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METHODES SUB-OPTIMALES POUR LA SUPPRESSION ADAPTATIVE DU FOUILLIS

A SUB-OPTIMUM APPROACH TO THE ADAPTIVE CLUTTER FILTERING IN RADAR

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RESUME

Dans plusieurs situations opérationnelles l'interférence des radars est composée d'un numero limité de sources de fouillis (typiquement, jusqu' a deux) plus bruit blanc.
Dans ce papier on présente une méthode paramétrique pour l'élimination adaptative de plusieurs sources de fouillis.

Le filtre de suppression a tous les zéros sur le cercle unitaire; leur position dépends ou bien du rapport de puissance des sources (adaptivité paramétrique partielle) ou encore de leur corrélation (adaptivité paramétrique totale).

Des stratégies simplifiées pour l'allocation des zéros comportent des trés petites pertes du facteur d'amelioration.

Les filtres paramètriques optimal et sub-optimal ont été analyseés d'une façon detailée; les principaux résultats sont la position des zéros et le facteur d'amelioration avec deux sources de fouillis, sans erreurs d'éstimation.

SUMMARY

In most operational situations the disturbance environment of radars is composed by a limited number of clutter sources (typically, up to two) plus white noise.

In this paper, a parametric approach to the adaptive cancellation of clutter from multiple sources is presented. The cancellation FIR filter has all zeros on the unitary circle; the position of the zeros just depends upon the power ratio of the clutter sources (partial parametric adaptivity) or depends on their correlation coefficients too (complete parametric adaptivity).

Simplified strategies for the allocation of nulls lead to very reduced Improvement Factor losses with respect to the optimum allocation.

A detailed analysis of the complete (optimum) and partial (suboptimum) parametric filters has been carried out; the main presented results are the location of zeros and the Improvement Factor of both solutions in a two clutter sources environment, in the absence of estimation errors.

1. INTRODUCTION

The detection problem of a known signal in a background of coloured gaussian noise is extensively treated in the literature /1/.
In the case that the useful signal is a coherent train of N pulses, the pertaining optimum detector, shown in Fig. 1, is linear and utilizes a FIR filter with N complex weights:

$$\underline{W}_T = w_1, w_2 \ldots\ldots w_N \qquad (1)$$

to be selected in order to maximize the signal-to-interference power ratio. In the radar applications, an important interference is the so called clutter, i.e. the unwanted echo of land, sea and rain, that is highly correlated along the train of pulses, /2/.

Assuming that clutter is a discrete-time gaussian process, it is completely characterized by the NxN covariance matrix $\underline{M}$:

$$\underline{M} = E\left\{\underline{C}^* \, \underline{C}_T\right\} \qquad (2)$$

where $\underline{C}$ is the vector of N clutter samples, taken at the pulse-repetition frequency (PRF) of the radar.

The figure of merit of the considered receiver is the Improvement Factor, η , defined as:

$$\eta = \frac{(SCR)_o}{(SCR)_i} \qquad (3)$$

i.e. the signal-to-clutter power ratio at the output of the filter divided by the ratio at the input.

2. OPTIMUM FILTERING FOR UNKNOWN SIGNAL FREQUENCY

This paper deals with the case that the doppler frequency of the signal is random, uniformly distributed in the (O - PRF) interval. The pertaining expression of η is:

$$\eta = \frac{\underline{W}_T^* \underline{W}}{\underline{W}_T^* \underline{M} \underline{W}} \qquad (4)$$

where stationarity is assumed (i.e. $\underline{M}$ is not only Hermitian , but also of the Toeplitz form /5/) and the clutter input power is normalized (i.e. $M_{ii}=1$, $i = 1,2,...N$).

The maximization of η /4/, /5/, leads to the following optimum weights:

$$\underline{W} = \underline{E}_{min} \qquad (5)$$

where $\underline{E}_{min}$ is the eigenvector corresponding to the minimum eigenvalue, λ_{min}, of $\underline{M}$; the related maximum Improvement Factor is:

$$\tilde{\eta} = \frac{1}{\lambda_{min}} \qquad (6)$$

and the related filter, or "eigenfilter", has the following response:

$$H_D(z) = \sum_{k=0}^{N-1} w_{k+1} z^{-k} \qquad (7)$$

and its zeros lie on the unitary circle /3/, /4/, /5/

The doppler frequency response H(f) of the filter is:

$$H(f) = H_D\left[z = \exp(j\, 2\pi f/PRF)\right] \qquad (8)$$

The (N-1) zeros of H(f) in the (0-PRF) unambiguous doppler interval identify the stop-bands (or cancellation bands). They can be computed by solving the eigenvalues equation (5) and finding the phase of the zeros of (7).

