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ON USING SCATTERING STATISTICS FOR ULTRA WIDEBAND ELECTROMAGNETIC TARGET CLASSIFICATION AND IDENTIFICATION

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INTRODUCTION

An interrogating electromagnetic field has information encoded upon it by any target from which it scatters. This process presents the electomagneticest/signal processor with a problem that ranges across questions such as the following, in increasing order of specificity and information requirements:

1) Detection--Is there a target?

2) Classification--to which class does that target belong?

3) Identification--what specific member of that class is the target?

4) Reconstruction--what are the target's electrical and/or geometrical properties?

Radar systems have been analyzed primarily from the perspective of Question 1 above. Recently, increasing attention has been devoted to Questions 2-4, as the need for more specific and complete information beyond target detection is desired. In the following discussion, we present conceptually a statistics, information-oriented approach to this general class of problems. Our goal is to assess the information requirements related to classification/ identification (C/I). In particular, we consider the possibility of using statistical analysis as an intermediary between imaging targets, an approach that requires an excessive amount of data, and such feature-based techniques as using poles. We speculate that probability density functions (PDFs) of the aspect-angle-dependent radar cross section (RCS) provide an attractive opportunity for reducing the data requirements of imaging while avoiding some of the disadvantages of resonance techniques.

Our discussion on the use of scattering statistics for C/I is developed in three phases. The first phase, the least data-intensive approach, uses expected values of target RCS (<RCS>, averaged over aspect angle) as a function of frequency. In the second phase, *a priori* knowledge of the aspect-angle-dependent PDFs is added to the process, with the goal of improving C/I performance at the expense of needing a more detailed data base and more computations. In the third phase, with a further increase in the amount of data and computation, a knowledge of the aspect-dependent scattering patterns is added in an attempt to reduce the ambiguity caused by scattering from aspect-angle variation. For brevity, we refer to the overall approach as statistical C/I or SCI.

Our discussion begins with some background, then continues with sections addressing each of these three phases. Two final sections consider the questions of observability and discriminability, followed by some concluding comments. Throughout this discussion, we assume the availability of the kinds of scattering data needed to "profile" a target by plotting scattering strength versus range, but we consider alternative uses for such data. Specifically, we assume data is available over an ultra-wide-bandwidth, though not necessarily obtained from impulse measurements but possibly instead being derived from discrete frequency sampling. Our approach is conceptual; no actual data are employed in this discussion except for "data images" as defined below. Our purpose is to suggest that SCI may be achievable by analyzing data and using stored-library information, a prerequisite of all C/I schemes, in a manner different from that of developing radar images using profiling.

BACKGROUND

The basic C/I problem considered here can be simply stated as follows:

PROBLEM--Find the target, T_i, from a set of T targets, that has produced the observed data.

STRATEGY--Minimize the data needed to accomplish C/I in terms of the required data base, the needed measurements, and the processing required of those measurements and data base.

ASSUMPTION--Discrete samples obtained across a wide enough bandwidth and range of viewing angles will permit C/I to be accomplished to some desired level of performance.

The overall problem involves data collection, information processing and decision making for which at least three distinct approaches can be identified. Perhaps most straightforward, but also most data intensive, is profiling and imaging, which require wide bandwidth (relative to wavelength change with respect to target size) and many aspect angles. This approach can yield target images of near photographic quality, but it is not considered further here. An apparently less data-demanding approach is one which is feature-based and derived from electromagnetic physics to reduce the number of frequencies and/or aspects that may be needed. Techniques that employ the idea of body resonances (SEM poles) would fall into this category. They offer the tantalizing possibility of realizing aspect-independent C/I, which is one reason why pole-based techniques have attracted much attention. The third approach, the one considered in most detail here, is also feature-based, but it employs more *ad hoc* features. Its data requirements might fall somewhere between the other two approaches, as will be illustrated conceptually in the discussion that follows.

Before presenting the details of our SCI approach, we first make some general observations concerning C/I or, as the problem is also known, automatic target recognition (ATR).

