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# SYSTEMES OPTIMALES ET SUB-OPTIMALES POUR LA SUPPRESSION DU FOUILLIS DANS LES RADARS A IMPULSIONS AVEC ESTIMATION EN TEMPS REEL

# OPTIMAL AND SUB-OPTIMAL TECHNIQUES FOR CLUTTER SUPPRESSION IN PULSED RADARS BY REAL-TIME ESTIMATION OF THE INTERFERENCE

S. BARBAROSSA*, G. GALATI*[+], G. PICARDI[x]

* SELENIA S.p.A. - Via TIBURTINA Km. 12,400 ROME ITALY

[+] UNIVERSITY OF L'AQUILA

[x] INFO-COM DPT, UNIVERSITY OF ROME.

## RESUME

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Ce papier traite le probléme de l'élimination adaptative d'interférences trés corrélées (fouillis) dans les radar cohérents à impulsions.

Les filtres à treillis resultent convénient pour la réalisation de l'algorithme optimale de prédiction linéaire. Ces filtres usent ou bien une forme convéniente de l'éstimateur de Burg ou encore un estimateur nouveau, le CHS.

Le facteur d'amélioration des filtres est évalué pour les deux cas en situations typiques (une source et deux sources de fouillis).

## SUMMARY

ABSTRACT

The problem of the adaptive suppression of correlated interference (clutter) in coherent radar systems is considered.

A convenient implementation of the optimal linear prediction algorithm is found to be the lattice filter, that utilizes either a suitable form of the Burg estimator or a novel multiplication-free estimator, the CHS.

The Improvement Factor of the adaptive filter is evaluated for both estimators in typical (single and double clutter sources) situations.

## 1. INTRODUCTION

In many operational environments of radar systems /1/ the main interference is due to a limited number of clutter sources (i.e. land, land plus rain, sea plus rain etc.) whose power is much greater than the useful signal.

In the case that the latter is a coherent train of pulses and the interference is gaussian (and coloured, due to the addition of strongly-correlated clutter sources and receiver noise), the optimum detector /2/ is linear and utilizes a FIR filter followed by a decision threshold.

The two main optimisation criteria refer (i) to maximise the signal-to-interference increase due to the filter, referred to as Improvement Factor (approach by Hsiao: see /3/ and its bibliography), and (ii) to minimise a prediction error (Linear Prediction approach and Wiener filtering, /4/). Both apply when the doppler frequency of the useful signal, being unknown a priori, is assumed to be a random variable with uniform probability density in the [0, PRF] interval, where PRF is the pulse-repetition frequency of the radar. Both criteria aim to minimize the interference power at the filter output; their difference is in the constraint on the coefficients of the filter:

$$\underline{W}_T = (W_1, W_2 \ldots\ldots W_N)$$

In the Hsiao approach the constraint is:

$$\underline{W}_T^* \cdot \underline{W} = \text{constant}$$

whereas in the linear prediction approach it is:

$$\underline{W}_T^* \cdot \underline{S} = \text{constant}$$

where $\underline{S}$ is a particular "steering" signal, namely:

$$\underline{S}_T = (0, 0 \ldots . 0, 1)$$

and the index T stands for transposed, the asterix indicates complex conjugate.

The former approach leads to an eigenvector problem /3/, while the latter, that is the one considered in this paper, leads to a linear prediction problem /4,5,6/, namely to the design of the optimum (in the minimum-mean-square-error, MMSE, sense) filter for the prediction of the last (n-th) interference sample given the previous N-1.

This filter tends to "whiten" (decorrelate) the disturbance; its coefficients are the solution of the so-called "normal equations" /4/:

$$\underline{W} = \underline{M}^{-1} \cdot \underline{S} \qquad (1)$$

where $\underline{M}$ is the normalized, NxN covariance matrix of the disturbance $\underline{c}$:

$$\underline{M} = N\ E\ (\underline{c}^{*} \cdot \underline{c}_T)\ /E\ (\underline{c}_T^{*} \cdot \underline{c}) \qquad (2)$$

Considering the correlated part (clutter) of the interference, a commonly accepted model for its spectrum is the Barlow's /1/ one, i.e. for a single clutter source the element of $\underline{M}$ of order i and k is:

$$M_1\ (i,k) = \rho_1^{\ (i-k)^2}\ \exp\ (j\, \alpha_1 (i-k)) \qquad (3)$$

where $\rho_1$ is the "correlation coefficient "at lag T = 1/PRF of the source and $\alpha_1$ is its "doppler coefficient" ($\alpha_1 = 2\pi\ f_d/PRF$ where $f_d$ is the average doppler frequency). Typical values of $\rho_1$ are between 0.85 and 0.999.

