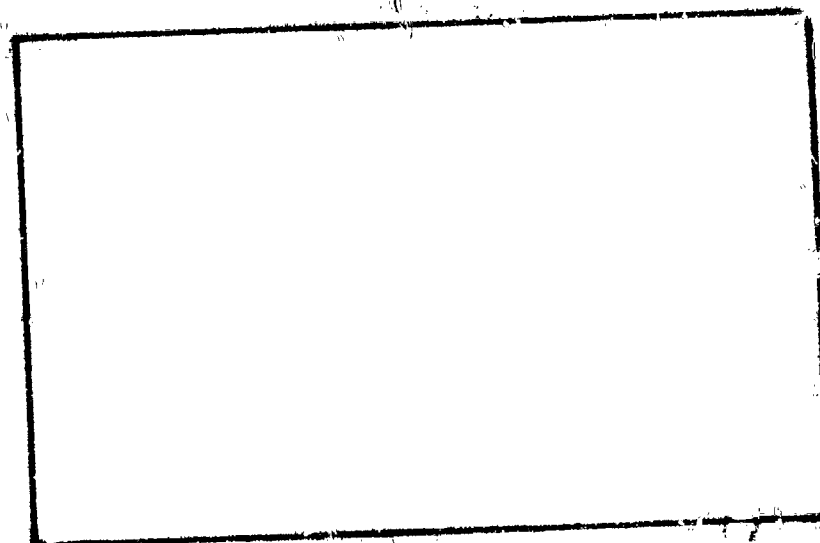




COMMUNICATIONS LABORATORY

Department of Information Systems
University of Chicago, Chicago, Illinois
Box 4340, Chicago, IL 60680 USA

AD A116391



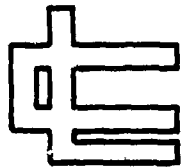
DTIC FILE COPY

DTIC

JUL 2 1982

APPROVED FOR PUBLIC RELEASE
DISTRIBUTION UNLIMITED

82 07 02 000



COMMUNICATIONS LABORATORY

Department of Information Engineering
University of Illinois at Chicago Circle
Box 4348, Chicago IL 60680, USA



BASIC CONCEPTS OF RADAR POLARIMETRY AND ITS APPLICATIONS TO TARGET DISCRIMINATION, CLASSIFICATION, IMAGING AND IDENTIFICATION

W-M. Boerner

COMMUNICATIONS LABORATORY
ELECTROMAGNETIC IMAGING DIVISION
Electrical Engineering and Computer Science
University of Illinois at Chicago
851 S. Morgan St., P.O. Box 4348
Chicago, IL. 60680

Report No: EMID-CL-82-05-18-02
Contract No: NAV-AIR-N00019-80-C-0620
1982 May 18



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER EMID-CL-82-05-18-02	2. GOVT ACCESSION NO. AD-A116 391	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Basic Concepts of Radar Polarimetry and Applications to Target Discrimination, Classi- fication, Imaging and Identification.		5. TYPE OF REPORT & PERIOD COVERED
7. AUTHOR(s) Wolfgang-Martin Boerner		6. PERFORMING ORG. REPORT NUMBER
8. PERFORMING ORGANIZATION NAME AND ADDRESS Electromagnetic Imaging Division Communications Laboratory, UIC P.O. Box 4348, SEO-1141, Chicago, IL 60680		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Systems Command Headquarters, AIR-310B, Washington, DC 20361 Attn: Mr. James Willis		12. REPORT DATE May 18, 1982
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Chicago Branch Office, Office of Naval Research 536 S. Clark St., Chicago, IL. 60605 Attn: Mr. Gordon I. Lovitt		13. NUMBER OF PAGES 56 +
		15. SECURITY CLASS. (of this report)
		16a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) See list appended, otherwise: Distribution by permission of Naval Air Systems Command		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES The findings of this report are not to be construed as an official Department of the Navy position unless so designated by other authorized documents.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Polarization, radar polarimetry, target discrimination, classification, imag- ing, optimal polarization nulls, polarization transformation matrix, Mueller matrix, radar scattering matrix, polarization fork.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) In meticulous detail, a succinct summary of basic electromagnetic wave polarization descriptors, of the various scatterer polarization transformation and of the scatterer descriptive operators is introduced. It is then shown how the five (5) independent matrix parameter for the relative phase mono- static scattering matrix describing an isolated, yet regionally distributed, target in a reciprocal propagation medium can be recovered from (i) amplitude- only, (ii) mixed amplitude plus partial phase, (iii) complete two-step (Cont'd)		

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 68 IS OBSOLETE
S/N 0102-LF-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT

amplitude-phase measurements. Basic properties of the radar target scattering matrix for linear (H, V) and circular (R, L) polarization basis are described in terms of geometrical target features as functions of the specular point surface coordinate parameters, known as gaussian principal, main and related curvature functions. Based upon this succinct background introduction on radar polarimetry, the concepts are applied mainly for the coherent case to various classes of increasing order of sophistication, as defined in detail in the INTRODUCTION, to the problem of radar target handling for the non-cooperative, limited-data case.

Accession For	
DTIC	☒
DDI	☐
UL	☐
CU	☐
By	
Date	
Aval	
A.	
Det	Sp
A	



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

1

BASIC CONCEPTS OF RADAR POLARIMETRY
AND ITS APPLICATIONS TO
TARGET DISCRIMINATION, CLASSIFICATION, IMAGING AND IDENTIFICATION

Wolfgang-Martin Boerner
Electromagnetic Imaging Division, Communications Laboratory
College of Engineering, The University of Illinois at Chicago
P.O. Box 4348, 851 S. Morgan St., 1141-SE0, Chicago, IL. 60680

ABSTRACT

In meticulous detail, a succinct summary of basic electromagnetic wave polarization descriptors, of the various scatterer polarization transformation matrices, and its invariants of the associated optimal matrix polarizations, and of the scatterer descriptive operators is introduced. It is then shown how the five (5) independent matrix parameter for the relative phase mono-static scattering matrix describing an isolated, yet regionally distributed, target in a reciprocal propagation medium can be recovered from (i) amplitude-only, (ii) mixed amplitude plus partial phase, (iii) complete two-step amplitude-phase measurements. Basic properties of the radar target scattering matrix for linear (H, V) and circular (R, L) polarization basis are described in terms of geometrical target features as functions of the specular point surface coordinate parameters, known as gaussian principal, main and related curvature functions. Based upon this succinct background introduction on radar polarimetry, the concepts are applied mainly for the coherent case to various classes of increasing order of sophistication, as defined in detail in the INTRODUCTION, to the problem of radar target handling for the non-cooperative, limited-data case.

KEYWORDS: Polarization, radar polarimetry, target discrimination, classification, imaging, optimal polarization nulls, polarization transformation matrix, Mueller matrix, radar scattering matrix, polarization fork.

PREAMBLE: In the pursuit of this research on radar target recognition/handling within the m-to-mm wavelength region we are dealing with wide interdisciplinary research areas for which not all studies carried out in the past are available in the open literature. In seeking for a unified approach of treating this complex problem, it can happen that one may overlook some important base studies; and, therefore, the paper presented here is a revised, highly updated version of earlier similar papers. Specifically, we owe our apologies to Dr. Glendon McCormick, Mr. Archibald Hendry and Mr. Laverne E. Allan, Electromagnetics Division, NRC, Ottawa, Canada, for not having paid due attention to their outstanding contributions to polarimetric radar meteorology. The major relevant contributions of their research are now included in this paper.

1. INTRODUCTION

The interaction of electromagnetic waves with a geometrically bounded, material body may best be described as a

"Polarization-Sensitive Scatterer Feature Spatial and Temporal
Resonance Phenomenon",

This research was supported under NAV-AIR Systems Command Contract
No.: N00019-80-C-0626.

particularly when the spatial and temporal periods become of the order of a target characteristic features and motional dimensions. Specifically, for the limited data, non-cooperative target case, there exists an hierarchy in complexity, amount, quality and accuracy of radar data required to obtain an "immediate (instantaneous) decision operator" in tactical (seeker) radar for the distinct radar problems of:

- Target versus clutter discrimination: Various methods may be applicable, yet we found that in a hostile clutter and/or chaff environment such as (i) the marine boundary layer, (ii) the atmospheric ground-based battle-field scene, or (iii) for low-flying tactical aircraft involved in support of ground/sea-based battle actions, we must incorporate complete CW polarimetric target/clutter scattering matrix information. Specifically, we require to utilize the dynamic polarimetric fork properties. Whereas, for distributed clutter/chaff, the vector scattering centers are distributed more densely and separated by a small fraction of a wavelength, resulting in a more stable motion of the associated co-polarization nulls (prongs of polarization fork) on the Poincare sphere; those of isolated larger, more complex (man-made) objects are separated by distances being comparable to the wavelength and larger, resulting in a rapid circular path loci motion on the polarization sphere. Therefore, the highly varied behavior of the dynamic polarization fork motions of target (rapid) versus clutter/chaff (slow) on the polarization sphere will provide an indispensable target versus clutter/chaff discrimination operator as was demonstrated without further doubt by Poelman (1977 to 1982). We note that we also will need to reassess the merit factor definitions of optimal target signal versus clutter-plus-noise separation which need to be based on Huynen's N-target theories (Huynen, 1978) and Poelman's (1981) maximum entropy approach for extracting the most useful stochastic merit factor parametric diagrams based on Kennaugh's optimal target polarization null theory.
- Target-versus-target and clutter-versus-clutter classification: Because of the fact that the vector scattering centers of larger, more complex isolated targets are separated by longer electric lengths resulting in a rapid circular path motion of the polarization fork, in general, over the entire Poincare sphere in case of "not-symmetrical" reciprocal targets, we find that a monochromatic CW, limited aspect, complete polarimetric approach for the backscatter (monostatic) radar case will not suffice; and, in addition, we require polarimetric target downrange silhouette resolution. Although the mean optimal polarization null locations and their spread can be obtained for clutter and/or chaff rather accurately if the polarimetric clutter matrix information is recovered within time frames lying below the clutter vector scattering center reshuffling time; improved clutter classifi-

cation (surface versus inhomogeneous volumetric underburden scatter can only result from broadband complete polarimetric clutter information (Fung and Eom, 1982; Morgan and Weisbrod, 1982; McCormick and Hendry, 1982; Boerner and Huynen, 1982).

We re-emphasize that, given complete broadband polarimetric scatter matrix information, target classification for the non-cooperative target versus target, target versus clutter, and clutter versus clutter case is guaranteed (Rooz, 1980, Banks, 1981).

Target imaging in inhomogeneous media and/or clutter environments:

In case the target does not possess rotational symmetry but is of general "not-symmetrical" reciprocal shape, in addition to complete polarimetric downrange linear chirp maps along the rotational axis of invariance, we will require such data over a wide cone of the unit sphere of directions in dependence of data completeness, quality, etc. or, additional "equivalent a priori" target shape information. In case the target is embedded in weakly diffracting clutter, the G.O. superlimited parallelbeam methods of projection tomography do not suffice; then we must, at least, incorporate back-propagation tomographic methods based on the Born/Rytov approximation to apply, which represent a dramatic improvement over Radon's single ray (straight or bent) projection reconstruction theory. Furthermore, as we are strictly dealing with an electromagnetic vector inverse problem, the scalar back-propagation tomographic method must be extended to vector back-diffraction tomography for the general case of a target embedded in the type of clutter described above. For the application of general vector back-diffraction tomography to target imaging in dense depolarizing clutter, we also must develop direct scattering theories incorporating a polarimetric vector radiation transfer approach utilizing a Stokes' vector formulation which implicitly must also contain multi-scatter phase information.

Target identification: Complete single target identification in shape and material decomposition will strictly require solutions to all of the above three (3) tasks, plus incorporation of complete doppler and scatterometric information within the various windows of the m-to-sub-mm wavelength region. Therefore, we need to develop complete polarimetric broadband (discrete linear chirp) doppler radar systems within the various windows of the 1-400 GHz e.m. spectral region so that optimal target information can be extracted from electromagnetic wave/target interaction which is a "polarization-sensitive target feature spatial and temporal resonance phenomenon", i.e., amplitude, phase polarization, frequency, doppler information, all are equivalently and equally important

Criteria for the Assessment of Available Complete Polarimetric Measurement Methods:

The main obstacle towards realizing incorporation of complete polarimetric radar target theory into target versus clutter discrimination, target versus target classification, target in clutter imaging, single target identification until recently was the underdeveloped state of broadband polarimetric antenna theory and design. It was not possible to recover for the general not-symmetrical reciprocal target case (which must be the basic requirement here), i.e., both amplitude and relative polarization phase of the scattering matrix elements at time frames below the vector scattering center reshuffling time of clutter/chaff. Until very recently, complete ellipsometric amplitude-only measurement principles had to be used which require nine (9) rather time-consuming independent amplitude-only measurements for a selected set of linear, circular and elliptical base polarizations. For the complete symmetric (H, V, aligned) target case, Copeland (1960) and Huynen (1960) independently developed polarization rotation-sweep techniques, which were shown to be sufficient to recover the optimal polarization nulls of aligned, symmetric targets only on the polarization sphere from co-polarized amplitude-only measurements. In a next step, a method of recovering the co/cross-polarization phase ϕ_{AB} or ϕ_{BA} for S_{AA}/S_{AB} or S_{BB}/S_{BA}

measurements was developed using fast magnetic waveguide switches and/or pin-diode switches. This method, when re-designed for the circular left/right polarization base vector pair does provide a two-step complete measurement approach, as e.g., was developed by McCormick/Allan/Hendry (1977-1982) for polarimetric radar meteorology, for which target reciprocity must apply as well as complete target symmetry with respect to the linear H, V polarization basis which certainly is a rather unrealistic assumption for the case of tactical target detection in meteorological clutter. More recently with the advanced pin-diode switching technology, it is now possible to recover complete polarimetric scattering matrix information for the general "not-symmetrical" reciprocal target case within the time frames which lie below the reshuffling time of vector clutter scattering centers, i.e., we are now witnessing the realistic phase of incorporating complete radar polarimetric concepts into the general radar target description problem.

In the following sections, a survey of the important concepts of radar polarimetry is presented and relevant examples are provided.

2. POLARIZATION DESCRIPTORS

In this brief survey of optimal polarization descriptors, we will schematically introduce basic definitions (Table 1), describing the polarization ellipse in time and frequency domain (Fig. 1) and its relationship with the Poincare sphere.

TABLE 1: POLARIZATION DESCRIPTORS

PARAMETER	DEFINITION
a. <u>Radar Cross Section</u>	
i) no polarization corrections	$\sigma = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{ \underline{E}^s ^2}{ \underline{E}^i ^2} = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{ \underline{H}^s ^2}{ \underline{H}^i ^2} \quad (1)$
ii) with polarization corrections	$\sigma_{rc} = \lim_{R \rightarrow \infty} 4\pi R^2 \frac{ \underline{h}^r \cdot \underline{E}^s ^2}{ \underline{h}^r ^2} \quad (2)$
b. <u>The Polarization Vector</u>	
i) time domain	$\underline{h}(t) = a_H \cos \omega t \hat{h}_H + a_V \cos (\omega t + \delta) \hat{h}_V$ where $\delta = \delta_V - \delta_H$ (3)
ii) frequency domain	$\underline{h}(t) = \text{Re}\{\underline{h} e^{j\omega t}\}, \text{ where} \quad (4)$ $\underline{h} = a_H e^{j\delta_H} \hat{h}_H + a_V e^{j\delta_V} \hat{h}_V$
iii) geometric parameter	$\underline{h} = a \begin{pmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{pmatrix} \begin{pmatrix} \cos \tau \\ j \sin \tau \end{pmatrix} e^{j\alpha} \quad (5)$
iv) polarization ratio	$\underline{h} = a_H e^{j\delta_H} (\hat{h}_H + \rho \hat{h}_V), \text{ where } \rho = \frac{a_V}{a_H} e^{j\delta} \quad (6)$
c. <u>The Polarization Ellipse</u>	$\left(\frac{h_H}{a_H}\right)^2 + \left(\frac{h_V}{a_V}\right)^2 - 2\left(\frac{h_H}{a_H}\right)\left(\frac{h_V}{a_V}\right) \cos \delta = \sin^2 \delta$ Linear: $\delta = 0$, horizontal ($a_V = 0$), vertical ($a_H = 0$), linear 45° ($a_H = a_V$) (7) Left circular (LC): $\delta = 90^\circ$, $a_H = a_V$ Right circular (RC): $\delta = 90^\circ$, $a_H = -a_V$ Left elliptic: $\sin \delta > 0$ Right elliptic: $\sin \delta < 0$

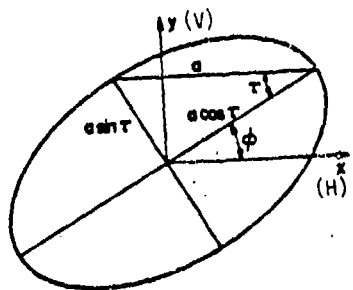


Fig. 1

Table 1 (Cont'd): Polarization Descriptors

d. The Stokes Vector

$$\underline{g} = \begin{pmatrix} g_0 \\ g_1 \\ g_2 \\ g_3 \end{pmatrix} = \begin{pmatrix} |h_H|^2 + |h_V|^2 \\ |h_H|^2 - |h_V|^2 \\ 2\text{Re}\{h_H h_V^*\} \\ -2\text{Im}\{h_H h_V^*\} \end{pmatrix} = \begin{pmatrix} a_H^2 + a_V^2 \\ a_H^2 - a_V^2 \\ 2a_H a_V \cos\delta \\ 2a_H a_V \sin\delta \end{pmatrix} = \begin{pmatrix} a^2 \\ a^2 \cos 2\tau \cos 2\phi \\ a^2 \cos 2\tau \sin 2\phi \\ a \sin 2\tau \end{pmatrix} = \begin{pmatrix} 1 \\ Q \\ U \\ V \end{pmatrix} \quad (8)$$

where

$$g_0^2 = g_1^2 + g_2^2 + g_3^2 = 1^2 = Q^2 + U^2 + V^2$$

$$H: \underline{g} = \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix}, V: \underline{g} = \begin{pmatrix} 1 \\ -1 \\ 0 \\ 0 \end{pmatrix}, LC: \underline{g} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix}, RC: \underline{g} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ -1 \end{pmatrix}$$

$$\text{Modified Stokes Vector } \underline{g}_m = \{\frac{1}{2}(1+Q), \frac{1}{2}(1-Q), U, V\}$$

e. The Polarization Ratio

$$\rho = \frac{h_V}{h_H} = \left(\frac{a_V}{a_H} \right) e^{j\delta} = \tan\epsilon e^{j\delta} \quad (9)$$

Linear: $\text{Im}\{\rho\} = 0$, H: $\rho = 0$, V: $\rho = \infty$ Circular: $\text{Re}\{\rho\} = 0$, LC: $\rho = j$, RC: $\rho = -j$ Elliptic: Left elliptic: $\text{Im}\{\rho\} > 0$, right elliptic: $\text{Im}\{\rho\} < 0$

TABLE 1 (Cont'd): Polarization Descriptors

f. The Poincare Sphere

i) Cartesian Coordinates = (g_1, g_2, g_3) ii) Spherical = $(g_0, \frac{\pi}{2} - 2\tau, 2\phi)$

iii) In terms of Polarization ratio

$$u = \frac{1 - jp}{1 + jp}, \theta = \cos^{-1} \left\{ \frac{|u|^2 - 1}{|u|^2 + 1} \right\}, \phi = \text{phase}(u) \quad (10)$$

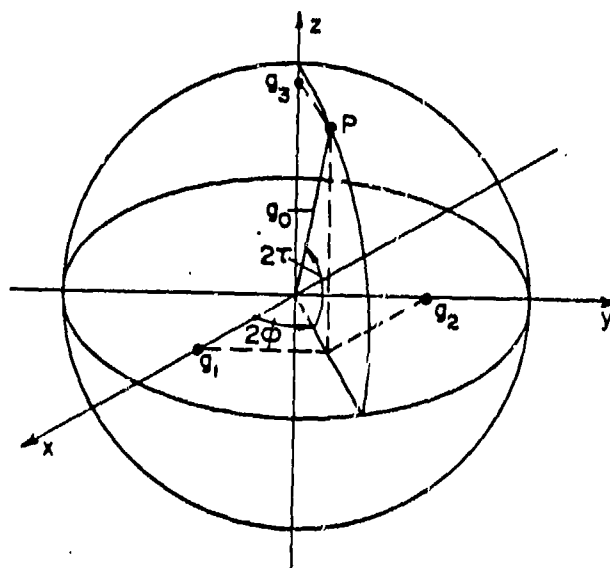


Fig. 2 POINCARÉ SPHERE

3. SCATTERING MATRICES: $[S]$, $[M]$, $[P]$

There exist three matrices of specific value to the description of hydrometeor ensembles in the coherent and the incoherent cases which are defined here and the interactions are derived (Boerner, et al, 1981, Chan, 1981).

3.1 The Scattering Matrix $[S]$

The 2×2 complex scattering matrix $[S]$ is relating the polarization vector of the scattered field $\underline{h}^s$ to the corresponding one of the incident field $\underline{h}^i$ through the relation

$$\underline{h}^s = [S] \underline{h}^i \quad (11)$$

Different representations for $[S]$ with absolute and relative phase in the bistatic and monostatic cases are summarized as follows: in the bistatic case, the scattering matrix with absolute phase is defined by

$$\begin{aligned}
 [S]_{SMA} &= \begin{pmatrix} S_{AA} & S_{AB} \\ S_{BA} & S_{BB} \end{pmatrix} = \begin{pmatrix} |S_{AA}|e^{j\phi_{AA}} & |S_{AB}|e^{j\phi_{AB}} \\ |S_{BA}|e^{j\phi_{BA}} & |S_{BB}|e^{j\phi_{BB}} \end{pmatrix} \\
 &= \begin{pmatrix} |S_{AA}|e^{j(\phi_{AA} - \phi_{AB})} & |S_{AB}| \\ |S_{BA}|e^{j(\phi_{BA} - \phi_{AB})} & |S_{BB}|e^{j(\phi_{BB} - \phi_{AB})} \end{pmatrix} e^{j\phi_{AB}} \quad (12) \\
 &= e^{j\phi_{AB}} [S]_{SMR},
 \end{aligned}$$

where ϕ_{AB} is the absolute phase*, $[S]_{SMR}$ is the target scattering matrix with relative phase and it can be written in the bistatic case as

$$[S]_{SMR} = \begin{pmatrix} |S_{AA}|e^{j(\phi_{AA} - \phi_{AB})} & |S_{AB}| \\ |S_{BA}|e^{j(\phi_{BA} - \phi_{AB})} & |S_{BB}|e^{j(\phi_{BB} - \phi_{AB})} \end{pmatrix} \quad (13)$$

Eqs. (12), (14) satisfy the reciprocity condition $S_{AB} = S_{BA}$ ($|S_{AB}| = |S_{BA}|$, $\phi_{AB} = \phi_{BA}$) in the monostatic case. In this paper, we are considering the monostatic case only.

