SIGNAL PROCESSING FOR THE DETECTION OF EXTENDED TARGETS IN NOISE AND REVERBERATION: THEORETICAL ASPECTS

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1. INTRODUCTION

The aim of this paper is to investigate two different signal processing methods for the detection of extended targets in noise and reverberation: The matched filter with post detection integration, and the split-spectrum-averaging processor. The transmitted waveform can be a wide-band frequency-modulated signal. It is shown by a theoretical target and channel model that the two processing methods can, under reasonable assumptions, have almost equal detection performance since they generate the same statistics and have equal temporal resolution. The arguments for the split-spectrum processor are based on spectral properties of signal returns from extended targets. The development then makes it possible to study the effect of increased signal bandwidth, and the difference between point targets and extended targets for the split-spectrum processor is elucidated. Some results with real data are presented, which underline the validity of the theoretical model.

2. SIGNAL PROCESSING FOR THE DETECTION OF EXTENDED TARGETS

The first signal processor implemented is the matched filter (replica correlator), followed by a square-law device and an integrator. It is well known that for a linear FM with bandwidth B, the matched filter leads to pulse compression, and the temporal resolution of the compressed signal is 1/B. The integrator is needed, since for optimum detection the integrator must match the final resolution to the target length. (Note that all figures and calculations are for complex baseband-demodulated signals).

The second processor considered is the split-spectrum processor from the literature on ultrasonic testing; see Newhouse et al. [1]. The main point of this method is that, first, a full correlation is performed by multiplication in the spectral domain, and the result is split into n (possibly windowed and overlapping) frequency cells, which are then transformed back into the time domain, squared, and added (Fig.1). However, it turns out that this is nothing more than a flexible and elegant realisation of a segmented replica correlator with individual replicas that are disjunct in the frequency domain. This processor, the segmented replica correlator with square-law device, delay lines and summation, is shown in Fig. 2. Again, if each of the n replicas is a linear FM with bandwidth B/n, pulse compression leading to a resolution of n/B occurs, and hence an integrator might have to be added if $n/B < T_L$, where T_L denotes the virtual target length in seconds. Therefore, by a suitable choice of bandwidths and integration time, the two processors can achieve the same temporal resolution, matched to the target length.

