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What is the Radar Tracking "Glint" Problem and can it be Solved?

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FOREWORD

The work described in this report was performed during the 1993 fiscal year as part of an effort to improve missile signal processing capabilities. This problem continues to be central to radar research programs and considerable effort has been expended within the last few decades in attempts to solve it.

There seems to be a good deal of confusion about the glint problem in radar target tracking. Judging by the many requests for information that I have received within the last year, this confusion seems to be a result of the preponderance of literature in the area and the (relatively) high level of understanding these works presuppose of the reader. Moreover, many significant questions have not been addressed in a frank and decisive way.

It is hoped that this introductory tutorial will help answer some of the questions that are frequently asked and are not adequately answered by existing documents. However, while introductory in intent, several of the approaches that we have used are nontraditional and provide for more definitive conclusions.

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(U) We present an elementary tutorial on the glint problem in radar tracking. Our approach uses a very simple model yet, because of several original observations, it allows us to make some very general observations about glint. In addition, we briefly survey the collected standard mitigating approaches and comment on their relative merits and shortcomings.

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1. INTRODUCTION

Interference effects in radar scattering from extended unresolved targets (leading to the "glint problem") have been recognized and examined for five decades. Despite these long and continuing efforts, the associated problems are still being studied and efforts to mitigate their effects are still being devised. For example, one of the most recent areas of applied missile research deals with the problem of "predictive fusing" that attempts to locate a target in space, at unusually large range (for a fusing situation) and with unprecedented accuracy.

The original (unclassified) work in the glint tracking problem can be traced to the early 1950s [References 1 through 4]. These early efforts were concerned with a statistical characterization of glint "noise"—the idea being to apply filtering techniques to eliminate it [References 4 through 6]. As a consequence, most of the relevant subsequent literature has been dominated by statistical considerations and the uninitiated reader may spend considerable effort in trying to understand the role of various target models and the conclusions which are made from them. Worse, it may be very difficult to understand just what glint is and to sort-out fact from conjecture.

The present discussion is a brief tutorial on the glint problem and is intended to explain the important ideas and problems in an introductory way. We believe that an understanding of all of the basic ideas involved can be had without a detailed description of probability distributions or power spectra. In carrying out this program, we have developed several fresh approaches that we have found to be quite helpful in answering some surprisingly complex questions. For the most part, however, the discussion is kept at a very simple and traditional level.

We begin by defining what glint is and why it is a problem for radar tracking systems. Then we examine the properties of glint and show how they can be related to target size and scattered field strength. Finally, we discuss (in very general terms) several of the most promising methods that have been proposed as solutions of the glint problem.

2. GLINT—WHAT IS IT?

One of the few "nice" things about glint is its simplicity of description. All of the relevant properties of glint can be understood by examining a very elementary target scattering model and in the following; we shall include only as much complexity as is required to make our observations. First, of course, we need to understand what kind of information a radar uses to track a target.

The standard approach to radar-based target tracking begins with a description of the radar itself: the sum and difference pattern; the difference between conical scan and monopulse; and the difference between phase and amplitude tracking [References 7 and 8]. While this method is of particular interest to radar engineers, it is not particularly essential to an understanding of the glint problem because true glint is a consequence of coherent scattering from a complex target and is independent of the system which measures it. To understand this statement, consider the ideal radar situation in which a plane wave (launched from a "perfect" radar) is reflected from a single scatterer and returned to the radar where its properties are measured without error. If

$$E_{inc}(y, t) = E_o \exp[j(k\hat{R} \cdot y - \omega t)] \quad (1)$$

denotes a plane wave with amplitude E_o , direction \hat{R} , wave number $k = \omega / c$ associated with the carrier frequency ω , and incident upon a target with position y , then the scattered wave in the far-field approximation is of the form

$$E_{scat}(y, t) = \frac{E_o}{2\pi y} S(\theta, \varphi) \exp[j(2k\hat{R} \cdot y - \omega t)] \quad (2)$$

The quantity $S(\theta, \varphi)$ is the so-called far-field pattern associated with the target and has magnitude proportional to the fraction of the incident wave scattered toward the spherical angles θ and φ (defined with respect to target orientation). The factor of 2 accounts for the 2-way wave travel distance.