3. A CLUTTER MODEL

A widely used clutter model considers a given number (one, two or three) of independent clutter sources, each with a gaussian spectrum. The normalized covariance matrix of this model (in the case of two sources) is:

$$\underline{M} = \frac{Q}{1+Q}\underline{M}_1 + \frac{1}{1+Q}\underline{M}_2 \qquad (9)$$

where:

$Q= C_1/C_2$ is the ratio of the clutter-to-noise power ratio of the first source (C_1) and the one of the second (C_2).

$\underline{M}_1$ and $\underline{M}_2$ are the normalized covariance matrix of the two sources, respectively. The (i,k) element of M_1 is:

$$M_1(i,k) = \rho_1^{(i-k)^2} \exp\left[(j\alpha_1(i-k))\right] \qquad (10)$$

where ρ_1 is the "correlation coefficient" of the first source, and α_1 is its "doppler coefficient", related to the average doppler frequency f_1 by:

$$\alpha_1 = 2\pi\, f_1/PRF \qquad (11)$$

Equivalent parameters describe $\underline{M}_2$.

The "two sources" model describes a typical situation of land clutter (with doppler coefficient zero, if the radar is fixed, and correlation coefficient very close to one, e.g. equal to 0.995) and rain clutter (with doppler coefficient generally different from zero and a smaller correlation coefficient, e.g. 0.85) in the same radar resolution cells.

Note that considering the thermal noise contribution (with NCR_2 = power ratio of the noise to clutter source number two) the expression (9) should be rewritten as:

$$\underline{M}' = \frac{Q}{1+Q+NCR_2}\underline{M}_1 + \frac{1}{1+Q+NCR_2}\underline{M}_2 + \frac{NCR_2}{1+Q+NCR_2}\underline{I}$$

However, the addition of the last term does not alter the eigenvectors of $\underline{M}$, and the optimum filter remains the same; moreover, the Improvement Factor is commonly referred to the "clutter only" situation.

Therefore, expression (9) is used throughout this paper.

4. BEHAVIOUR OF THE OPTIMUM FILTER

It may be interesting to evaluate the optimum filter response, eqns. (5), (7) and (8), and performance, eqn. (6), for the "two clutters" environment of the previous paragraph.

In the frequency domain, the situation is sketched in Fig. 2 where the solid line is the power spectral density of the clutter and the dashed line is the modulus of H(f) of the optimum, 4 samples filter.

The avalaible three zeros are allocated on the frequency axis in such a way as to provide greater cancellation on the strongest source, that is clutter 1. The distance between the two zeros in the clutter 1 spectral region depends upon the pertaining correlation coefficient, i.e. increases with the spectral width increasing. The remaining zero is allocated at the centre of the spectrum of clutter 2, in order to maximise its suppression.

As one could expect, this behaviour /6/ depend just on the two parameters: Q and $(\alpha_2 - \alpha_1)$.

If the α are fixed, e.g. $\alpha_1 = 0$ and $\alpha_2 = \pi$ (corresponding to the greatest doppler separation), the zeros remain quite fixed for a wide interval of variation of Q, and sharply move in correspondance to a very limited number of values of Q.

Therefore, an attempt can be made to approximate the optimum filter by estimating Q, α_1 and α_2 and setting the zeros according to a suitable strategy.

Once again, the detection of a signal in an unknown interference (clutter) background requires four steps:

a) Modeling of the power spectral density of interference
b) Designing the optimum filter according to the model
c) Estimating the parameters of the model from actual data
d) Selecting the pertinent coeffients of the filter .

Widely used models /7/ are the all-pole or Auto regressive (AR) one, that leads to the Yule-Walker equations, and the Pisarenko harmonic decomposition, that leads to an eigenvector problem. The former is computationally much more attractive when the weights have to be computed in real-time; however, in the radar case the matching of the model with a typical situation of two clutter sources requires /8/ a fairly high (more that ten) number of poles.

In this paper, the clutter is modeled in a straight- forward way (two or more gaussian spectra) and the number of parameter to be estimated is kept to the minimum, c.e. 2K-1 real quantities (K is the number of clutter sources) when correlation coefficients are assumed "a priori" and 3K-1 when correlation coefficients have to be estimated. Therefore, this approach will be referred to as "parametric filtering", and as "partial adaptivity" when the filter is designed for "a priori" correlation coefficients (in particular, equal to one).