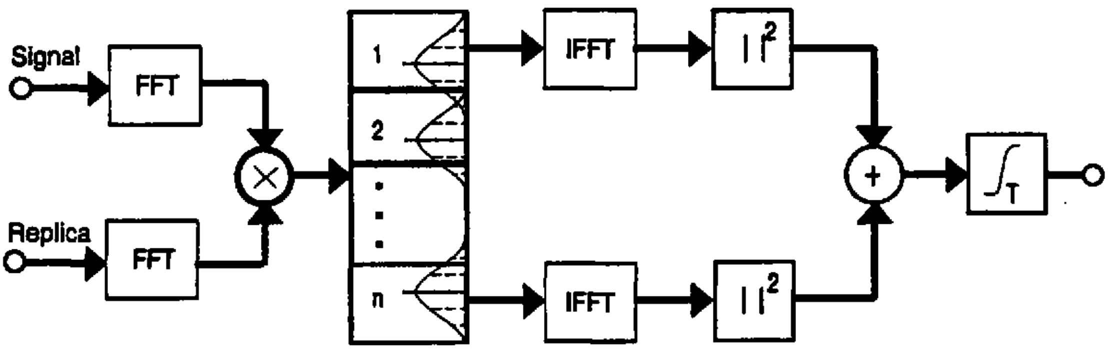

Fig. 1: Split-spectrum processor

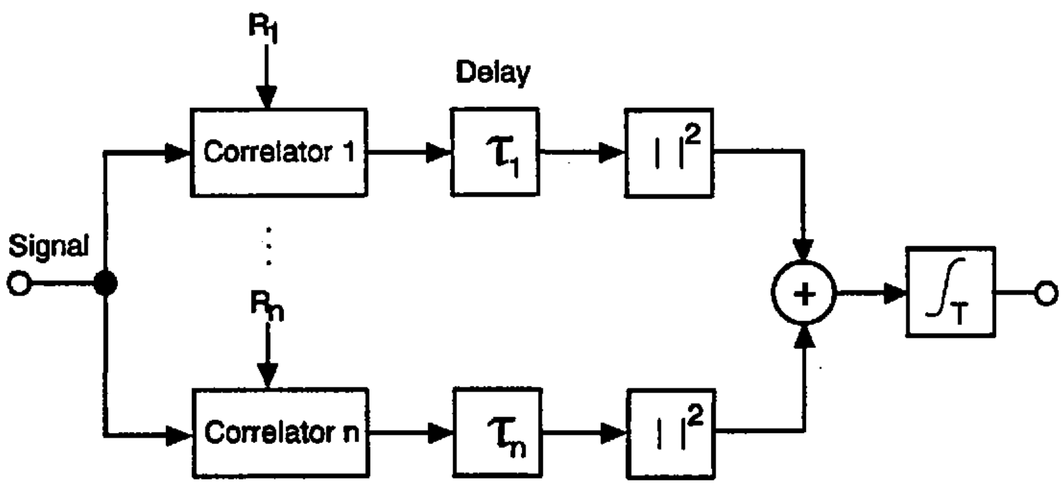

Fig. 2: Segmented replica correlator

3. THEORETICAL ASPECTS OF THE DETECTION PROBLEM

An overview and short derivations of some theoretical results will be given in this section. First, the target model is presented. The terminology from van Trees [5] is used, so that the definitions do not have to be repeated. The main assumptions are that the target and reverberation can be modelled as zero-mean complex Gausssian processes $b_T(x)$ and $b_R(x)$, respectively, and the signal reflected from the target and the reverberating environment is given by the following (note that capitals denote Fourier transforms, * complex conjugate, $*$ convolution and $\otimes$ correlation):

$$a_T(t) = \sqrt{E_t} \int_{x_1}^{x_2} f(t-x) b_T(x)\,dx := \sqrt{E_t}\,(f * b_T)(t) \text{ and } a_R(t) = \sqrt{E_t}\,(f * b_R)(t).$$

E_t is the emitted energy, x_1 and x_2 are given by the target dimensions. Absence of Doppler spread is required. The noise n(t) is white and Gaussian with average intensity N_0. The emitted signal f(t) with bandwidth B and energy normalised to 1 is now chosen such that it can be decomposed into n signals g_i, each with bandwidth B/n and energy 1/n which are disjunct in the frequency domain, such that

$$f(t) = \sum_{i=1}^{n} g_i(t), \quad |G_i(v)|^2 = 1/B \text{ for v in } D_i; \text{ and } |G_i(v)|^2 = 0 \text{ for v not in } D_i,$$

where the D_i are disjunct frequency cells with bandwidth B/n each.

Then at each of the branches of the split-spectrum processor (after the inverse FFT, but before the squaring operation), the following appears:

$$r_i(t) = \sqrt{E_t}\,((b_R + b_T) * (g_i \otimes g_i))(t) + (n \otimes g_i)(t).$$

This is the sum of three Gaussian processes which can be shown to be mutualy uncorrelated under the usual assumptions of independent target, reverberation and noise processes. Now, the covariance of r_i and r_j is computed by the following formula, bringing the expectation inside integrals:

$$E(r_i(t) r_j(t)^*) = E_t \int_{x_1}^{x_2} (s_R(t-x) + s_T(t-x))(g_i \otimes g_i)(x)(g_j \otimes g_j)^*(x)\,dx + (N_0/n)\,\delta_{ij},$$

where

$$s_R(x) := E\{|b_R(x)|^2\} \text{ and } s_T(x) := E\{|b_T(x)|^2\}$$

are the range-scattering functions of reverberation and target. Now, using the convolution and correlation Fourier transform relationships, the covariance expression can be described in the frequency domain for t=0, the signal present case, by

$$E(r_i(t=0)\, r_j(t=0)^*) = E_t \int_{D_j} \int_{D_i} \{S_R(u-v) + S_T(u-v)\} |G_i(v)|^2\,dv\, |G_j(u)|^2\,du + (N_0/n)\,\delta_{ij}$$

where S_R and S_T are the two-frequency correlation functions for the reverberation and target processes. If the range-scattering function of the reverberation equals a constant power density R (this means that the returned reverberation can be modelled as a weak-sense stationary process, the power spectrum of which has the same shape as the spectrum of the emitted signal), then $S_R(v)$ is equal to R $\delta(v)$, and the above expression can be further simplified to

$$E_t \int_{D_j} \int_{D_i} S_T(u - v)\,(1/B)dv\,(1/B)du + (E_t R)/(nB)\delta_{ij} + (N_0/n)\delta_{ij}.$$