The simplest approximation—the point scatterer—sets $S(\theta, \varphi) = Ae^{j\psi}$, a constant independent of θ and φ . In this case, the scattered field is a spherically symmetric wave train, centered on the target, with amplitude A and phase shift ψ .

Directions defined by a scalar-valued field is found from the field's gradient. We could, for example, use the radar to estimate the gradient of the amplitude of the scattered field or we could estimate the gradient of its phase. In either case, the gradient of the field of (2) points in the direction of the normal to the surfaces of constant phase (phase fronts) which, in this case, point toward the target. In the following, then, we shall assume that our perfect radar performs a phase-gradient measurement on the scattered field to obtain target bearing. (As we shall see below, there is an even closer relationship between amplitude gradients and phase gradients than simply the direction toward which they point.)

Tracking glint error comes about when the target is not a simple point scatterer. Real targets can be considered to be made up of a collection of point scattering elements—

each element responding to the incident plane wave and each contributing to the scattered field. The simplest approximation treats these scatterers as independent and non interacting. In this "weak scatterer" treatment, the incident wave is the only wave that a scatterer sees and the secondary wave scattered from one point cannot excite another. In the far-field approximation, the total field returned from this complex N -point target is simply the sum of the fields scattered from the collection of point scatterers:

$$E_{scatt}(\mathbf{R}, t) = \frac{E_o e^{j(2kR - \omega t)}}{2\pi R} \sum_{n=1}^N A_n \exp[j(2k\hat{\mathbf{R}} \cdot \mathbf{x}_n + \psi_n)] \quad (3)$$

Here we use $\mathbf{x}_n = \mathbf{R} + \mathbf{y}_n$ to represent the position of the point scatterer in space and set \mathbf{R} , $|\mathbf{R}| \gg |\mathbf{y}_n|$, as the origin of a coordinate system fixed within the target. If we write $E_{scatt} = |E|e^{j\phi}$ then the directional, derivative of the phase in a direction $\hat{\mathbf{u}} \perp \hat{\mathbf{R}}$ is

$$\hat{\mathbf{u}} \cdot \nabla \phi(\mathbf{R}, t) = \text{Im} \left(j \frac{E_{scatt}^* e^{j(2kR - \omega t)}}{|E_{scatt}|^2} \sum_{n=1}^N \frac{2k\hat{\mathbf{u}} \cdot \mathbf{x}_n}{R} A_n \exp[j(2k\hat{\mathbf{R}} \cdot \mathbf{x}_n + \psi_n)] \right) \quad (4)$$

Equation (4) is our result and displays all of the behavior associated with glint.

Figure 1 is a plot of the glint error (the difference between estimated and actual target bearing) based on Equation (4) for a 5-point target. This target was computer generated by randomly fixing 5 scattering "centers," of the form of Equation (2), on a line target support of length 10 m. The amplitudes and phase shifts of these scatterers were also chosen to be random. The target was rotated through a sequential set of angles ($\theta = 0$ is target "broadside") and Equation (4) was used with $\omega = 10$ GHz to calculate the pointing error (scaled to range). The angular bearing error at a particular range can be obtained by dividing the displayed values by range (in meters).