The normalized covariance matrix of a "L clutter sources" situation is:

$$\underline{M} = \sum_{n=1}^{L} Q_n \underline{M}_n \Big/ \sum_{n=1}^{L} Q_n \qquad (4)$$

where $Q_n$ is the power ratio of the n-th source to the L-th one ($Q_L = 1$).

Expression (4) does not contain the thermal noise contribution that is not considered in this paper to limit the number of parameters to vary in the evalutions. In a "two clutter sources" situation (e.g. rain and land clutter for a shipborne radar) the relevant parameters with this simple model /3/ are just five, i.e. $\rho_1$, $\rho_2$, Q, $\alpha_1$ and $\alpha_2$.

## 2. THE LATTICE FILTER

The adaptivity to the a-priori unknown interference requires a real-time solution of equation (1) to obtain the weights of the whitening filter $\underline{W}$.

A computationally efficient procedure utilizes the Levinson algorithm /7/ that is conveniently implemented by a lattice filter /5/, /6/ /13/. The coefficients of the lattice, known as "reflection" (or "partial correlation") coefficients, result from the Levinson recursion, but are more conveniently obtained by estimating the one-lag cross-correlation coefficient between the "forward" and the "backward" prediction errors, at each stage.

A block diagram of the adaptive canceller is shown in Fig. 1 where the inputs to the "correlation estimator" are from different range bins.

By minimising the power of the forward (f) and the backward (b) prediction errors for the i-th stage of the lattice the "forward reflection coefficient" $k_i^{(f)}$ and the "backward reflection coefficient" $k_i^{(b)}$ are evaluated.

A common estimation technique for the coefficients of the lattice is the armonic average of $k_i^{(f)}$ and $k_i^{(b)}$, leading to the Burg's estimator /9/:

$$k_i^{B} = - \frac{E\left[ e_{i-1,n} \cdot b^{*}_{i-1,n-1} \right]}{\frac{1}{2}\left\{ E\left[ |e_{i-1,n}|^2 \right] + E\left[ |b_{i-1,n-1}|^2 \right] \right\}} \qquad (5)$$

where E(.) indicates the statistical expectation, that in practice is approximated by an average.

The choice of the geometric mean leads, on the other hand, to the maximum likelihood estimator (MLE) of the correlation coefficient between $e_{i-1,n}$ and $b_{i-1,n-1}$ that in practice does not significantly differ from the Burg one, both from its statistical properties and from the filter behaviour.

To reduce the computational cost, simpler estimators (with reduced performances) may be utilized. Among them, a suitable complex version (CHS) /5/, /9/, of the "hybrid sign" estimator (HS) /8/, /11/, /12/, that has been recently analized just require sums for evaluating the numerator and the denominator of the reflection coefficients.

The HS estimator of the correlation coefficient between two real zero-mean variables x and y has the following expression:

$$\rho_{XY}^{HS} = \frac{E\left[ x \cdot \mathrm{sign}(y) \right]}{E\left[ |x| \right]} \qquad (6)$$

where

$$\mathrm{sign}\ (x) = \begin{cases} -1 & \text{if } x < 0 \\ \ \ 0 & \text{if } x = 0 \\ +1 & \text{if } x > 0 \end{cases}$$

In radar applications, stationarity inside the "clutter patch", i.e. for a limited (order of ten) number of range and azimuth bins, is assumed. Therefore, the statistical average of expressions (5) and (6) is substituted by a sample average over a given number of range bins (independent samples) and a given number of azimuth bins or sweeps (correlated samples). Only the independent samples average is considered in this work as the contribution of correlated samples is less important.

The behaviour of the lattice filter without estimation errors is conveniently described by the location of its zeros (remember that the filter transfer function is that of a FIR filter) in typical environments.

A "two clutter sources" environment (section 1) is considered here, with the power ratio of source 1 to source 2 varying and with doppler frequency equal to zero for source 1, and to one-half the PRF (i.e. $\alpha_2 = \pi$) for source 2. The correlation coefficients are $\rho_1 = 0.995$ and $\rho_2 = 0.85$ respectively.

The pertaining results, shown in Figures 2 and 3 for a fourth-order filter (four samples, three zeros) and in Figures 4 and 5 for a fifth-order filter (four zeros), can be compared with the equivalent ones of /3/ for the Hsiao filter.

