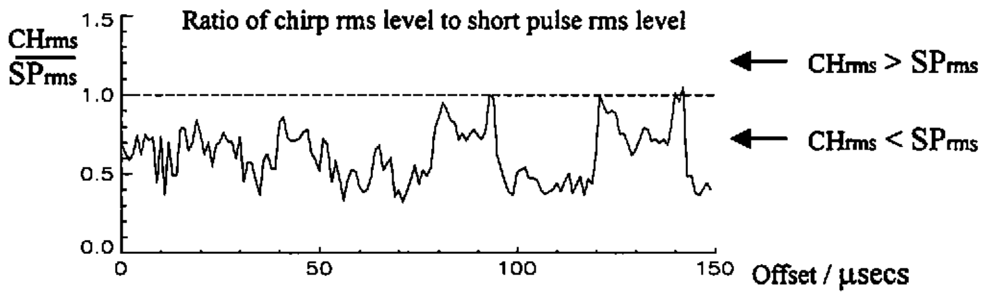
The rms diagrams in the previous sections on multipath have all indicated that there are regions where the rms level of the chirp reverberation is greater than the rms level of the short pulse. This was rarely noticed in practice, so this section deals with the possibility that lifetime and multipath offset fluctuations combine to create a reverberation model in which the rms ratio hardly ever exceeds 1.0 and pulse elongation and the $1/\sqrt{N}$ effect are visible.

As the scatterers on the water's surface are subject to wave motion, a scatterer in view one moment could well be obscured the next. This movement is likely to be slow compared to the short pulse length (of the order of 100 μseconds) whilst the chirp will almost certainly be affected due to the much longer pulse length.

The short pulse can be modelled as in the previous sections but the chirp scatterers may have frequency components missing where they have been obscured, giving rise to a relatively slow random variation in amplitude with a fraction of the chirp duration missing.

This has the effect of lowering the correlator reverberation level whilst keeping the short pulse reverberation level constant. An rms diagram of reverberation (4 kHz bandwidth) with multipath offset fluctuations of ± 5μsecs and lifetime effects (30% of chirp waveform, randomly removed) is shown in figure 10.

Figure 10 : rms diagram for reverberation with multipath fluctuations and lifetime



3.8 Comparison of modelled multipath reverberation with results obtained in practice

To compare modelled reverberation with practical results it is necessary to arrive at suitable values for number of paths, offset time and scatterer lifetime. An example of a practical result from a 1987 trial is shown in figure 11, where it can be seen from the auto-correlation plot that the short pulse is subject to elongation (region a in figure 9.a). It is highly probable that the enhanced reverberation ratio is primarily due to the degradation of the short pulse performance, hence scatterer lifetime is not required in this case. A value for the offset of 70 μsecs is chosen for region a) in the rms diagram (figure 9.b) and 20 paths were considered adequate for the model. The modelled results are shown in

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figure 11.b where it can be seen that there is an encouraging similarity between practical and modelled results.

A further example of a practical result is shown in figure 12.a, where it can be seen from the auto-correlation plots that short pulse echo elongation is absent. It is therefore highly likely that diversity receiver action of the correlator is the predominant effect. To account for this, a mean offset time of 33 μsecs with a random fluctuation of ±5 μsecs is chosen, avoiding regions a), b) and c) of figure 9.a. In addition, a scatterer lifetime effect is introduced by randomly removing 30% of the chirp waveform as described in section 3.7. Again, it is encouraging to note the close similarity between the modelled and practical results.