Experimental Design:

*As more confidence in C/I is desired, more information/data is required.
*As target numbers increase, more information needed to maintain a specified confidence level.
*The amount of information available increases with bandwidth and the number of aspect angles available.
*If data are available across a wide-enough bandwidth, then fewer aspect angles are needed (i.e., bandwidth trades for aspect).
*The basic problem of ATR-C/I is one of developing more appropriate knowledge representation so that a better data-acquisition strategy can be defined and better use can be made of that data.

Target Set Considerations:
*For a given set of targets, some set of observation variables will be optimum with respect to minimizing the measurement requirements for a specified confidence level to be achieved in C/I.
*The number of needed frequencies can be minimized if the frequencies sampled are optimized with respect to their information content.
*Higher spatial resolution requires wider bandwidth (i.e., $\Delta x \Delta f \sim$ constant).
*Imaging is overkill for most C/I applications.
*Just as images are not necessary for C/I, physical features are also optional.
*The more similar the targets, the more data that will be required to accomplish C/I to a desired level of confidence.

Data Representation and Processing:
*Target responses can be represented as feature vectors and intersecting regions in N-space.
*Target regions overlap to the extent that information is inadequate or unavailable.
*Feature-vector overlap can be reduced with more data and/or more data accuracy.
*Feature-vector overlap increases with increased noise and more targets.
*The C/I process begins with an imperfect data base and must be able to handle imperfect measurements.
*Redundant data can reduce noise effects and increase information, thereby increasing reliability and confidence.
*The quantity of information available increases with the data accuracy.
*Poles represent physics, so even if inaccessible they can provide insight concerning observables.
*Aside from differences in scattering physics, a 1GHz data bandwidth centered at 1 GHz is equivalent in information concent to 1 GHz centered at 10 GHz.

We also note that all available *a priori* knowledge should be used to reduce data requirements. For example, knowing that the targets of interest are airborne, unlikely objects, such as tanks and ships, should not need consideration (unless they are being dropped by parachute!). Or, aspect angles can be limited if one knows a target’s track and takes into account that airplanes don’t fly sideways. Or, if only size is important for C/I, then only a few resonance peaks in the frequency-dependent RCS may be needed. Assuming that the same data are available whatever approach is to be used for C/I, the goal is to make optimal use of that data.

USING EXPECTED VALUES OF RCS FOR SCI

A commonly encountered question in inverse problems such as C/I is “At what frequencies should measurements be made, given a class of known targets, to maximize ATR reliability subject to certain constraints such as total bandwidth, number of sampling frequencies, number of aspect angles, signal-to-noise ratio, etc?" This question might be stated somewhat differently: "At what frequencies are the targets of interest most separable, or where are their frequency-dependent signatures most nearly orthogonal?"

A possible procedure for finding this set of frequencies can be outlined as follows:

1) For target i = 1, find $\langle R_i(\omega;\theta,\varphi)\rangle$ over 4π steradian incident angles for a set of frequency samples ω_j, j = 1, . . . , F
2) Repeat for i = 2, . . . , T targets to obtain the matrix $M_{i,j}$.
3) Normalize the results for each target to get $\underline{M}_{i,j}$ (this may be unnecessary if the absolute value of the RCS can be measured).
4) Compute the distance (norm) measure d_i between $\underline{M}_{i,j}$ at each ω_j for each target pair for a total of $T^2/2 - T$ values and sum to obtain D_j for j = 1, . . . , F.
5) Order the D_j from maximum to minimum values.
6) Select the set of frequencies F' for C/I from the largest of the D_j obtained.

Target C/I might then be attempted as follows:

7) Renormalize the $M_{i,j}$ for the new set of frequencies f'_j = 1, . . . , F'.
8) From the unknown target return T_x, compute $d'_{i,j}$, i = 1, . . . , T, j' = 1, . . ., F', from the target library.
9) Sum the $d'_{i,j}$ over frequency to obtain D'_i, the target measures.
10) The library target with smallest value of target measure identifies unknown.

The goal is to identify the frequencies where the expected values of target RCSs are most different as illustrated graphically in Fig. 1. If the only information available were the aspect-angle-averaged RCS data, then the best measurement frequencies for C/I might be selected as indicated here. However, if the variances of the PDFs for the targets of interest are nonzero (assured for all but spherical targets) and their PDFs are also overlapping, the probability of a false identification can be higher than is acceptable. In that case, the target PDFs would also be needed, as is discussed in the next section.