## 3. PERFORMANCE OF THE ADAPTIVE FILTER

The performance of the adaptive canceller when a single clutter source is present depend on its correlation coefficient (i.e. its spectral width), on the order of the filter and on the estimation of the coefficients.

A typical situation of a fourth order filter with sixteen independent samples estimation ($N_R$ = 16) is considered here. Figure 6 shows the Improvement Factor of the filter versus the correlation coefficient in three cases: (a) ideal estimation (no errors), (b) Burg estimator and (c) CHS estimator.

The Improvement Factor $\eta$ is the signal-to-disturbance increase due to the canceller, with the doppler of the signal equally probable in the $[0, \text{PRF}]$ interval, and is related to the coefficients $\underline{W}$ of the equivalent FIR by:

$$\eta = \frac{\underline{W}_T^* \cdot \underline{W}}{\underline{W}_T^* \cdot \underline{M} \cdot \underline{W}} \qquad (7)$$

where $\underline{M}$ is the matrix $\underline{M}_1$ of expression (3).
The Improvement Factor losses w.r.t. the ideal case, for $\eta < 55$dB, are less than 1 dB for the Burg estimator and less than 3 dB for the CHS estimator.
The performances with the two clutter sources referenced in the previous section and the same estimators as in this section are shown in Figures 7 and 8 for a fourth order and a fifth order filter, respectively. The Improvement Factor $\eta$ (exp. (7) with $\underline{M}$ given by expr. (4) is plotted versus the power ratio Q of clutter 1 to clutter 2 for the three cases (a), (b), and (c) described before with $N_R = 16$.
The Improvement Factor losses of the CHS estimator w.r.t. the ideal case are less than 3 dB; the highest losses (i.e. 2.5 to 2.7 dB for the CHS estimator and 2 to 2.2 dB for Burg estimator) occur when the two clutter sources have nearly the same power.

## 4. CONCLUSIONS

The lattice filter is a promising tool for the adaptive cancellation of multiple clutter sources (e.g. rain and land in a naval application).
The Improvement Factor losses due to the estimation over a given number $N_R$ of independent samples are acceptable, (namely less than 3 dB for $N_R = 16$), when compared to the ones due to other reasons /10/ (finite word lenght for the signal and the coefficients; I and Q amplitude and phase unbalance etc.). Other important features of this adaptation procedure will be treated in further papers, including:

i) Performance in other clutter environments.
ii) The effect of thermal noise.
iii) Adaptive selection of the order of the filter.
iv) Comparison with "parametric" adaptation techniques /3/.

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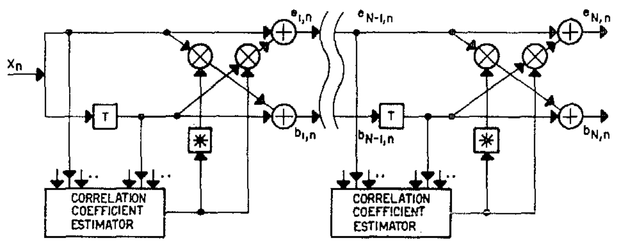


Fig. 1 Lattice filter
- T = pulse repetition period
- * : complex conjugate operator

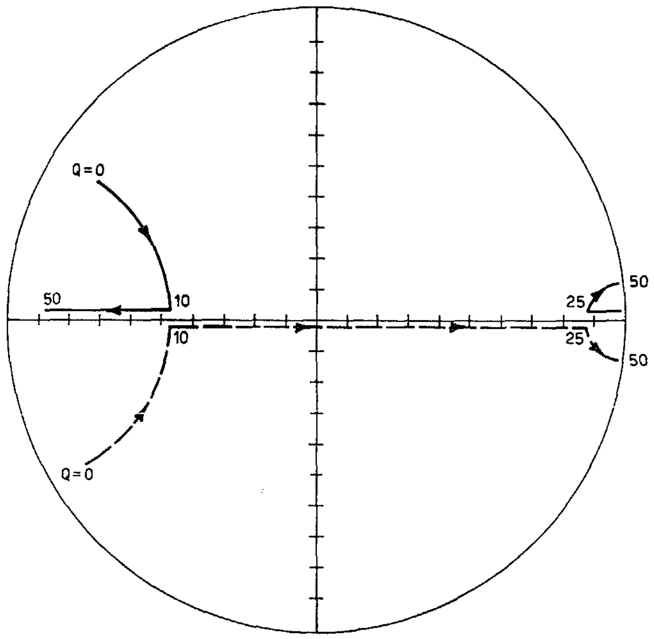


Fig. 2 Zeros location in the complex plane vs. power ratio Q two clutter sources
- filter order = 4

