Interaction Notes

Note 500

21 January 1994

Signature-Based Target Identification

Carl E. Baum

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Abstract

In the identification of a particular target (or target class) out of a library of possible targets one can use the scattering signatures from a transient (broad-band) type of radar. These signatures are parameter sets (using aspect-independent and/or aspect-dependent parameters) in some scattering model. There are various such models of interest based on the symmetries (or partial symmetries) of the various target features (geometric shapes, including constitutive parameters), of both local and global varieties. Such symmetries have significance for the signal processing as well, so that the signatures can be better extracted from the noise and clutter background. Based on such symmetries one can organize the target features, models, signatures, and signal processing into the habitats of a zoo.

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In the identification of a particular target (or target class) out of a library of possible targets one can use the scattering signatures from a transient (broad-band) type of radar. These signatures are parameter sets (using aspect-independent and/or aspect-dependent parameters) in some scattering model. There are various such models of interest based on the symmetries (or partial symmetries) of the various target features (geometric shapes, including constitutive parameters), of both local and global varieties. Such symmetries have significance for the signal processing as well, so that the signatures can be better extracted from the noise and clutter background. Based on such symmetries one can organize the target features, models, signatures, and signal processing into the habitats of a zoo.

I. Introduction

Besides locating a target, one would like to have some kind of radar which could identify the target, i.e., tell what kind of aircraft, etc. was being observed. This concept goes by several names: target identification, discrimination, categorization, and classification. Basically, one assumes that there is a set of targets called a target library $\{X_n\}$ for n = 1,2,...,N_T where each X_n represents a particular target or target class. All targets that scatter an incident wave in the same way to produce a far scattered field (have the same scattering operator) are electromagnetically identical for our purpose and are assigned the same value of n. The problem is to obtain sufficient information about the scattering operator to identify a particular X_n as the target, i.e., assign a value to n.

Identifying some target from a library assumes that the target is in the library. There can be cases when some new (unknown) target is sensed by the radar. A good identification scheme should still be able to tell that this target is not in our library. Note that target identification, as we have defined it here, is in general a simpler problem than inverse scattering in which one tries to define the shape and constitutive parameters of an unknown target from appropriate scattering data.

There are various ways one can approach this target identification. One common technique is referred to as imaging which can be performed at microwave frequencies in a manner similar to optical imaging (as in a photograph). At microwave frequencies, however, it is difficult to obtain sufficient angular resolution without a very large antenna aperture. This difficulty is presently overcome by SAR (synthetic aperture radar) and ISAR (inverse synthetic aperture radar) in which the radar and target respectively are moved in desirable ways. This technique, however, requires a lot of measurements and implies a certain amount of cooperation, or at least non evasion, by the target.

This paper concentrates on the case that one has basically only one angle of incidence $\vec{1}_i$ and one direction to the observer $\vec{1}_o$ with respect to the target as illustrated in fig. 1.1. Let the incident wave have the form (at least near the target) of a plane wave as

$$\tilde{\vec{E}}^{(inc)}(\vec{r},s) = E_0 \, \vec{1}_p \tilde{f}(s) e^{-\gamma \vec{1}_i \cdot \vec{r}}$$

$$\vec{E}^{(inc)}(\vec{r},t) = E_0 \, \vec{1}_p f\left(t - \frac{\vec{1}_i \cdot \vec{r}}{c} \right)$$