3.2 The Mueller Matrices

The Mueller (Stokes reflection) matrix $[M]$, the modified Mueller matrix $[M_m]$, and the symmetrized Mueller matrix $[M_s]$ are presented in this section. The reconstruction of these matrices from the scattering matrix elements is given in Table 2. (Boerner et al, 1981, Jan & Sept.)

The 4×4 real Mueller matrix $[M]$ relates the scattered Stokes vector $\underline{g}^s$ to the corresponding incident vector $\underline{g}^i$ with the following relationship

$$\underline{g}^s = [M] \underline{g}^i, \quad (14)$$

where the Stokes vector is defined in Table 1. A similar relationship relating the modified scattered and incident Stokes vectors is given by

$$\underline{g}_m^s = [M_m] \underline{g}_m^i. \quad (15)$$

The relationship between $[M]$ and $[M_m]$ is given by (Boerner et al, 1981), also by Gerrard & Burch et al, (1975).

$$[M_m] = [R] [M] [R^{-1}] \quad (16)$$

and

$$[M] = [R^{-1}] [M_m] [R] \quad (17)$$

*We note that this specific choice need not be the best one as e.g., in the case of a circular polarization basis (also see Huynen, 1970).

where the constant transformation matrix $[R]$ becomes

$$[R] = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} & 0 & 0 \\ \frac{1}{2} & -\frac{1}{2} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (18)$$

The Mueller matrices are 4×4 real and asymmetric. The symmetric Mueller matrix $[M_s]$ can be deduced as follows: the received power (Huynen, 1970; Kennaugh, 1949-54 #9) is

$$P_r = \frac{1}{2} [g_0^s g_0^r + g_1^s g_1^r + g_2^s g_2^r - g_3^s g_3^r] = [Q] \underline{g}^s \cdot \underline{g}^r, \quad (19)$$

where $\underline{g}^s, \underline{g}^r$ are the scattered wave and receiving antenna Stokes vectors respectively and $[Q]$ is a constant matrix and is given by:

$$[Q] = \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

substituting (16) into (19), then

$$P_r = [Q][M] \underline{g}^i \cdot \underline{g}^r = [M_s] \underline{g}^i \cdot \underline{g}^r, \quad (20)$$

where $[M_s] = [Q][M]$ is a symmetric Mueller matrix.

3.3 Graves Power Scattering Matrix $[P]$ and Its Associated $[P_H]$ and $[P_V]$

The total backscattered power from a target is given by (Graves, 1956)

$$P_b = \underline{h}^{s*} \cdot \underline{h}^s = (\underline{h}^{s*})^T \underline{h}^s, \quad (21)$$

where $\underline{h}^s$ is the backscattered polarization vector. Substituting (11) into (21)

$$P_b = (\underline{h}^i)^T [S^T]^* [S] \underline{h}^i = (\underline{h}^i)^T [P] \underline{h}^i, \quad (22)$$

where the matrix $[P]$ is known as Graves Power scattering matrix and it is given by

$$[P] = [S^T]^* [S] = \begin{pmatrix} a & c \\ c^* & b \end{pmatrix}, \quad (23)$$

where a, b are real and c is complex. The reconstruction of the elements of $[P]$ in terms of the elements of the scattering matrix $[S]$ is given in Table 2 (Chan, 1981).

The matrix $[P]$ can be decomposed into two measurable matrices $[P_H]$ and $[P_V]$, where

$$[P] = [P_H] + [P_V] \quad (24)$$

The elements of $[P_H]$ and $[P_V]$ in terms of the elements of $[S]$ are also shown in Table 2 (Chan, 1981).

TABLE 2: RECONSTRUCTION OF $[M]$, $[M_m]$, $[P]$, $[P_H]$, $[P_V]$ AND OPTIMAL POLARIZATION FROM $[S]$

$[M]$	$[M_m]$
$m_{11} = \frac{1}{2}(S_{AA} ^2 + 2 S_{AB} ^2 + S_{BB} ^2)$	$M_{11} = S_{AA} ^2$
$m_{12} = m_{21} = \frac{1}{2}(S_{AA} ^2 - S_{BB} ^2)$	$M_{12} = S_{AB} ^2 = M_{21}$
$m_{13} = m_{31} = \text{Re}\{S_{AA}S_{AB}^* + S_{AB}S_{BB}^*\}$	$M_{13} = \text{Re}\{S_{AA}S_{AB}^*\} = \frac{1}{2}M_{31}$
$m_{14} = -m_{41} = \text{Im}\{S_{AA}S_{AB}^* + S_{AB}S_{BB}^*\}$	$M_{14} = \text{Im}\{S_{AA}S_{AB}^*\} = \frac{1}{2}M_{41}$
$m_{22} = \frac{1}{2}(S_{AA} ^2 - 2 S_{AB} ^2 + S_{BB} ^2)$	$M_{22} = S_{BB} ^2$
$m_{23} = m_{32} = \text{Re}\{S_{AA}S_{AB}^* - S_{AB}S_{BB}^*\}$	$M_{23} = \text{Re}\{S_{AB}S_{BB}^*\} = \frac{1}{2}M_{32}$
$m_{24} = -m_{42} = \text{Im}\{S_{AA}S_{AB}^* - S_{AB}S_{BB}^*\}$	$M_{24} = \text{Im}\{S_{AB}S_{BB}^*\} = -\frac{1}{2}M_{42}$
$m_{33} = \text{Re}\{S_{AA}S_{BB}^*\} + S_{AB} ^2$	$M_{33} = \text{Re}\{S_{AA}S_{BB}^*\} + S_{AB} ^2$
$m_{34} = -m_{43} = \text{Im}\{S_{AA}S_{BB}^*\}$	$M_{34} = \text{Im}\{S_{AA}S_{BB}^*\} = -M_{43}$
$m_{44} = m_{33} + m_{22} - m_{11}$	$M_{44} = M_{33} - 2M_{12}$

TABLE 2: (Cont'd)

$[P] = [P_H] + [P_V]$	CO-POL & X-POL NULLS
$[P] = \begin{pmatrix} a & c \\ c^* & b \end{pmatrix}, \quad \begin{aligned} a &= S_{HH} ^2 + S_{HV} ^2 \\ b &= S_{HV} ^2 + S_{VV} ^2 \\ c &= S_{HH}^* S_{HV} + S_{HV}^* S_{VV} \end{aligned}$	COLATITUDE: $\theta = \cos^{-1} \left\{ \frac{ u ^2 - 1}{ u ^2 + 1} \right\}$ LONGITUDE: $\phi = \tan^{-1} \left\{ \frac{\text{Im}(u)}{\text{Re}(u)} \right\}$
$[P_H] = \begin{pmatrix} a_H & c_H \\ c_H^* & b_H \end{pmatrix}, \quad \begin{aligned} a_H &= S_{HH} ^2 \\ b_H &= S_{HV} ^2 \\ c_H &= S_{HH}^* S_{HV} \end{aligned}$	where: $u = \frac{1 - \rho}{1 + \rho}$, and $\rho = \frac{-B + \sqrt{B^2 - 4AC}}{2A}$
$[P_V] = \begin{pmatrix} a_V & c_V \\ c_V^* & b_V \end{pmatrix}, \quad \begin{aligned} a_V &= S_{HV} ^2 \\ b_V &= S_{VV} ^2 \\ c_V &= S_{HV}^* S_{VV} \end{aligned}$	<u>CO-POL Nulls</u> $A = S_{BB}$ $B = 2S_{AB}, \quad C = S_{AA}$ <u>X-POL Nulls</u> $A = S_{BB} S_{AB}^* + S_{AA}^* S_{AB} = -C^*$ $B = S_{AA} ^2 - S_{BB} ^2$

4. THE CONCEPT OF THE OPTIMAL POLARIZATION PAIRS

It was first shown by Kennaugh (1952) that there exist two pairs of optimal polarizations which can be useful in describing target properties at one aspect and at one frequency (Kennaugh, 1949-1952 #9). The concept is based on invariance of polarization state transformation under consideration of reciprocity as we will introduce next.

4.1 Polarization State Transformation

In the following we shall limit ourselves exclusively to the monostatic case ($\theta_i = \theta_r, \phi_i = \phi_r$) and we may define the "normalized monostatic scattering matrix S with relative phase" in terms of two arbitrary elliptically orthogonal polarization base vectors $\hat{h}_A$ and $\hat{h}_B$ so that with $\underline{h} = \hat{h}_A \hat{h}_A + \hat{h}_B \hat{h}_B$

$$\underline{h}^s = [S]\underline{h}, \quad [S] = \begin{pmatrix} S_{AA} & S_{AB} \\ S_{BA} & S_{BB} \end{pmatrix} \quad \begin{aligned} S_{AB} &= S_{BA} \\ \phi_{AB} &= \phi_{BA} = 0 \end{aligned} \quad (25)$$

Thus, assuming reciprocity of the propagation path ($S_{AB} = S_{BA}$) and conservation of energy, we require five real quantities to determine $[S]$ completely (Kennaugh, 1949-1952 #1, #4). However, we note that in case $S_{AB} \neq S_{BA}$, i.e., reciprocity of the propagation paths is violated, the definition of $[S]$ (25) cannot be used (Kanareykin et al, 1966) as may be encountered for a propagation path within a highly ionized cloud containing various dense liquid and solid ice states of hydrometeors (Jeske, 1976).

Assuming reciprocity holds, there exists an infinite number of general pairs of orthonormal elliptical polarization vectors $\hat{h}_A, \hat{h}_B$ and an infinite number of possible invariant transformations (Kennaugh, 1949-1952 #12). Numerically, the transformation properties of $S(A,B)$ assuming no polarization losses from any one orthonormal polarization pair $\underline{h} = \hat{h}_A \hat{h}_B + \hat{h}_B \hat{h}_A$ to another orthonormal pair $\underline{h} = \hat{h}_A \hat{h}_A + \hat{h}_B \hat{h}_B$, can be expressed in terms of the geometric parameters τ and ϕ , or polarization ratio parameters γ and δ , mathematically expressed in matrix form

$$[T] = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} \cos\tau & j\sin\tau \\ j\sin\tau & \cos\tau \end{pmatrix} \quad (26)$$

which implies rotation of coordinate axes and deformation of ellipticity of the polarization ellipse. $[T]$ may also be defined according to Maffett (Crispin, and Siegel, 1968)

$$[T] = \begin{pmatrix} e^{j\psi_1} \cos\gamma & e^{j\psi_2} \sin\gamma \\ -e^{j\psi_3} \sin\gamma & e^{j\psi_4} \cos\gamma \end{pmatrix} \quad (27)$$

and in order for $[T]$ to be unitary, the following condition on ψ 's has to be imposed $\psi_2 - \psi_1 = \psi_4 - \psi_3$, where in our work, we chose $\psi_1 = \psi_4 = 0$. Thus, having $\psi_2 = -\psi_3 = \delta \pm \pi$, the $[T]$ matrix reduces to

$$[T] = \begin{pmatrix} \cos\gamma & -e^{j\delta} \sin\gamma \\ e^{-j\delta} \sin\gamma & \cos\gamma \end{pmatrix} \quad (28)$$

The two transformations [(26) and (28)] are equivalent, and can be represented on the Poincare sphere as shown in Fig. 3.

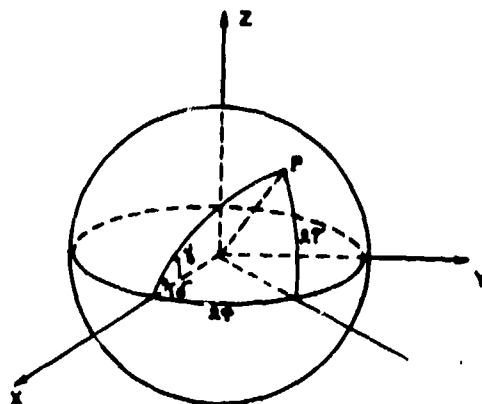


Fig. 3
DESCHAMPS' SPHERE

Equation (26) can also be expressed in terms of polarization ratio $\rho = \tan \gamma e^{j\delta}$ and after normalizing [T] it takes on the following form

$$[T] = (1 + \rho \rho^*)^{-1/2} \begin{pmatrix} 1 & -\rho^* \\ \rho & 1 \end{pmatrix} \quad (29)$$

The transformed elements of the scattering matrix $[S'(A', B')] = [T]^T [S(A, B)]$ [T] are given for the general bistatic case by

$$\begin{aligned} S'_{A'A'} &= (1 + \rho \rho^*)^{-1} [S_{AA} + \rho^2 S_{BB} + \rho (S_{AB} + S_{BA})] \\ S'_{A'B'} &= (1 + \rho \rho^*)^{-1} [-\rho^* S_{AA} + S_{BB} + S_{AB} - \rho \rho^* S_{BA}] \\ S'_{B'A'} &= (1 + \rho \rho^*)^{-1} [\rho^* S_{AA} + S_{BB} - \rho \rho^* (S_{AB} + S_{BA})] \\ S'_{B'B'} &= (1 + \rho \rho^*)^{-1} [\rho^* S_{AA} + S_{BB} - \rho^* (S_{AB} + S_{BA})] \end{aligned} \quad (30)$$

satisfying the transformation invariants $\det\{[S'(A', B')]\} = \text{invariant}$ when $\det\{[T]\} = \pm 1$, otherwise $\det\{[S'(A', B')]\}$ is different by a factor of $\exp(2\text{ARG}\{\det[T]\})$ and

$$\begin{aligned} \text{Span}\{[S(A, B)]\} &= |S_{AA}|^2 + |S_{AB}|^2 + |S_{BA}|^2 + |S_{BB}|^2 = p \\ &= \text{Span}\{[S'(A', B')]\} = |S'_{A'A'}|^2 + |S'_{A'B'}|^2 + |S'_{B'A'}|^2 + |S'_{B'B'}|^2 \\ &= \text{invariant.} \end{aligned} \quad (31)$$

We note that if $S_{AB} = S_{BA}$, then $S'_{A'B'} = S'_{B'A'}$ for all ρ ; i.e., if reciprocity is satisfied for any one pair of orthogonal polarizations, it is satisfied for all such pairs. Furthermore, we must emphasize the important property that for any one given aspect and for one frequency, the transformation is polarization invariant, i.e., the transformation occurs on one and the same polarization sphere of radius $p = \text{span}\{[S(A, B)]\}^*$. Thus, if $[S(A, B)]$ is known and reciprocity as well as conservation of energy is satisfied, $[S'(A', B')]$ for any other orthogonal pair $\underline{h}(A', B')$ can be obtained as is known for example for the transformation from linear to circular polarization base vectors in Long (1975). In case of polarization losses properties of the coherency matrix need to be used (Kraus, 1966), and the transformation will not occur on the same polarization sphere (Deschamps, 1953; Deschamps and Mast, 1973).

4.2 Transformation from Linear (H,V) to Circular (R,L) Polarization Bases

Based on equation (28) we can construct a transformation from a linear to a circular polarization base. The parameters in equation (28) are set to the following values

$$\gamma = \pi/4 \text{ and } \delta = 3\pi/2$$

*We note that Huynen (1970) chose target maximum power m to represent the radius.

The resulting transformation matrix $[T]$ is

14

$$[T] = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \quad (32)$$

The relationship between the unit vectors $(\hat{h}_H, \hat{h}_V)$ of the linear basis and $(\hat{h}_R, \hat{h}_L)$ in the circular basis can now be written as:

$$\begin{bmatrix} \hat{h}_R \\ \hat{h}_L \end{bmatrix} = [T] \begin{bmatrix} \hat{h}_H \\ \hat{h}_V \end{bmatrix} \quad (33)$$

Equation (33) holds in the incident system, its counterpart in the scattered system is

$$\begin{bmatrix} \hat{h}_R \\ \hat{h}_L \end{bmatrix} = [T]^* \begin{bmatrix} \hat{h}_H \\ \hat{h}_V \end{bmatrix}$$

the two systems are illustrated in Fig. 4.

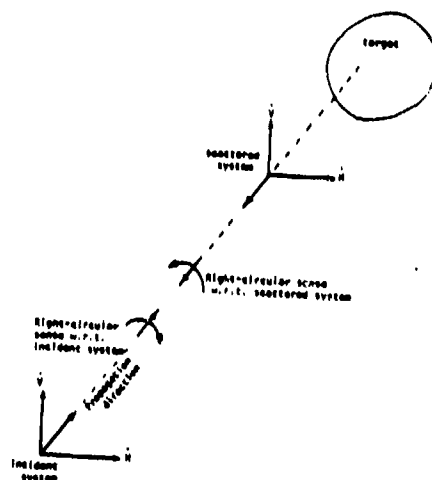


FIGURE 4: INCIDENT AND SCATTERED FIELD COORDINATES

It can be shown that the scattering matrix in the circular basis $[C(R,L)]$ is

$$[C(R,L)] = [T(RL, HV)] [S(HV)] [T(RL, HV)]^T \quad (34)$$

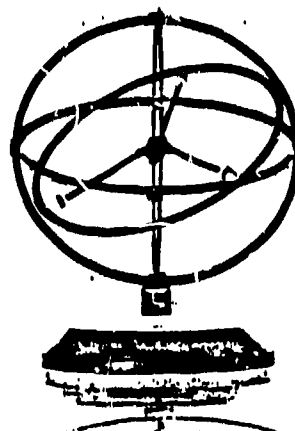
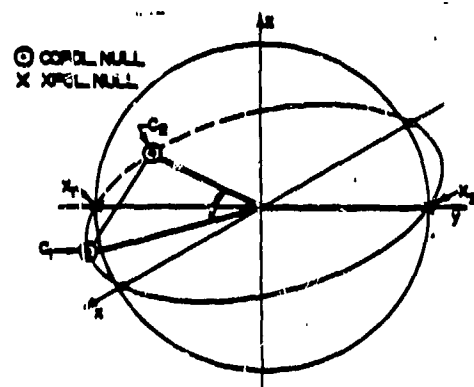
Substituting equations (32) into equation (34) we obtain the scattering matrix in the circular polarization basis in terms of elements of its counterpart in the linear basis.

$$[C(RL)] = \begin{bmatrix} \frac{S_{HH} - S_{VV}}{2} + j S_{HV} & j \frac{S_{HH} + S_{VV}}{2} \\ j \frac{S_{HH} + S_{VV}}{2} & \frac{S_{VV} - S_{HH}}{2} + j S_{HV} \end{bmatrix}$$

4.3 Calculation of the Optimal Polarizations

It was shown by Kennaugh (1949-1952) that there exist two pairs of optimal polarizations, the Co-Polarization Null Pair for which $S'_{A'A}$ and $S'_{B'B}$ in (27) vanish and the Cross-Polarization Null Pair for which $S'_{A'B}$ and $S'_{B'A}$ vanish. In Table 2, the optimal polarization (CO-POL and X-POL) nulls are given in terms of $[S]$ elements and are represented on the Poincare sphere.

It should be noted that the CO-POL and X-POL nulls lie on one major circle on the Poincare polarization sphere and that their locations define the polarization fork (Fig. 5). The X-POL nulls are anti-podal on this sphere and the line joining them bisects the angle between the CO-POL nulls as shown in Fig. 5. We note here that this unique description of a scatterer under monostatic conditions given for one frequency and aspect is of paramount importance to target description at one aspect and one frequency and its properties have been overlooked in practice (Kennaugh, 1949-1952; Kanaravkin, et al, 1966).



POELMAN'S
ADJUSTABLE
POLARIZATION
FORK

Fig. 5: The Polarization Fork (Huynen 1970)

4.4 Reconstruction of $[S]_{SMR}$

The reconstruction of $[S]_{SMR}$ from $[M]$, $[M]$, $[P]$, $[P]$ and $[P]$ or optimal polarizations is shown in Table 3. This means that Tables 2 and 3 give a complete interrelationship between these scattering matrices as well as the optimal polarizations. From a measurement point of view, this is very important because it suffices to measure one of the matrices or the optimal polarization to calculate the other matrices. The reconstruction of $[S]_{SMR}$ from the optimal polarizations is of great importance to target polarization synthesis. In these Tables, A and B are any two orthogonal bases e.g. horizontal and vertical. We note here that in the incoherent or quasi-coherent case, clustering properties of the CO-POL nulls need to be taken into consideration.