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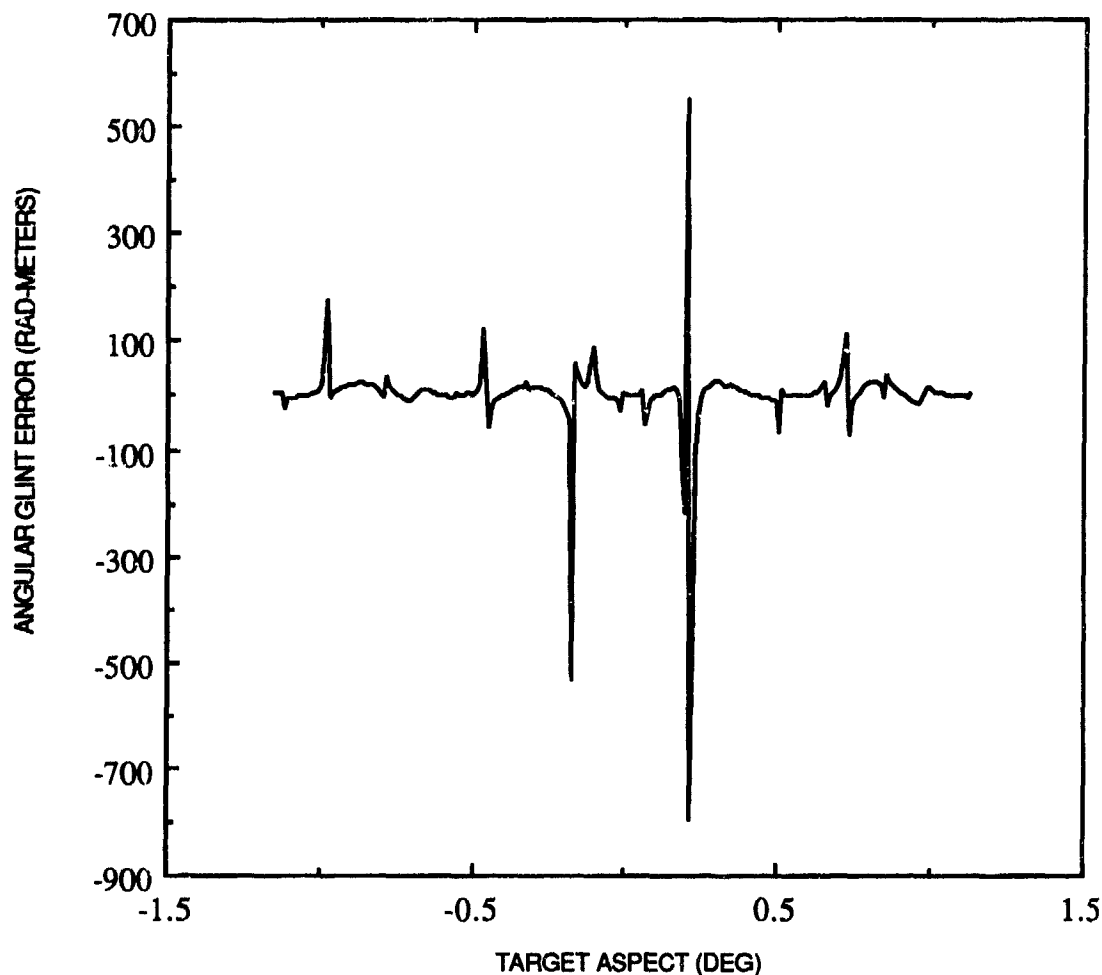


FIGURE 1. Calculated Glint Error as a Function of Target Aspect Based on Equation (4) for a 10-m-Long 5-Point Target in X-Band.

3. THE RELATIONSHIP BETWEEN GLINT "SPIKES" AND AMPLITUDE FADES

It has long been recognized that large glint errors (or glint "spikes") are correlated with drops in the amplitude of the scattered field. To some extent, this can be deduced from Equation (4). However, since the numerator of this expression cannot be expressed as a function of the denominator, it is not completely clear just what the relationship between spikes and fades is—does every spike correspond to a fade or is this property only mostly true? By expressing the scattered field in more general terms we can answer

this question and in addition, point the way to glint mitigation approaches that will be examined in greater detail later.

An important property of the complex scattered field of Equation (3) is its analyticity. For example, the analytic property means that the real and imaginary parts of this field are related and one can be determined from the other. Of particular interest to our purposes is the fact that analyticity of (3) also implies that

$$\frac{\partial \ln E_{\text{scat}}(\xi)}{\partial \xi} = \frac{\partial \ln |E(\xi)|}{\partial \xi} + j \frac{\partial \phi(\xi)}{\partial \xi} \quad (5)$$

is analytic everywhere except at the branch points. (ξ parameterizes some curve in aspect-space.)

The real and imaginary parts of an analytic field is a Hilbert transform pair [Reference 9]. Since our field is not analytic everywhere, we need to accommodate the branch points and the relationship between real and imaginary parts is a little more complicated. The more careful analysis is performed in Reference 10 and is simply stated here:

$$\frac{\partial \phi(\xi)}{\partial \xi} = -\frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{1}{\xi' - \xi} \frac{\partial \ln |E(\xi')|}{\partial \xi'} d\xi' + \frac{\partial \phi(0)}{\partial \xi} + 2 \operatorname{Im} \sum_i \operatorname{Res}_i(\xi) \quad (6)$$

where $P \int (*)$ denotes the principal value integral, Res_i is the functional contribution due to the i th zero, and the sum is over all such contributions from complex zeros in the upper half-plane. It was shown in Reference 10 that the integral term in Equation (6) dominates the collective effects of the residues for high frequency scattering situations.