5. TYPICAL RESULTS

Some typical results related to the performance of a parametric filter without any estimation error (item (b) of the previous paragraph) are shown in the following.

The considered clutter environment has two sources (source 1 being a typical ground, source 2 a typical rain) with:

$$\rho_1 = 0.995, \; f_1 = 0$$
$$\rho_2 = 0.85, \; f_2 = 0.5 \text{ PRF}$$

The power ratio $Q = C_1/C_2$ varies between -50 dB and +50 dB. The absolute value of the power of one source (e.g. C_2) is not relevant as the considered covariance matrix (expr. (9)) does not contain the white noise contribution, as explained in sect. 4.

Figure 3 shows the normalized frequency of each of the three zeros of the four sample optimum filter, versus Q, i.e. the solutions of the equation $H(f) = 0$, with $H(f)$ given by (8).

For Q lower than -15 dB, the optimisation algorithm (expression (5)) uses all three nulls to reject the No. 2 source, i.e. the strongest one.

For Q between -15 and +13 dB one null is used for clutter No. 1 and the other two remain on No. 2 with a narrower frequency separation. The reason for this is the smaller number of nulls that are required by clutter No. 1 for a given degree of rejection, due to its narrower spectral width (higher correlation coefficient), with respect to No. 2.

Figure 4 shows the "partial Improvement Factors" η_1 and η_2 of each source, defined by expression (4) with $\underline{M}_1$ and $\underline{M}_2$ in place of M, and the "total" Improvement Factor η (expressions (4) and (9)).

Similar results, in the same clutter environment as above and for a five sample filter, are shown in Figg. 5 and 6.

The behaviour of the "phase plots" of figure 3 leads to consider a strategy in which the nulls are moved in steps, depending on Q exceeding suitable threshold values (parametric filter). The pertaining phase plots are shown in figure 7 and the Improvement Factor values in figure 8. Comparison of figure 8 with figure 4 shows very reduced and practically negligible losses.

Finally, the "partial adaptivity" case is considered, i.e. the correlation coefficients ρ_1 and ρ_2 approaches the unity, leading to coincident nulls (binomial cancellers) for each isolated clutter source.

The pertaining phase plots are shown in Figure 9 and the Improvement Factor values are shown in figure 10. The maximum loss of the "partial adaptive" filter is lower than 3 dB for the most of Q values.

CONCLUSIONS

A parametric approach to the adaptive cancellation of multiple clutter sources is described. The pertaining filter has all zeros on the unitary circle; their position depend on the power ratio of the clutter sources (partial adaptivity) and on their correlation coefficients ("complete" parametric adaptivity). Simple strategies for the allocation of nulls lead to very reduced Improvement Factor losses with respect to the optimum allocation, obtained by solving an eigenvector problem.

The effect of errors in estimating the relevant parameters will be discussed in a future work.