TABLE 3: RECONSTRUCTION OF $[S]_{\text{SMR}}$ from $[M]$, $[M_m]$, $[P_H]$, $[P_V]$ and
OPTIMAL POLARIZATIONS

elements of $[S]_{\text{SMR}}$	from $[M]$	from $[M_m]$	from $[P_A]$ and $[P_V]$ ($A=H, B=V$)
$ S_{AA} $	$\sqrt{\frac{1}{2}(m_{11} + 2m_{12} + m_{22})}$	$\sqrt{M_{11}}$	$\sqrt{a_A}$
$ S_{AB} = S_{BA} $	$\sqrt{\frac{1}{2}(m_{11} - m_{22})}$	$\sqrt{M_{12}}$	$\sqrt{b_A} = \sqrt{a_B}$
$ S_{BB} $	$\sqrt{\frac{1}{2}(m_{11} - 2m_{12} - m_{22})}$	$\sqrt{M_{22}}$	$\sqrt{b_B}$
$\phi_{AA} - \phi_{AB}$	$\tan^{-1} \left\{ \frac{m_{14} + m_{24}}{m_{13} + m_{23}} \right\}$	$\tan^{-1} \left\{ M_{14}/M_{13} \right\}$	$\tan^{-1} \frac{\text{Im } C_A}{\text{Re } C_A}$
$\phi_{BB} - \phi_{AB}$	$\tan^{-1} \left\{ \frac{m_{41} - m_{42}}{m_{31} - m_{32}} \right\}$	$\tan^{-1} \left\{ M_{42}/M_{32} \right\}$	$\tan^{-1} \frac{\text{Im } C_B}{\text{Re } C_B}$

from optimal polarizations

$$[S(A,B)] = K \begin{bmatrix} x & z \\ z & y \end{bmatrix}$$

CO-POL Nulls are known:

$$K = \sqrt{\frac{P}{2}} \{ |\rho_1^{\text{CO}}|^2 + |\rho_2^{\text{CO}}|^2 + 2|\rho_1^{\text{CO}} \rho_2^{\text{CO}}| \}^{-\frac{1}{2}}$$

$$x = -2\rho_1^{\text{CO}} \rho_2^{\text{CO}} \exp(-j\phi_E), \quad \phi_E = \text{phase}(\rho_1^{\text{CO}} + \rho_2^{\text{CO}})$$

$$y = -2 \exp \{-j\phi_E\}$$

$$z = |\rho_1^{\text{CO}} + \rho_2^{\text{CO}}|$$

One CO-POL and one X-POL are known:

$$K = \sqrt{P/D}, \quad D = 2(|\rho^X|^* (\rho^{\text{CO}})^2 + |\rho^X|^2 + |\rho^{\text{CO}}|^2 \{ |\rho^{\text{CO}} - \rho^{\text{CO}}| |\rho^X|^2 - 2|\rho^X|^2 \} \\ + |2\rho^{\text{CO}}(\rho^X)^* - |\rho^X|^2 + 1|^2$$

$$x = \rho^{\text{CO}} [|\rho^{\text{CO}} - \rho^{\text{CO}}| |\rho^X|^2 - 2|\rho^X|^2] \exp(-j\phi_E), \quad \phi_E = \text{phase}(\rho^X)^* (\rho^{\text{CO}})^2 + |\rho^X|^2$$

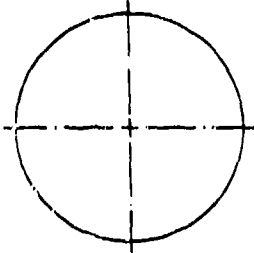
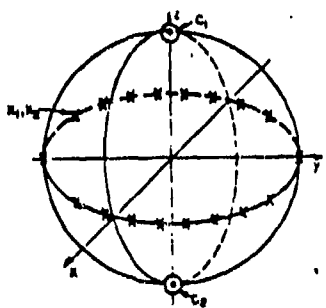
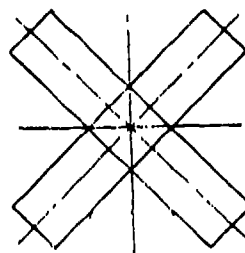
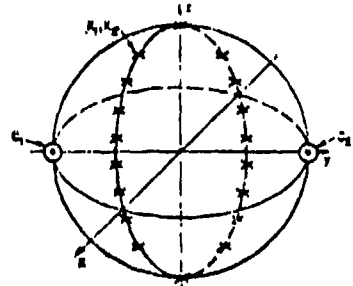
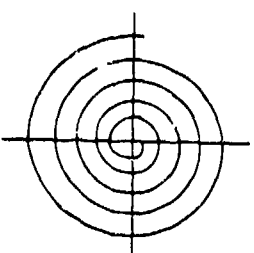
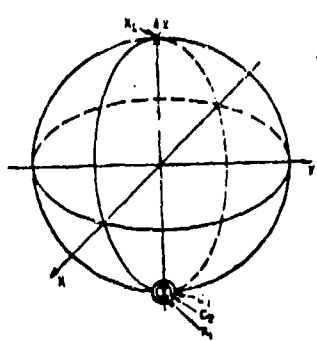
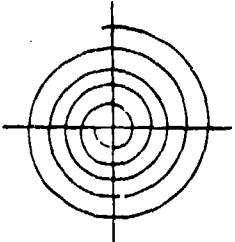
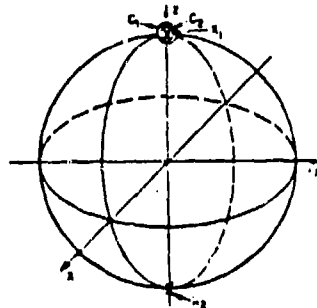
$$y = -[2\rho^{\text{CO}}(\rho^X)^* - |\rho^X|^2 + 1] \exp(-j\phi_E)$$

$$z = (\rho^X)^* (\rho^{\text{CO}})^2 + |\rho^X|^2$$

4.5 Optimal Polarizations for Different Isolated Simple Target Shapes

The CO-POL and X-POL nulls are calculated here for different target shapes. Table 4 shows the calculated nulls for simple shapes, e.g. ideally conducting flat plate or sphere, metallic trough, right and left metallic helices.

TABLE 4: CO-POL AND X-POL NULL FOR SIMPLE TARGET SHAPES

TARGET	SCATTERING [S] AND MODIFIED MUELLER [M _m] MATRICES	CO-POL (C) AND X-POL (X) NULLS ON POINCARÉ SPHERE
 a. Ideally conducting flat plate or sphere	$[S] = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ $[M_m] = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$	
 b. Metallic trough	$[S] = \pm \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ $[M_m] = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$	
 c. Metallic helix (right screw)	$[S] = \frac{1}{2} \begin{pmatrix} 1 & -j \\ -j & -1 \end{pmatrix}$ $[M_m] = \frac{1}{2} \begin{pmatrix} 1 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ -2 & -2 & 0 & -2 \end{pmatrix}$	
 d. Metallic helix (left screw)	$[S] = \frac{1}{2} \begin{pmatrix} 1 & j \\ j & -1 \end{pmatrix}$ $[M_m] = \frac{1}{2} \begin{pmatrix} 1 & 1 & 0 & -1 \\ 1 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 2 & 2 & 0 & -2 \end{pmatrix}$	

5. FREQUENCY-DEPENDENT RELATIONSHIP OF POLARIMETRIC SCATTERING MATRIX ELEMENTS WITH SPECULAR POINT CURVATURE

The time-domain first order polarization-dependent correction to the physical optics impulse response has been given by Bennett et al (1973, 1977 and 1981) as

$$r_{0s}^{\vec{H}}(p01)(\vec{r}, t) = \frac{K_u - K_v}{4\pi} [\hat{a}_u H_{ui} - \hat{a}_v H_{vi}] \frac{dA}{dt}$$

where $\hat{a}_u, \hat{a}_v$ are unit vectors along the directions of the principal curvatures at the specular point; H_{ui}, H_{vi} are the components of the incident field in the directions of $\hat{a}_u, \hat{a}_v$ respectively; K_u, K_v are the principal curvatures at the specular point; and A is the silhouette area of the scatterer as delineated by the incident impulsive plane wavefront moving at half the free space velocity.

An expression for the far scattered impulse response field was found in [Bennett et al, (1973) and (1977)]

$$r_{0s}^{\vec{H}}(p0)(\vec{r}, t) = \frac{1}{2\pi} \frac{d^2 A}{dt^2} \hat{a}_H$$

which is the Kennaugh-Cosgriff formula, (Kennaugh & Cosgriff, 1958; Kennaugh & Moffatt, 1965). The corrected total field is thus

$$r_{0s}^{\vec{H}}(\vec{r}, t) = r_{0s}^{\vec{H}}(p0)(\vec{r}, t) + r_{0s}^{\vec{H}}(p01)(\vec{r}, t)$$

which is transformed to the frequency domain, and is directly related to the scattering matrix which exhibits total polarization/depolarization effects (Chaudhuri et al, 1982). Ignoring scale factors, the matrix elements are given by

$$\begin{aligned} S_{11} &= \frac{1}{2\pi} (jk)^2 A_F(k) - (jk) A_F(k) \frac{K_u - K_v}{4\pi} \cos 2\alpha \\ S_{22} &= \frac{1}{2\pi} (jk)^2 A_F(k) + (jk) A_F(k) \frac{K_u - K_v}{4\pi} \cos 2\alpha \\ S_{12} &= (jk) A_F(k) \frac{K_u - K_v}{4\pi} \sin 2\alpha \end{aligned} \quad (35)$$

where k is the wave number, $A_F(k)$ is the Fourier transform of $A(t)$, the polarization angle α is defined in Figure 6a. The validity of (35) requires high frequency interrogation with smooth, convex, conducting targets. (Fig. 6b)

A complex function $\frac{1 - \tilde{R}}{1 + \tilde{R}}$ (where $\tilde{R} = \frac{S_{22}}{S_{11}}$) is defined, and curvature information can be extracted from it at high frequencies. A relationship between the phase factors of the scattering matrix elements and the principal curvatures is then established (Chaudhuri et al, 1982)

$$\frac{K_u - K_v}{2} = - \frac{k}{\cos 2\alpha} \tan \frac{\phi_d}{2} \quad (36)$$

where $\phi_d = \phi_{22} - \phi_{11}$.

The cross-pol nulls are also found to be along the directions of principal curvatures. These directions can be recovered from the scattering matrix elements (Chaudhuri et al, 1982).

The curvature recovery model is based on the first order correction to the Physical Optics approximation. Higher order corrections are investigated by directly extending the space-time integral equation approach of Bennett et al, (1977). The second order correction current is found to be very insignificant when compared to the first order one (Chaudhuri et al, 1982) and (Foo, 1982).

The phase-curvature relationship (36) is tested by applying it to theoretical, as well as, experimental backscattering data obtained for a prolate spheroidal scatterer, as shown in Figures 6 to 8. Both sets of data support the relationship well. Figure 8a is a direct verification of (36) with theoretical data; Figure 8b depicts that the quantity $k \operatorname{Im} \left\{ \frac{1-R}{1+R} \right\}$ converges to $\frac{K_u - K_v}{2}$ as kb increases; Figure 8c is a plot of the imaginary part versus the real part of $k \left[\frac{1-R}{1+R} \right]$, and shows that, as predicted from theory, it converges to (or hovers around) a point on the imaginary axis as frequency increases. The distance of this point on the imaginary axis from the origin equals the required value $\frac{K_u - K_v}{2} = 0.375$ for the specular point of interest.

Figures 8a-8c refer to the broadside incidence to a 2:1 prolate spheroid in Figure 6b with $\phi = 90^\circ$. For useful presentation of results from experimental data, the complex plot, such as that in Figure 8c, is found to be most interpretative (Chaudhuri et al, 1982) and (Foo, 1982). Figures 8d-8f are the experimental versions of Figures 8a, b and c. Deviations from the theoretical predictions are mainly attributed to the k factor and the tangent function in (36), and the relative phase error between the TE and TM incidences, all of which become more significant at higher frequencies (Chaudhuri et al, 1982) and (Foo, 1982).

While the phase difference of like-polarized terms, however small, contains curvature information, the phase sum, regardless of the type of orthogonal polarization bases, tends to a value which is twice the argument of the Fourier transform of the silhouette area of the target (Foo, 1982), i.e.,

$$\phi_{11} + \phi_{22} \rightarrow 2 \operatorname{Arg} A_F(k) \quad (37)$$

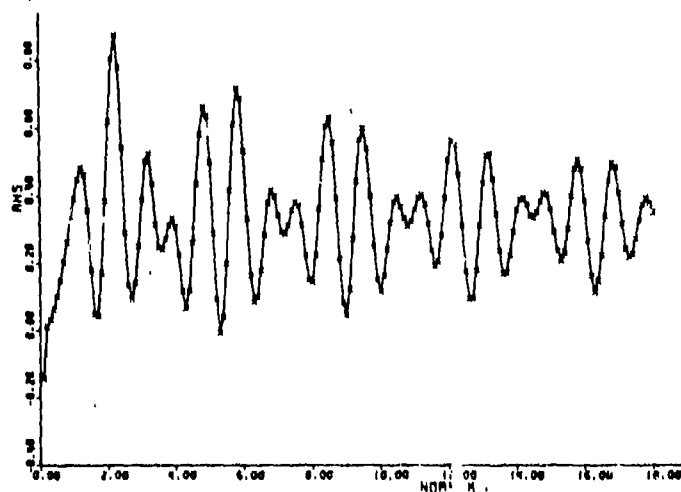
The phase sum also tends to the argument of the scattering ratio defined as the ratio of the determinant to the span of the scattering matrix

$$D \equiv \frac{S_{11}S_{22} - S_{12}^2}{|S_{11}|^2 + |S_{22}|^2 + 2|S_{12}|^2} \quad (38)$$

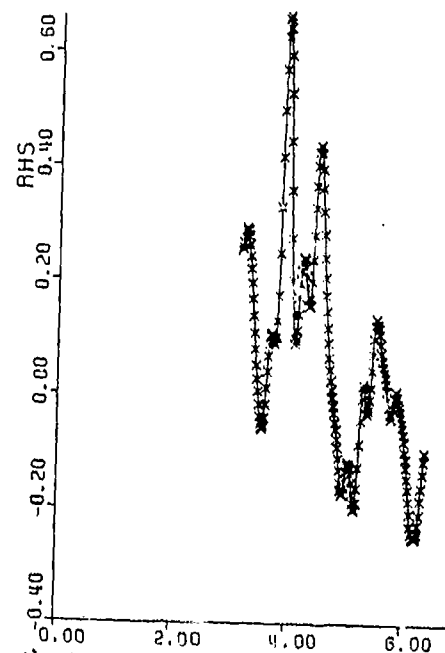
$$\phi_{11} + \phi_{22} \rightarrow \operatorname{Arg} D \quad (39)$$

The magnitude of the scattering ratio, whose definition is immaterial of whether linear, circular or general elliptic polarization is used, approaches 0.5 rapidly as frequency is increased, i.e.

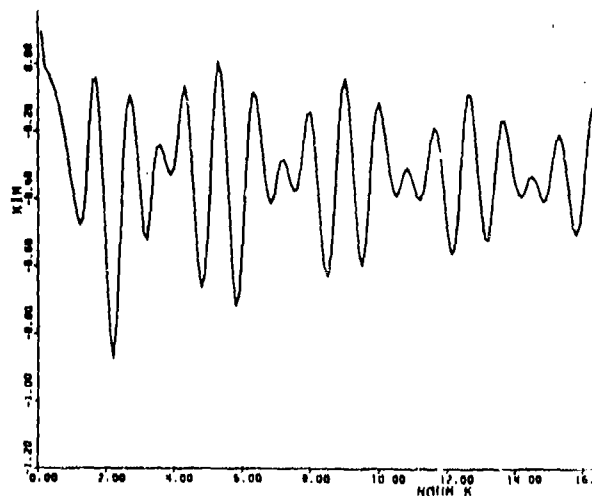
$$|D| \rightarrow 0.5 \quad (40)$$



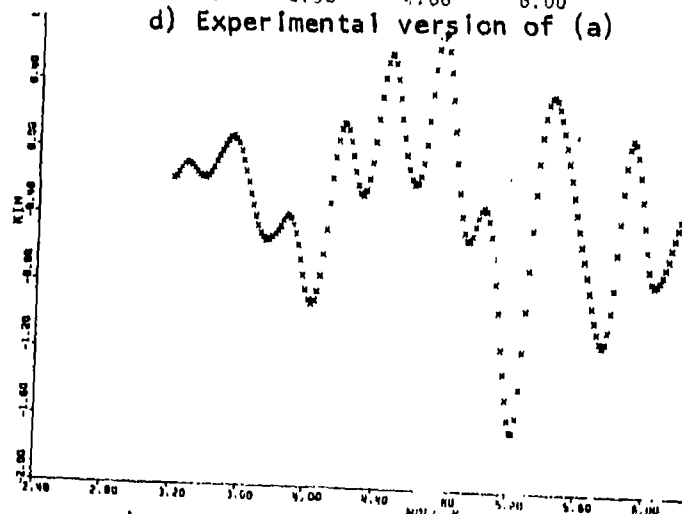
a) Direct Verification of Phase-Curvature Relationship (theoretical)



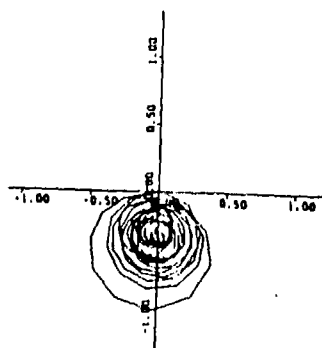
d) Experimental version of (a)



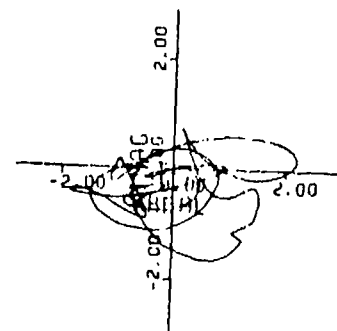
b) Convergence of $k \operatorname{Im} \frac{(1-R)}{(1-R)}$



e) Experimental Version of (b)



c) The Scattering Chart



f) Experimental Version of (c)

FIGURE 8 Comparison of Phase-curvature Relationships for theoretical and experimental data (Foo, 1982)

The magnitude of the ratio is interpreted as the ratio of the maximum radar cross section to the trace of the power scattering matrix $[P]$ at high frequencies, i.e.,

$$\frac{\sigma_{\max}}{\text{Tr}[P]} \rightarrow 0.5 \quad (41)$$

where $\sigma_{\max}$ is the optimum radar cross section defined in Kennaugh (1949-1954), Sinclair (1948), as

$$\sigma_{rt} = |\underline{h}^r \cdot [S] \underline{h}^t|^2$$

In the above, it is assumed that identical transmitting and receiving antennas are used; $\underline{h}^t$ and $\underline{h}^r$ are the antenna heights, and are normalized to unity; $[P]$ is the Graves power scattering matrix defined in Graves (1956), as

$$[P] = [S]^{*T} [S]$$

The complex plots of the scattering ratio provide a simple check on the accuracy of high frequency polarimetric measurements (Foo, 1982). The complex plot and the amplitude plot of the ratio are depicted in Figures 7a and 7c, respectively, for theoretical data. In Figures 7b and 7d, the respective plots for measurement data are provided which demonstrates the usefulness of introducing Eq. (38)

Another curvature recovery equation has been derived (Foo, 1982) in circular polarization basis vector notation

$$\left(\frac{K_u - K_v}{2} \right)^2 = -k^2 \frac{C_{RR} C_{LL}}{C_{LR}^2} \quad (42)$$

where the C 's denote the elements of the circular polarization scattering matrix. It is to be noted that the quantity $|C_{RR}| |C_{LL}| - |C_{RL}|^2$ (Morgan and Weisbrod 1982) can be interpreted as,

$$(|C_{RR}| |C_{LL}| - |C_{RL}|^2) = [-(1/2\pi)^2 k^4 |A_F(k)|^2], \quad (43)$$

which reveals area information for a smooth, convex, conducting target at high frequencies (Foo 1982).

The curvature recovery model is proven to satisfy the image reconstruction identities of invariant transformation (Foo 1982). It is found that the determinant of the scattering matrix is strictly transformation-invariant if (Foo 1982)

$$\text{Det } [T] = \pm 1$$

where $[T]$ is the unitary transformation matrix, whereas, the invariance of the span of the scattering matrix necessitates no restriction (Foo 1982), i.e.,

$$\text{Det } [C] = e^{j2\text{Arg}(\text{Det } [T])} : \text{Det } [S] \quad (44)$$

and

$$\text{Span } [C] = \text{Span } [S] \quad (45)$$

where $[C]$ can be extended to the scattering matrix resulting from transforming $[S]$ to the general elliptic polarization.

Finally, the values of kb (Chaudhuri et al, 1982) have been found to be most potentially suitable for curvature recovery of the 6" x 12" prolate spheroid (and probably targets of similar size and shape), provided that polarimetric measurements can be improved to a better accuracy. Not only is this range of kb valid for the first order correction to physical optics, but it is also a compromise range between the high frequency condition required by the curvature recovery model and the drawback to lower frequencies required to prevent critical magnification of measurement errors (Chaudhuri et al, 1982).

6. MEASUREMENTS OF $[M]$, $[P]$, and $[S]$

The measurements of the scattering matrices $[S]$, $[P]$, and $[M]$ are intricate, and various methods exist which have been summarized recently by Chan, 1981. Of particular interest here is the measurement of $[S]$ and, specifically, the retrieval of both amplitude and phase of all of the relevant elements of $[S]_{\text{SMR}}$, i.e., $|S_{AA}|$, $|S_{BB}|$, $|S_{AB}| = |S_{BA}|$, ϕ_{AA} , ϕ_{BB} assuming that $\phi_{AB} = \phi_{BA} = 0$. Since this brief introduction does not allow a complete treatment, we refer to the above report and point out only that it is necessary to recover the relative phase between the two co-polarized components in addition to the relative phase between the co-/cross-polarized components, as well as the amplitudes of $|S_{AA}|$, $|S_{BB}|$, $|S_{AB}|$, which requires isolation of at least 25 to 30 dB between co- and cross-polarized channels.

6.1 Amplitude-Only Measurements

When amplitude alone is measured, cross-section measurements do not lead to a direct determination of the scattering matrix. But, rather, the measured data provide the coefficients of equations from which the magnitudes and relative phases of the matrix elements are deduced. Hence, only $[S]_{\text{SMR}}$ can be derived from the measurements.

a) Measurement of $[M_S]$: The Mueller matrix $[M]$ of a target at one aspect angle can be readily obtained from its associated S_{SMR} as shown in Table 2. As for the measurement of the average Mueller matrix $\langle[M]\rangle$ of a target, a set of nine (9) independent measurements of average power for various combinations of antenna polarizations are required to obtain $\langle[M]\rangle$. All elements of the symmetric $[M_S]$, as defined in Eq. (20), can be obtained with the set of transmitting and receiving antenna combinations as shown in Table 5.