$$\vec{1}_i \equiv \text{direction of incidence}$$

$$\vec{1}_p \equiv \text{incident polarization}$$

$$\vec{1}_i \cdot \vec{1}_p = 0$$

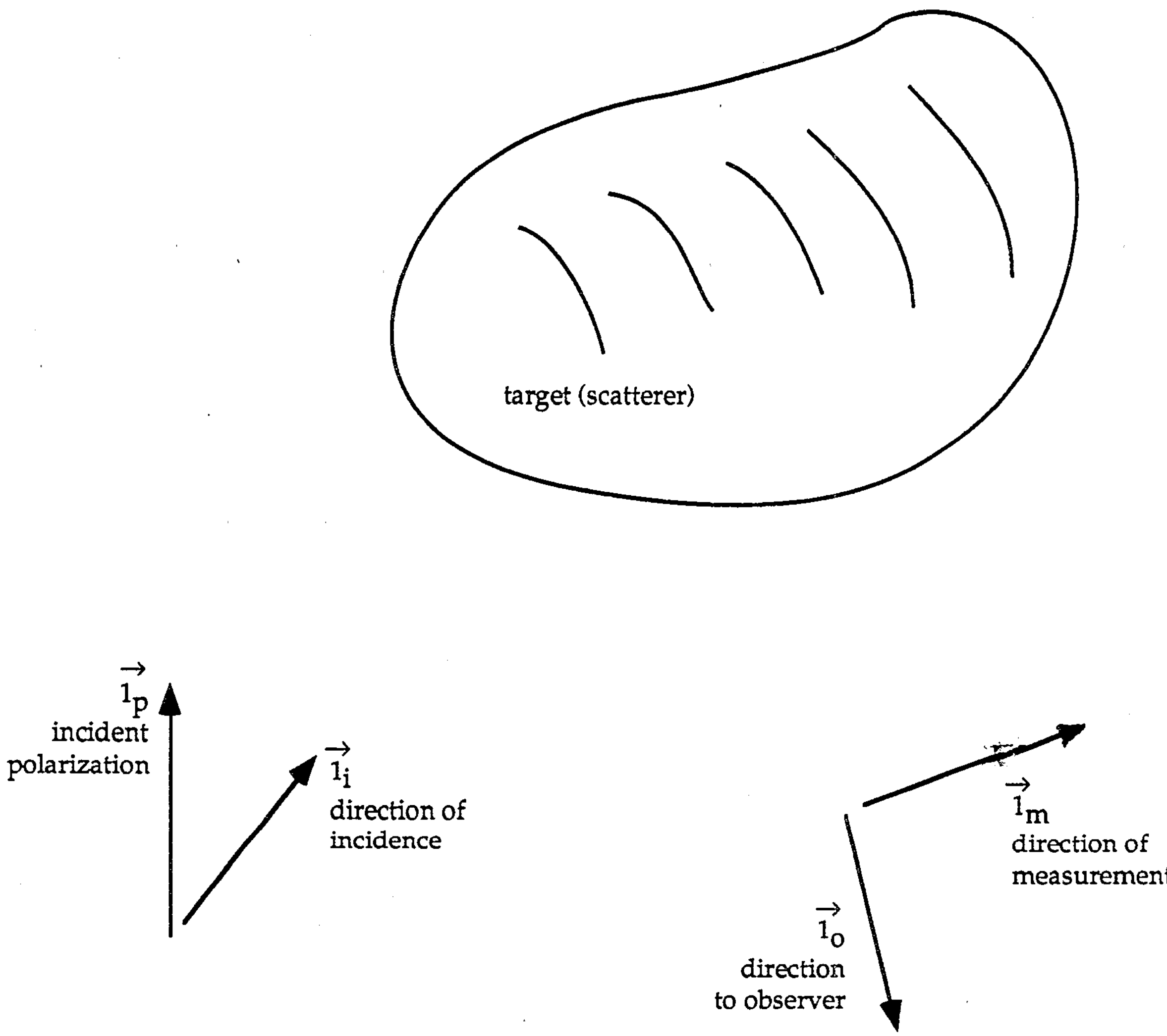

Fig. 1.1. Scattering of Incident Wave by Target

$$s \equiv \Omega + j\omega \equiv \text{Laplace - transform variable or complex frequency} \tag{1.1}$$

$$\sim \equiv \text{two - sided Laplace transform (with respect to time, t)}$$

$$c \equiv [\mu_0 \varepsilon_0]^{-\frac{1}{2}} \equiv \text{speed of light}$$

$$f(t) \equiv \text{incident waveform}$$

$$\gamma \equiv \frac{s}{c} \equiv \text{propagation constant}$$

Note that for a fixed angle of incidence we still have two independent polarizations (two choices of $\vec{1}_p$) available to us. There is also some flexibility in the choice of the incident waveform. Note that the medium surrounding the target is assumed to be free space for present purposes. However, much of the considerations carry over to other media as well.