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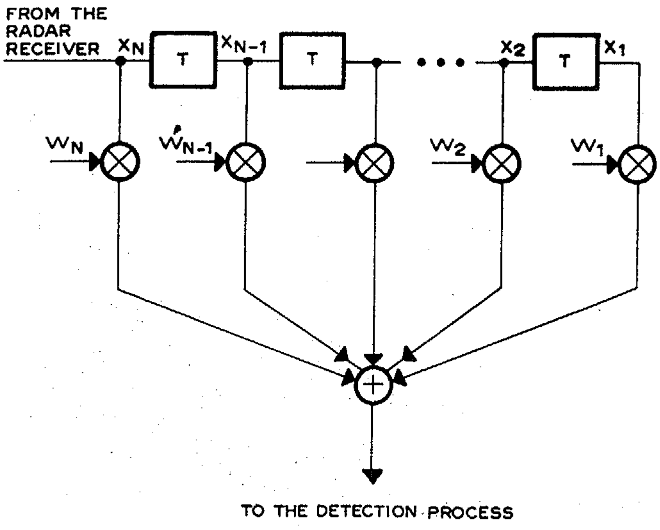
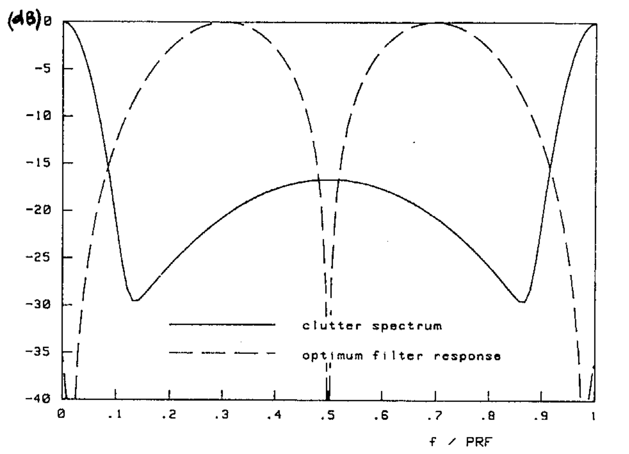
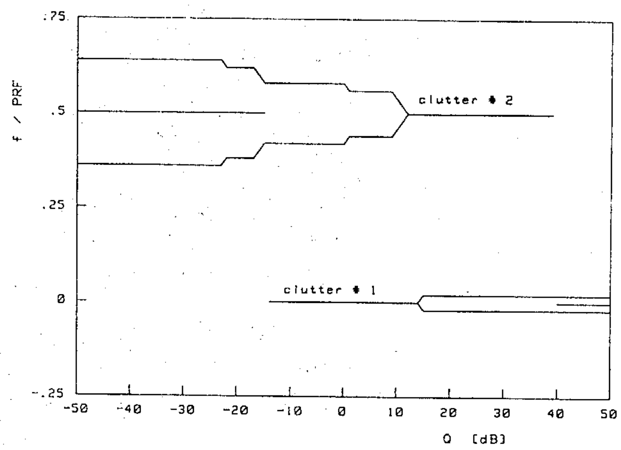


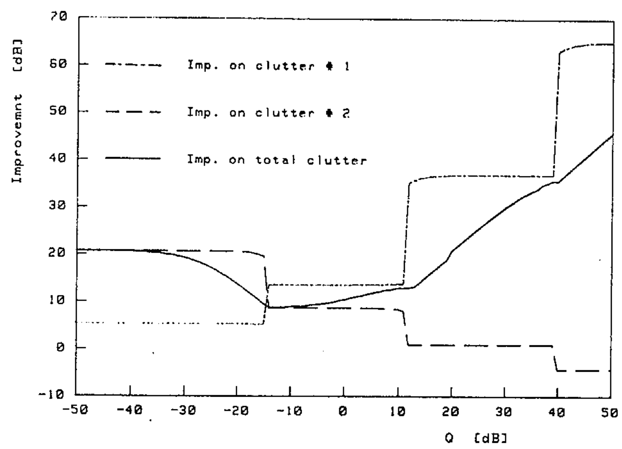
1 : FIR filter structure.



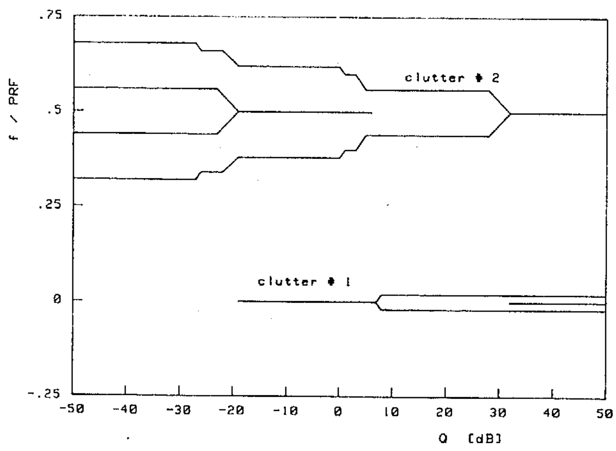
2 : Disturbances spectrum and optimum filter transfer function.



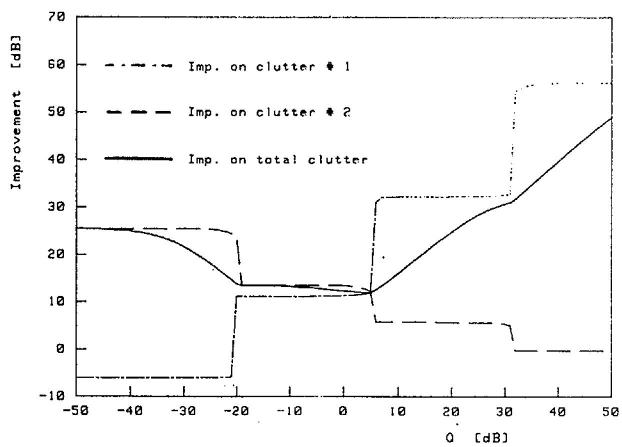
3 : Zeros phase plots for optimum filter (N = 4).