TABLE 5: ANTENNA POLARIZATION FOR THE MEASUREMENT OF THE SYMMETRIC $[M_S(\bar{m}_{ij})]$

<u>Transmission</u>	<u>Reception</u>	<u>Average received power</u>
$\phi=45^\circ$	$\phi=45^\circ$	$\frac{1}{2}(\bar{m}_{11}+\bar{m}_{33}+2\bar{m}_{13})$
$\phi=135^\circ$	$\phi=135^\circ$	$\frac{1}{2}(\bar{m}_{11}+\bar{m}_{33}-2\bar{m}_{13})$
Horizontal	Horizontal	$\frac{1}{2}(\bar{m}_{11}+\bar{m}_{22}+2\bar{m}_{12})$
Vertical	Vertical	$\frac{1}{2}(\bar{m}_{11}+\bar{m}_{22}-2\bar{m}_{12})$
Left circ.	Left circ.	$\frac{1}{2}(\bar{m}_{11}+\bar{m}_{44}+2\bar{m}_{14})$
Right circ.	Right circ.	$\frac{1}{2}(\bar{m}_{11}+\bar{m}_{44}-2\bar{m}_{14})$
$\phi=45^\circ$	Horizontal	$\frac{1}{4}(\bar{m}_{11}+\bar{m}_{12}+\bar{m}_{13}+\bar{m}_{23})$
$\phi=45^\circ$	Left circ.	$\frac{1}{4}(\bar{m}_{11}+\bar{m}_{13}+\bar{m}_{14}+\bar{m}_{34})$
Horizontal	Left circ.	$\frac{1}{4}(\bar{m}_{11}+\bar{m}_{12}+\bar{m}_{14}+\bar{m}_{24})$

Note that the expressions in the average received power column of Table 6.8 have different signs from those derived by Kennaugh [2: No. 7]. In Kennaugh's report, the Stokes vector for horizontal polarization is defined as $\underline{g}_H = 1/\sqrt{2} [1 - 1 0 0]^T$, whereas, here it is defined as $\underline{g}_H = 1/\sqrt{2} [1 1 0 0]^T$.

b) Measurement of $[S]_{SMR}$: The monostatic $[S]_{SMR}$ is specified by five (5) independent parameters, namely three (3) unsigned amplitudes and two (2) relative phases. In order to determine these five (5) parameters, five (5) independent magnitude-determining measurements have to be made. In general, therefore, seven (7) amplitude measurements are needed to completely determine the $[S]_{SMR}$.

Kennaugh (1949-1954) suggested measurements using the same transmitting and receiving antenna polarizations. Only one of these measurements need be other than linear polarization. The measured data are used to locate the CO-POL nulls of the $[S]_{SMR}$ on the Poincare sphere. Once the CO-POL nulls have been determined, the corresponding S_{SMR} can be completely specified (Boerner et al, 1981). The combinations of transmitting and receiving antenna polarizations are summarized in Table 6.

**TABLE 6: TRANSMITTING AND RECEIVING ANTENNA POLARIZATIONS
FOR AMPLITUDE-ONLY MEASUREMENT**

<u>Transmission</u>	<u>Reception</u>	<u>Measured Parameters</u>	<u>Calculated Parameters</u>
(1) Vertical Vertical	Vertical Horizontal	$ S_{VV} $ $ S_{HV} $	
If $ S_{HV} \neq 0$ in (1), proceed with the following measurement			
(2) Vertical Vertical Horizontal Horizontal Horizontal	$\phi=45^\circ$ Right circular Horizontal Right circular $\phi=45^\circ$	$ S_{HH} $	$\cos(\phi_{VV}-\phi_{HV})$ $-\sin(\phi_{VV}-\phi_{HV})$ $-\sin(\phi_{HH}-\phi_{HV})$ $\cos(\phi_{HH}-\phi_{HV})$
If $ S_{HV} = 0$, replace (2) by (3)			
(3) Horizontal $\phi=45^\circ$ $\phi=45^\circ$	Horizontal $\phi=45^\circ$ Right circular	$ S_{HH} $	$\cos(\phi_{VV}-\phi_{HH})$ $\sin(\phi_{VV}-\phi_{HH})$

ROSS AND FREENY (1964)

c) Measurement of [P]: The power scattering matrix [P] specifies the total power backscattered from the target for any transmitting antenna polarization, hence, it can be found by measuring only the total power in the backscattered return, no phase measurement is necessary. The form of the power scattering matrix is $PB(HV)$ is

$$\begin{aligned}
 [P(HV)] &= [S(HV)]^{T*} [S(HV)] \\
 &= \begin{bmatrix} |S_{HH}|^2 + |S_{HV}|^2 & S_{HH}^* S_{HV} + S_{HV}^* S_{VV} \\ (S_{HH}^* S_{HV} + S_{HV}^* S_{VV})^* & |S_{HV}|^2 + |S_{VV}|^2 \end{bmatrix} \\
 &= \begin{bmatrix} k_1 & K \\ K^* & k_2 \end{bmatrix} \quad (46)
 \end{aligned}$$

where k_1 and k_2 are real, K is complex. $[P]$ can be completely specified by transmitting at horizontal, vertical, $\phi = 45^\circ$ linear polarization and right-handed circular polarization and measuring the *total* power backscattered, no phase measurements are necessary (Graves, 1956).

For example, if horizontal polarization is transmitted, i.e.,

$$\underline{h}^t = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (47)$$

then, from $P_b = (\underline{h}^t)^T [P] \underline{h}^t$, we have

$$P_b^H = [1 \ 0] \begin{bmatrix} k_1 & K \\ K^* & k_2 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = k_1 \quad (48)$$

where the superscript indicates the polarization of the transmitting antenna. The result is summarized in Table 7. It should be noted that $[P]$ cannot be obtained using linear polarizations only. Rather, linear, as well as, circular polarizations are required.

TABLE 7: TRANSMITTING ANTENNA POLARIZATIONS FOR THE MEASUREMENT OF $[P]$

<u>Transmitting Polarization</u>	<u>Total backscattered power</u>	<u>Measured Parameters</u>
Horizontal	P_b^H	k_1
Vertical	P_b^V	k_2
$\phi = 45^\circ$	$P_b^{45^\circ}$	$\frac{1}{2}(k_1 + k_2) + \text{Re}\{K\}$
Right Circ.	P_b^{RC}	$\frac{1}{2}(k_1 + k_2) + \text{Im}\{K\}$

d) Measurement of $[P_H]$ and $[P_V]$: The elements of $[P_H]$ and $[P_V]$ can be determined by power measurements similar to those for obtaining $[P]$. For the determination of $[P_H]$, we transmit horizontal, vertical, $\phi = 45^\circ$ and right circular, and then receive with horizontal polarization only, i.e., the power backscattered in the horizontal channel. As for $[P_V]$, we receive with horizontal polarization only, i.e., the power backscattered in the vertical channel. The results are tabulated in Table 8 and Table 9.

TABLE 8: TRANSMITTING ANTENNA POLARIZATIONS FOR THE MEASUREMENT OF $[P_H]$

<u>Transmitting polarization</u>	<u>Backscattered power in horizontal channel</u>	<u>Measured parameters</u>
Horizontal	P_{bH}^H	$ S_{HH} ^2$
Vertical	P_{bH}^V	$ S_{HV} ^2$
$\phi=45^\circ$	$P_{bH}^{45^\circ}$	$\frac{1}{2}(S_{HH} ^2 + S_{HV} ^2) + \text{Re}\{S_{HH}^* S_{HV}\}$
Right circ.	P_{bH}^{RC}	$\frac{1}{2}(S_{HH} ^2 + S_{HV} ^2) + \text{Im}\{S_{HH}^* S_{HV}\}$

TABLE 9: TRANSMITTING ANTENNA POLARIZATIONS FOR THE MEASUREMENT OF $[P_V]$

<u>Transmitting polarization</u>	<u>Backscattered power in vertical channel</u>	<u>Measured parameters</u>
Horizontal	P_{bV}^H	$ S_{HV} ^2$
Vertical	P_{bV}^V	$ S_{VV} ^2$
$\phi=45^\circ$	$P_{bV}^{45^\circ}$	$\frac{1}{2}(S_{HV} ^2 + S_{VV} ^2) + \text{Re}\{S_{HV}^* S_{VV}\}$
Right circ.	P_{bV}^{RC}	$\frac{1}{2}(S_{HV} ^2 + S_{VV} ^2) + \text{Im}\{S_{HV}^* S_{VV}\}$

6.2 Amplitude and Relative Phase Measurement

The technique of measuring amplitude and relative phase has been used to obtain scattering matrix data by Kennaugh (1949-1954), Ross and Freeny (1964), Crispin et al (1961), and Huynen (1965).

In the following, several more useful methods are summarized.

6.2A Linear Polarization Basis

The 10 cm CHILL Meteorological Radar is one such system that has the capability of measuring both the amplitude and relative phase of the scattering matrix. The CHILL system is a coherent radar which has the ability to rapidly switch from vertical to horizontal polarization. The polarization switching is accomplished by use of a switchable ferrite circulation which is located behind the parabolic antenna (Mueller, 1981).

Measurement with the "fast switch" requires that the switch be transferred after each transmitter pulse. First, a horizontal polarization, and then a vertical polarization measurement is obtained. Two separate channels are used to keep the horizontal and vertical measurements separate. It should be noted that the same logarithmic receiver, sample and hold, and A/D converter are used for both channels. Thus, any non-linearities of these analog circuits are reflected in both channels, and will tend to cancel. The signal processing is achieved with an A/D converter and a floating point integration. The five (5) most significant bits are separated from the eight (8) bit digital word and used to represent the horizontal power and then the vertical return power are integrated separately in the floating point integration.

With additional modification, the dual polarization antenna switching capability can be enhanced to 834 μ sec which will complete recovery of the polarization phase information so that the relative phase scattering matrix $[S]_{SMR}$ can be measured within less than 4 μ sec time frames, which would be just below the projected decorrelation time for hydrometeor investigations.

Similar experiments have been carried out by Ross and Freeny (1964), and their results are summarized in Table 10.

**TABLE 10: TRANSMITTING AND RECEIVING ANTENNA POLARIZATIONS
FOR AMPLITUDE AND RELATIVE PHASE MEASUREMENT**

<u>Transmission</u>	<u>Reception</u>	<u>Measured Parameters</u>
(1) Vertical	Vertical } simul- Horizontal } taneous } recept- } ion	$\left. \begin{array}{l} S_{VV} \\ S_{HV} \end{array} \right\} \phi_{VV} - \phi_{HV}$
If $ S_{HV} \neq 0$, proceed with the following measurement		
(2) Horizontal	Horizontal } simul- Vertical } taneous } recept- } ion	$\left. \begin{array}{l} S_{HH} \\ S_{HV} \end{array} \right\} \phi_{HH} - \phi_{HV}$ Continued

TABLE 10: (CONTINUED)

If $ S_{HV} = 0$, replace (2) by (3)		
(3) $\phi = 45^\circ$	Horizontal Vertical $\left\{ \begin{array}{l} \text{simul-} \\ \text{taneous} \\ \text{reception} \end{array} \right.$	$\left. \begin{array}{l} S_{HH} /\sqrt{2} \\ S_{VV} /\sqrt{2} \end{array} \right\} \phi_{HH} - \phi_{VV}$

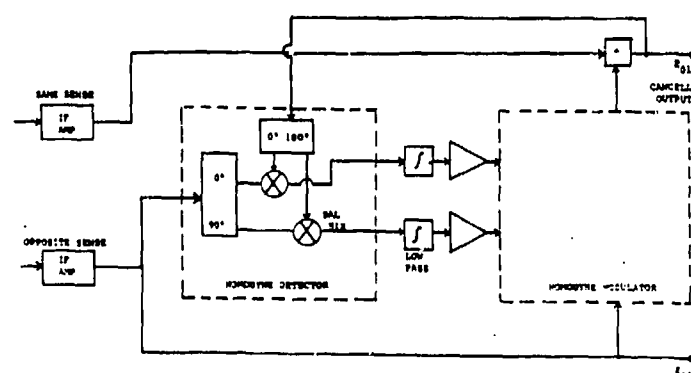
6.2B Circular Polarization Basis

The information of the backscattered characteristics of a radar target can be greatly improved if successful suppression of clutter return can be achieved. Advances in the field of radar polarimetry have clearly shown the usefulness of knowledge of the complete vector characteristics of the scattered fields which led to the development of dual-channel polarization diversity radar. Such a system is capable of transmitting arbitrary polarization and receiving the backscattered wave in two channels, one of which is polarized parallel to the transmitting channel, while the other is orthogonal to it. The complete scattering matrix can be measured in an arbitrary polarization basis by alternately switching the transmitting and receiving channels.

Successful use of this type of system has been documented by such investigators as G.C. McCormick and A. Hendry, F.E. Nathanson and A. Poelman. Their published works are referenced in the attached bibliography.

A brief description of the systems used by the above-mentioned investigators is given here:

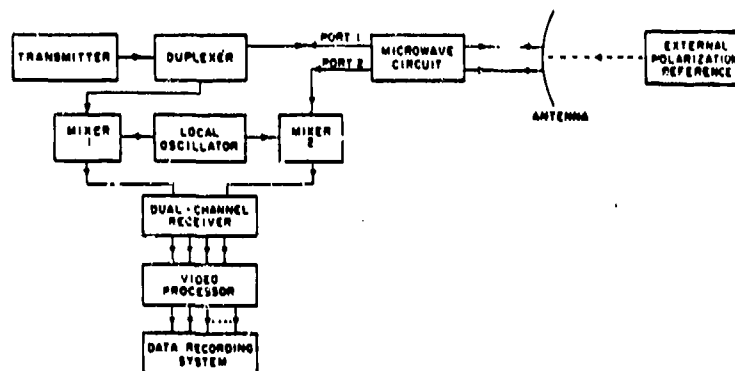
Nathanson (1975): Has proposed a technique to discriminate effectively against rain clutter which is implemented in a two (2) channel system with the same and opposite sense of polarization (circular) to that of a transmitter available at the inputs. The schematic diagram is shown in Figure 15.



Circuitry for adaptive circular polarization (Homodyne Modulator = same circuitry as Homodyne Detector).

FIGURE 15: Nathanson (1975)

McCormick and Hendry (1975): Realized a system determining certain parameters of rain clutter using "the ideal polarization diversity radar" (1975). See Figure 16.

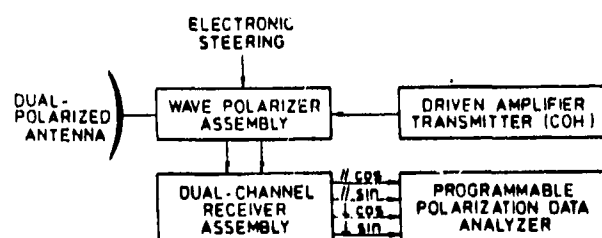


Block diagram of radar apparatus

FIGURE 16: McCormick and Hendry (1979)

Poelman (1981): Introduced another way of suppressing rain clutter in an X-Band radar facility for polarization signature studies of targets and clutter. This system has a dual-polarized antenna which receives all back-scattered power of the target in the parallel and orthogonal polarizations in separate channels.

It can utilize both linear and circular polarization, the latter used primarily for rain clutter suppression; whereas, the first for target in clutter discrimination.



Block diagram of existing experimental X-band radar facility for polarization studies.

FIGURE 17: Poelman (1981)

6.3 Amplitude and Absolute Phase Measurements

The method of measuring amplitude and absolute phase information can be used to determine the scattering matrix completely by transmitting only two (2) linear polarizations and receiving three (3) linear polarizations, see Table 11.

**TABLE 11: TRANSMITTING AND RECEIVING ANTENNA POLARIZATIONS
FOR AMPLITUDE AND ABSOLUTE PHASE MEASUREMENT**

<u>TRANSMISSIONS</u>	<u>RECEPTIONS</u>	<u>MEASURED PARAMETERS</u>
Vertical	Vertical	$ S_{VV} , \phi_{VV}$
Vertical	Horizontal	$ S_{HV} , \phi_{HV}$
Horizontal	Horizontal	$ S_{HH} , \phi_{HH}$

FREENY (1965)

The amplitudes and phases of the elements of the scattering matrix were measured at ElectroScience Laboratory of Ohio State University (ESL-OSU). The experiments were conducted (Walton 1982) on a frequency domain range yielding the backscattered returns S_{VV} and S_{HH} (S_{HV} and S_{VH} being zero in this case).

7. ASPECT-DEPENDENT PROPERTIES OF OPTIMAL POLARIZATION NULL LOCUS MOTION ON THE POLARIZATION SPHERE

7.1 Vector Scattering Center Interaction

Of particular relevance to this electromagnetic target scattering problem is the interaction of polarization/depolarization sensitive scattering centers on a single closed target of irregular shape, which was first attacked rigorously by Huynen (1960) in his dissertation. In this masterpiece, he developed his little understood "N-target decomposition theorem", utilizing canonical properties of the distributed target's Stokes matrix, which specifically applies to clutter analysis and multiple vector scattering center interaction of single targets. This theory is of paramount importance to further advancement in radar polarimetry. Although it still requires extensive extension, it clearly paves the single unique method of complete polarimetric description of radar clutter and average object, an immensely complicated electromagnetic inverse problem. We are fortunate to have the senior expert in the field, Dr. J. Richard Huynen (1982), join the efforts of this research task, and in a separate report entitled, "A revisitation of the phenomenological approaches with application to radar target decomposition", he has further developed on his N-target decomposition theory.

Whereas, in collaboration with Morgan and Weisbrod (Teledyne Micro-netics) to polarimetric CW radar target characteristics description, we are following the direction of extracting a complete set of most simple canonical target shapes (such as the sphere, the linear wire target, the n-bounce corner reflector, the left/right winding helices, the cone-tip/ogival and/or spherical capped truncated cylinders with and without fins, bumps, protrusions, etc. treated in Boerner et al, Jan 15/Sept, 1982), in consultation with Bennett and Mieras (1982), Sperry Research Center, use of a CW vector dumbbell scattering center (matrix) interaction was chosen. Both methods have proven to provide useful results and can be used for interpretation of the motion of the Huynen polarization fork as function of frequency, relative aspect angle (with respect to line joining the vector scattering centers) and the electric separation of both.

7.2 Dynamic Polarization Fork Motion

Specifically, we observe that for linear (H, V) polarization base pair anchoring, the cross-polarization null move only whenever the principal target symmetry axis is rotated about the line of sight orthogonal to (H, V); and that the co-polarization null locations move on a quasi-circular spiral non-closing paths as function of differential change in aspect angle where, for small electric separation of vector scattering centers the circles remain with isolated patches, whereas, for large electric separation on large circles encircling the total polarization sphere. Furthermore, the specific character of the vector scattering center (as e.g. smooth versus cone-tipped) dictates the relative differential speed with which these loci are transversed (slow versus rapid) as functions of differential aspect angle. We also note that for a large ensemble of closely packed vector scattering centers, the loci of the co-polarization nulls remain within rather small isolated patches on the polarization sphere which is indicative of clutter-type. Furthermore, the specific quasi-circular paths drawn are indicative of clutter motion. We note that the analytical result was verified experimentally by Poelman (1980-1982) as explained in detail in (Boerner, STIS 1914, Sept. 30, 1981), and this specific phenomenon of the dynamic fork motion of time frames of below the vector scattering center reshuffling time requires further extensive analytical and experimental studies. In general, the cross-polarization null location for linear symmetric targets is of slow precession type, and the rapid quasi-circular path motion of the co-polarization null location is nutative gyroscopic in nature. We note that this specific dynamic polarization fork behavior is well described by Huynen's "single target" description into five target characteristic parameters ($p_m, \gamma, \nu, \tau_m, \psi$) as detailed in (Huynen, 1982).

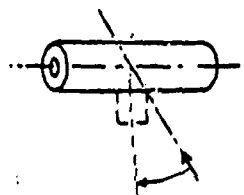
However, the electromagnetic inverse problem of decomposing a single radar target into its characteristic polarimetric target vector scattering centers is very complicated and still not resolved.