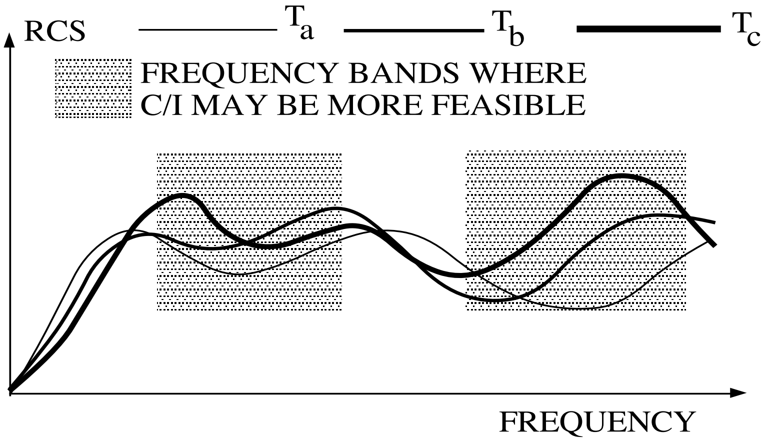

Figure 1. A conecptual frequency plot of the expected values for three radar targets illustrating the idea that some frequency bands might be more useful for target C/I.

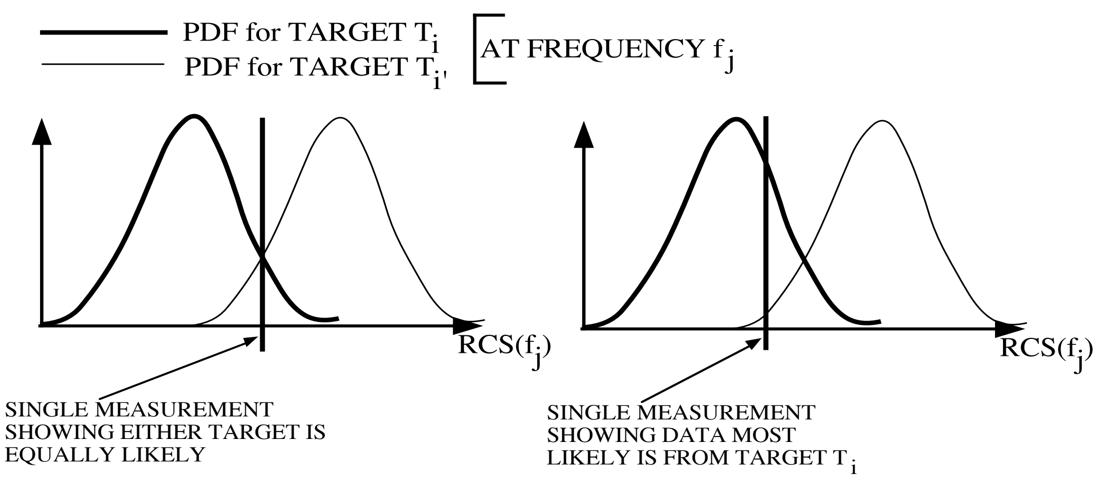

Figure 2. Plots of the PDFs for two targets to illustrate how a single RCS data value might be interpreted. If the measured value were to fall midway between the two PDFs at their crossover point, as in the left-hand plot, then neither target would be more likely to have produced that measurement. On the other hand, if the measured value were to be located as on the right-hand plot, then target T_i would be the more likely.