Equation (6) shows that the relationship between fades and spikes is a little more complicated than might be expected from a casual examination of the measured data. This equation displays the unfortunate property associated with all Hilbert transform type reconstructions—namely that to obtain the real (imaginary) part of an analytic function at a point one needs to know the imaginary (real) part everywhere. For our purposes, however, we can use a local approximation to the integral in (6) from which we can draw conclusions.

The strongest contribution to the integral term in (6) comes from the deep fades in the field amplitude. Phenomenologically, we know that these fades are isolated and so we can make the approximation

$$-\frac{1}{\pi} \int_{-\infty}^{\infty} \frac{1}{\xi' - \xi} \frac{\partial \ln|E(\xi')|}{\partial \xi'} d\xi' \approx -\frac{1}{\pi} \left(\frac{\partial \ln|E(\xi)|}{\partial \xi^+} - \frac{\partial \ln|E(\xi)|}{\partial \xi^-} \right) \quad (7)$$

where $\partial/\partial \xi^\pm$ denote left and right derivatives. If $|E(\xi)|$ is modeled as being roughly symmetric about the fade, then we can make the further approximation

$$\frac{\partial \ln|E(\xi)|}{\partial \xi^+} - \frac{\partial \ln|E(\xi)|}{\partial \xi^-} \approx 2 \frac{\partial \ln|E(\xi)|}{\partial \xi^+} \quad (8)$$

(which should be fairly accurate in behavior, if not actual value, in the region around the fade).

For a target rotating through a small aspect angle θ we have $\xi \approx k\theta$ and Equation (6) becomes

$$\frac{\partial \phi_k(\theta)}{\partial \theta} \approx \frac{\partial \ln|E_k(\theta)|}{\partial \theta^+} = \frac{1}{|E_k(\theta)|} \frac{\partial |E_k(\theta)|}{\partial \theta^+} \quad (9)$$

where we have included the subscript k to explicitly remind us that the result depends upon wave number.

Equation (9) represents the behavior of the glint error in the neighborhood of a glint spike.

4. THE RELATIONSHIP BETWEEN GLINT AND TARGET SIZE

Equation (9) can be used to explain another observed property of glint. An important theorem from complex analysis tells us how often we can expect to see amplitude fades (zeros) for fields defined by Equation (3). By virtue of (9), this theorem also tells us how often we should expect to see glint spikes. The Titchmarsh theorem [Reference 11] says, in the present (high frequency) case that the number of amplitude zeros in the aspect interval $\Delta\theta$ is approximately

$$\Delta\eta \approx \frac{kL}{\pi} \Delta\theta . \quad (10)$$

where L is the crossrange extent of the target. (We have checked this simple prediction against actual radar data and found it to be remarkably accurate.)

An immediate consequence of Equation (10) is that large targets are "glintier" than small ones. The reader is no doubt unimpressed by this fact (which may appear obvious from the discussion of Section 2), but many early radar engineers viewed the "paradox"—that large targets are *harder* to hit than small ones—with great suspicion. Nowadays, this property still presents difficulties and it must be remembered that the problem of correctly tracking a small target drone is easier than that of accurately tracking a large bomber.

Another easy conclusion that can be drawn from (10) is that, for fixed L , the number of zeros in the interval increases with wave number. As a result, the *position* of these zeros must also vary with frequency. We shall shortly return to this fact.

5. WHY "USUAL" SIGNAL PROCESSING TECHNIQUES ARE INEFFECTIVE FOR MITIGATING GLINT

From the beginning, glint error has been viewed as a type of "noise" problem—one that could be dealt with by designing the correct "filter." To be sure, this design problem was recognized as difficult since the statistics of glint noise are non-Gaussian [References 1 through 6] and because of Equation (4), they are nonstationary (changing with target orientation). Perhaps the earliest approach was to simply slow down the "tracking loop." This is a form of low-pass filtering and was expected to work because the glint spikes would be filtered away and the tracking information to be used would be a more correct "average."