For the observer sufficiently far from the scatterer one has a far-field approximation as [5,6]

$$\tilde{\vec{E}}^{(sc)}(\vec{r},s) \simeq \tilde{\vec{E}}_f(\vec{r},s) = \frac{e^{-\gamma r}}{4\pi r}\tilde{\overleftrightarrow{\Lambda}}\left(\vec{1}_o, \vec{1}_i; s\right) \cdot \tilde{\vec{E}}^{(inc)}(\vec{0},s)$$

$$\vec{E}_f(\vec{r},t) = \frac{1}{4\pi r}\overleftrightarrow{\Lambda}\left(\vec{1}_o, \vec{1}_i; t\right) \overset{\circ}{\cdot} \vec{E}^{(inc)}\left(\vec{0}, t - \frac{r}{c}\right)$$

$$r \equiv \text{distance to observer}$$

$$\vec{1}_o \equiv \text{direction to observer}$$

$$\vec{1}_m \equiv \text{polarization of measurement at observer}$$

$$\vec{1}_m \cdot \vec{1}_o = 0 \tag{1.2}$$

$$\tilde{\overleftrightarrow{\Lambda}}\left(\vec{1}_o, \vec{1}_i; s\right) \equiv \text{scattering dyadic (2 x 2)}$$

$$\overleftrightarrow{\Lambda}\left(\vec{1}_o, \vec{1}_i; t\right) \circ \equiv \text{scattering dyadic operator}$$

$$\circ \equiv \text{convolution with respect to time}$$

Here the target is assumed linear and time invariant, allowing the Laplace transform and related properties. Note that for a fixed direction to the observer there are still two independent polarizations (two choices of $\vec{1}_m$) available to us. Note that reciprocity (also assumed) implies

$$\tilde{\overleftrightarrow{\Lambda}}\left(\vec{1}_o, \vec{1}_i; s\right) = \tilde{\overleftrightarrow{\Lambda}}\left(-\vec{1}_i, -\vec{1}_o; s\right) \tag{1.3}$$

A special (and commonly encountered) case is that of backscattering for which

$$\vec{1}_o = -\vec{1}_i$$

$$\tilde{\overleftrightarrow{\Lambda}}_b\left(\vec{1}_i, s\right) = \tilde{\overleftrightarrow{\Lambda}}\left(-\vec{1}_i, \vec{1}_i; s\right) = \tilde{\overleftrightarrow{\Lambda}}_b^T\left(\vec{1}_i, s\right) \tag{1.4}$$

In this case the scattering dyadic is symmetric for a reciprocal target, an important property to be exploited.

At this point one should note that $\vec{1}_i$ and $\vec{1}_o$ are defined with respect to the target, i.e., the target aspect (orientation in space) with respect to the incident and scattered wave is assumed fixed at one choice of these angles. The target is assumed not to be rotated (significantly) during the time of observation, so that only one aspect is available to the observer. One may not know a priori which particular aspect a target may have with respect to the radar. Other information (such as target track from other radars) may be used to infer the aspect, thereby simplifying the identification somewhat.

II. General Identification Scheme for Single Angles of Incidence and Scattering

Target identification involves many steps. For our assumed case of a single target aspect these are summarized in table 2.1. This begins with the generation and radiation of some temporal waveforms containing some broad band of frequencies with large band ratios (ratio of upper to lower significant frequencies), perhaps of the order of a decade. (As an alternative one might transmit a sequence of narrow-band waveforms spanning the same frequency range.) Note the use of dual polarization and perhaps multiple interrogating waveforms (perhaps adaptive to match to the target being identified and maximize signal-to-noise ratio in the received waveforms). The last step is the actual identification of the target as some particular X_n in the library (or decision that it is not in the library). Simultaneously one may also obtain an estimate of the target aspect due to its presence in various of the target signatures. Particularly due to the presence of noise in the recorded signals, no identification is perfect. At this point, probabilistic estimates [14] can perhaps be introduced. Note, however, the various steps that can be accomplished to achieve better estimates at this last step.

This target-identification concatenation (or linking of steps as in a chain) involves many parts, all of which need to be optimized. An optimal solution will, in general, also depend on the target library to which the radar is to be applied, and on the conditions under which the radar is to be used. The concatenation in table 2.1 is then a way to think about the problem in an ordered way.