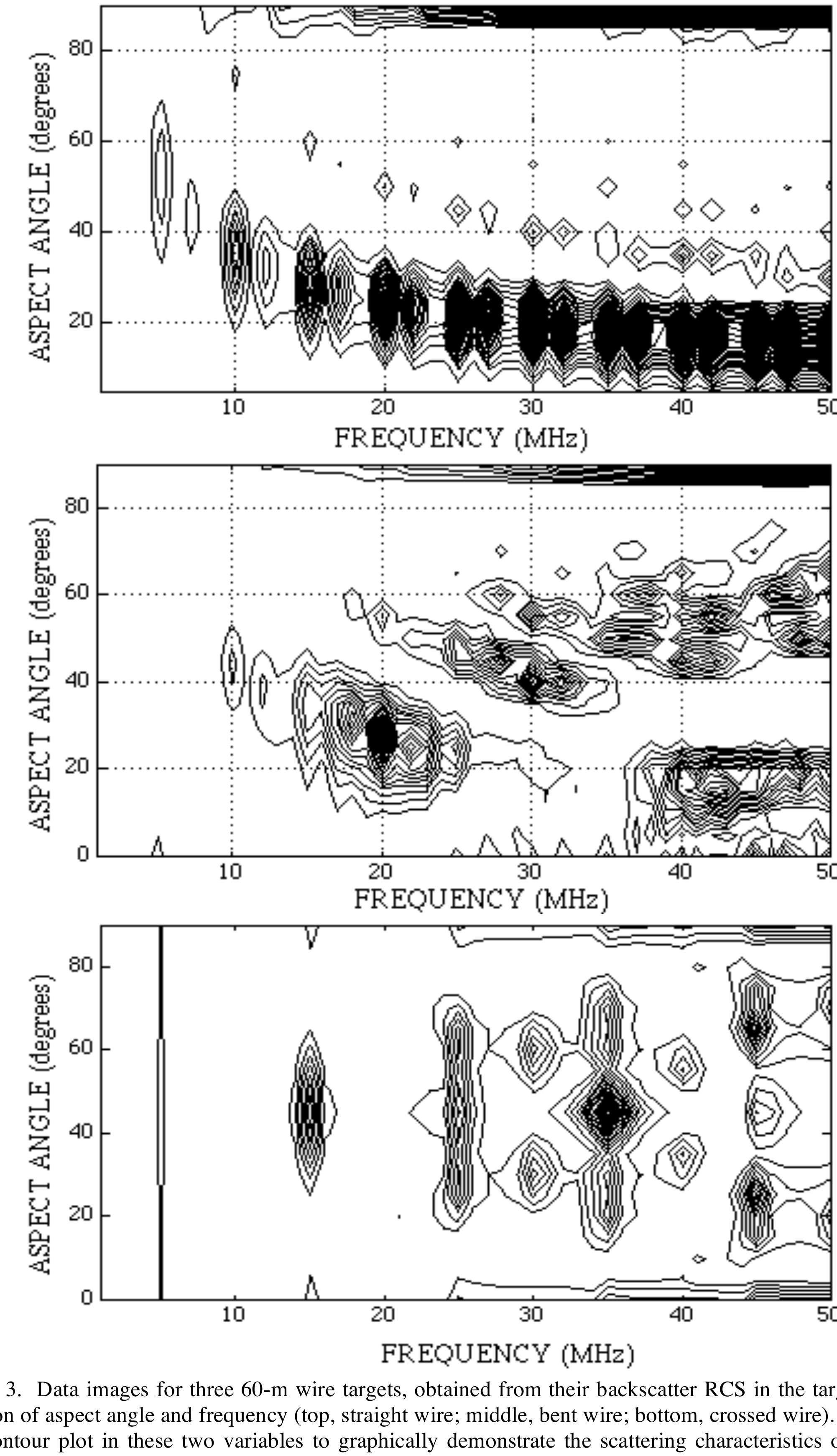

Figure 3. Data images for three 60-m wire targets, obtained from their backscatter RCS in the target plane as a function of aspect angle and frequency (top, straight wire; middle, bent wire; bottom, crossed wire). The “image” is a contour plot in these two variables to graphically demonstrate the scattering characteristics of targets in a common format. A data image can provide much more information than the usual aspect angle-RCS plot. Although aspect angle is a function of two angles, elevation and azimuth, by transforming them to a single variable, for example, by measuring aspect angle on a downward spiral from one pole of a spherical coordinate system to the other, a single variable would result.

