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OBJECT

Conduct a Study and Investigation to Determine
an Optimum Method of Identifying Military Targets by Radar

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1. PURPOSE (This Section is UNCLASSIFIED)

The purpose of this program is to conduct an investigation to determine an optimum method of identifying military targets by radar means.

2. ABSTRACT (This Section is UNCLASSIFIED)

A new filter is devised which depends on a parameter so that the filter varies continually from the inverse to the matched filter. This 'mixed' filter then permits a compromise between the requirements of resolution and of discrimination. The mixed filter is now being used in the simulation program.

A uniform method of describing targets in terms of their frequency signatures is proposed. By means of this scheme we hope to be able to arrive at quantitative discrimination criteria for different targets.

3. VISITS AND CONFERENCES (This Section is UNCLASSIFIED)

3.1 Visit of Mr. Charles Eason to the Radiation Laboratory.

The mixed filter and target signature description schemes were discussed with Mr. Eason on 29 August 1963. Present were R.E. Hiatt, B.A. Harrison, O.G. Ruehr, Z.A. Akcasu and R.F. Goodrich.

3.2 Visit of Radiation Laboratory Personnel to Fort Monmouth, N. J.

On 7 June 1963, R.E. Hiatt, G. Rabson and R.F. Goodrich made an informal presentation of the work performed and planned under the contract at Fort Monmouth. Personnel contacted included Leonard Hatkin, Charles Eason, William Fishbein and Ralph Dunn. The topics emphasized in the presentation and later discussions were the use of the inverse filter and the problem of finding frequency signatures for the various targets. A point emphasized by G. Rabson was that the inverse filter is an excellent method of data reduction and should be considered such in conjection with the extremely short pulse research being done by General Dynamics.

An important problem presented by the Radiation Laboratory group was that of finding a uniform method of target signature characterization so that a quantitative criterion of target discrimination could be found. (For a tentative resolution of this problem, see Sec.4.4).

Mr. William Fishbein of the Signal Corps pointed out that the use of the inverse filter imposed rather extreme requirements on the signal-to-noise ratio. This observation led to our consideration of the matched filter and then the mixed filter of Sec.4.2.

In conjunction with the conference with the Signal Corps personnel, R.E. Hiatt and R.F. Goodrich attended the Ninth Annual Radar Symposium on June 4 - 6, 1963 at Fort Monmouth, New Jersey.

4. TECHNICAL WORK - 1 June through 31 August 1963 (This Section is UNCLASSIFIED).

4.1 Introduction

In this report we describe in Sec. 4.2 a more versatile filter which we are now analyzing and using in our machine simulation program (Sec. 4.3). The filter is designed to enable us to determine the best compromise between the conflicting requirements of resolution and discrimination.

In Sec. 4.4 we describe a proposed scheme for a uniform way of describing the various targets.

4.2 A Mixed Filter

The two problems of the target signature study, target discrimination and target resolution, are in a sense antithetical. Since, for best resolution an inverse filter is optimum; for best discrimination a matched filter is optimum, we propose a 'mixed' filter. We parameterize a filter so that it varies continuously from the inverse to the matched filter as a function of the parameter.

Although there are arbitrarily many ways of affecting the parameterization we have chosen one because it gives a simple representation of the filter and also the specific form of the parameterization is not important for our purposes.

We start with the return r(t) in the time domain:

$$r(t) = \sum_{\alpha,\beta} a_{\alpha\beta}\, s_\alpha(t-t_{\alpha\beta}) + n(t) \qquad (1)$$

where the index α indicates the type of the targets, and β distinguishes between the targets of the same type. Furthermore, $t_{\alpha\beta}$ is the time required for the signal to return from the β-th target of type α, and $a_{\alpha\beta}$ are constants depending on relative distances. The function $s_\alpha(t)$ characterizes the return signal from a target of type α, and n(t) is the noise (white, gaussian).