1. Transmitter
   - generators (waveform sources)
   - filters (physical, perhaps adaptive)
   - antennas (dual polarization)

2. Interrogating (transmitted) waveforms
   - both polarizations (h, v)
   - possibly multiple waveforms
   - large band ratio of frequencies

3. Target feature (physical)
   - geometry
   - constitutive parameters

4. Scattered waveforms
   - contain scattering dyadic $\overleftrightarrow{\Lambda}$ which contains signatures (model based parameters)
   - combinations of incident and scattered polarizations (in backscatter (h,h), (v,v), (h,v) = (v,h))

5. Receiving antennas
   - include possible filters (physical, perhaps adaptive)
   - dual polarization

6. Recorder
   - digital, analog

7. Signal processing
   - remove antenna and associated filter characteristics (for both transmission and reception)
   - bring out signatures
   - suppress noise and clutter

8. Identification and orientation (aspect)
   - match signatures to those of a particular target (class) in target library
   - probabilistic estimates

Table 2.1. Target-Identification Concatenation

III. Target Signatures

A key item in the identification procedure is the target signatures. Let us try to define this a little more precisely.

A related concept is model-based parameters [9,10,15,17]. By a model we mean some mathematical expression with a not-too-large set of parameters which represents the scattering (whether exact or approximate) over some region of time, frequency, etc. (or combinations thereof). The parameters may be aspect dependent or aspect independent. From this define a signature type as

signature type:
a set of parameters associated with a scattering model

At this point the parameters (scalars, vectors, etc.) do not have specific values. This comes when one applies the model to a particular target X_n. Then one has a specific signature for this target. So let us define

signature:
a set of specific parameter values (including aspect dependence) associated with a signature type and related scattering model.

This allows the possibility that a target may have more than one signature due to the applicability of more than one model. Use of multiple signatures (all in agreement for a particular target X_n) can give a more reliable identification. In some cases a signature may be thought of as some part of a time-domain waveform described by a few numbers (parameters) (e.g., one or a few damped sinusoids), but the concept is more general in that various manipulations of the data may be needed to bring out parameter sets that are not apparent just from a casual look at the data.

Now a particular X_n has, for a given model, a particular set of parameter values (real, complex, vector, dyadic, etc.). Some of these parameters may be a function of aspect, and others may be aspect independent. Provided that the set of these (the signature) is different from the set for X_m ($m \neq n$) then the two signatures are different and one target can be distinguished from the other. For the case of aspect independent parameters (such as natural frequencies) this simplifies matters considerably since each X_n is allowed to appear before the radar at any aspect (or some range of aspect (angles)). For aspect dependent parameters, aspect will need to be taken into account unless there is some aspect-independent relationship among the parameters, or the two sets of parameters are sufficiently separated from each other over the aspects of interest, or the aspects of the targets are known from other information.

Parameters and signatures can be illustrated by examples [5,6]. The SEM form for backscattering is

$$\overleftrightarrow{\Lambda}_b\left(\vec{1}_i,t\right)=\sum_{\alpha} e^{s_\alpha t_i}u(t-t_i)\vec{c}_\alpha\left(\vec{1}_i\right)\vec{c}_\alpha\left(\vec{1}_i\right)$$

$$+ \text{ entire function (transformed to time domain)}$$

$$s_\alpha \equiv \text{aspect-independent natural frequency (parameter)}$$

$$\vec{c}_\alpha\left(\vec{1}_i\right)\equiv \text{residue vector (2 component)}$$

$$\equiv \text{target polarization vector (parameter, aspect-dependent)} \tag{3.1}$$

$$\vec{c}_\alpha\left(\vec{1}_i\right)\cdot\vec{1}_i=0$$

$$t_i \equiv \text{initial time (chosen for convenience and related to definition of } t = 0)$$

This model (the singularity expansion method or SEM) can be used to describe global scattering (major body complex resonances) or local scattering (substructure resonances), in which case different time regimes are appropriate. Much attention has been paid to estimating parameters in experimental data [11]. Here the model is used in a late-time sense where a small number of poles (in s domain) dominate the response. At early times an entire function is needed in general (except for special cases) for the far-scattering problem (as distinguished from the currents on the target) [1]. So it is some particular set of s_α and $\vec{c}_\alpha$, a signature of target X_n, that is obtained from the later-time portion of the target-response waveforms.