ADDING ASPECT-ANGLE STATISTICS FOR SCI

The RCS of large, complex targets is a rapidly varying function of aspect angle. Consequently, even though one measurement at a single frequency might enable discrimination among two, three, or even more targets with different <RCS> values, this possibility decreases with increasing target numbers because the RCS values will be distributed about the median and their PDFs are likely to overlap. This leads to the situation depicted in Fig. 2 in which the PDFs of two targets are seen to overlap significantly. Thus, even though their <RCS> values are distinctly different, they share a range of possible RCS values, making a decision about which target has produced the data less certain.

As a way to visualize the differences (or similarities) between different targets, including their aspect-angle dependence, we can develop a data "image" of the target's electromagnetic response (Fig. 3) for three simple wire models. These results, which were obtained from the computer model NEC [Breakall et al. (1985)], depict the aspect-dependent RCS as a function of frequency for a straight wire, a bent wire (having two right-angle bends one quarter of the distance from each end), and a crossed wire, all with the same overall length of 60 m.

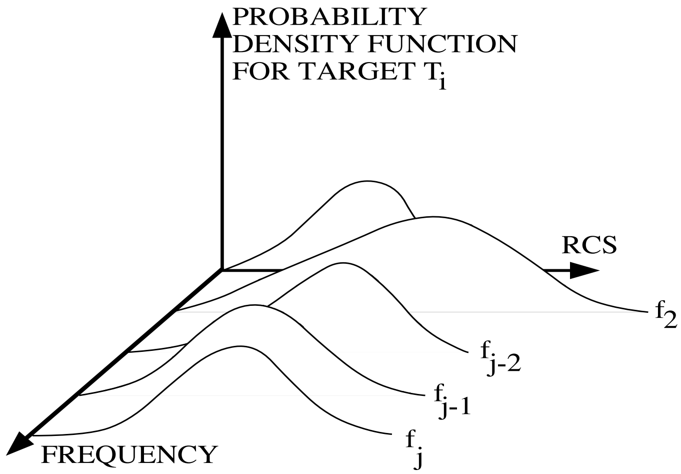

Figure 4. The PDFs of target T_i for a number of different frequencies.

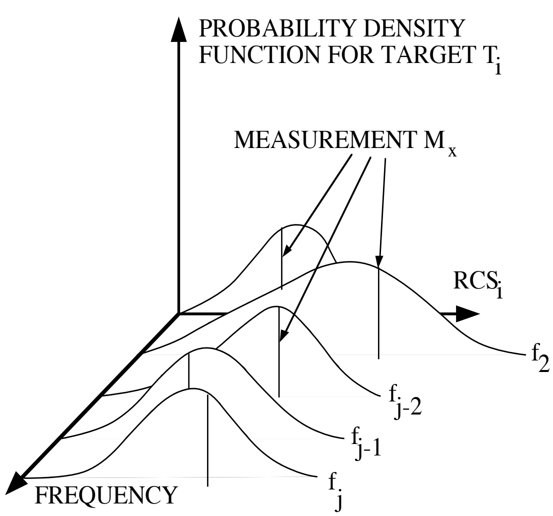

Figure 5a

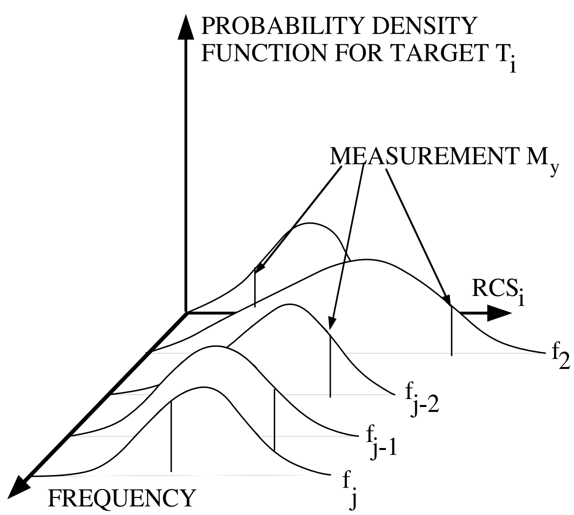

Figure 5b

Results from two different measurements plotted on the PDFs of target T_i. The data from measurement M_x, as depicted here, is more compatible with target T_i of the data base than is measurement M_y.