Finite Fourier transform of r(t) gives:

$$R(\omega) = \int_{-T}^{+T} r(t) e^{-i\omega t} dt = \sum_{\alpha,\beta} a_{\alpha\beta}\, e^{-i\omega t_{\alpha\beta}} \int_{-(T-t_{\alpha\beta})}^{T-t_{\alpha\beta}} s_\alpha(u) e^{-i\omega u} du + \epsilon(\omega), \qquad (2)$$

where

$$\epsilon(\omega) \equiv \int_{-T}^{T} e^{-i\omega t}\, n(t)\, dt \ . \tag{3}$$

Assuming that the integration time 2T is large compared to $t_{\alpha\beta}$, and defining

$$S_{\alpha}(\omega) \equiv \int_{-T}^{T} s_{\alpha}(u)\, e^{-i\omega u}\, du \tag{4}$$

one obtains $R(\omega)$ as follows:

$$R(\omega) = \sum_{\alpha,\beta} a_{\alpha\beta}\, e^{-i\omega t_{\alpha\beta}}\, S_{\alpha}(\omega) + \epsilon(\omega) \ . \tag{5}$$

Note that $R(-\omega) = R^{*}(\omega)$, $S_{\alpha}(-\omega) = S_{\alpha}^{*}(\omega)$ and $\epsilon(-\omega) = \epsilon^{*}(\omega)$. If we process $R(\omega)$ with the 'mixed' filter using the filter function

$$X_m(\omega) \equiv \frac{S_{\alpha}^{*}(\omega)}{m^2 + |S_{\alpha}(\omega)|^2} \tag{6}$$

we obtain a function $D_{\alpha_0}(t)$ as follows:

$$D_{\alpha_0}(t) = \frac{1}{A_{\alpha_0, m}} \int_{-\Omega}^{+\Omega} R(\omega)\, X_m(\omega)\, e^{i\omega t}\, d\omega \tag{7}$$

where $A_{\alpha_0 m}$ is the normalization factor defined by

$$A_{\alpha_0, m} \equiv \int_{-\Omega}^{+\Omega} \frac{\left|S_{\alpha_0}(\omega)\right|^2}{m^2 + \left|S_{\alpha_0}(\omega)\right|^2} \, d\omega \ , \tag{8}$$

where Ω is a constant frequency determining the range of integration.

The explicit form of $D_{\alpha_0}(t)$ is obtained by substituting $R(\omega)$ from (5) into (7):

$$D_{\alpha_0}(t) = \frac{1}{A_{\alpha_0, m}} \sum_{\alpha, \beta} a_{\alpha\beta} \int_{-\Omega}^{+\Omega} \frac{S_\alpha(\omega)\, S^*_{\alpha_0}(\omega)\, e^{-\omega(t - t_{\alpha\beta})}}{m^2 + \left|S_{\alpha_0}(\omega)\right|^2} \, d\omega$$

$$+ \frac{1}{A_{\alpha_0, m}} \int_{-T}^{+T} n(u)\, du \int_{-\Omega}^{+\Omega} \frac{S^*_{\alpha_0}(\omega)\, e^{i\omega(t-u)} \, d\omega}{m^2 + \left|S_{\alpha_0}(\omega)\right|^2} \ . \tag{9}$$

Obviously, $D_\alpha(t)$ is a real quantity. The 'matched' filter limit is obtained by letting $m \rightarrow \infty$:

$$D_{\alpha_0}(t) = \frac{1}{A_{\alpha_0}} \sum_{\alpha, \beta} a_{\alpha\beta} \int_{-\Omega}^{+\Omega} S_\alpha(\omega)\, S^*_{\alpha_0}(\omega)\, e^{i\omega(t - t_{\alpha\beta})} \, d\omega$$

$$+ \frac{1}{A_{\alpha_0}} \int_{-T}^{+T} n(u)\, du \int_{-\Omega}^{+\Omega} S^*_{\alpha_0}(\omega)\, e^{i\omega(t-u)} \, d\omega \ , \tag{10}$$

where

$$A_{\alpha_0} \equiv \lim_{m \to \infty} m^2 A_{\alpha_0, m} = \int_{-\Omega}^{+\Omega} \left|S_{\alpha_0}(\omega)\right|^2 d\omega \tag{11}$$