7.3 Optimal Polarization Null Characteristics of Buoy-Target Models (using measurement data of TELEDYNE-MICRONETICS, L.A. Morgan and S. Weisbrod)

In (Boerner et al, Sept., 1981) the optimal target polarization null concept, introduced briefly in this paper, is applied to experimental amplitude-plus-phase matrix data measured by Teledyne-Micronetics for two specific classes of water submerged buoy targets (six types of dihedral corner reflectors and twelve types of cylindrical open-ended pipe sections with specific termination). For the purpose of extracting useful target classification algorithms and also in order to analyze the aspect-angle dependent behavior, the three measured radar cross sections ($\sigma_{HH}, \sigma_{VV}, \sigma_{VH}$), the

span $\{[S]\}$, the $\det \{[S]\}$; $\text{Re} \{ (C_{RR}C_{LL}) / (C_{RL})^2 \}$, $\{ |C_{RR}| |C_{LL}| - |C_{RL}|^2 \}$, the spherical angle spanned by two co-pol nulls, and the co/cross-polarization null loci are plotted as functions of aspect angle. In Figures 18a and b, the polarimetric target behavior for a horizontal, truncated open pipe-section above a sea bed, and a vertical pipe section of the same dimensions in isolation,

Target S31
Diameter 2.5"
Length 3'
Wall Thickness 1 1/8"
Height Above Water 2"
Frequency 3.15 GHz



Horizontal

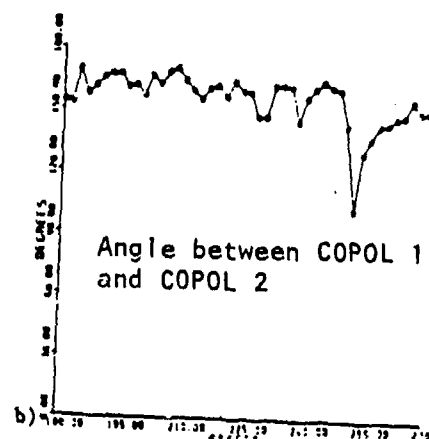
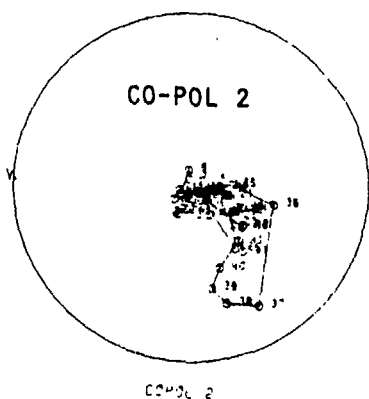
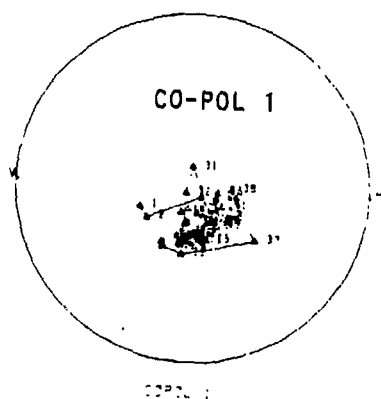
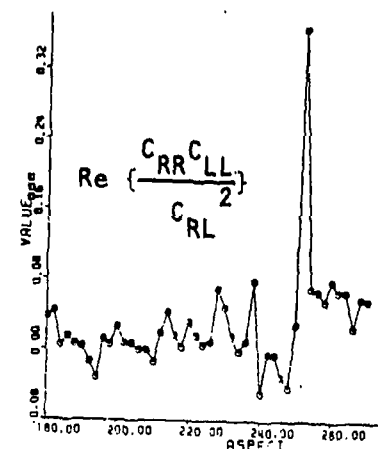
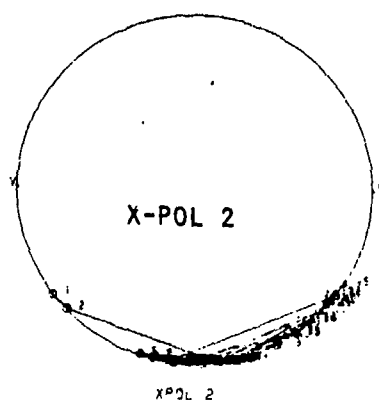
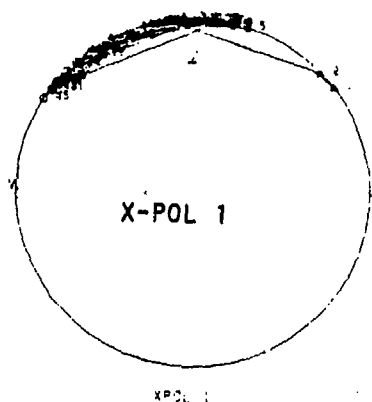
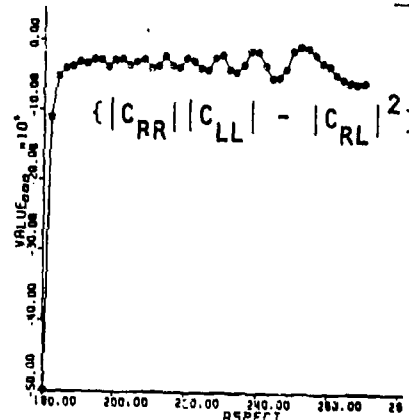
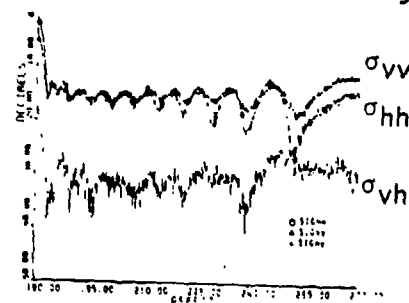
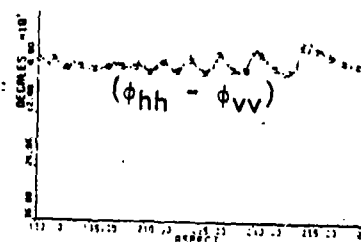
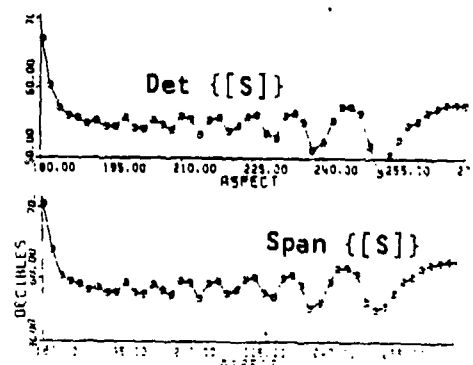
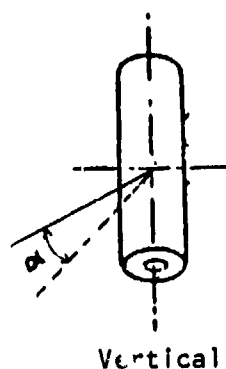
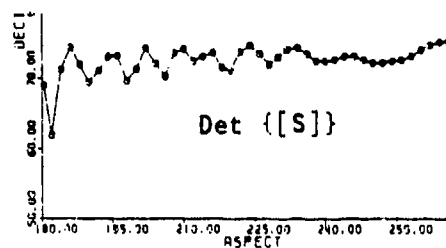


Figure 18a Polarimetric Target Behavior (Horizontal, Truncated Open Pipe-section above Sea-Level)

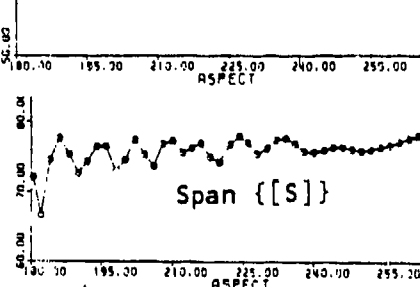
Target S31
 Diameter 2.5"
 Length 3'
 Wall Thickness 1 1/8"
 Frequency 3.15 GHz



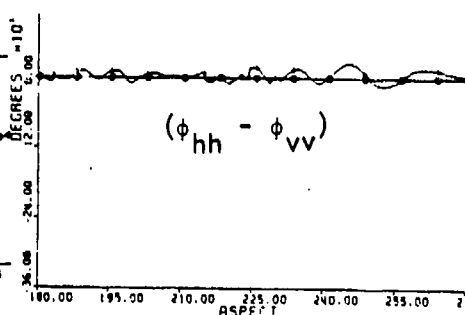
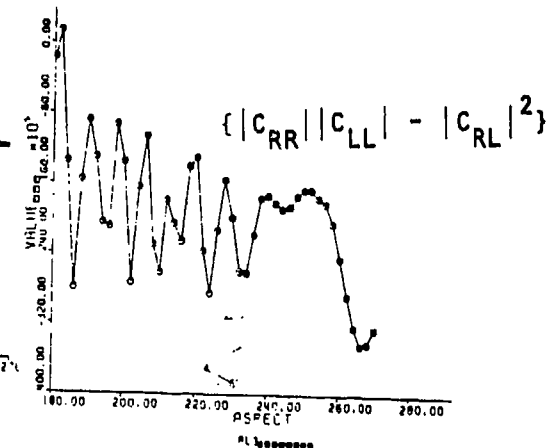
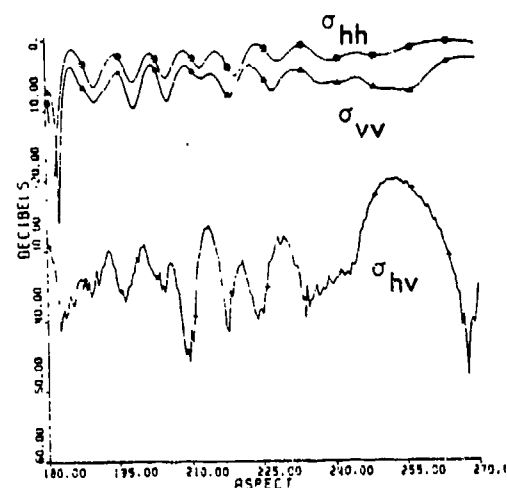
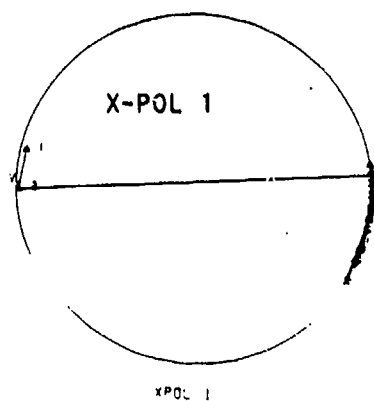
Vertical



Det {[S]}

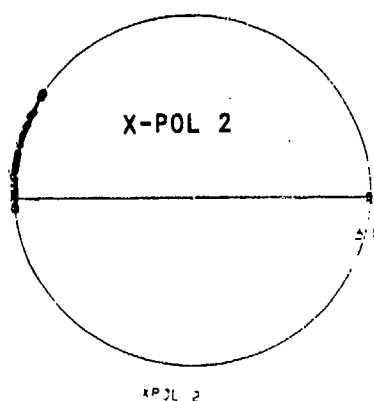


Span {[S]}

 $(\phi_{hh} - \phi_{vv})$  $|C_{RR}| |C_{LL}| - |C_{RL}|^2$ 

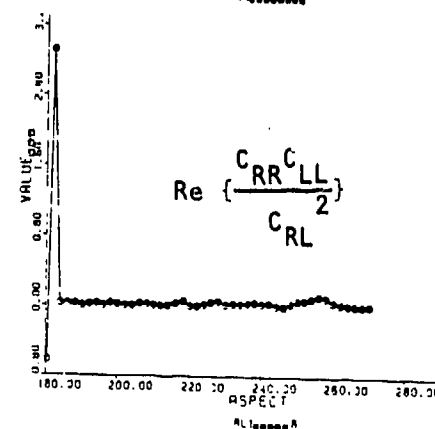
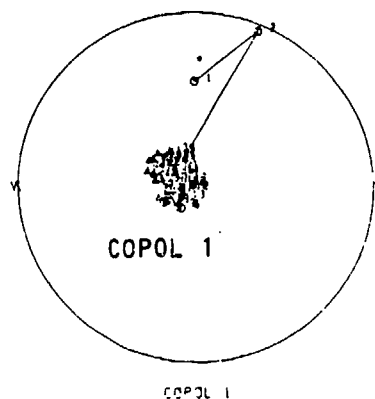
X-POL 1

XPOL 1



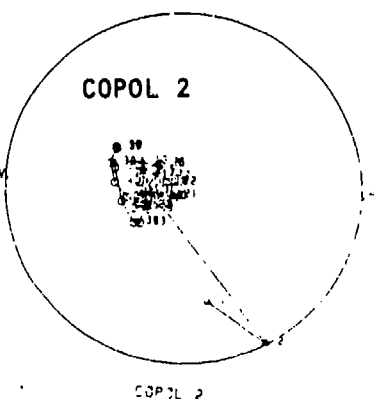
X-POL 2

XPOL 2

 $\text{Re} \left\{ \frac{C_{RR} C_{LL}}{C_{RL}^2} \right\}$ 

COPOL 1

COPOL 1



COPOL 2

COPOL 2

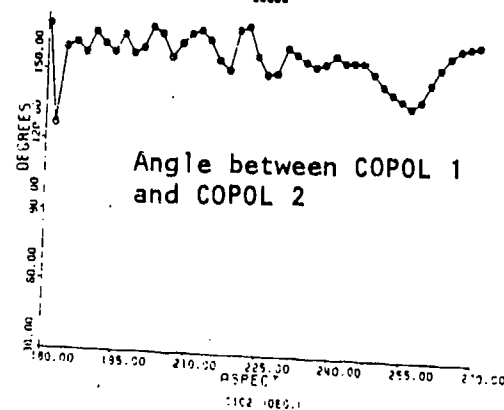
Angle between COPOL 1
and COPOL 2

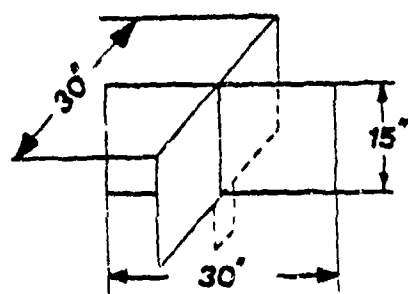
Figure 18b Polarimetric Target Behavior (Vertical Truncated Open Pipe-Section in Isolation)

respectively, is presented, whereas in Figures 19a and b that for a four-corner dihedral reflector above a sea-bed and in isolation, respectively. Comparing the data obtained for targets above the sea-bed with those in isolation, the expected interference behavior for Figures 18a/19a versus Figures 18b/19b is apparent and will not be further analyzed in detail, and we refer to the associated report by L.A. Morgan and S. Weisbrod(1982) for further relevant interpretations (also see Figure 20).

By analyzing the various plots for the two principal target categories considered, we are able to verify the fundamental theorems which can be derived from Huynen's polarization fork concept (Huynen, 1960, 1970, 1978, 1982); the target vector scattering interaction theory (Bennett and Mieras, 1982); the relationship between relative scattering matrix co-polarization phase and specular point curvature perturbations of Kennaugh's target silhouette area function(Foo, 1982); and the dynamic behavior of the polarization fork motion(Poelman, 1980-1982). Although, we have considered here the monochromatic (CW) backscattering case for reciprocal symmetrical targets only, it is evident that very definite target polarization properties exist which may be utilized as target characteristics classifiers and identifiers. In the following, we will first summarize our observations and then extract most important polarimetric target classifiers.

Observations

- (i) Polarization Fork Behavior: The X-POL nulls are in all cases antipodal, and the line joining the X-POL nulls bisects the spherical angle between the COPOL nulls on the polarization sphere. NOTE, this specific polarization fork behavior represents a very efficient method of checking on the accuracy of monostatic scattering matrix data for the reciprocal target case (i.e. an isotropic target embedded in an isotropic propagation medium).
- (ii) Huynen's Target Characteristic Angle γ : The spherical angle between the two COPOL nulls exhibits very distinct target characteristic behavior in dependence of strength and separation of the target's most definite vector scattering centers(We will have to await the detailed analyses of Bennett and Mieras(1982) to obtain more comprehension of this aspect of the problem).
- (iii) Polarization Transformation Invariants: It was clearly established that the two target polarization transformation invariants, i.e. $\text{Det} \{[S]\}$ and $\text{Span} \{[S]\}$ do provide constants for whatever measurement polarization basis is being used. In addition, these invariants, which exhibit identical aspect dependence, but not frequency dependence(see Section 5; and in more detail(Foo, 1982)), are contributing parameters towards establishing useful target characteristic classification algorithms.
- (iv) Relative Scattering Matrix Copolarization Phase ($\phi_{HH} - \phi_{VV}$): In strict compliance with the results presented in(Foo,1982), the relative scattering matrix copolarization phase ($\phi_{HH} - \phi_{VV}$) certainly plays a dominant role in classifying undulating smooth versus rugged edged surfaces. We note here that the circular polarization base identities, derived in Foo's thesis(Foo, 1982) and investigated, in parts, in the associated report by Morgan and Weisbrod(1982), i.e. $\{|C_{RR}|^2 + |C_{LL}|^2 - |C_{RL}|^2\}$



Target 4C1
Height above water 2'
0° Conical cut
Frequency 3.15 GHz

36

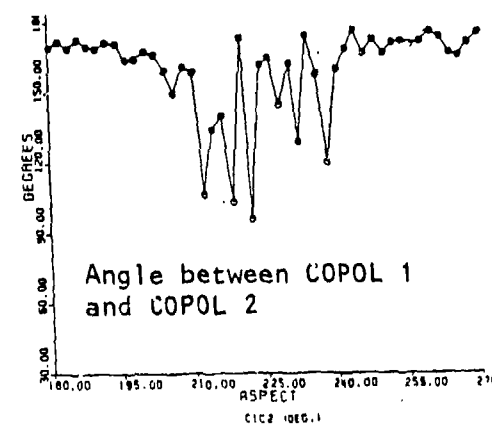
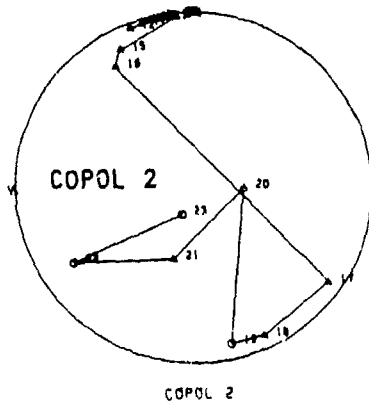
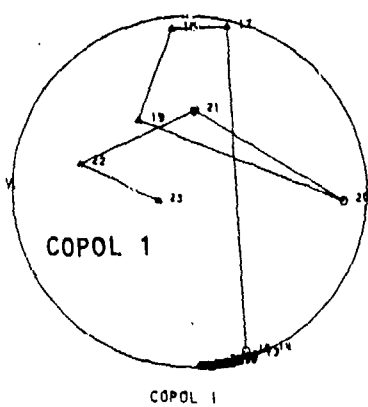
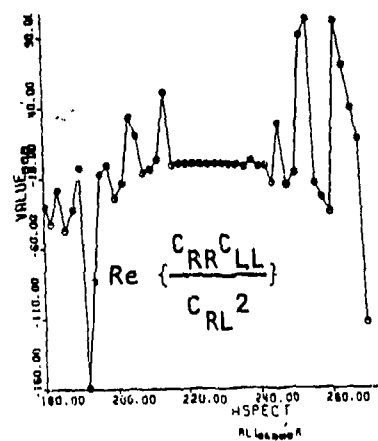
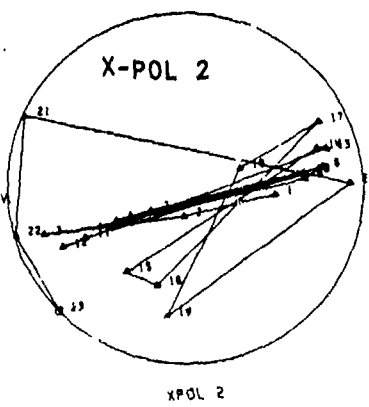
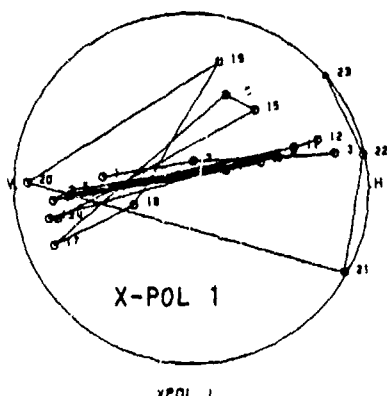
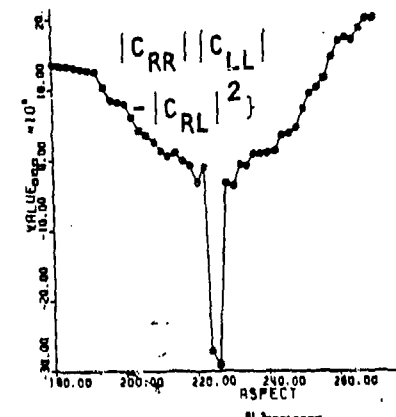
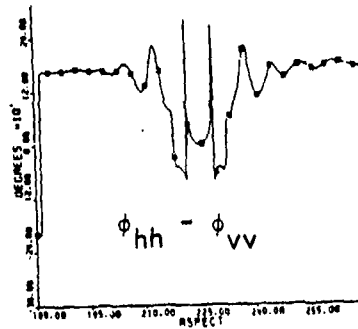
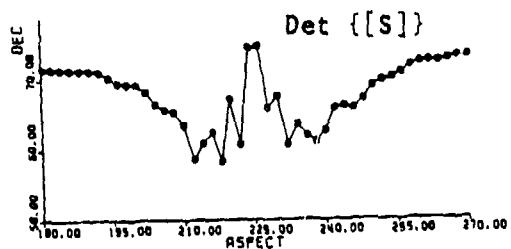
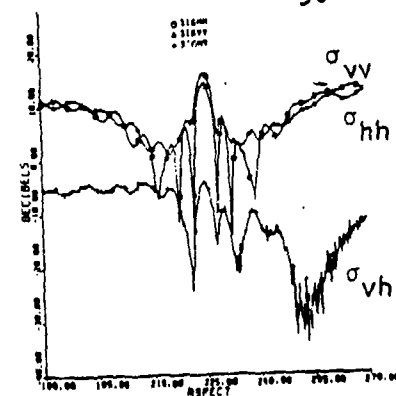


Figure 19a Polarimetric Target Behavior(Four Corner Dihedral Reflector above Sea-Level)