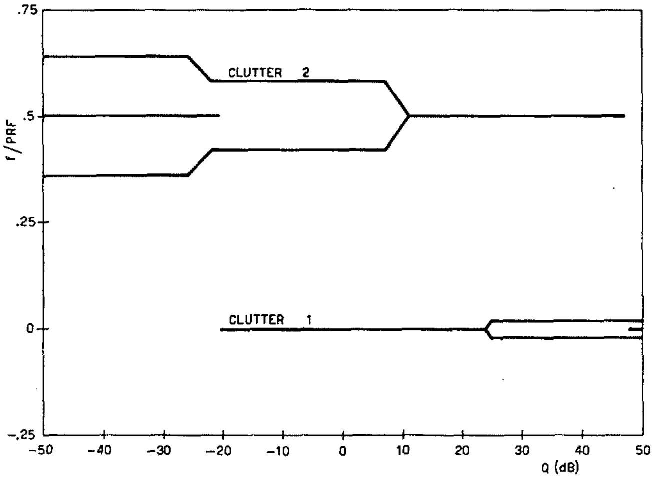


Fig. 3 Zeros location in the frequency domain vs. Q - two clutter sources
- filter order = 4

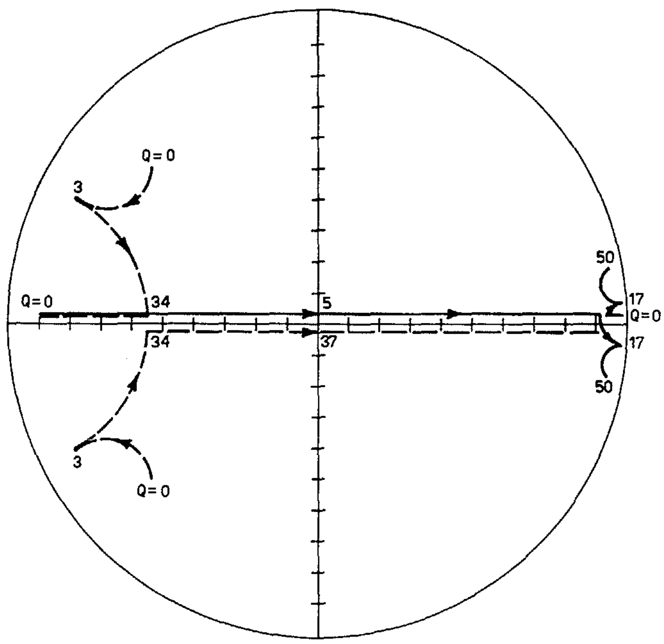


Fig. 4 Same as Fig. 2 with filter order = 5

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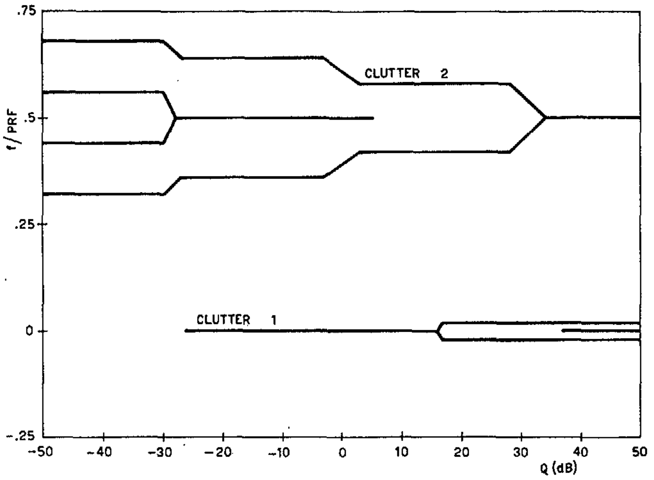