The expected value of $D_{\alpha_0}(t)$ is the first term on the right-hand side of (9), because the mean value $\overline{n(u)}$ of the noise is zero. Let $\overline{D_{\alpha_0}}(t)$ denote the expected (or mean) value of $D_{\alpha_0}(t)$. One can express $\overline{D_{\alpha_0}}(t)$ as follows:

$$\overline{D_{\alpha_0}}(t) = \sum_{\beta} a_{\alpha_0\beta} \int_{-\Omega}^{+\Omega} \frac{|S_{\alpha_0}(\omega)|^2 \, e^{i\omega(t-t_{\alpha_0\beta})}}{A_{\alpha_0,m}\left[m^2+|S_{\alpha_0}(\omega)|^2\right]} \, d\omega$$

$$+ \sum_{\alpha\neq\alpha_0,\beta} a_{\alpha\beta} \int_{-\Omega}^{+\Omega} \frac{S^*_{\alpha_0}(\omega)\, S_{\alpha}(\omega)\, e^{i\omega(t-t_{\alpha\beta})}}{A_{\alpha_0,m}\left[m^2+|S_{\alpha_0}(\omega)|^2\right]} \, d\omega \; . \qquad (12)$$

Before beginning to discuss the various aspects of this expression, it seems to be in order to consider the variance of $D_{\alpha_0}(t)$.

<u>Noise-to-Signal Ratio</u>: We define the noise-to-signal ratio ρ_{α_0} as

$$\rho_{\alpha_0} \equiv \left[\overline{\left[D_{\alpha_0}(t)-\overline{D_{\alpha_0}}(t)\right]^2}\right]^{1/2} \; . \qquad (13)$$

Using (9), one obtains

$$\rho^2_{\alpha_0} = 2\pi\left(\frac{\sigma}{A_{\alpha_0,m}}\right)^2 \int_{-\Omega}^{+\Omega} \frac{|S_{\alpha_0}(\omega)|^2}{\left[m^2+|S_{\alpha_0}(\omega)|^2\right]^2} \, d\omega \; . \qquad (14)$$

In obtaining (14), we have used the fact that the noise is white, viz.,

$$\overline{n(u)n(u')} = \sigma^2 \, \delta(u-u') \; ,$$

and the approximation

$$\int_{-T}^{+T} e^{-i(\omega+\omega')t} \, dt \cong 2\pi\,\delta(\omega+\omega') \;.$$

It is noted that (ρ_{α_0}/σ), where σ is the effective value of the noise, depends on the type of the target as well as on m. The variation of (ρ_{α_0}/σ) with m is of interest. Qualitatively, this variation is expected to be as shown in Fig. 1.

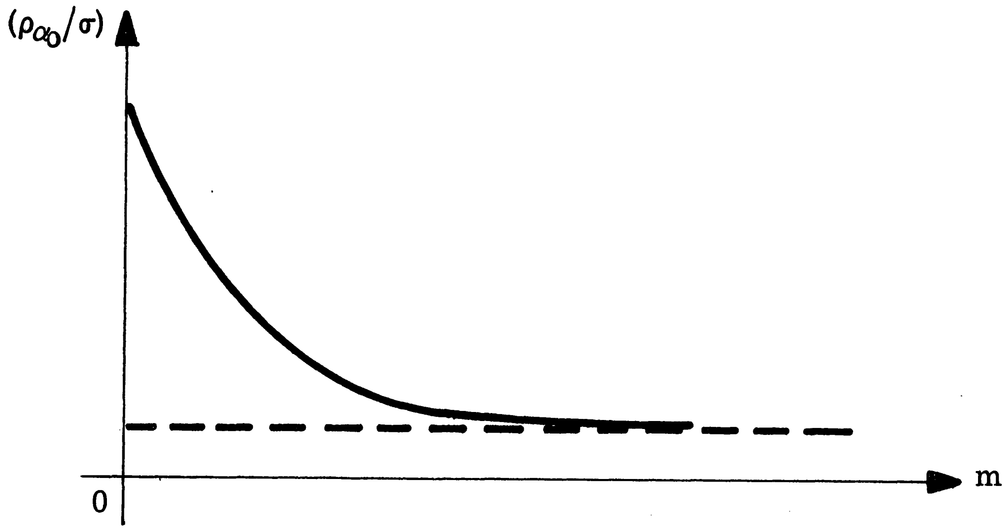

FIG. 1:

For m = 0, one has

$$\left(\frac{\rho_{\alpha_0}(0)}{\sigma}\right)^2 = \frac{\pi}{2\,\Omega^2}\int_{-\Omega}^{+\Omega}\frac{d\omega}{\left|S_{\alpha_0}(\omega)\right|^2}\,, \tag{15}$$

which corresponds to the 'inverse' filter. When m $\rightarrow \infty$, the 'matched' filter limit is obtained:

$$\left[\frac{\rho_{\alpha_0}(\infty)}{\sigma}\right]^2 = \frac{2\pi}{\int_{-\Omega}^{+\Omega}\left|S_{\alpha_0}(\omega)\right|^2 d\omega}\,. \tag{16}$$

The fact that the above value of the noise-to-signal ratio represents the smallest possible value is proven in the theory of matched filters.