For a discussion, the following cases can now be distinguished:

2.1 Target length very short (point target). This means $S_T(v)$ approximates a constant T, and hence the signals in the different branches of the split-spectrum processor become correlated. Therefore, the squaring operation before the summation should be avoided; this is underlined by the fact that coherent addition of the branches leads to a full correlation of the input signal, which is nothing else than the classical matched filter for a point target. The average signal-to-noise ratio at each of the branches of the processor is

$$\frac{S}{N} = \frac{1}{n}\,\frac{E_t\,T}{E_t\,(R/B) + N_0}$$

and it is seen that partitioning of the signal leads to loss in S/N at the output of the branches.

2.2 The target is very long. This is characterised by $S_T(v)$ approaching a T $\delta(v)$-behaviour. Then r_i and r_j are uncorrelated, with the average signal to-noise-ratio in each branch given by

$$\frac{S}{N} = \frac{E_t\,(T/B)}{E_t\,(R/B) + N_0}.$$

Clearly, in this case the signal should be partitioned into as many g_i as possible, until case 2.3 is reached.

2.3 The length of the target is such that G_i matches the bandwidth of S_T (a match of the shape would be even better). Then the output variables are statistically independent Gaussian with average signal to-noise-ratio given by

$$\frac{S}{N} = \frac{E_t\,(1/B)}{E_t\,(R/B) + N_o} \int_D S_T(v) \int_{Di} |Gi(u+v)|2\,|Gi(u)|2\,du\,dv.$$

It should be noted that the integral over S_T is extended over a frequency cell D with width B/n; this means that increasing n without increasing B means loss in S/N.

The statistics of the sum of squares for cases 2.2 and 2.3 is given by the well-known central chi-square distribution (see Whalen [5], van der Spek [3,4]) with the corresponding signal-to-noise ratio from 2.1, 2.2 or 2.3, respectively. On the other hand, with this target model, the analysis of the matched filter with incoherent integration leads to the same statistics with the same parameters, as long as the number of integrated independent samples is the same for both processors. The argument is that the first processor sums independent time samples. For this statistics at the detector output, there are extensive results for the detection performance, including bandwidth (resolution) effects; see van der Spek [3,4]. Note that the number of independent samples is proportional to resolution, or bandwidth. The results shown in the next section underline the validity of these results.

Hence, following the arguments from van der Spek [3,4], the influence of resolution or bandwidth on detection quality can be roughly characterized as follows: their increase increases the number of integrated independent time or frequency samples. This leads to different effects in the noise-limited and reverberation-limited cases, since the signal-to-noise ratio behaves in a different way.

-In the noise-limited case, typically no more than three samples from the target should be integrated, since we then have the change from fluctuation gain to detector or integration loss.

-In the reverberation-limited case, the resolution or bandwidth should be increased as long as the model assumptions remain valid, as can be seen from the formula in 2.3.

Another interesting aspect of the spectral point of view that can be mentioned here is that (see Papoulis [2] p.365) $b_T(x)$ can be considered as non-stationary white noise, so its stochastic Fourier transform is a stationary process with autocorrelation equal to $S_T(v)$. Therefore, it is worth trying to compute the frequency-domain autocorrelation of $a_T(t)$ to get an estimate of S_T. The result is shown in Fig. 3.A. The high peak in the centre comes from the reverberation, as can be seen in Fig. 3.B., where the frequency correlation of reverberation only is shown. There is clearly a difference, and the bandwidth of S_T corresponds to the physical dimensions of the real target.