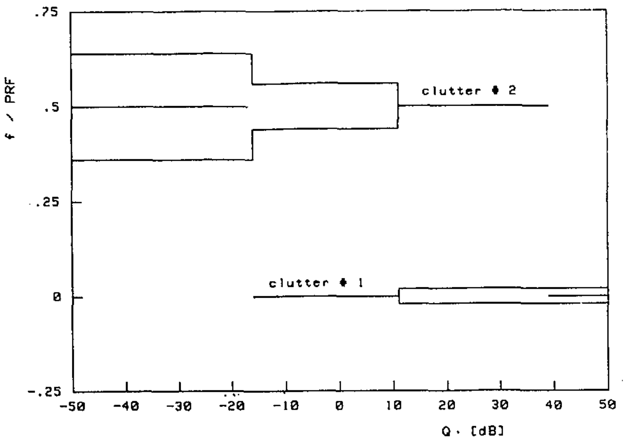
4 : Improvement factors η_1, η_2, η of optimum filter (N = 4).



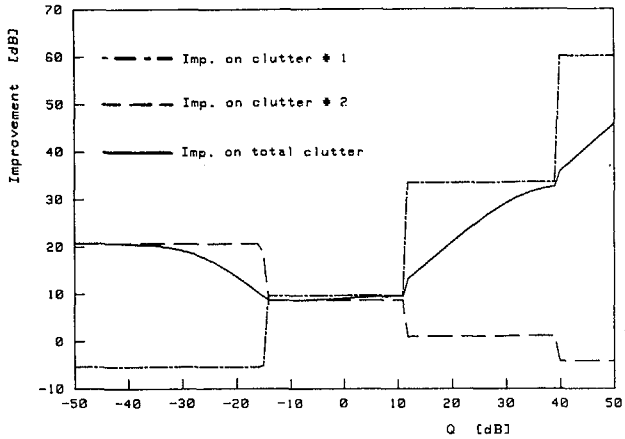
5 : Zeros phase plot[illegible] optimum filter (N = 5).



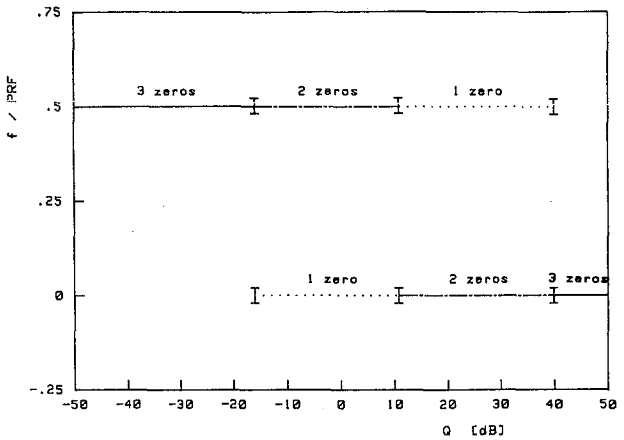
6 : Improvement factors η_1, η_2, η of optimum filter (N = 5).



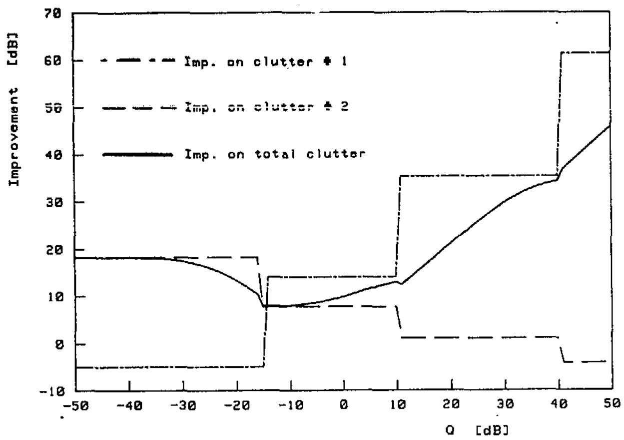
7 : Zeros phase plot for suboptimum parametric filter (N = 4).



8 : Improvement factors η_1, η_2, η of suboptimum (parametric) filter (N = 4).



9 : Zeros phase plot for suboptimum (partial adaptivity filter) (N = 4).



10: Improvement factors η_1, η_2, η of suboptimum (partial adaptivity) filter (N = 4).