Quantitative analysis of these kinds of data presentations for a variety of targets should help reveal the similarities (and differences) between the EM observables for such targets and should reveal the most suitable frequencies, across some band, for discriminating among them. One way to do such an analysis, is to develop the PDFs for targets of interest from data such as that shown in Fig. 3. A set of PDFs like those shown in Fig. 4 might then be obtained (those shown here are for conceptual purposes only, and do not represent a real target). Given a set of measurements M_x at frequencies $f_1, f_2, \ldots, f_j$, to be plotted on the PDF-frequency plot (Fig. 5a), we might conclude that the observed data have a high probability of coming from T_i. The basis for our conclusion is that the measured RCS values are generally found near the peaks of the PDFs for this target, or near the most probable RCS values. If the measurements produced the kind of plot seen in Fig. 5b, however, then it would be more likely that some other target generated the data because the measured RCS values in this case fall further into the tails of these PDFs. A quantitative measure of target-identification probability might simply be obtained by summing the PDFs of each target over the set of measured frequencies. Of course, a more rigorous measure would be preferred, using Bayesian or other statistical approaches to compute probabilities. Also note that specular-flash returns might significantly affect target PDFs, and thus require special consideration in the treatment outlined here, but that topic is deferred to a later discussion.

ESTIMATING ASPECT ANGLES FOR IMPROVED SCI

The PDFs alone cannot be expected to convey enough information to accomplish successful SCI for target sets that are large-enough and/or similar-enough. As more confidence is required in target identification, more information will be necessary. As a logical next step beyond using only <RCS> or PDF information, we now consider the possibility that the angle-dependent scattering patterns are also available as part of the data base to which we have access. Assume that the RCS of an unknown target is available at F frequencies across some bandwidth for which an *a priori* data base has been established. The library data might be stored as x-y plots of RCS vs aspect angle, where the latter could be compressed into one dimension from the usual elevation-azimuth, two-dimensional coordinates by using an angle variable that spirals outward and downward from one pole of a spherical coordinate system towards the other. Alternatively, this information could be stored in the form of data images (such as those shown in Fig. 3) to capture the frequency-aspect information.

For any target other than a sphere and except at extrema, the backscatter pattern will contain two or more aspect angles at which the same RCS will be observed. The scattering pattern becomes more multiple-valued with increasing frequency, producing increasing ambiguity in aspect angle. However, the number of possible aspect angles at which a target might have been illuminated to produce a given RCS value at any frequency, although possibly large, will nonetheless be limited, assuming of course that the measurement falls within the range of values produced by that target. If RCS values are measured simultaneously (for a moving target), then they will all share a common aspect angle, providing an opportunity for reducing aspect-angle ambiguity or, possibly, of performing C/I itself.

The basic approach is to determine, for each target in the data base, that set of aspect angles consistent with the measured RCS at each of the available sampled frequencies, as is illustrated conceptually in Fig. 6 for the data image of the 2-bend wire. An angle of about 33 degrees is seen to be a common aspect angle for the frequencies shown. The result of this exercise could be visualized in a three-dimensional array, or template, of binary entries that contain x's where there is an angle match and no entry where there is none as in Fig. 7. Ideally, the correct target would be identified as the one whose backscatter patterns produce a single matching angle, to within some experimental error, at all observation frequencies.

ADDITIONAL CONSIDERATIONS

In just considering the possibility of using radar for C/I, the properties of observability and discriminability are crucial for success. In this discussion these terms are defined as follows:

> OBSERVABILITY--measures how accessible are the features that might differentiate the various targets from the observations available,

and

> DISCRIMINABILITY--measures how dissimilar these features are, for the target set of interest.

An implicit assumption in even considering the possibility of successful C/I, is that both properties are present to the extent necessary, a somewhat imprecise but quantifiable, measure. When these properties are more pronounced for the target set and measurements available, the amount of data needed, and the processing of those data that may be necessary for acceptable C/I performance, can be expected to be less. Conversely, when these properties are less pronounced, the amount of data, and processing, can be expected to increase.