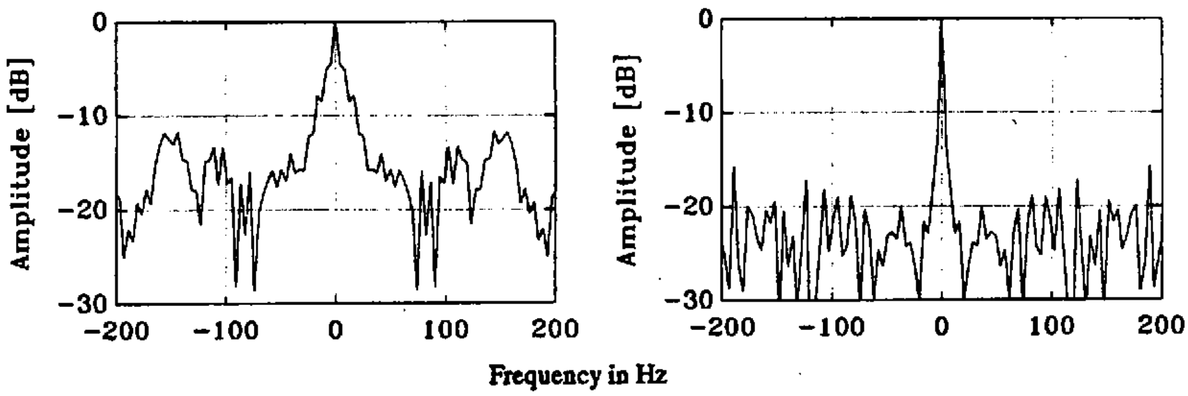

Fig. 3 A. Frequency autocorrelation of target

Fig. 3 B. Freq. autocorr. of reverb.

4. EXPERIMENTAL RESULTS

The experimental data were recorded in the following way: signals were emitted and collected by a stationary antenna, and an extended target was present in a reverberating environment. Among the signals were several wide-band frequency-modulated pulses. Doppler spread induced by the medium and target motion was measured using long CW-signals. The spectral analysis reveals a negligible Doppler spread for the pulse lengths used in the trials. This means that the signals can be processed coherently. A broadband spectral analysis of the data considered here shows that the noise level is much smaller than the reverberation level, hence we are in the reverberation-limited case.

As a second test, the reflected wide-band signals were passed through a filter bank, where the bandwidth of the individual filters B_f was $B_f = 1/T_L$, and were square-law-detected in order to analyze the amplitude fluctuations dependent on frequency. The amplitude fluctuations are uncorrelated from pulse to pulse and from frequency cells more than B_f apart. This corresponds to the theoretical results from van Trees [5] for signals reflected by extended, statistically reflecting targets. This underlines the validity of the target model considered in Section 3.

Now, typical examples of processed target echoes are shown for the two processors. First, in Figs. 4 - 6, plots of different processor outputs for the same set of data, based on a linear FM with B = 500 Hz, are shown. In Fig. 4, the squared output of the correlator is shown. Since the resolution of 2 ms without integration is much too high for the target, we have a poor signal-to-noise ratio. Fig. 5 shows what happens if an integrator with a Gaussian shape and an effective duration of 12 ms is used, i.e. six independent samples are integrated. The result of the segmented replica correlator, implemented as a split-spectrum processor with overlapping, Gaussian windowed frequency cells with an effective bandwidth of 83 Hz, is shown in Fig. 6. Note that Figs. 5 and 6 look almost identical, which is to be expected from the theory.