Fig. 5 Same as Fig. 3 with filter order = 5

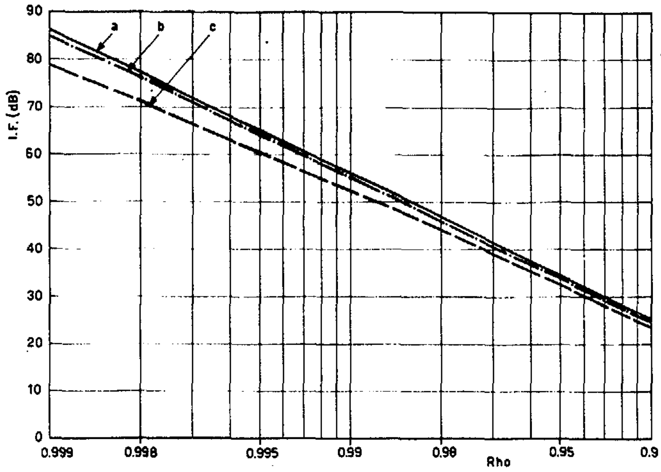


Fig. 6 Improvement Factor values vs. correlation coefficient (one clutter), for a filter order=4:
a) theoretical value;
b) Burg estimation
c) CHS estimation

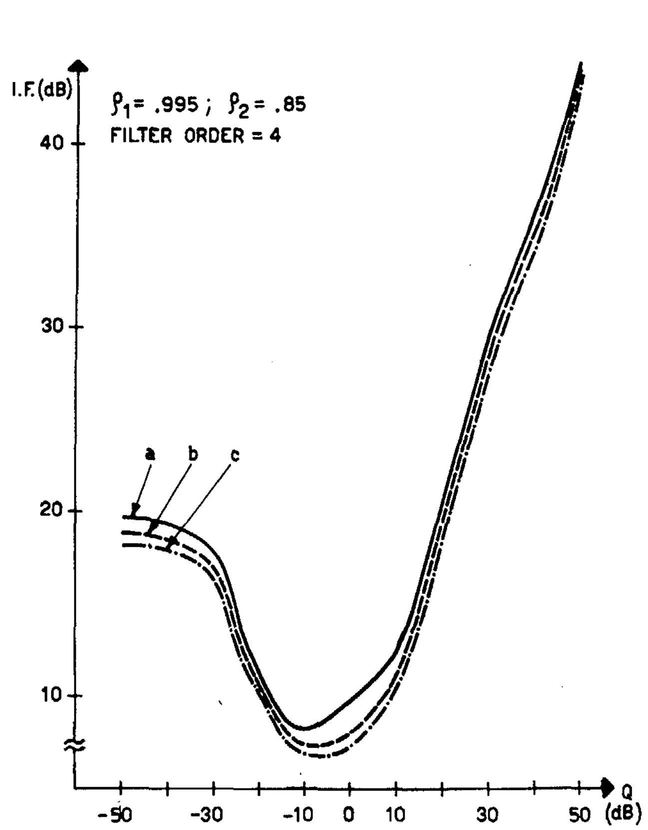


Fig. 7 Same as Fig. 6 but for two clutter sources.

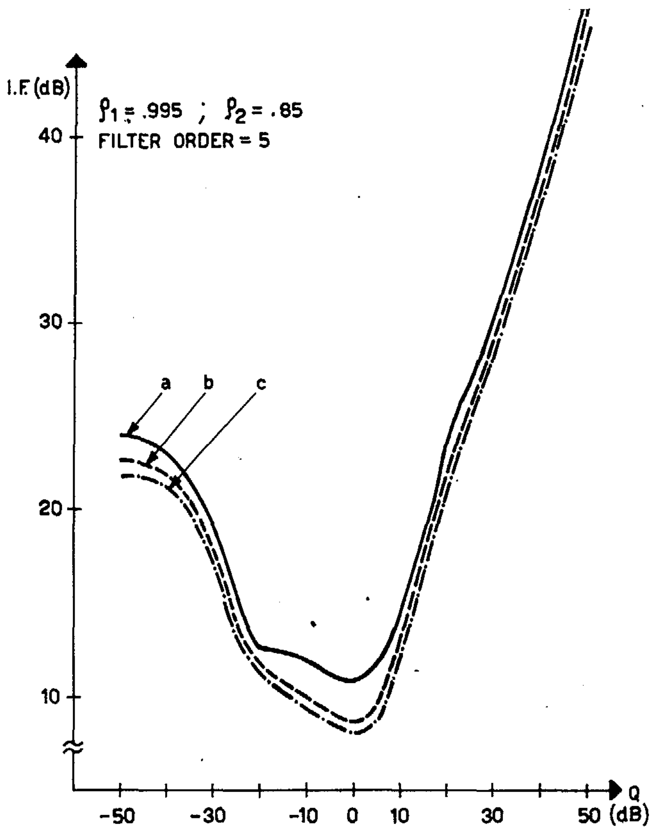


Fig. 8 Same as Fig. 6 but for two clutter sources and a filter order = 5.