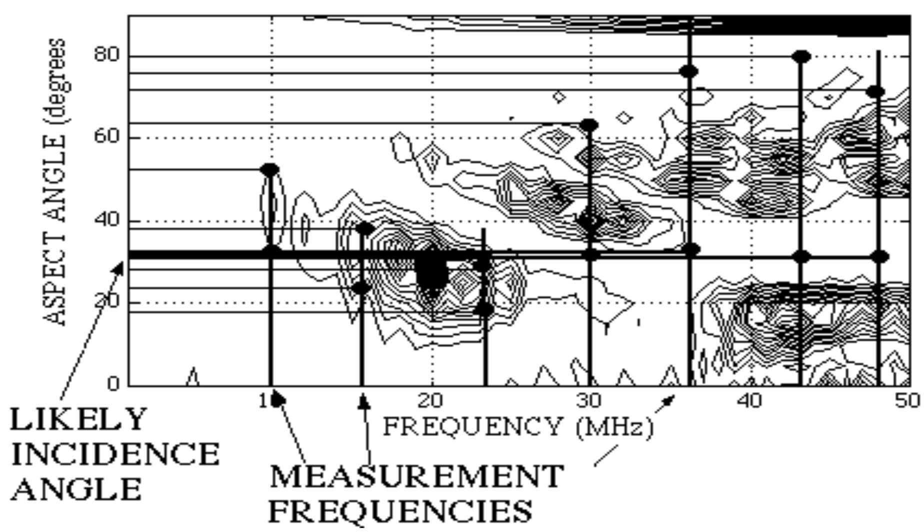

Figure 6. Plot for the bent-wire target demonstrates how the aspect angle might be determined from RCS measurements made at several different frequencies. An angle of about 33 degrees is a common aspect angle for the frequencies shown.

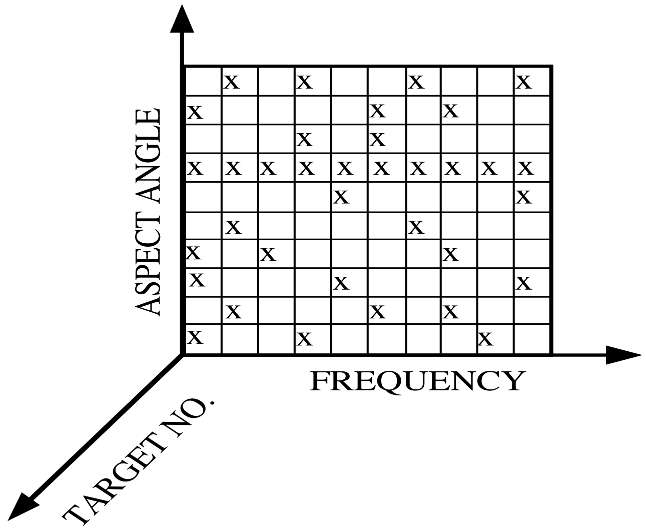

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Figure 7. A matching angle-frequency template for one target from a set of T targets, showing how the aspect angle might be determined and target identification achieved, by finding that aspect angle consistent with a data base of scattering patterns for the target set of interest.

As a specific example of how both observability and discriminability can depend on a specific choice of features, consider the use of resonances or poles for C/I. For transient data of given accuracy, the oscillatory components of the poles can be more accurately estimated than the damping components [Dudley and Goodman (1986)], as illustrated conceptually in Fig. 8. Thus, we can generally conclude that the damping rates are less observable than the oscillation rates, as determined from processing transient data. The implications of this result for target discriminability then directly follow when it is noted that the oscillation rate is more sensitive to target *size*, while the damping rate is more sensitive to target *shape* [Miller (1991)]. Therefore, if targets of similar size but different shape form the set of interest, that poles would probably not be a good choice for a feature set. Conversely, if target size is the discriminant, poles might be a more reasonable choice for discriminants or features.