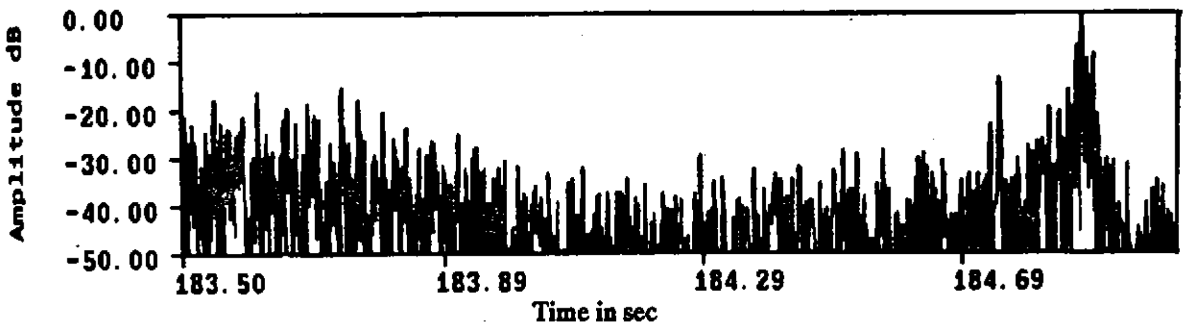

Fig. 4: Squared output of correlator

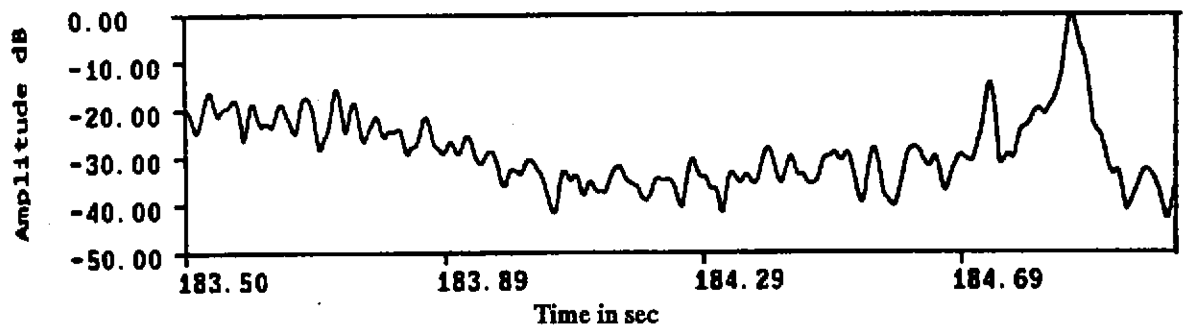

Fig. 5: Correlator with Gaussian integrator

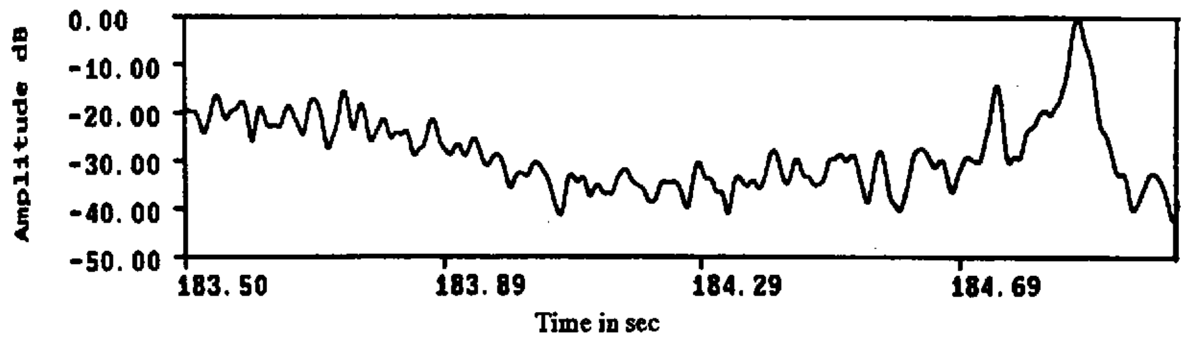

Fig. 6: Split-spectrum, Gaussian windows

Doubling the integration time for the first processor and doubling the number of frequency cells for the second processor leads again to a strong similarity. Further increase of the integration time or number of frequency cells leads to deterioration, since the resolution cell becomes larger than the target length, which means loss in signal-to-noise in the reverberation-limited case, as can also be seen from the results of Section 3; see van der Spek [3,4]. Similar results have been obtained with frequency-modulated pulses of different bandwidths. Also, the influence of increased bandwidth on detection quality in reverberation has been observed.

Now, the practical importance of the equal detection quality of the two processors is as follows: if the Doppler spread in the medium increases, the full replica correlator, which has the advantage of allowing a high target resolution (Fig. 4), which might be desirable for classification purposes, will begin to suffer and will finally fail if the coherence length becomes shorter than the pulse length. The segmented replica correlator is more robust, since the length of the individual replicas is much shorter than the pulse length, and the coherence length required only has to be adapted to allow coherent processing of the segments. Therefore, if it is suspected that Doppler spread may cause problems, a segmented replica correlator should be used. Since the split-spectrum processor contains both methods, and since they are based on the same type of pulse, a software implementation makes it possible to choose the processor adapted to the environmental conditions.

5. CONCLUSION

Two different signal processors for the detection of extended targets are presented, and a theoretical analysis of the split-spectrum processor for extended targets is given. Results of the processing of real data of a wide-band FM are shown. The experimental results confirm the theoretical target and channel model.

6. REFERENCES

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