<u>Pulse Width:</u> We now turn to the first term in (12), and investigate the quantity

$$d_{\alpha_0\beta}(t) \equiv \frac{1}{A_{\alpha_0} m}\int_{-\Omega}^{+\Omega}\frac{\left|S_{\alpha_0}(\omega)\right|^2 e^{i\omega(t-t_{\alpha_0\beta})}}{m^2+\left|S_{\alpha_0}(\omega)\right|^2}\,d\omega\,,$$

which is a typical term in the summation on β. It represents a peaked function at $t=t_{\alpha_0\beta}$ with a height 1 . The half-width W(m) of this peak is defined by

$$\int_{-\Omega}^{+\Omega}\frac{\left|S_{\alpha_0}(\omega)\right|^2}{m^2+\left|S_{\alpha_0}(\omega)\right|^2}\,e^{i\omega W(m)/2}\,d\omega = \frac{A_{\alpha_0} m}{2}\,. \tag{17}$$

The dependence of W(m) on m is also of interest. Fig. 2 depicts the predicted qualitative variation of W(m) with m.

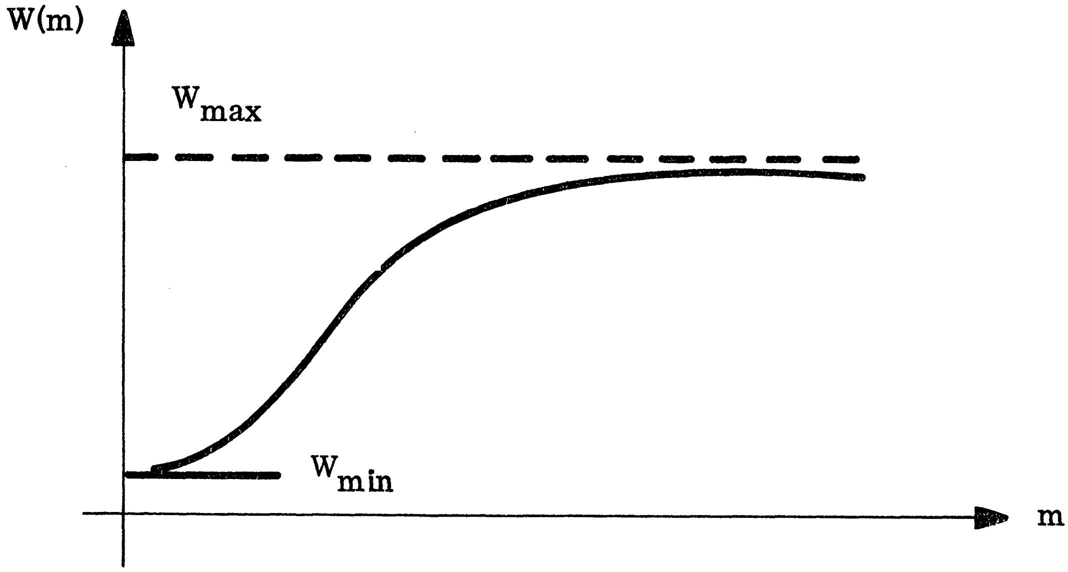

FIG. 2:

The minimum value of the width is obtained from (17) as the root of

$$\sin (W_{min}\Omega/2) = (\Omega W_{min}/4) \tag{18}$$

which is approximately given by

$$W_{min} \approx \frac{2\sqrt{3}}{\Omega} \quad . \tag{19}$$

This is the minimum width attainable by any filter.