Unfortunately, this works well for stationary targets but fails when the target undergoes a rapid maneuver. By eliminating all spikes, the filter discards not only the glint noise but also the very real information needed to stay "on-track." "Tuning" the time-constant; so that, glint noise is discarded while tracking information is retained is equivalent to altering the filter parameters and does not work very well: to a radar, target maneuvers simply "look" too much like glint. (This is usually what is meant by radar engineers when they refer to "the glint problem.")

In fact, even accounting for the non-Gaussian and nonstationary character of the glint statistics should not be expected to solve the glint problem. Such approaches usually deal only with the tracking data itself and cannot always separate out the relevant effects of target maneuvers from the "irrelevant" interference effects of the target's subscatterers in a meaningful way—that is, a predictive way. Of course, it is known that glint error averages to zero and so almost any filtering process can be made to work if given enough

data. However, should the target maneuver out of the radar illumination beam then the data stream is immediately truncated and nothing further can be done.

6. TECHNIQUES THAT SHOULD WORK (AND WHY THEY USUALLY CAN'T BE USED)

While typical tracking data alone do not contain enough information to distinguish between glint noise and target maneuvers, we can frequently use additional information to help us make the distinction. Often, this added information comes to us in the form of a relevant target model. Sometimes we need to acquire additional data.

As we have already observed, the location of the amplitude fades changes with frequency. This property is the basis of the so-called "frequency diversity" or "frequency agility" methods of glint error reduction [References 12 through 17]. The idea here is to estimate target bearing at several different frequencies and perform a weighted average to determine which of the estimates are good and which are in error. A recipe [Reference 14] is often quoted and yields the bandwidth required of the frequency-agile system. Application of this "rule," for example, to a 6 m (downrange) target results in a needed bandwidth of 500 MHz to reduce the glint error by a factor of three. (There is also a criteria for the frequency step-size that should be used within the band [Reference 14].)

The derivation of this bandwidth result has been model-dependent and is therefore, subject to possible criticism. An easier way to understand frequency agility, and the associated bandwidth requirement, is to reconsider the fundamental cause of glint. Single scatterers do not display glint: the effect only occurs when two or more scattering centers are illuminated simultaneously. However, if two scatterers are displaced in downrange position from the radar, and if the sampling bandwidth is sufficiently large in the frequency domain that the scatterers are not simultaneously illuminated (i.e., the pulse is sufficiently narrow in the time domain), then there can be no interference. In this way the target relevant substructure will be "resolved"—as well as the glint problem. A bandwidth of 600 MHz corresponds (roughly) to 1 m of range resolution. Consequently, if the dominant scatterers of a complex target are separated downrange by more than 1 m, then 600 MHz of bandwidth will be enough to satisfy the requirements of zero interference.

This time domain visualization of how frequency diversity works is useful, but it is not how the technique is actually applied. In the frequency domain, we need some kind of weighting criteria to determine which information should be used. Various schemes have been examined [Reference 16] and it is now believed that some form of amplitude weighting is probably optimal. Equation (9) displays the correlation between small values of amplitude and large values in glint error. By "weighting" the validity of the bearing estimate at a given frequency by the magnitude of the field measured at that same frequency we can guarantee that the glintier estimates will be given less credence. In fact, it appears that the best estimation scheme discards all of the bearing estimates except the *one* with the largest amplitude.

Unfortunately, 500 MHz of bandwidth has been hard to achieve at x-band frequencies in practical missile systems and frequency diversity methods have not been well-used. (Note, this is a minimal bandwidth figure and in practice, we may require several GHz to assure sufficient error reduction.) Since the carrier frequency does not formally enter into the bandwidth requirement rule, many investigators have suggested that the tracking radar should not try to function at 10 GHz but rather, at much higher frequencies. Radar bandwidth is often expressed as a percentage of the carrier frequency and the difficulty in achieving a bandwidth is roughly proportional to this fraction. (For example, 500 MHz is 5% bandwidth at 10 GHz but only 1% bandwidth at 50 GHz.) This reasoning is problematic, however, since the number of target subscatterers also increases with frequency and we should therefore, expect the downrange separation of these scatterers to *decrease*. This means that bandwidth requirements will probably increase with frequency—although it is an open question as to how much of a problem this will turn out to be.