Figure 11.a : Practical results obtained in 1987

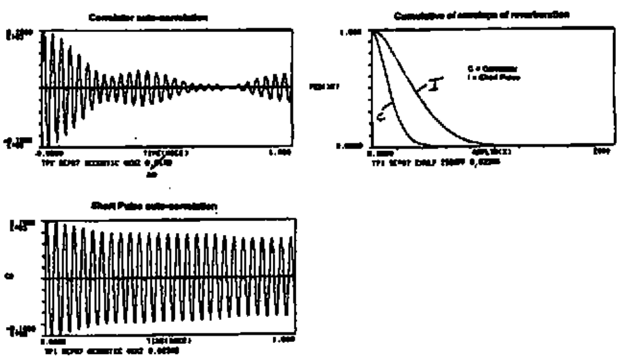


Figure 11.b Example of modelled results using 20 paths, offset = 70 μsecs

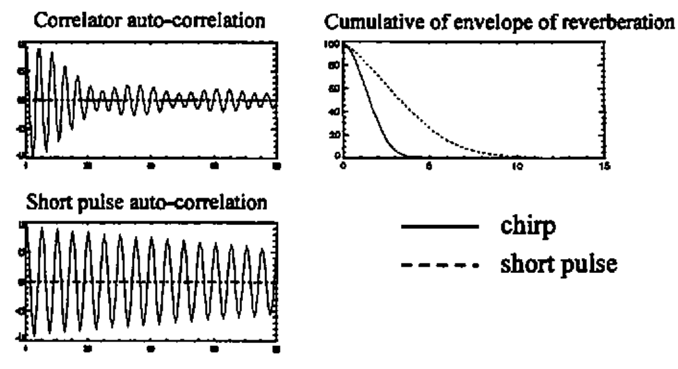


Figure 12.a Practical result obtained in 1985

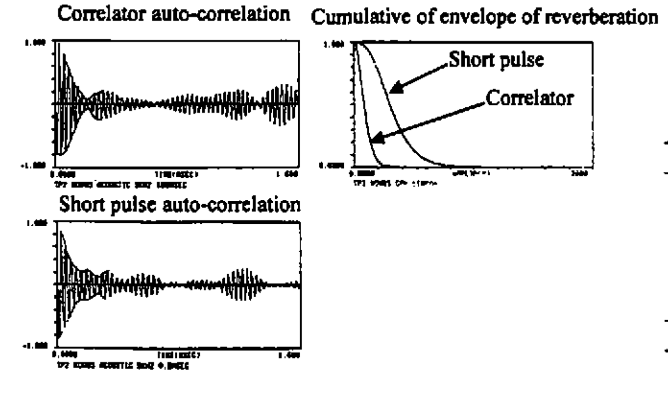
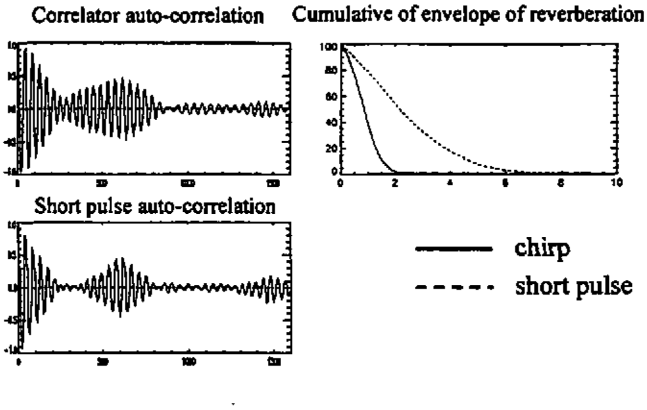


Figure 12.b Modelled results using 20 paths, offset = 33 ± 5 μsecs, with lifetime effects (30% of chirp scatterers removed)



4. CONCLUSIONS

The improved echo stability and enhanced reverberation level, under multipath conditions, provided by the cross correlator compared with the equivalent short pulse receiver, has been the subject of a series of trials measurements made over the past 20 years or so.

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Analysis of the results has appeared in [5] and a computer modelling study [2] provided the first stages of an explanation as to the possible mechanisms involved in the improved correlator performance. Reference [2] modelled a fixed environmental situation that was deduced from observations on the behaviour of a rapid sequence of short pulse transmissions during just one trials session.

This latest modelling work covers a wide range of values of a key environmental parameter, the offset time between paths of the multipath. The ratio of rms levels of reverberation for the correlator and short pulse receiver has been plotted against offset time and is referred to as the 'rms diagram' (for example figure 7, section 3.3.2). This diagram conveniently summarises performance against multipath and environmental conditions, indicating values of offset where :-

a) the short pulse reverberation is simply degraded,

b) diversity receiver or $1/\sqrt{N}$ improvement of correlator reverberation occurs and

c) there is no difference in reverberation levels.

The effects of signal bandwidth have also been included in the study and again the rms diagram is applicable where a general form of diagram can be constructed (figure 9.b, section 3.4). As the signal bandwidth is increased, for a fixed centre frequency, so the number of opportunities for improved reverberation performance is reduced. The diagram does, however, highlight the point that the number of opportunities for favourable reverberation results is primarily dependent on the ratio of bandwidth to centre frequency, as discussed in section 3.5.

The effects of pulse length have been adequately described by the $1/\sqrt{N}$ effect, bearing in mind the effect of possible underwater medium instabilities (such as offset fluctuations) on the practical measurements at the longer pulse lengths (figure 5, section 2.3).

Modelling of the target echo stability has been adequately represented by a simple two-path model and a fluctuating offset, where the improved performance of the correlator can be attributed to an averaging or smoothing action during the pulse length.

Overall, this study has demonstrated that signal processor performance in multipath can be modelled to match results observed in practice by suitable selection of offset characteristic, with a modicum of fluctuation, and a value for the lifetime of the reverberating scatterers.

5. REFERENCES

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