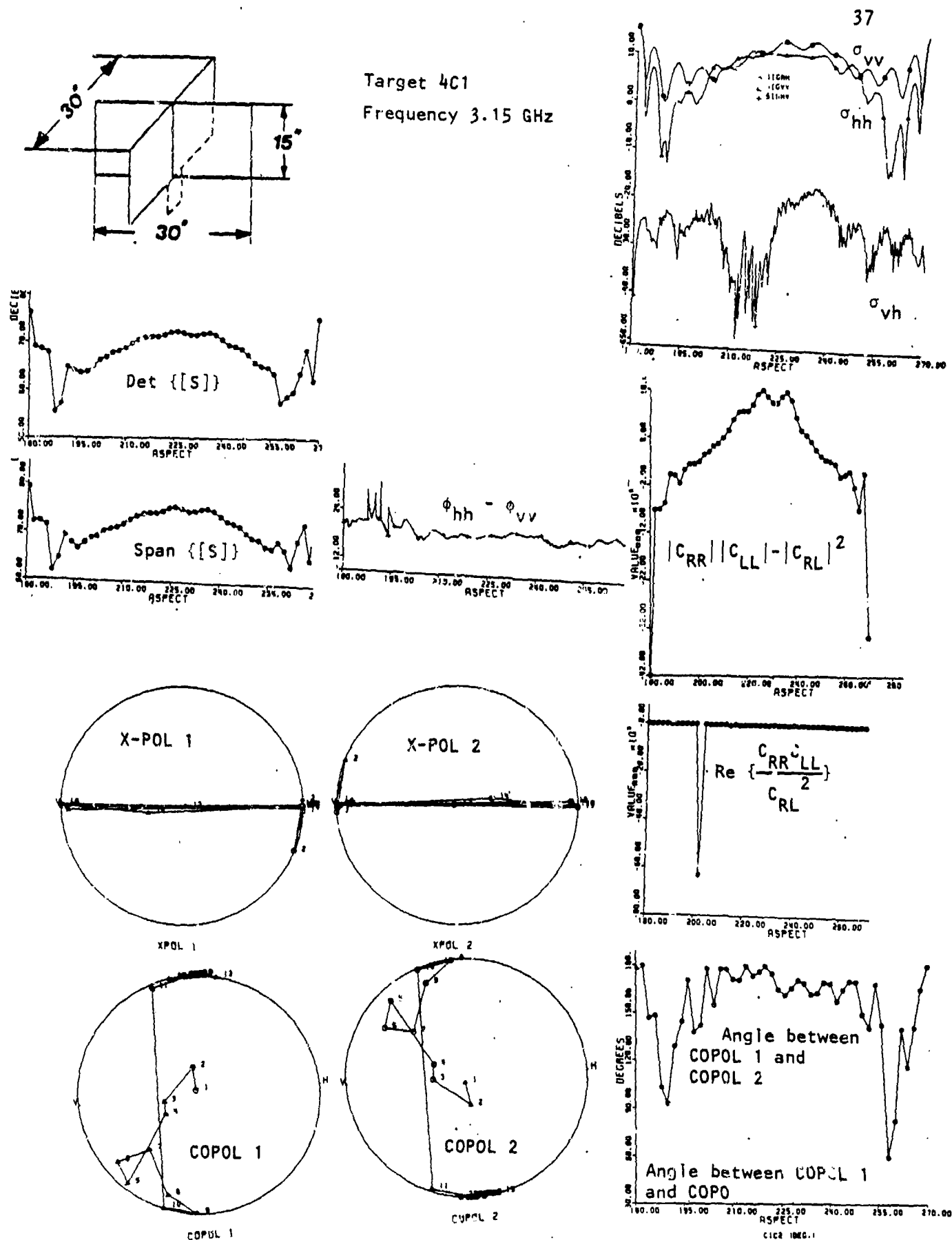


Figure 19b Polarimetric Target Behavior (Four-Corner Dihedral Reflector in Isolation)

and $\{ \text{Re}[(C_{RR} C_{LL}) / (C_{RL})^2] \}$, contain rather similar information to $(\phi_{HH} - \phi_{VV})$. From an examination of the relevant plots in Figures 18a/b, 19a/b, it is evident that the theories on target curvature at the specular point developed in (Foo, 1982) and summarized in Section 5 do present rather important target characteristic classification as well as identification algorithms. For example, the relevant figures $\{(\phi_{HH} - \phi_{VV}); \text{Re}[(C_{LL} C_{RR}) / (C_{RL})^2]\}$ in Figure 18b for the vertical pipe section amplify the correctness of the formulas resulting from the theories developed in (Chaudhuri et al, 1982; Foo, 1982). In (Morgan and Weisbrod, 1982), the relevance of the quantity $\{|C_{RR}| |C_{LL}| - |C_{RL}|^2\}$, closely related to $\text{Det}\{[C]\}$, is emphasized. This peculiar expression is shown to be a maximum for dihedral, minimum for a plate or sphere, and zero for a linear or helical target. Here we reproduce Figure 5 of (Morgan and Weisbrod, 1982) in Figure 20, which is being explained and interpreted in

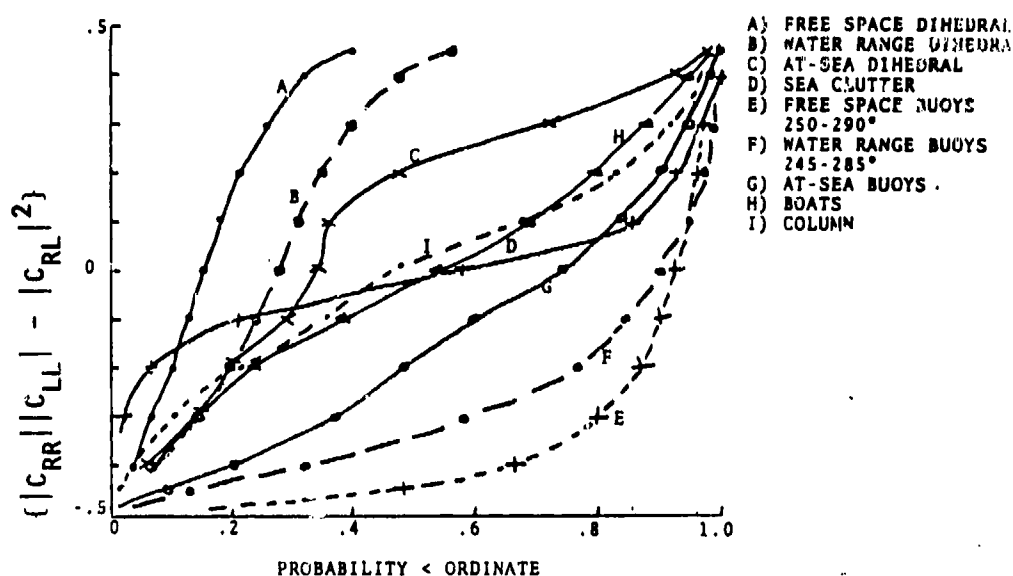


Figure 20 Probability Distribution for $\{|C_{RR}| |C_{LL}| - |C_{RL}|^2\}$ according to Figure 5 in (Morgan and Weisbrod, 1982). Reproduced with the permission of the authors and the responsible NAV-AIR Contract Officer (J.W. Willis).

detail in their report.

7.4 Recommendations on Pursuing Aspect-Plus-Frequency Dependent Dynamic Polarization Fork Analyses in terms of Vector Scattering Center Interaction Models and Huynen's N-target Decomposition Theory

There exists one major problem in applying polarimetric techniques derived from the optimal target polarization theory to the polarimetric transient time-

dependent problem of ramp response target cross-sectional area projection shape reconstruction, because this optimal polarization target null theory is derived in the frequency only as a mono-frequency theory. Both Kennaugh (1949-1981) and Huynen (1960, 1970, 1978, 1982) were aware of this complication in their pioneering and continuing research efforts of advancing the state-of-the-art in radar target polarimetry. What we urgently need is a time-dependent polarization-sensitive target feature descriptive theory which is still not completely available.

8. CONCLUSIONS

We have demonstrated in our analyses on radar target polarimetry that broadband radar polarimetry deserves the full attention of Naval Research Centers involved in target/clutter handling in the boundary layer of an ocean environment.

Specifically, the propagation assessment of electromagnetic waves along the marine boundary layer in an ocean environment is of justifiable concern to the Navy and applies to improving techniques of surveillance, communications, navigation, electronic warfare, and optimum sensor design. Considerable efforts have been made, primarily at NOSC, NADC, NWC, and NRL, to characterize the marine boundary layer using electromagnetic (EM: specifically microwaves and millimeter waves) and electro-optical (EO: infrared and visible) remote probing methods. Utilizing, in parts, the electromagnetic wave interrogation properties at frequencies from 200 MHz to 100 THz led to the development of such lower atmospheric assessment systems as IREPS (Integrated Refractive Effects Prediction System), PREOS (Prediction of Performance and Range for EO System), and TESS (Tactical Environment Support Systems).

A thorough literature analysis on the available EM/EO systems shows, however, that hitherto, no, or extremely little, use of the broadband polarization vector properties of the electromagnetic wave have been made. This apparent shortcoming can result in considerable ambiguity of environmental assessment, particularly in the spectral band of 1 GHz to 400 GHz. Therefore, the main objective of this research is to promote the efficient use of novel polarimetric radar techniques, to improve upon the assessment performance of existing m-to-mm-wave radar systems, and to develop complete polarimetric chirp radar systems which allow sub-millisecond acquisition of the radar scattering matrix and real-time sea clutter and/or target classification and identification. We emphasize that electromagnetic vector wave interrogation with material bodies can best be identified as a polarization-sensitive target feature (spatial and temporal) spectral frequency resonance phenomenon. Every effort needs to be made to implement these important polarimetric/scatterometric methods into existing and newly-to-be-developed vector wave scattering techniques for a more reliable propagation assessment of electromagnetic waves along the marine boundary layer in an ocean environment.

9. ACKNOWLEDGMENTS

First of all, I wish to acknowledge my graduate research assistants who, with their enthusiasm and diligence, contributed to the preparation of this annual report: B.Y. Foo, C.Y. Chan, Sasan S. Saachi, Marat Davidovitz, Benjamin Beker, Mr. Jerry Nespor, Mr. Anthony Manson and Chau-Wing Yang.

In addition, I wish to thank Drs. Sujeet Chaudhuri and J. Richard Huynen for their input into our research efforts, to Dr. Jonathan D. Young and Mr. William Leeper for supplying the transient measurement data and to Mr. Lee A. Morgan and Dr. Steven Welsbrod for providing the aspect-dependent data.

We wish to thank Mr. James W. Willis for his interest and continual encouragement in the pursuit of this polarimetric research effort, and Mr. Jack Daley for his guidance and the provision of reports and data.

10. REFERENCES

L.E. Allan, G.C. McCormick, "Measurements of the Backscatter Matrix of Dielectric Spheroids", IEEE TRANS. Antennas and Prop., Vol. AP-26, #4, July 1978, pp. 579-587.

L.E. Allan, G.C. McCormick, "Measurements of the Backscatter Matrix of Dielectric Bodies", IEEE TRANS. Antennas and Prop. Vol. AP-28, March 1980, pp. 166-169.

Y.M.M. Antar, A. Hendry, I.J. Schlesak, R.L. Olsen, R.C. Be'Rube', "Ice-Crystal Depolarization Measurements at 28.6 GHz with Simultaneous 16.5 GHz Polarization Diversity Radar Observations", Electronics Letters Vol.16(1980) #21, pp.808-809.

D. Atlas, "Advances in Radar Meteorology" in Advances in Geophysics, New York, London: Academic Press, 1964, pp. 317-478.

D.L. Banks, "Advanced Millimeter Wave Radar Sensor Development", NAEGON-82, (also see: Variable Polarization Radar for Non-imaging Target ID, non-cooperative Target Recognition Conference 1980).

B.L. Barge, R.G. Humphries, "Identification of Rain and Hail with Polarization and Dual-Wavelength Radar", 19th Conference on Radar Meteor., Miami Fla. 15-18, 1980.

L.J. Battan, J.B. Theiss, "Depolarization of Microwaves by Hydrometeors in a Thunderstorm", J. ATMOS. SCI., 27, 974-977.

J.W. Battles, "95-GHz Radar Measurements", Naval Weapons Center China Lake, CA 93553, Nov. 1975.

M.E. Bechtel, R.A. Ross, "Interim Report on Polarization Discrimination", Cornell Aeronautical Lab. Inc., Ithaca, New York, Report UB-1376-S-105, Sept. 1962.

P. Beckmann, A. Spichizzino, "The Scattering of Electromagnetic Waves from Rough Surfaces", MacMillan, New York, 1963.

C.L. Bennett, "Time Domain Inverse Scattering", IEEE Trans. AP-29(2), pp.213-219, (Special Issue on "Inverse Methods in Electromagnetics"), March 1981.

C.L. Bennett, H. Mieras, "Dynamic Polarization Fork Properties of the Vector Dumbell Model", private communication, Feb. 1982.

C. L. Bennett, J.D. Lorenzo, A.M. Auckenthaler, "Integral Equation Approach to Wideband Inverse Scattering", Sperry Rand Res. Center, Sudbury, Mass., Final Rept., No. SCRRCR-Cr-73-1, 1973.

C.L. Bennett, R.M. Hieronymus, "A Time Domain Approach to the EM Inverse Problems", Proc. URSI-Int. Symposium: Electromagnetic Wave Theory, June 20-24, 1977, pp.156-158, 1977 (see: Uslenghi, 1978, pp. 393-429).

C.L. Bennett, W.L. Weeks, "Transient Scattering from Conducting Cylinders, IEEE Trans. AP-18(5), 1970, pp. 627-633 (see also: C.L. Bennett: A Technique for Computing Approximate EM Impulse Response of Conducting Bodies, PhD. Thesis, Purdue Univ. 1968).

R.S. Berkowitz, "Modern Radar Analysis Evaluation and System Design", John Wiley & Sons, N.Y. 1965.

S.H. Bickel, "Polarization Extensions to the Monostatic-Bistatic Equivalence Theorem", The MITRE Corp., Bedford, Mass.

S.H. Bickel, "Some Invariant Properties of the Polarization Scattering Matrix", Proc. IEEE, Vol. 53, pp. 1070-1072, Aug. 1965.

A.J. Blanchard, "Error in the Determination of Subsurface Backscattering Field as Determined by Rouse", Tech. Memor. RSC-134, Remote Sensing Center, Texas A&M Univ., College Station, Texas, June 1976.

A.J. Blanchard, J.W. Rouse, "Depolarization of Electromagnetic Waves Scattered from an Inhomogeneous Half Space Bounded by a Rough Surface", Radio Science, Vol. 15, #4, pp. 776-779, July-Aug. 1980.

W-M. Boerner, M.B. El-Arini, S. Saatchi, M. Davidovitz, J. Nespor, "Polarization Utilization in Radar Target Reconstruction; Buoy Targets", Final Rept., UICC, EL-EMIC, NANRAR, 81-03, (NAV-AIR Contract N00019-80-C-0260, Sept. 15, 1981).

W-M. Boerner, "Polarization Utilization in Microwave Imaging, Radar Target Mapping, and Electromagnetic Inverse Scattering", A State-Of-The-Art Review, Comm. Lab., Rept.#78-3, Communications Lab., Inf. Eng. Dept., SE0-1104, UICC, Chicago, Oct. 1978.

W-M. Boerner, "Polarization Utilization in Electromagnetic Inverse Scattering", Ch. 7 in Inverse Scattering Problems in Optics, Vol. 2 (Ed. H.P. Baltes), Topics in Current Physics, Vol. 20, Springer Verlag, July 1980, pp. 237-305.

W-M. Boerner, "Polarization Microwave Holography: An Extension of Scalar to Vector Holography"(invited), 1980 Intern. Opt. Computing Conf., SPIE's Techn. Symp. East, Washington D.C., April 9, 1980, Sess. 3B, paper# 231-23(11 pages) 1980, pp. 188-198.

W-M. Boerner, "Use of Polarization in Active and Passive Precipitation Radar Measurements", Workshop in Precipitation Measurement from Space NASA. Goddard Space Flight Center, Greenbelt. Md, April 28-May 1, 1981, pp. D-326 to D-340.

W-M. Boerner, "Polarization Sensitivity of Near-to-ground Clutter at mm and near-mm wavelengths", Battelle Delivery No. STAS 1914, Contract No. DAAG 29-76-D-0100, USA-MICOM-DRSNI-REL, Sept. 30, 1981.

W-M. Boerner, M.B. El-Arini, C.Y. Chan, S. Saatchi, W.S. Ip, M. Mastoris, B.Y. Foo, "Polarization Utilization in Radar Target Reconstruction", Tech. (Interim) Report, UIC, CL-EMID-NANPAR-S1-01, Communications Lab., Information Eng. Dept., SEO-1104, Chicago, Ill., Jan. 1981.

W-M. Boerner, M.B. El-Arini, "Utilization of Optimal Polarization Concept in Radar Meteorology", XXth Conf. on Radar Meteorology, Boston, Mass., Nov. 30-Dec. 3, 1981, pp. 656-665.

W-M. Boerner, "Use of Polarization in electromagnetic inverse scattering", Radio Science, Vol. 16, No. 6 (Special Issue Including Papers: 1980 Symposium on electromagnetic waves) pp. 1037-1045. Nov/Dec 1981.

M. Born, E. Wolf, "Principles of Optics, 3rd ed.", Pergamon Press, London N.Y., 1965.

J.J. Bowman, T.B.A. Senior, P.L.E. Uslenghi, "Electromagnetic and Acoustic Scattering by Simple Shapes", North Holland Publ. Co., Amsterdam, Netherlands, 1969.

V.N. Bringi, T.A. Seliga, "Scattering from Axisymmetric Dielectrics or Perfect Conductors Imbedded in an Axisymmetric Dielectric", IEEE Trans. AP-25, pp. 575-580, 1977.

V.N. Bringi, S.M. Chery, M.P.M. Hall, T. A. Seliga, "A new accuracy in determining rainfall rates and attenuation due to rain by means of dual polarization radar measurements", IEEE Conf. Publ. No. 169 on "Antennas and Propagation", London, Nov. 1978.

H. N. Chait, "Arbitrary Polarized Antenna System", Patent No. 2, 619, 635, U.S. Pat. Off., Application June 19, 1950.

C. Y. Chan, "Studies on the Power Scattering Matrix of Radar Targets", M.Sc. Thesis, May 1981, InfE. Dept., UICC, Chicago, Illinois Dept. No. CI-EMID-81-02--A Tutorial Exposition on the Power Scattering Matrix.

S. K. Chaudhuri, B.Y. Foo, W-M. Boerner, "High frequency inverse scattering model to recover the specular point curvature from polarization scattering matrix data," submitted to IEEE Trans. AP-30, April 1982.

S.K. Chaudhuri, W-M. Boerner, "A Monostatic Inverse Scattering Model Based on Polarization Utilization", Applied Phys., Vol. 11, No. 4, Springer Verlag, pp. 337-350, 1976.

S.K. Chaudhuri, W-M. Boerner, "Polarization Utilization in Profile Inversion of a Perfectly Conducting Prolate Spheroid", IEEE Trans. AP-25, No. 4, pp. 505-511, July 1977.

- P.K. Cheo, J. Renau, "Wavelength dependence of total and depolarized back-scattered laser light from rough metallic surfaces", J. Opt. Soc. Amer. 59(7), 1969, pp. 821-826.
- S. M. Cherry, J.W.F. Goddard, M.P.M. Hall, "Examination of Rain Drop Sizes using a Dual-Polarization Radar", Amer. Meteor. Soc., 19th Conf. Radar Meteor., Miami Fla., April 1980.
- S.M. Cherry, J.W.F. Goddard, M.P.M. Hall, "Use of Dual Polarization Radar to Assess Attenuation on an OTS Satellite-to-ground Path", URSI Symp. on Effects of the lower atmosphere on radio prop. at freq. above 1 Ghz., Lennoxville, Canada, May 1980.
- C.W. Chuang, D.L. Moffatt, "Complex natural resonances of radar targets via Prony's method, 1975 URSI Meeting, UIUC, June 3-5, 1975.
- B. Chytil, "Polarization-Dependent Scattering Cross-sections", Prace Ustava Radiotech. Electroniky (Czech) 21, pp. 13-21, 1961.
- L. Clyton, S. Hollis, "Antenna Polarization Analysis by Amplitude Measurements of Multiple Components", Microwave J. 8(1), pp. 35-41, Jan. 1965.
- J.R. Copeland, "Radar Target Classification by Polarization Properties", Proc. IRE. Vol. 48, pp. 1260-1296, July 1960.
- J.W. Crispin, E.M. Siegel, "Methods of Radar Cross-Section Analysis", Academic Press, N.Y., 1968.
- J.C. Daley, "Sea Clutter Measurements on Four Frequencies", NRL Report 6806, Nov. 1968.
- J. C. Daley, "Radar Sea Return in High Sea States", NRL Report 7142, Sept. 1970.
- J.C. Daley, "Radar Target Discrimination Based on Polarimetric Effects", NRL Rept., Washington D.C., March 1978.
- G. A. Deschamps, "Geometric Viewpoints in the Representation of waveguide junctions", Proc. Symposium on Modern Network Synthesis, Poly. Inst. of Brooklyn, New York, N.Y., April 16-18, 1962, pp. 277-295.
- G. A. Deschamps, P.E. Mast, "Quadratic antenna systems and noise excited antennas", IEEE Trans. AP-21(4), 1973, pp. 479-483.
- G. A. Deschamps, "Part II-Geometric Representation of Polarization of a Plane Electromagnetic Wave", Proc. IRE, Vol. 39, pp. 540-544, May 1951.
- G.A. Deschamps, "A Hyperbolic Protractor for Microwave Impedance Measurements and other Purposes", Federal Telecomm. Lab, N.J., 1953.
- G.A. Deschamps, P.E. Mast, "Poincare Sphere Representation of Partially Polarized Fields", IEEE Trans. AP-21(4), pp. 474-478, 1973.
- A.J. Devaney, "Inverse-scattering theory within the Rytov approximation", Opt. Letters 6(8), pp. 373-376, August 1981.

A.J. Devaney, "A computer simulation study of diffraction tomography" IEEE Trans. Ultrasonic Imaging, submitted for publication March 16, 1982.

R.J. Doviak, D. Sirmans, "Doppler Radar with Polarization Diversity", Journal of Atmos. Sciences, 30, pp. 737-739, 1972.

S.O. Dunlap, "Investigation of Polarimetric Processing via Digital Simulation", Workshop on Polarimetric Tech., pp. 25-26, June 1980.

H.A. Ecker, J.L. Eaves, T.M. Miller, "Investigation of Polarization Agility as a Radar Parameter", 17th Annual Tri-service Radar Symp., pp. 25-27, May 1971.

H.A. Ecker, J.L. Eaves, "Study of Polarimetric Techniques for Target Enhancement", Tech. Rept. AFAL-TR-67-102, 1968.

G. Elachi, W.E. Brown, "Models of Radar Imaging of the Ocean Surface Waves", IEEE Trans. AP-25 (11), pp. 94-95, 1977.

B-Y. Foo, "A High Frequency inverse scattering model to recover the specular point curvature from polarimetric scattering data", M. Sc. Thesis, College of Graduate Studies, UIC, Chicago, Ill., May 1982.

C.C. Freeny, "Experimental and Analytical Investigations of Target Scattering Matrices", Tech. Rept. No. NADC-TR-65-298, Rome Air Development Center, Research and Technology Division, Griffis Air Force Base, N.Y., Dec. 1965.

A.K. Fung, "Scattering and depolarization of Electromagnetic Waves from a Rough Surface", Proc. IEEE (Letters), Vol. 54, pp. 395-398, March 1966.