The asymptotic value of W(m) as m $\rightarrow \infty$ follows from (17) as the solution of

$$\frac{1}{2}\int_{-\Omega}^{+\Omega} |S_{\alpha_0}(\omega)|^2 d\omega = \int_{-\Omega}^{+\Omega} |S_{\alpha_0}(\omega)|^2 e^{i\omega \frac{W_{max}}{2}} d\omega \ , \tag{20}$$

which can be approximated by

$$W_{max}^2 \approx 4 \, \frac{\int_0^{\Omega} |S_{\alpha_0}(\omega)|^2 \, d\omega}{\int_0^{\Omega} \omega^2 \, |S_{\alpha_0}(\omega)|^2 \, d\omega} \quad . \tag{21}$$

Counting the Number of Identical Targets: When there is only one type of target, (12) reduces to

$$\overline{D}(t) = \sum_{\beta} a_{\beta} \int_{-\Omega}^{+\Omega} \frac{|S(\omega)|^2 \, e^{i\omega(t-t_{\beta})}}{A_m \left[m^2 + |S(\omega)|^2\right]} \, d\omega \tag{22}$$

where we have dropped the subscript α_0 which is now unnecessary.

If one is interested primarily in the number of targets, and if the ranges determined by t_{β} do not have to be determined with the maximum possible accuracy, one may choose $m \rightarrow \infty$, viz., 'matched' filter, since it provides the minimum noise-to-signal ratio. The possibility of overlapping peaks can be handled by forming the product of the pulse height and the pulse width. When the two pulses representing two different targets coincide completely, the height of the resultant peak is 2, and the width is just W_{max} given by (20). Therefore the product

$$\eta = \frac{\text{height x width}}{W_{max}} \quad , \tag{23}$$

is also 2. On the other hand, if the two peaks are adjacent and the tip of the resultant curve is obscured by the noise, one would interpret the result as one peak of height 1, but with a width $2W_{max}$. Thus, again the product η would be 2. It follows that the number of targets corresponding to an observed peak can be predicted from the values of η. If $.5 < \eta < 1.5$ there is one target, and if $1.5 < \eta < 2.5$ there are two targets, etc. This procedure can be applied, of course, to the finite values of m, also. In that case, the η will be normalized to the width W(m) which is obtained by (17) for the chosen value of m. Whether one can increase the accuracy in the determination of t_β, and thus of the range, by choosing a smaller m, will depend on the relative shape of the curves giving the m-dependence of the pulse width and the noise-to-signal ratio. Therefore, it is desirable first to plot these curves, for a few target types, by computing (14) and (17) numerically.

Distinguishing Between Two Different Types of Targets: Suppose that there are two different targets at the same distance. Then, (12) gives

$$\overline{D}_{\alpha_1}(t) = 1 + \int_{-\Omega}^{+\Omega} \frac{S^*_{\alpha_1}(\omega)\, S_{\alpha_2}(\omega)}{A_{\alpha_1, m}\left[m^2 + |S_{\alpha_1}(\omega)|^2\right]}\, d\omega\,, \tag{24}$$

where we denoted the targets by α_1 and α_2. If one processes the same return by the mixed filter corresponding to the target α_2, one obtains

$$\overline{D}_{\alpha_2}(t) = 1 + \int_{-\Omega}^{+\Omega} \frac{S^*_{\alpha_2}(\omega)\, S_{\alpha_1}(\omega)}{A_{\alpha_2} m\left[m^2 + |S_{\alpha_2}(\omega)|^2\right]}\, d\omega \quad . \tag{25}$$

On the other hand, if the return is processed by the filter corresponding to a third filter α_3, the outcome will be

$$\overline{D}_{\alpha_3}(t) = \int_{-\Omega}^{+\Omega} \frac{\left[S_{\alpha_2}(\omega) + S_{\alpha_1}(\omega)\right]\, S^*_{\alpha_3}(\omega)}{A_{\alpha_3} m\left[m^2 + |S_{\alpha_3}(\omega)|^2\right]}\, d\omega \quad . \tag{26}$$

In the case of a matched filter, (24) takes the following form:

$$\overline{D}_{\alpha_1}(t) = 1 + \frac{\int_{-\Omega}^{+\Omega} S^*_{\alpha_1}(\omega)\, S_{\alpha_2}(\omega)\, d\omega}{\int_{-\Omega}^{+\Omega} |S_{\alpha_1}(\omega)|^2\, d\omega} \quad .$$

Similar expressions are obtained for (25) and (26) when $m \to \infty$.