A second example concerns the scattering from a general cone satisfying dilation symmetry [3,4] which includes an arbitrary cross section, dielectric materials, resistive sheets, and combinations of these. In backscattering this takes the form (has the model)

$$\vec{E}_f(\vec{r},t)=\frac{c}{4\pi r}\overleftrightarrow{K}^{(c)}\left(\vec{1}_i\right)\cdot\int_{-\infty}^{t}\vec{E}^{(inc)}\left(\vec{0},t'-\frac{r}{c}\right)dt'$$

$$\overleftrightarrow{K}^{(c)}\left(\vec{1}_i\right)= \text{real, symmetric, 2 x 2 dyadic (parameter) containing aspect information}$$

$$\int_{-\infty}^{t}(\cdots)\,dt' \equiv \text{aspect-independent temporal integration (parameter)} \tag{3.2}$$

$$\overleftrightarrow{\Lambda}_b\left(\vec{1}_i,t\right)=c\overleftrightarrow{K}^{(c)}\left(\vec{1}_i\right)u(t)$$

noting that $u(t)\circ$ is the same as temporal integration. Here the temporal operation (integration) is regarded as a parameter. In complex frequency domain this is just s^{-1} which may look more familiar as a parameter. However, it is more appropriate to use the time-domain form since for a truncated cone (non-infinite, the practical case) there is some time of validity t_v after the incident wave first reaches the cone tip) at $\vec{r} = \vec{0}$) as seen in the far field (retarded time) for which the model is *exact*. So this is an early-time model which might be applied to some substructure of a more general target. Note that $\overleftrightarrow{K}^{(c)}(\vec{1}_i)$ can always be diagonalized with two real eigenvalues and associated real orthonormal eigenvectors (representing real directions (target aspect) in space). Note that there is a limitation on the allowable angular range of the direction of incidence $\vec{1}_i$ and the cone geometry such that the first scattered signal to reach the observer comes from the cone tip. As discussed in [4] this model can be extended to include finite wedges and half spaces with the additional imposition of translation symmetry. In this case the exact model contains a few terms based on cone tips, wedge edges, and half-space face, each with temporal integration I of order I^{d-2} where d is the number of spatial dimensions characterizing these geometric target features. In this case integration order d-2 is another parameter of interest. Again a set of the above parameters is a signature type with a specific set of values as a signature.

A third example is the high-frequency method (HFM). In this model the scattering dyadic takes the general form

$$\tilde{\overleftrightarrow{\Lambda}}\left(\vec{1}_o, \vec{1}_i; s\right) = \sum_p \overleftrightarrow{D}_p\left(\vec{1}_o, \vec{1}_i\right) \frac{e^{-st_p}}{s^p} \quad \text{as } s \to \infty \tag{3.3}$$

where p (itself a parameter) can take on fractional values as well as integers. While formally similar to the second example, this model is asymptotic as $s \to \infty$ (instead of exact in time domain). The t_p represent the times the observer sees various discontinuities encountered by the incident wave. The dyadic diffraction coefficients $\overleftrightarrow{D}_p$ contain information regarding the target aspect, as do the t_p.

A fourth example is a model appropriate to a linear array of scatterers (such as a linear array of windows) [6] as

$$\begin{aligned}
\tilde{\overleftrightarrow{\Lambda}}\left(\vec{1}_o, \vec{1}_i; s\right) &= \tilde{\overleftrightarrow{\Lambda}}^{(0)}\left(\vec{1}_o, \vec{1}_i; s\right)\tilde{W}(s) \\
\tilde{W}(s) &= \frac{1-e^{-N_s T_0}}{1-e^{-sT_0}} \equiv \text{ scattering array factor} \\
T_0 &\equiv \text{ additional delay time for sign to reach observer from each successive scatterer} \\
\tilde{\overleftrightarrow{\Lambda}}^{(0)}\left(\vec{1}_o, \vec{1}_i; s\right) &= \text{ scattering dyadic for one scatterer in array}
\end{aligned} \tag{3.4}$$

where mutual interaction between the scatterers is assumed negligible. For large N (number of scatterers) this model gives approximate poles at $s = s_m = j\omega_m = j2\pi m / T_0$ (m integer) which are aspect dependent (and hence not natural frequencies). Here the set of s_m (or equivalently T_0) is a signature.