A.K. Fung, H.J. Eom, "Multiple Scattering and Depolarization by a Randomly Rough Kirchhoff Surface", IEEE Trans. AP-29, pp. 463-471, May 1981.

A. K. Fung, H.J. Eom "Effects of a Rough Boundary Surface on Polarization of the Scattered field from an Inhomogeneous Medium", Proc. IGARSS, June 1-4, 1982, Munich, FRG.

A.K. Fung, H.J. Eom, "A Theory of Wave Scattering from an Inhomogeneous layer with an Irregular Interface", IEEE Trans., AP-29, pp. 899-910. November 1981.

H. Gent, "Elliptically Polarized Waves and their Reflection from radar Targets", Telecomm. Res. Est., TRE Memo. pp. 584, March 1954.

A. Gerard, J.M. Burch, "Introduction to Matrix in Optics", John Wiley & Sons, Ltd., London, 1975.

D.T. Gjessing, "Remote Surveillance by Electromagnetic Waves for Air-to-Water-Land", Ann Arbor MI., Ann Arbor Pub., Inc., 1978.

D.T. Gjessing, "Adaptive Techniques for Radar detection and Identification of Objects in an Ocean Environment", J. Ocean. Eng., OE-6 (1), 1981, pp. 5-17.

D.T. Gjessing, "Adaptive Radar in Remote Sensing, Ann Arbor Science Publ., Ann Arbor, MI, 1981.

D.T. Gjessing, J. Hjelmstad, and T. Lund, "A Multifrequency Adaptive Radar for Detection and Identification of Objects: Results of preliminary experiments on aircraft against sea clutter, IEEE TRANS. Antennae and Prop. 30(3), pp. 351-365, May 1982.

W.B. Goggins, "Identification of Radar Targets by Pattern Recognition", Ph.D. Thesis UASF Institute of Technology, Air University, Dayton, Oh, June 1973.

M.M. Gorshov, "Ellipsometry", Sovetskoye Radio Press, (in Russia), 1974.

P.T. Gough, W-M. Boerner, "Depolarization of Specular Scatter as an Aid to Discriminating Between a Rough Dielectric Surface and an 'identical' rough metallic surface." J. Opt. Soc. Am., 69(9), pp. 1212-1217, Nov. 1979.

G. Graf, "A System for On-line Imaging of Scattering Centers on Rotating Radar Targets", IEEE Trans. AP-25(4), pp. 592-593, July 1977.

G. Graf, "On the Optimization of the Aspect Angle Windows for the Doppler Analysis of Radar Returns of Rotating Targets", IEEE Trans. AP-24(3), 1976, pp. 379-381.

C. D. Graves, "Radar Polarization Power Scattering Matrix", Proc. IRE, Vol. 44, pp. 248-252, Feb. 1956.

M. P. M. Hall, S. M. Cherry, J. W. F. Goddard and G. R. Kennedy, "Raindrop Size and Raindrop Rate Measured by Dual-Polarized Radar", Nature 285, pp.195-199, May22, 1980.

P. S. Hauge, "Mueller Matrix Ellipsometry with Imperfect Compensators", J. Opt. Soc. Am. , Vol. 68, pp. 1519-1528, Nov. 1978.

E. Hecht and A. Zajac, "Optics", Addison-Wesley Publishing Co., Menlo Park, Ca., 1976.

A. Hendry, G. C. McCormick, B. L. Barge, "The Degree of Common Orientation of Hydrometeors Observed by Polarization Diversity Radars", J. of Appl. Met. Vol. 15 (1976) No. 6, pp.643-640.

A. Hendry, G. C. McCormick, B. L. Barge, "K-Band and S- Band Observations of the Differential Propagation Constant in Snow", IEEE Trans. on Ant. and Prop. Vol. AP-24 (1976) NO. 4, pp.521-525.

A. hendry and G. C. McCormick, 1971: "Polarization Properties of Precipitation Scattering", Bull Radio Elect. Engr. Div., National Res. Council 21, pp 9-20.

A. Hendry and L. E. Allan, 1973: "Apparatus for the Real-Time Display of Correlation and Relative Phase Angle Data from the Alberta Hail Studies Radar. Rept. ERB-875, Radio and Electrical Engineering Div. , National Res. Council of Canada, Ottawa.

A. Hendry and G. C. McCormick, "Polarization Properties of Precipitation Particles Related to Storm Structure", J. De Rech. Atmos. (1974), pp. 189-200.

A. Hendry and G. C. McCormick, "Deterioration of Circular Polarization Clutter Cancellation in Anisotropic Precipitation Media", Electronics Letters, Vol. 10, pp. 165-166, May 1974.

W. A. Hiltner, "Polarization Measurements", Astron. Technique, Chicago University Press, 1962.

J. S. Hollis, T. G. Hickman and T. J. Dyon, "Polarization Theory," in Microwave Antenna Measurements, Ed., by J. S. Hollis, T. J. Lyon and L. Clayton, Scientific-Atlanta, Inc., Atlanta, Georgia, July 1970.

H. C. Van De Hulst, "Light Scattering By Small Particles", New York: John Wiley, 1957.

R. G. Humphries, 1974: Observations and Calculations of Depolarization Effects at 3 Ghz Due to Precipitation ", J. Rech Atmos. 8, pp. 165-161.

R.G. Humphries, "Observations and Calculations of Depolarization Effects at 3 Ghz due to Precipitation", J. of Rech. Atmos., 8, pp. 155-161.

R.G. Humphries, P.L. Barge, "Polarization and dual Wavelength Radar Observations of the Bright Band", IEEE Trans. on Geoscience Electronics, Vol. GE-17, No. 4, pp. 190-195, Oct. 1979.

J. R. Huynen, "Measurement of the Target Scattering Matrix", IEEE Proc. 53(8), pp. 936-946, 1965.

J. R. Huynen, "Dynamic Radar Cross-Section Measurements", IRE Intern. Intern. Conf. Rec., Pt. 5, Vol. 10, pp. 3-11, 1962.

J. R. Huynen, "Study on Ballistic-Missile Routing Based on Radar Cross-Section Data, Sc. Rept. No. 4 ; Radar Target Sorting Based on Polarization Signature Analysis, Lockheed Aircraft Corp., Missiles and Space Division, Rept. LMSD-288216, May 1960, Contract AF19(604)5550).

J. R. Huynen, "Phenomenological Theory of Radar Targets, Chapt.11 in "Electromagnetic Scattering" (P. L. E. Uslenghi, ed), Acad. Press, New York, 1978.

J. R. Huynen, "Phenomenological Theory of Radar Targets", Ph. D. Dissertation, Drukkerij Bronder-Offset, N. V. Rotterdam, 1970.

J. R. Huynen, "Radar Measurements of Scattering Operators", Proc. 6th Symp. on Ballistic Missile and Aerospace Technology, Vol. 11, Academic Press, New York, 1961.

J. R. Huynen, F. McNolty, E. Hanson, "Component Distribution for Fluctuating Radar Targets", IEEE Trans. AES 11(6), pp.1316-1332, 1965.

IEEE Special Issue on "Radar Reflectivity", IEEE Proc., Vol. 53(8), Aug. 1965.

IEEE Standard Number 149-1979, "Test Procedures for Antennas", published by The Institute of Electrical and Electronics Engineers, Inc., New York 1979.

J. R. Huynen, A Revisitation of the Phenomenological Approach With Application to Radar Target Decomposition, EMID-CL-UIL Dept. 82-04, May 1982.

IEEE, Transactions of the Antennas and Propagation Society (Editor: Prof. Raj Mittra), SPECIAL ISSUE ON INVERSE METHODS IN ELECTROMAGNETICS, (invited guest editor: Prof. Wolfgang-M. Boerner), IEEE Trans. AP-29 pp. 185-418, Vol. 2, March 1981..

G. A. Ioannidis, D. E. Hammers, "Optimum Antenna Polarization for Target Discrimination in Clutter", IEEE Trans. Antenna Prop., AP-27, pp.357-363, May 1979.

H. E. Jeske, (Ed.) "Atmospheric Effects on Radar Target Identification and Imaging", Proc. NATO ASI, Goslar, 1975, (D. Reidel Publ. Co., Dodrecht, Holland, 1976.

D. S. Jones, "The Theory of Electromagnetism", McMillian, N. Y., 1964.

R. C. Jones, "New Calculus for the Treatment of Optical Systems. V. A. More, General Formulation and Description of Another Calculus", J. Opt. Soc Amer., 37, p. 107, 1947.

R. C. Jones, "New Calculus For the Treatment of Optical Systems I. Description and Discussion of the Calculus", J. Opt. Soc. Amer. 31, p. 488, 1941.

D. B. Kanareykin, N. F. Pavlov, and U. A. Potekhin, "The Polarization of Radar Signals", Sovyetskaye Radio, Moscow 1966 (in Russian): (English Trans.of Chaps. 10-12: Radar Polarization Effects, CCM Inf. Corp, G. Collier and McMillian, 900 Third Ave., New York, N.Y. 10023).

D. B. Kanareykin, V. A. Potekhin and M. F. Shisikin, "Maritime Polarimetry", Sudostroyenie, Leningrad, 1968.

D. B. Kanareykin, N. F. Pavlov and V. A. Poetkhin, 1966: "Polarization of Radar Signals", Sovetskoye Radio, Moscow, Chaps. 1-10.

I. Katz, "Introductory Remarks to Backscatter Measurements Session", Proc. Workshop on Radar Backscatter From Terrain", pp. 33, U.S. Army Eng. Top. Lab., Ft. Belvoir, V. A., Jan. 9-11, 1979. (University of Kansas : RSLTR 374-2).

R. E. Kell , "On the Derivation of Bistatic RCS from Monostatic Measurements", Proc. IEEE 53, pp. 983-988, 1965.

E. M. Kennaugh, "The K-Pulse concept", IEEE Trans. AP-29(2), pp.327-331, March 1981, (Special Issue on Inverse Methods in Electromagnetics).

E. M. Kennaugh, "Polarization dependence of RCS - a geometrical interpretation", IEEE Trans. AP-29(2), PP. 412-413, March 1981, (Special Issue on "Inverse Methods in Electromagnetics").

E. M. Kennaugh, "Interpretation of the Physical Optics Approximations in the time Domain", Proc. GISAT II Symp., Vol. II, Part I, Oct. 2-4, 1967, Mitre Corp., Bedford Mass., AD 839700.

E. M. Kennaugh, R. L. Cosgriff, "The use of Impulse Response in Electromagnetic Scattering Problems", IRE Nat. Convention Record, Part I, pp. 72-77, 1958.

E. M. Kennaugh, D. L. Moffat, "Transient and Impulse Response in approximations", IEEE Proc. 53 (8), pp. 893-901, 1965.

E. M. Kennaugh, "Effects of Type of Polarization on Echo Characteristics: Monostatic Case", Repts 389-1 (Sept. 16, 1949) and 389-4 (June 16, 1950), The Ohio State University, Antenna Laboratory, Columbus, Ohio. 43212.

E. M. Kennaugh, "Polarization Properties of Radar Reflections", M. Sc. Thesis, Dept of Elect. Eng., The Ohio State Univ., Columbus, Ohio. 43212, 1952.

G. H. Knittel, "The Polarization Sphere as a Graphical Aid in Determining the Polarization of an Antenna by Amplitude Measurements Only", IEEE Trans. Antennas and Propag., AP-15, pp. 217-221, March 1967.

Y. B. Kobzarev, (Ed.), Modern Radar, (Soyetskoye Radio Press, 1969; in Russian).

K. Y. Kondratyev, "Radiative Heat Exchange in the Atmosphere", Pergamon Press, New York, 1965.

A. L. Kozlov, "Radar Contrast of Two Objects", Izvesta VUZ, Radioelektronika, Vol. 22, No. 7, pp. 63-67, July 1979.

J. D. Kraus, Guest Editor, IEEE Trans. AP-12(7), Dec. 1964, "Special Issue on RADAR ASTRONOMY".

J. D. Kraus, "Antennas", McGraw-Hill Book Co., New York, 1950.

J. D. Kraus, "Radio Astronomy", McGraw-Hill Book Co., New York, 1966.

J. D. Kraus, 1966: Radioastronomie, McGraw-Hill.

Ksienski, A.A. and Lin, H., "Optimum Frequencies for Aircraft Classification", IEEE Trans on Aerospace & Electronic Systems, Vol AES-17, No. 5, Sept. 1981, pp. 656-665.

F. Kuhl and R. Covelli, "Object Identification by Multiple Observations of the Scattering Matrix", Proc. IEEE 53, pp. 1110-1115, August 1965.

N. R. Landry, "Measuring the Phase and the Amplitude of Backscattered Radar Energy on a Static Range", Radar Reflectivity Measurements Symp., Vol. 1, pp. 146, Report RADU-TDR-65-24, 1964.

R. W. Larson, P. L. Jackson, R. J. Dallaine, R. Schuman, R. Rawson, "Interpretation of Multichannel Microwave SAR Imagery", Symp. on Remote Sensing of the Environment ERIM, Univ. of Michigan, Proc, Vol. 11, pp. 53-64, 1977.

J. C. Leader, "Bidirectional Scattering of Electromagnetic Waves from Rough Surfaces", J. Appl. Phys., 42(12), pp. 4808-4816, 1971.

B. L. Lewis and I. D. Olin, "Experimental Study and Theoretical Model of High Resolution Radar Backscatter From the Sea", Radio Science, Vol. 15, No. 4, pp. 815-828, July-August 1980.

B. L. Lewis and I. D. Olin (1977), "Some Recent Observations of Sea Spikes", Radar 77 Conf. Publ, 155, PP. 115-119, Int. of Elect. Eng. , London.

R. Lehrmitte and P. R. Krehbiel, "Doppler Radar and Radio Observations of Thunderstorms", IEEE Trans. Geoscience Elec., Vol. GE-17, NO. 4, Oct. 1979.

Y. T. Lin and A. A. Ksienski, "Identification fo Complex Geometrical Shapes by Means of Low Frequency Radar Returns", Radio and Electronics Eng. 46(10), pp. 472-480, 1976.

M. W. Long, 1975, "Radar Reflectivity of Land and Sea", Chapt. 5, D. C. Heath, Lexington, Mass.

O. Lowenschuss, "Scattering Matrix Application", Proc. IEEE, 53(8), pp. 988-992, August 1965.

A.L. Maffett, "Scattering Matrices", In Methods of Radar Cross-Section Analysis, Ed. by J. W. Crispin, K. M. Siegel, Academic Press, N. Y. , 1968.

J. E. Manz, "A Radar Cloud Target Polarization Discrimination Technique", AFWL, Kintland AFB, Tech. Rept. AFWL-TR-70-76, Oct. 1970.

S. Marder, "Synthetic Aperature Radar", in E. J. Jeske, Ed., Atmospheric Effects on Radar Target Identification and Imaging, Proc. NATO-ASI, Goslar, 1975.

E. E. Martin, "Dual Polarized Radar Cross-Section Measuremants of Vehicles and Roadway Obstacles at 16 GHz and 69 GHz", Final Tech Rept., Industrial Agreement, Nov. 1973.

J. S. Marshall, W. Hitschfeld, "Interpretation of the Fluctuating Echo from Randomly Distributed Scatterers- Part 1, Can. J. Phys., Vol. 31, pp. 962-964, 1953.

B. H. McCormick, "Invariants and Representations of Mueller's Optical Algebra", B. Sc. Theses, MIT Phys. Dept., Cambridge, Mass., 1950, (Under supervision of Prof. Hans Mueller).

G. C. McCormick, A. Hendry, "Principles for the Radar Determination of the Polarization Properties of Precipitiaion", Radio Sci. , Vol. 10. No. 4, pp. 421-434, 1975.

G. C. McCormick, "Relationship of Differential Refractivity to Correlation in Dual-Polarization Radar", *Electronic Letters*, Vol. 15, No. 10, pp. 265-266, 1979.

G. C. McCormick, "Radar Measurement of Precipitation-Related Depolarization in Thunderstorms", *IEEE Trans. Geoscience Electl*, Vol. GE-17, NO.4, Oct. 1979.

G. C. McCormick, A. Hendry, "Techniques for the Determination of the Polarization Properties of Precipitation", *Radio Science*, Vol. 14, NO.6, pp. 1027-1040, Nov.-Dec. 1979.

G. C. McCormick, A. Hendry, "Principles for Radar Determination of the Polarization Properties of Precipitation", *Radio Science*, Vol.10, NO. 4, pp. 421-434, April 1975.

G. C. McCormick, A. Hendry, "Method for Measuring the Anisotropy of Precipitation Media", *Electronics Letters*, Vol. 9, May 17, 1973.

P. Meischner, A. Schrott, "Einsatz von Dual-Polarizations-Radarsystemen in der Wolkenphysik und Ausbreitungsforschung bei Mikrowellen", *DFVLR*, IB 553-82/1, 1981.

J. I. Metcalf, "Propagation Effects on a Coherent Polarization-Diversity Radar", *Radio Science*, Vol.16, 1981.

J. I. Metcalf, "Design Study for a Coherent Polarization-Diversity Radar", Georgia Inst. Tech., Eng. Experiment Station, Atlanta, Georgia 30332, Final Rept. AFGL-TR-80-0262, 1980.

J. I. Metcalf, "Polarization-Diversity Radar and Lidar Technology in Meteorological Research: A Review of Theory and Measurements", Eng. Exper. Georgia Inst. of Tech., Atlanta, Georgia, 30332, July 31, 1977.

J. I. Metcalf, J. D. Echard, "Coherent Polarization-Diversity Radar Techniques in Meteorology", *J. Atmos. Sci.*, 35, NO. 10, Oct. 1978.

G. Mie, "Beiträge zur Optik trüber Medien, Speziell kolloidaler Metallösungen", *ANN. Phys.*, 25, p.377, 1908.

R. Mittra, ed., "Computer Techniques for Electromagnetics", Pergamon Press, N. Y., 1973.

R. Mittra, ed., "Numerical and Asymptotic Techniques in Electromagnetics", *Topics in Applied Physics*, Vol. 3, Springer, New York, 1975.

D. L. Moffatt, J. D. Young, A.A. Ksienski, H. C. Lin, C. M. Rhoads, "Transient response characteristics in identification and imaging(invited)", *IEEE Trans. AP-29(2)*, pp.192-205. Special issue On Inverse Methods in Electromagnetics), March 1981.

D. L. Moffatt (coordinator/editor), *Radar Target Identification*, Class Notes of Workshop, Vol. I and Vol. II, Electro-Science Lab., Ohio State Univ., Columbus, Ohio, Sept. 1976.

D. L. Moffatt, E. M. Kennaugh, "The axial Echo Area of A Perfectly Conducting Prolate Spheroid", IEEE Trans. AP-13, pp. 401-409, 1965. (see also: IEEE Proc. 52(10), pp. 1252-1253, 1964).

D. L. Moffatt R. K. Mains, "Detection and Discrimination of Radar Targets", IEEE Trans, AP-23(3), pp. 358-367. 1975.

L. A. Morgan, S. Weisbrod, "A Feasibility Study of RCS Matrix Signatures for Target Classification", RADC Rept. RADC-TR8050, (Contract No. F30602-79-C0007), March 1980.

L. A. Morgan, S. Weisbrod, "Investigation on the use of Polarization Discrimination Techniques for Radar Detection of Sea Targets", Naval Air Systems Command, Contract No. N00019-76-C0612. 1976.

L. A. Morgan, S. Weisbrod, "Research on Radar Detection of Small Sea Targets", Naval Air Systems Command Contract No. N00019-76-C-0176, 1976.

L. A. Morgan, S. Weisbrod, "RCS Matrix Analysis of Sea Clutter and Targets", Teledyne Micronetics, San Diego, Final Rept., Naval Air Systems Command, Contract No. N00019-C-80-0595, Dec. 1981.

S. P. Morgunov, A. B. Shupyatskiy, "Evaluation of Artificial Modification Efficiency from the Polarization Characteristics of the Echo Signal", TR. TSENT, AEROL. OBSERV., No. 57, p.p. 49-54, 1964.

E. A. Mueller, "Implementation of Differential Reflectivity on the CHILL Radar, Proc. 20th Radar Meteorology Conf., 1-4 Dec, 1981, Boston MA, pp. 666-667.

H. Mueller, "Foundations of Optics", J. OPT. SOC. AMER. 38, 1949.

F. E. Nathanson, "Adaptive Circular Polarization", IEEE Intern, Radar Conf. IEEE Publ, 75 CHO 938-1 AES, pp. 221-225. 1975.

F. E. Nathanson, "Radar Design Principles, Signal Processing and the Environment", McGraw-Hill, N.Y., 1969.

Nexrad Joint Systems Program Office, "Next Generation Weather Radar Research and Development Plan", Dec. 1981.

W. L. Nowland, R. D. Olsen, I. P. Shkarrofsky, "Theoretical Relationship Between Rain Depolarization and Attenuation", Electron, Letters 13, pp. 676-678, 1977.

T. Oguchi, "Attenuation and Phase Rotation of Radio Waves Due to Rain: Calculations at 19.3 and 38.8 GHz.", Radio Sci., Vol. 8, pp. 31-38, 1973.

T. Oguchi, Y. Hosoya, "Scattering Properties of Oblate Raindrops and Cross-Polarization of Radio Waves due to the Rain (Part II) : Calculations at Microwave and Millimeter Wave Regions", J. Radio Res. Labs. (Japan), 21, pp. 191-259, 1974.

I. D. Olin, F. D. Queen, "Dynamic Measurement of Radar Cross Section", Proc. IEEE, Vol. 53, NO. 8, pp. 954-961, Aug. 1965.

R. L. Olsen, D. V. Rogers, D. B. Hodge, "The aR^b Relation in the Calculation of Rain Attenuation", IEEE Trans. on Ant and Prop., Vol. AP-26 pp.318-320, 1978.

S. Okamura, K. Funkawa, H. Uda, J. Kato, T. Oguchi, "Effect of Polarization and the Attenuation by Rain at Millimeter-Wave Length", J. Radio Res. Labs., pp. 73-80, Vol.8, 1961.