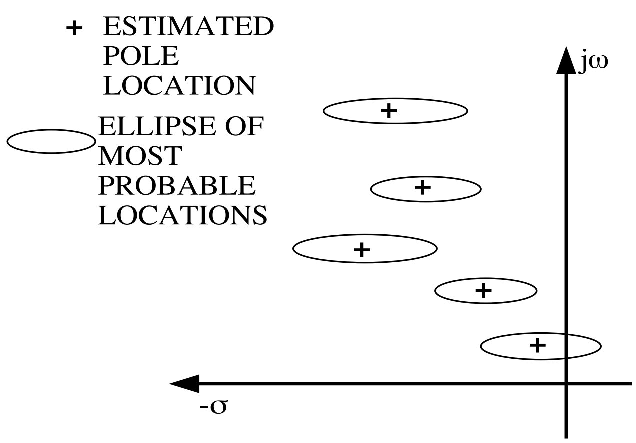

Figure 8. Plot of poles in complex frequency plane demonstrating the uncertainty in pole value when using transient data and a processing technique such as Prony's Method. Typically, the damping components of the poles are less accurate than the oscillation components.

The three phases of SCI considered here are intended to deal with increasing similarities of the target-set observables or with limitations in the available data. Expected values of the target

RCSs might provide the simplest discriminant. If, however,that is not feasible, the next level of discriminant would be to use the aspect-angle PDFs as a function of frequency. But if the PDFs and expected values of the RCSs are too similar, then the scattering patterns would need to be considered. If these in turn also prove inadequate, the targets of interest could be too similar to be reliably identified using radar measurements and considering the constraints. This sequence of steps is illustrated in Fig.9.

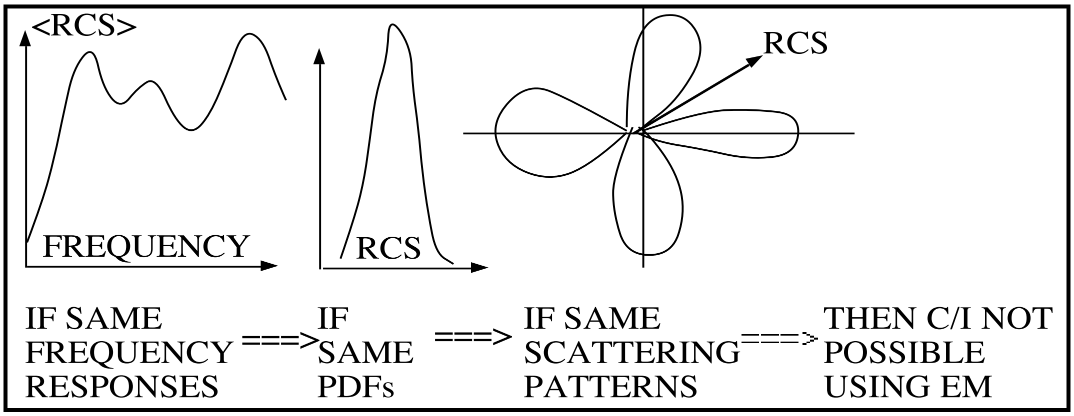

Figure 9. The sequence of steps followed in the above discussion and the implication that follows should the observables and associated features thereof be indistinguishable at any stage in the processing.

CONCLUDING REMARKS

We have discussed an approach to classification/identification (C/I) using statistical analysis of the aspect-angle-dependent RCS of a target over some frequency band. The basic idea is that, given the kind of data base needed for profiling and imaging prospective targets, where broadband data is needed over many aspect angles, alternative uses can be made of such data that might permit more parsimonious and efficient C/I to be realized. We suggest that, with such a data base, statistical analysis might permit us to attempt several stages of C/I, including the use of aspect-averaged RCS values; probability-density functions (PDFs) derived from using aspect angle as a random variable; and details of the angle scattering patterns themselves. This conceptual approach is speculative in that the ideas considered are not quantitatively tested here. The use of statistics as proposed for C/I, seems to be a logical extension of the basic detection problem, which, itself is a statistical problem.

The approach outlined here might be profitably implemented in a pre-classification or pre-conditioning stage as a prelude to profiling and imaging, in those cases where the latter might be found to be necessary for successful C/I. By following a “graded” approach, where the amount of data and processing progressively escalates only as C/I at a given stage is found inadequate, it should be possible to reduce the overall effort required to achieve a desired performance.

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