Note that the scattering dyadic for a single scatterer is completely separate, and this can also be considered for its signatures, if appropriate.

A fifth example is the scattering-center model [5,13]. In this model one assumes that there are some number N_c of points at $\vec{r} = \vec{r}_n$ for $n = 1, 2, \ldots, N_c$ (called scattering centers) which dominate the scattering in a short-time or high-frequency sense. One can then think of the scattering dyadic taking the form (in backscattering)

$$\overleftrightarrow{\Lambda}_b\left(\vec{1}_i, t\right) \simeq \sum_{n=1}^{N_c} \overleftrightarrow{\Lambda}_n\left(\vec{1}_i, t - 2\frac{\vec{1}_i \cdot \vec{r}_n}{c}\right) \tag{3.5}$$

where the individual dyadics $\overleftrightarrow{\Lambda}_n$ are assumed to be sufficiently localized in time to define some t_n for each $\vec{r}_n$. The set of such t_n are then a signature type (aspect dependent). If the $\vec{r}_n$ are fixed points on the body, then as the target is rotated the $\left|\vec{r}_n - \vec{r}_m\right|$ remain invariant and one can rotate each target in the library to attempt to reproduce a specific signature. Note, however, that some scattering centers (e.g., specular points on smooth surfaces) move on the target as it is rotated, complicating the simple picture in (3.5). Note the use of approximate equality in (3.5) since for low frequencies such a separation is not appropriate. So this is better thought of as a high-frequency or short-time model.

Various other scattering models and associated signature types can also be used. There is a low-frequency model (LFM) based on polarizabilities [5]. Target substructures can have point symmetries (reflection planes and/or rotation axes) [11], or discrete dilation and translation symmetries (such as conical-spiral and log-periodic antennas) [8] which give special properties (parameters) in the scattering dyadic.

These various examples illustrate the various kinds of models that can be used to define target signatures. These various models are, at a deeper level, consequences of symmetries in the target (geometry and constitutive parameters) and the Maxwell equations. So we can summarize:

symmetries $\Rightarrow$ models

models $\Rightarrow$ signature types (types of parameter sets) (3.6)

specific signature(s) $\Rightarrow$ specific target (or target class) X_n
(specific values
for parameters in
set(s), including
aspect dependence)

IV. Signature Enhancement

In order to identify a target by its signature(s), the signature(s) must be present in the set of scattered waveforms. The transmitted waveforms then must be of a kind which excite the signature(s). If a signature contains some set of frequencies, then the frequency spectrum of an incident waveform should contain such frequencies to see that a particular target X_n is actually there. Of course, one does not know a priori that X_n is the target, so the transmitted waveform (or a set of some transmitted waveforms) including polarization should excite at least one of the signatures for every target in the library.

Going beyond merely exciting a signature, incident waveforms can be designed to *enhance* a signature. If one is looking for scattering centers, a very narrow temporal pulse (perhaps with low frequencies filtered out) might be used. If one is looking for the natural frequencies, then for X_n one might deliberately transmit such damped sinusoids (perhaps with less damping) to "ring up" the resonances, and similarly transmit other damped sinusoids in successive waveforms which are matched to other targets in the library. Such signature enhancement is to raise the signature signal-to-noise ratio at the receiver. Noise here includes not only background, other sources, and recording error, but also other parts of the scattered waveforms not associated with the signature(s) of interest.

Signature enhancement then can demand much of the transmitter. Besides the two polarizations (h,v), the transmitter may need to send a sequence of different waveforms "tuned" to the different targets in the library. This can be accomplished in the signal generators and/or the filters one can include in the antenna feed. Besides changing these from pulse to pulse, one might also do this adaptively, i.e., change the transmitted waveform based on one's preliminary estimate of the target identity.

V. Signature-Based Signal Processing

After the scattered waveforms are received and recorded they need to be processed to bring out the signature(s) of the target. First, one can remove some of the characteristics of the transmitters and receivers from the waveforms [12], either by physical filters in the receiver signal path, or by numerical filters applied to the recorded data. One can then apply any of a variety of transformations to the data, e.g., K/E pulse, temporal or frequency wavelets, etc. However, this approaches signal processing from the wrong direction. The question is: based on the signatures of concern, what kind of signal processing can be designed for optimum target identification?