Equation (10) can be used to argue for a different type of diversity technique based upon spatial sampling [Reference 13]. The amplitude zeros (the glint spikes) are isolated on the target aspect axis. If this axis is sampled by the radar at a number of separate locations, then the same kind of processing that was applied to frequency diversity can be used to predict the minimal glint target bearing. Like frequency diversity, this method also has an easy interpretation: sampling in crossrange space effectively increases the aperture of the radar system and this, in turn, increases the resolution of the radar system. By better "resolving" the individual target scattering centers we can reduce the effects of their self-interference. (Note, the relevant target property in determining the effectiveness of this kind of diversity processing is its crossrange extent.)

The problem with space diversity is that the requisite aperture that must be sampled in x-band is about several meters (at least). This is well beyond the crossrange dimensions of guided missiles and it appears that straightforward space diversity techniques are inappropriate to these systems. However, the spatial aperture can be synthetically sampled in a way akin to ISAR imaging. Here, the aspect variation presented by the target as it maneuvers can be used to significantly reduce glint in small, single frequency systems [Reference 10].

Finally, polarization diversity has been studied as a way to avoid the problems associated with downrange and crossrange sampling [Reference 18]. So far, our presentation has been based on Equation (2) which is a scalar reduction of the actual (vector) electromagnetic scattering process associated with radar. To understand how polarization can help us, we need to replace Equation (2) with two equations of the same form: each equation representing the two polarizations of the scattered field. Following the derivation through for each of these scattering processes we can obtain two target bearing measurements. Now, *if* the two polarizations are associated with uncorrelated scatterers (that is, if at one polarization different scatterer locations are excited than at the other) then the glint errors will be uncorrelated and we can use the one associated with the greatest amplitude as the best estimate.

In reality, the scatterers are not really all that uncorrelated and the improvements are often modest (at best). Moreover, fully polarized radar systems are much more expensive than ordinary (singly polarized) systems. Variations on the theme use only a one polarization transmitter and receive the copolarized and cross-polarized returns (in an effort to keep costs down). However, this actually complicates the associated problems

since the strength of the cross-polarized return is very often significantly less than that of the copolarized return and so amplitude-based validity weighting may become ineffective.

7. SUMMARY AND RECOMMENDATIONS

Incomplete efforts in applying diversity techniques have led many to the mistaken conclusion that the glint problem cannot be solved at all. As we have seen, there is considerable, theoretical evidence that frequency diversity methods offer the greatest opportunity for resolving the glint problem. This conclusion is also justified by our intuition about radar resolution of target substructure. However, there is very little experimental evidence to justify these claims and so it is unlikely that meaningful frequency agility will be applied to missile systems any time soon: the expense and effort are simply too great. Spatial diversity methods offer a next-best alternative to frequency agility and in addition, may be able to be retrofitted to many existing missile systems.

A thorough and convincing investigation of diversity techniques requires a data base consisting of wideband glint azimuth and elevation measurements, and these are not to be found. There have been efforts to process existing wideband scattering data to extract the appropriate glint measurements that would have been made under the same situations. This synthesis method attempts to estimate the phase gradient components by numerically differentiating the scattered field obtained as a function of target aspect. While this kind of processing has the advantage of putting to use some of the data that have accumulated over the years (and might otherwise be ignored), it is not a correct approach. Numerical differentiation (whether performed in the space or Fourier domain) is a very ill-posed process (c.f., [Reference 19] and references cited therein). In practice, the overwhelming effects of noise are usually reduced by filtering (splines) and the resulting derivative estimates will be good if the true derivatives are slowly varying with respect to the additive noise term. However, spiky glint error is *not* slowly varying in this sense and filtering methods destroy much of the very information that the synthesized glint data are required to contain. The consequences of not filtering the derivative estimate is just as bad and the resulting glint estimate will display too much spiky behavior. A better approach for glint synthesis is to use the scattering data to image the target subscatterer strength and location, and apply Equation (4) as the estimate. (Of course, this may result in data which are not all together convincing to everyone.)

Finally, there are additional research and development efforts that could make use of wideband glint data; besides, those concerned with radar-based target tracking. It is known that there is a close connection between phase derivative measurements and measurements required to classify the radar target by size and shape [References 20 and 21]. Further, significant progress in all of these areas depends upon the establishment of an enlightened measurement program.

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