The foregoing formulas indicate that the different targets can be identified by using a matched filter if the following inequality is satisfied for all target pairs:

$$\int_{-\Omega}^{+\Omega} S_{\alpha_j}(\omega)\, S^*_{\alpha_i}(\omega)\, d\omega \ll \int_{-\Omega}^{+\Omega} |S_{\alpha_i}(\omega)|^2\, d\omega \quad . \tag{27}$$

The procedure to be followed is to process the return with the matched filters corresponding to the various targets, one at a time. The targets which are present in the return will be identified by a peak of a height greater than or equal to 1 if the left-hand side of (27) is positive. Those that are not present in the return will not give rise to a peak of any appreciable magnitude if (27) holds. Since the effective value of the noise at the output of the matched filter is given by (16) as

$$\left[\frac{\sigma^2}{\int_{-\Omega}^{+\Omega} \left| S_{\alpha_i}(\omega)\right|^2 d\omega}\right]^{1/2} ,$$

one finds that the false peaks corresponding to the missing targets will be buried in the noise if

$$\int_{-\Omega}^{+\Omega} S_{\alpha_j}(\omega)\, S^*_{\alpha_i}(\omega)\, d\omega \lessgtr \sigma \left[\int_{-\Omega}^{+\Omega} \left| S_{\alpha_i}(\omega)\right|^2 d\omega\right]^{1/2} . \qquad (28)$$

Our conclusion from the foregoing discussions is that the matched filter will be the best choice insofar as, a) counting the number of targets of the same type, b) identifying of different types of targets, are concerned. However, a computer study is needed for more definite conclusions.

4.3 Machine Simulation Using the Mixed Filter

We have completed a number of machine simulations using the mixed filter for various values of the parameter. The target and noise simulations are the same as some of the previous ones in which we used the inverse filter. We intend to make a detailed comparison of results for different values of the parameter, noise level, and targets. This comparison has not been completed by the end of this reporting period but will appear in the next report.

4.4 Representation of Target Signatures

A basic consideration in the target signature problem is the efficient organization and utilization of known target data. Presumably this information will be stored in some kind of analog or digital memory. Since processing time, signal quality, and memory size will be limited it is desirable to optimize the memory with regard to the class of targets expected and the signal processing.

Taking the prime function of the system to be the identification and counting of targets chosen from a fairly small class of similar targets, it becomes apparent that relative information is important. That is, a system of memory storage and signal processing which seeks out and magnifies the differences in target characteristics is likely to be the most efficient. One mathematical technique which holds considerable promise in this direction is the use of Wiener's translation expansion.[+]

[+] N. Wiener, "Tauberian Theorems," Annals of Math., Second Series, 33, No. 1, 1-25 (January 1932).

Wiener considers the set of all real translations of a complex-valued square-integrable function, f(x), and gives conditions under which the set is closed. That is, if the set of real zeros of the Fourier transform of f(x) is of zero measure, then a general square integrable function, F(x), may be approximated with arbitrary precision:

$$F(x) \sim \sum_{k=1}^{n} a_k f(x+\lambda_k) \quad .$$

The numbers $\{\lambda_k\}$ are real and the $\{a_k\}$ are in general complex. We may think of $\lambda = \{\lambda_k\}$ and $a = \{a_k\}$ as 'vectors' which describe the function F(x) <u>relative to f(x)</u>. Unfortunately, no recipe is given by Wiener for determining these vectors, although their existence is clearly established. Moreover, it seems natural that a dependence between a and λ must hold since in general one such 'vector' characterizes a function.

Suppose, now, that a class of targets, characterized by their frequency signatures $S_\alpha(\omega)$ is being investigated. For any particular target, described by $S(\omega)$, we have the expansions

$$S_\alpha(\omega) = \sum_{k=1}^{n} a_{k,\alpha} S(\omega + \lambda_{k,\alpha}) \quad .$$

Questions of identification and resolution can be answered by comparing vectors $\{a_\alpha\}$. In particular, we hope to find frequency intervals (described essentially by values of k) for which the variation of amplitude values over the class of targets (i) is sufficiently great to afford a high probability of discrimination and identification.

5. PROGRAM FOR NEXT INTERVAL (This Section is UNCLASSIFIED)

We will continue our studies of the mixed filter in order to determine the discrimination vs resolution criterion as a function of the filter parameter. This study will include both theoretical analysis and the use of simulation programs.

Making use of our previously computed signature of a vehicle model, we will perform a machine simulation study using in the filter the various component signatures of the vehicle model as well as various values of the filter parameter.

The study of the signature representation scheme (Sec. 4.4) will be continued.

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