In a formal sense the answer to this question is wave-oriented signal processing [16]. Since the important thing about the scattered waves is the signature information they contain, then we can sharpen this concept somewhat as *signature-based signal processing*. Based on a particular signature type of concern, one can construct particular filters (frequency domain) and/or windows (time domain) which are matched to this signature type.

In general, then one can envision a set of signature-based algorithms (signarithms?) for optimal signal processing. There may be as many specific optimal algorithms as there are signature types of interest for a particular application. Of course, the optimal choice may also be influenced by other factors such as the kinds of noise present and the number and kinds of targets in the library.

As we have seen, symmetry is an important concept in developing signatures. One should expect then that symmetry can play an important role in signal processing. Symmetries in the signal processing can be matched to those in the signatures. Note the relation between space (target features) and time (scattered waveforms) via the speed of light or causality (related to relativistic invariance, another symmetry). So spatial symmetry in target features may appear as a related symmetry in time (or frequency). A special kind of symmetry, referred to as partial symmetry, occurs when one is able to isolate a signature of a target substructure from the scattering from the rest of the target by use of time windowing, polarization etc. While this is not a symmetry of the entire target geometry, it can still be used in some cases to give signatures which can be used in signal processing. Table 5.1 lists some of the kinds of signal processing transforms and the kinds of symmetries that are related to them. Perhaps additional kinds of signal processing can be devised based on other symmetries which can be incorporated in the transformations.

Signal processing	Symmetry
Laplace/Fourier transform and inverse transform	time invariance and linearity of target
filter (multiplication in frequency domain)	same as above
window (multiplication in time domain)	exhibition of target substructures to use their symmetries (partial symmetries)
temporal wavelet	affine transformation (translation and dilation) in time
frequency wavelet	affine transformation (translation and dilation) in frequency

Table 5.1. Symmetry in Signal Processing

VI. Organization of Target Features, Signatures, and Data Processing by Symmetry: The Zoo

One way to organize specific signatures is by the target X_n to which they belong. As discussed previously the set $\{X_n\}$ forms what has been referred to as a *library*. Each X_n is analogous to a *book*. Within each book a chapter is analogous to a *specific signature* (a set of specific parameter values, including aspect dependence) corresponding to the particular X_n.

Another kind of organization is according to symmetry type. Analogous to the elementary-particle zoo based on quantum-mechanical symmetries one can define a target-feature/signature/signal-processing *zoo* based on the symmetries inherent in these things. Another analogy is to the periodic table of the elements based on the quantum symmetries in the electron shells. Summarizing we have:

$$\begin{aligned} \text{symmetry in Maxwell equations and target features} &\Rightarrow \text{symmetry in models} \\ &\Rightarrow \text{symmetry in signature types} \\ &\Rightarrow \text{symmetry in signal processing} \end{aligned} \qquad (6.1)$$

It is then the symmetries and associated groups [8] which one uses as the organizing principle for the zoo. Each symmetry type is analogous to a *habitat* in the zoo [5]. So habitats also correspond to models, signature types, and signal processing algorithms. If one wishes, a specific signature (one of those for an X_n) can be included within a habitat, a part of which by analogy is a *beast*. However, different specific signatures for the same target X_n belong, in general, in different habitats.

Symmetries are associated with groups [8]. So group theory may shed some light on how to further organize the zoo. Symmetry groups can be combined (adjoined) to form groups with a larger number of elements. Groups often have subgroups (subsets of the original group which are also groups). So habitats can be decomposed and combined to form a richer structure (hierarchy) for the zoo.

VII. Concluding Remarks

We can begin to see a structure emerging for signature-based target identification. The present paper provides some of this, but much research is needed to fill in the structure. We need to add to our parametric models, and associated signatures and signal processing techniques. The present discussion has concentrated on targets in a free-space environment. However, other targets such as those buried in soil can also be identified by similar signatures [2,7], but there are quantitative differences.

Here signatures have been discussed in the context of a single target aspect, this being a significant case of interest. Of course, if one has additional information the concept of signatures can be applied here as well. For example, in some cases imaging can be attempted leading to other signatures based on the geometric shape of the image. One need not consider single aspect and multiple-aspect signatures in isolation since they can be combined to give a more reliable identification.

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