O. M. Phillips, "The Dynamics of the Upper Ocean ", Cambridge, England, University Press, pp. 131-135, 1966.

W. J. Plant, "Studies of Backscattered Sea Return with a CW Dual-Frequency X-Band Radar", IEEE Trans. ant. and Prop., AP-25(1), 1977.

A. J. Poelman, "The Applicability of Controlable Antenna Polarization to Radar Systems", Tijdschrift van het Netherlands Electronica en Radiogenootschap 44(2), pp. 93-106, 1979.

A. J. Poelman, "Features of Multipurpose Experimental X-Band Radar Facility", Informationen anlässlich eines Besuches am SHAPE Technical Centre, Den Haag, Holland, 1981.

A. J. Poelman, F. L. Timmens, "Detection Performance of an Incoherent Radar with two Orthogonally Polarized Receiving Channels", SHAPE Tech. Center, TM-435, June 1974.

G. C. Pomraning, "Radiation Dynamics", Pergamon Press Ltd., Headington Hill Hall, Oxford, 1973.

H. Poincare, "Theorie Mathematique de la Lumiere", 11-12. pp. 282-285, George Carre, Paris, 1882.

V. A. Potekin, A. N. Glukhov, A. P. Rodimov, "The Choice of Radar Signal Polarization", Radio Eng and Electr. Phys. 14(3).

Lord Rayleigh, "On the Incidence of Aerial and Electrical Waves Upon Small Obstacles", Phil. Mag. , 44, p. 28, 1897.

A. G. Repjar, A. A. Ksienski and L. J. White, "Object Identification from Multi-frequency radar returns". The Radio and Electronic Engineer, 45, pp. 161-167, April 1975.

J. H. Richter, H. G. Hughes, "Electrooptical Atmospheric Transmission Effort in the Marien Environment", MOSC TR 696, 12, May 1981.

G. C. Rider, "A Polarization Approach to the Clutter Problem", IEEE Radar Conf. Publ. No155, pp.130-134, 1977.

L. W. Root, Chairman, Workshop on: "Polarimetric Radar Technology", 25-26, June 1980, USA-MICOM-DRSMI-REG, Redstone Arsenal, Proceedings, Vol.1, published by GACIAC, 11TRI, 10 W. 35 th St., Chicago, Il., 60610. (GACIAC, PR-81-02, Feb. 1981.

R. Rosian, D. Hammers, G. Ionnidis, J. Bell, J. Nemit, "Implementation Techniques for Polarization Control in ECCM", RADC-TR-79-4, Griffis AFB, Rome, New York 13441, Feb. 1979.

R. A. Ross, C. C. Freeny, "An Analysis of the Scattering Matrix Measurement Capabilities of a Ground Plane Radar Cross Section Range", Tech Rept. No RADC-TDR-64-317, Rome Air Development Center, Research and Technology Division, Griffis Air Force Base, New York, June 1964.

G. T. Ruck, D. E. Burrick, W. D. Stuart, C. K. Kirchbaum, "Radar Cross-Section Handbook, Vols. I and II, Plenum Press, New York, 1970.

V. H. Rumsey, "Part I-Transmission Between Elliptically Polarized Antennas", Proc. IRE, Vol. 39, pp. 535-540, May 1951.

K. Sassen "Laser Depolarization "Bright Band" From Melting Snowflakes", Nature, 225, pp. 316-318. 1975.

K. Sassen, "Depolarization of Laser light Backscattered by Artificial Clouds", J. Applied Meteor., 13, 923-933.

J. K. Von Schlachta, "A Contribution of Radar Target Classification", Radar 1977, IEEE Conf. Publ. 155, 1977, pp. 135-139. (See Also: Über eine Klassifizierungsmöglichkeit von Radar-Zielen mittels kohärent gemessener Echosignale, Dr. Ing, Diss., D-83, Tech Univ, Berlin, 1977).

A. B. Schneider and P. D. L. Williams, "Circular Polarization in Radars", The Radio and Electronic Eng., Vol. 47, pp. 11-29, Jan/Feb. 1976.

A. Schrott, "Rahmenbetrachtungen and Experimentvorschläge zum geplanten 20/30-GHz- Satellitenexperiment", DFVLR, Institut für Hochfrequenztechnik, IB 551-80/14 (1980).

H. Schuster, "Systemstudie Wolkenradar: Planung eines C-Band Puls-Doppler-Radars mit Polarisationsrichtung für die Atmosphärenforschung im mesoskaligen Bereich", DFVLR, Institut für Physik der Atmosphäre, 1980.

T. A. Seliga, N.M. Bringi, H.H. Al-khatib, "Differential Reflectivity, Measurements of Rainfall Rate", Rainuage Comparisons 19th Conference on Radar Meteorology, Miami Beach, Fl., Am. Met. Soc. Proc., 1980.

R. G. Semonin, E.A. Mueller, "Nexrad Pre-design Studies, Final Report to the National Oceanic and Atmospheric Administration", No. NA800AA-0-00059, Champaign, Illinois, Nov. 1981.

A.G. Shupyatskii, S.P. Morganov, "The Application of Polarization Methods to Radar Studies of Clouds and Precipitation", AFCRL, L.G. Hanscom Field Mass. Techn. Rept. AFCRL-68-0483, Sept. 1968, (Translation from Russian).

W.A. Shurcliff, "Polarized Light", Harvard University Press, Cambridge, Mass., 1962.

G. Silverman, "Chaff dispersion and polarization", J. of Elect. Defense, pp. 39-52, Nov./Dec. 1978.

G. Sinclair, "Modification of the Radar Equation for Arbitrary Targets and Arbitrary Polarization" Rept. No. 302-19, Antenna Laboratory, OSU, Columbus, Ohio, 1945.

G. Sinclair, "The Transmission and Reception of Elliptically Polarized Waves", Proc. IRE, Vol. 39, pp. 148-151, Feb. 1950.

M. E. Skolnik, "Radar Handbook", New York: McGraw-Hill, 1972.

K.H. Steinbach, "Nonconventional Aspects of Radar Target Classification by Polarized Properties", USAMERDC, Fort Belvoir. Vol. 22060, Rept. 2065, June 1973(AD763155). (See Also: On the Polarization Transform Power of Radar Target in E. Jeske, Ed., Atmospheric Effects on Radar Target Identification and Imaging, D. Reidel Co., Dordrecht, Holland, pp. 65-82, 1976.

J. A. Stiles, J.C. Holtzman, Proc. Workshop on "Radar Backscatter from Terrain", U.S. Army Engineering Topographic Labs, Fort Belvoir, Va., RSL-TR pp. 374-382, 9-11 Jan. 1979.

G.G. Stokes, "Stokes' Mathematical and Physical Papers", Univ. Press, Cambridge, 1901.

E. Stratman, D. Atlas, J.H. Richter, D.R. Jensen, "Sensitivity Calibration of a Dual-Beam Vertically Pointed FM-CW Radar", J. Applied Met., Vol. 10, No. 6, Dec. 1971.

J. H. Straus, "Polarization as a Anticluttr Technique", Naval Air Dev. Center, Johnsville, Pa., AEEL-Rept. No. NADL-EL-6415, March 1964.

M. A.F. Thiel, "Darstellung und Transformations-Theorie quasi-monochromatischer Strahlungsfelder", Zusammenfassender Bericht, Beiträge zur Radioastronomie, Band I, Heft 5, Max-Planck-Institut für Radioastronomie, Bonn, FRG, Ferd. Dümmler's Verlag, Bonn, March 1970.

H. S. Tan, A. K. Fung and H. Eom, "A Second-Order Renormalization Theory for Cross-polarized Backscatter from a Half Space Random Medium", Radio Science, Vol. 15, NO. 6, pp. 1059-1065, November-December 1980.

G. Tricoles and E. L. Rope, "Polarization Independent Radomes", GACIAC PR-81-02, pp.121.

C. H. Tsao, R. Mittra, "A Spectral-Interactive approach for analyzing scattering from frequency selective surfaces", IEEE Trans. AP-30(2), pp.303-308, March 1982.

R. Tsu, "The theory and application of the Scattering Matrix for Electromagnetic Waves", PhD. Dissertation, Dept. of Elect. Engr., Ohio State University, Columbus, OH. 1960.

P. L. E. Uslenghi (Ed), "Electromagnetic Scattering ", (Selected papers of a National Conference on Electromagnetic Scattering, UICC, Chicago, IL., June 15-18, 1976). Acad. Press, N. Y. ,1978.

F. T. Ulaby and R. K. Moore, "Radar Spectral Measurements of Vegetation", Proc. 11973 ASP/ASCM Fall Conf. m October 2-5. 1973, Orlando, Florida.

G. M. Vachuela and R. M. Barnes, "Sperry Research Center Polarization Signal Processing", Sperry Research Center, Sudbury , MA. TIM-371-17, Feb. 1981.

G. R. Valenzuela, "Scattering of Electromagnetic Waves from a Tilted Slightly Rough Surface", Radio Science, Vol.3, No. 11, pp.1057-1066, Nov. 1968.

G. R. Valenzuela, "Theories for the Interaction fo Electromagnetic Waves and Ocean Waves", A Review, Boundary-Layer Meteriology 13, pp. 61-85, 1978.

G. R. Valenzuela, "Scattering of Electromagnetic Waves From the Ocean", in T. Lund (Ed.) Surveillance of Environmental Pollution and Resources by Electromagnetic Waves, pp. 199-226, 1978.

V. C. Vannicola, "On the Theory Radar Polarization Processing for Clutter Suppression", GACIAC PR-81-02, pp. 259-279.

M. L. Varshanchuk and V. O. Kobak, "Cross-correlation of Orthogonally Polarized Components of the Electromagnetic Field Scattered by an Extended Object", Radio Eng. Electr. Phys. 16, pp. 201-205, 1971.

M. Vogel, "Image and Sensor Data Processing for Target Asquisition and Recognition", Agard Conference Proceedings No. 290, November 1980.

M. Vogel "Über die Streueigenschaften von Flugzeugen bei Mikrowellen", DFVLR, Rept. No. 106, February 1960.

M. J. Walker, "Matrix Calculus and the Stokes Parameters of Polarized Radiation", Am. J. Phys. 22, pp. 170-174, 1954.

C. Warner and R. R. Rogers , "Polarization-Diversity Radar: Two Theoretical Studies, Sci. Rept. MV-90, Stormy Weather Group, McGill University., Montreal, Que. 1977.

P. A. Watson, N. J. McEwan, A. W. Dissanayake and D. P. Haworth, "Attenuation and Cross-Polarization Measurements at 20 GHz Using the ATS-6 Satellite with Simultaneous Radar Observations", IEEE Trans. on Ant. and Prop., Vol. AP-27 (1979) NO. 1, pp. 11-17.

J. A. Webb and W. P. Allen, "Precision Measurements of the Radar Scattering Matrix", Reflectivity Measurements Symp., Vol. 1, pp. 223. (See also: Lockheed Space and Missiles Company. Report RADCTDR-64-25, Vol. 1, April 1964.)

A. Weisbrod and L. A. Morgan, "RCS Matrix Studies of the Sea Clutter", Navair Review, Jan. 1979.

L. J. White and A. A. Ksienski, "Aircraft Identification Using a Bilinear Surface Representation of Radar Data", Pattern Recognition, 6, pp. 35-45, 1974.

W. D. White, "Circular Radar", Electronics, pp. 158-160, March 1958.

J. W. Wright, "Backscatter from Capillary Waves with Application to Sea Clutter", IEEE Trans. Ant and Prop. Vol. AP-14, pp. 749-754, Nov. 1966.

J. D. Young, "Target Imaging from Multiple Frequency Radar Returns", ESL-OSU, Columbus, Ohio, Tech. Rept. 2768-6, June 1971 (AD 728235) (see also: Radar Imaging from Ramp Response Signatures, IEEE Trans. Ant. and Propagation AP-24, pp. 276-282, 1976).

L. A. Zhivotovskiy, "Calculation fo the Depolarization Properties of Radar Targets", Radio Eng. 31 (pt.2) pp.46-48,1976.

L. A. Zhivotovskiy, "Dependence of the Power Flux Density of Echo Signals on Radar Signal Polarization", Radio Eng. 31(pt. 2), pp. 49-53, 1976.

L. A. Zhivotovskiy, "Optimum Polarization of Radar Signals", Radio Eng. and Electronic Phys. 18(4),pp. 630-632, 1973.

DISTRIBUTION LIST (A)-1

Commander
Naval Air Systems Command
ATTN: AIR-310B (2 cys quarterly, 5 cys final)
AIR-00D46 (14 cys final only)
AIR-370D/Mr. E. T. Hooper
Washington DC 20361

Commander
Naval Surface Weapon Center
ATTN: Dr. B. Hollmann (Code F12)
Mr. John Teti (Code DF34)
Dahlgren VA 22448

Commander
Naval Weapons Center
Electronic Warfare Department
Microwave Development Division
ATTN: Mr. F. F. St. George (Code 354)
China Lake CA 93555

Office of Naval Research
Code 427
800 North Quincy Street
Arlington VA 22217

The Ohio State University
ElectroScience Laboratory
ATTN: Dr. Jonathan Young
1320 Kinnear Road
Columbus OH 43212

Commanding Officer
Rome Air Development Center
ATTN: Mr. Durwood Creed/OSDR
Griffis Air Force Base NY 13440

Technology Service Corporation
ATTN: Dr. Fred Nathanson
8555 16th Street, Suite 300
Silver Spring MD 20910

Teledyne Micronetics
ATTN: Dr. Steven Weisbrod
7155 Mission Gorce Road
San Diego CA 92120

DISTRIBUTION LIST (A)-1

Commander
US Army Electronics Command
CS and TA Laboratory
ATTN: Mr. Boaz Gelerneter (DRSEL-CT-R)
Mr. Willy Johnson
Ft. Monmouth NJ 07703

Commander.
US Army Missile Command
ATTN: Mr. Lloyd Root (DRSMI-REG)
Redstone Arsenal AL 35809

Defense Documentation Center
Cameron Station
Alexandria VA 22314

Director
Naval Research Laboratory
4555 Overlook Avenue, SW
ATTN: Library, Code 2620
Washington DC 20375

Office of Naval Research
Mathematics Program, Code 432
Arlington VA 22217

Office of Naval Research
New York Area Office
715 Broadway-5th Floor
New York NY 10003

Command Officer
Office of Naval Research/Branch Office
536 South Clark Street
Chicago IL 60605

Command Officer
Office of Naval Research Eastern/
Central Regional Office
Bldg 114, Section D
666 Summer Street
Boston MA 02210

DISTRIBUTION LIST (A)-1

Commander
Air Force Avionics Laboratory
ATTN: Mr. Allen Blume (AFWAL/AADM)
Mr. Robert L. Davis (AFAL/WRP)
Mr. Harold Weber (AFWAL/AADM)
Wright-Patterson Air Force Base OH 45433

ETE
ATTN: Dr. A. Schell (RADC/ETE)
Hanscome Air Force Base MA 01731

General Electric/RSD
ATTN: Mr. A. B. Grafinger/Room 6258H
3198 Chestnut Street
Philadelphia PA 19101

R. C. Hansen, Inc.
Box 215
Tarzana CA 91356

ITT Gilfillan
ATTN: Dr. David E. Hammers
7821 Orion Avenue
P. O. Box 7713
Van Nuys CA 91409

Commander
Naval Avionics Center
ATTN: Mr. Paul Brink
21st & Arlington Avenue
Indianapolis IN 46218

Superintendent
Naval Postgraduate School
ATTN: Dr. Lonnie Wilson (Code 62W1)
Monterey CA 93940

Commanding Officer
Naval Research Laboratory
ATTN: Mr. John Daley (Code 7946)
Mr. Fred Staudaher (Code 5368)
Mr. Denzil Stilwell (Code 7910)
Washington DC 20375

Commander
Naval Sea Systems Command
ATTN: Mr. C. Jedrey (SEA-62R13)
Washington DC 20362

DISTRIBUTION LIST (A)-1

Command Officer
Office of Naval Research Western
Regional Office
1030 East Green Street
Pasadena CA 91106

Commander
Naval Air Development Center
Radar Division
ATTN: Dr. John Smith (Code 3022)
Warminster PA 18974

Office of Naval Research
ATTN: Code 414
800 North Quincy Street
Arlington VA 22217

Naval Ocean Systems Center
EM Propagation Division
ATTN: Dr. Juergen H. Richter
271 Catalina Blvd.
San Diego, CA. 92152

Atmospheric Physics Branch
NRL
ATTN: Dr. Lothar Ruhnke (Code 8320)
Washington, D.C. 20357

Naval Weapons Center
ATTN: Dr. Ing-Guenther Winkler (Code 381)
Dr. Robert Dinger
China Lake, CA. 93555

Naval Air Development Center
ATTN: Mr. Otto Kessler (Code 3022)
Warminster, PA. 18974

DISTRIBUTION LIST (DOMESTIC)

Dr. David Atlas (Code 910)
Laboratory for Atmospheric Sciences
NASA, Goddard Space Flight Center
Greenbelt, Maryland 20771

Dr. Adrian K. Fung
Department of Electrical Engineering
University of Kansas
Lawrence KS 66045

Dr. Mariin Gillette
Mailstop B-56
Bell Aerospace Textron
P. O. Box 1
Buffalo NY 14240

Dr. J. W. Goodman
Department of Electrical Engineering
Stanford University
Stanford CA 94305

Dr. Doran Hess, Chief Physicist
Scientific Atlanta
3845 Pdeusantdale Road
Atlanta GA 30340

Dr. Akira Ishimaru
Dept. of Electrical Engineering, FT-10
University of Washington
Seattle WA 98195

Dr. Edward Kennaugh
ElectroScience Laboratory
Department of Electrical Engineering
Ohio State University
1320 Kinnear Road
Columbus OH 43212

Dr. Louis N. Medgyesi-Mitschang
Senior Scientist
McDonnell Douglas Research Laboratory
Box 516
St. Louis MO 63166

Dr. James Metcalf
Radar Applications Group
Georgia Institute of Technology
Electrical Engineering Department
Atlanta GA 30332

DISTRIBUTION LIST (DOMESTIC)

Dr. C. Leonard Bennett
Manager, Systems Applications
Sperry Research Center
100 North Road
Sudbury MA 01776

Dr. Lawrence Weller
Mail Stop K75-50
Boeing Military Airplane Co.
3801 S. Oliver
Wichita KS 76210

Mr. David L. Banks, Manager
Mr. Thomas C. Bradley
RF Sensors Lab, Engineering Technology
Boeing Aerospace Co.
P.O. Box 3999
Seattle, Washington 98124

Dr. Archibald Hendry
Electromagnetic Engineering Section
Division of Electrical Engineering
National Research Council of Canada
Ottawa, Canada KIA OR8

Dr. Edwin R. Hiller
Missile Systems Division
Raytheon Company
Hartwell Road, Systems Building
Bedford, Mass. 01730

Dr. Bernard Lewis
Radar Division
Naval Research Laboratory
Washington, D.C. 20375

Mr. Lee A. Morgan
Senior Member Technical Staff
Teledyne Micronetics
7155 Mission George Road
San Diego, CA. 92120

DISTRIBUTION LIST (DOMESTIC)

Dr. H. Mullaney
Defense Systems, Inc.
6804 Poplar Place
McLean VA 22102

Mr. J. Willis
Naval Air Systems Command Headquarters
Jefferson Plaza #1
1411 Jefferson David Highway
Arlington VA 22516

Dr. Walter K. Kahn, Professor
Electrical Engineering and Computer Science
School of Engineering and Applied Science
The George Washington University
Washington DC 20052

Dr. Andrew J. Blanchard
Associate Research Engineer
Texas A&M University
Remote Sensing Center
College Station, Texas 77843

Mr. David Deeds
Radar Division
Advanced Sensor Division
Martin Marietta Aerospace Corp.
Orlando Division
P. O. Box 5837
Orlando FL 32855

Dr. Eckehard O. Rausch
Radar Application Group
Georgia Institute of Technology
Electrical Engineering Department
Atlanta GA 30332

Mr. Lloyd Root DRSMI-REG
Millimeter Guidance Technology
Advanced Sensory Directorate
U. S. Army Missile Laboratory
U. S. Army Missile Command
Redstone Arsenal AL 35898

DISTRIBUTION LIST (DOMESTIC)

Dr. E. K. Miller
Electronics Engineering Department
University of California
Lawrence Livermore Laboratory
P. O. Box 808
Livermore CA 94550

Dr. Charles Miller, Director
Electromagnetics Division
National Bureau of Standards
Boulder CO 80303

Dr. Allen Taflove
Research Engineer
EM Interaction with Complex Systems
IIT Research Institute
10 West 35th St.
Chicago IL 60616

Dr. Charles Warner
Department of Environmental Sciences
Clark Hall
University of Virginia
Charlottesville VA 22903

Dr. J. DeSanto
Electro Magnetic Applications, Inc.
1978 S. Garrison Street
Denver CO 80227

Dr. J. Heacock
Office of Naval Research
Code 463
Arlington VA 22217

Dr. G. Heiche
Naval Air Systems Command Headquarters
Jefferson Plaza #1
1411 Jefferson Davis Highway
Arlington VA 22516

Mr. Jack Daley
Naval Research Laboratory
Code 7946
Washington DC 20375

Dr. M. McKisic
Office of Naval Research
Code 486
Arlington VA 22217

DISTRIBUTION LIST (DOMESTIC)

Dr. Eugene A. Mueller
Meteorology Section
Illinois State Water Survey
605 East Springfield
P.O. Box 5050, Station A
Champaign, IL. 61820

Dr. Jim Wright
Mail Point 200
Radar Division
Martin-Marietta
P.O. Box 5837
Orlando, FL. 32855

Mr. William D. Fortner
General Dynamics
7464 Rondel Court
San Diego, CA. 92119

Dr. Constantine P. Tricoles
General Dynamics
Electronics Division
P.O. Box 81127
San Diego, CA. 92138

Dr. D.E. Hammers
ITT Gilfillan
7821 Orion Avenue
Van Nuys, CA. 91409

Dr. Samuel M. Sherman
Radar Systems Division
RCA Building, 108-210
Moorestown, N.J. 08057