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POLARIZATION CHARACTERISTICS OF RADAR ECHOES

by MAURICE W. LONG

25 January 1967

UNITED STATES OF AMERICA

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POLARIZATION CHARACTERISTICS OF RADAR ECHOES

INTRODUCTION

Much can be learned about electromagnetic scattering from the polarization properties of radar echoes. This report derives information on scattering by comparing data for various polarizations obtained at the Royal Radar Establishment (RRE), Great Malvern, Wiltshire, with data obtained elsewhere. To accomplish this, equations are developed that express scattering for transmitting circular polarization and receiving circular or linear polarizations in terms of scattering for transmitting linear and receiving linear polarizations.

The RRE data were obtained some years ago under a program directed by Mr. I.M. Hunter, who is now engaged in air traffic control activities with the Ministry of Aviation Headquarters. His current office address is: The Adelphi, John Adam Street, London, WC 2. I have had several delightful and profitable discussions with Hunter as a result of this investigation.

The RRE results were presented in References 1 and 2, which are, respectively:

1. M. Gent, I.M. Hunter, and N.P. Robinson, "Polarization of Radar Echoes, Including Aircraft, Precipitation and Terrain," Proc. IEEE 110, 12, p 2139, 1963

2. I.M. Hunter and T.B.A. Senior, "Experimental Studies of Sea-Surface Effects on Low-Angle Radars," Proc. IEEE 113, 11, p 1731, 1966

These papers contain significant radar data for transmitting circular (linear was sometimes transmitted) polarization measured with instrumentation for which great care was taken to assure that high accuracy was acquired in the relative magnitudes of variously polarized echoes. Let σ_{AB} denote the radar cross section for transmitting polarization A and receiving polarization B. To describe the data, R, L, H and V are used to denote right circular, left circular, horizontal and vertical polarizations. The specific observations made by Hunter, et al., considered in this report are as follows:

1. For all available conditions of seas at near-grazing incidence, averages of σ_{RR} and σ_{RL} were nearly equal.

2. For seas at near-grazing incidence, σ_{RV} and σ_{RH} were investigated (relative magnitudes given as $\pm$ 0.5 dB). It was found that the ratio of the averages σ_{RV}/σ_{RH} depends on sea state and azimuth, but that σ_{RV} nearly always exceeds σ_{RH}.

3. For seas at near-grazing incidence, average σ_{RH} sometimes exceeds average σ_{RV} by as much as 1 dB. When this happens, it occurs only if the antenna points crosswind, in general along the troughs in the waves.

4. For trees it was not possible to detect any difference between σ_{RV} and σ_{RH}, but σ_{RR} was less than σ_{RL} by about $1\frac{1}{2}$ dB on the average.

5. For airplanes measured, σ_{RR} and σ_{RL} are, on the average, equal within an accuracy of 2 dB or better. Under the conditions investigated, σ_{VH} was approximately 10 dB less than σ_{VV}.

Radar astronomers use circular polarization, as distinct from linear, to eliminate undesirable effects of ionospheric Faraday rotation. In order to acquire more insight into surface roughness, both circularly-polarized echo components are sometimes studied. Although circular polarization is commonly used, in civil and military applications, to reduce echo from rain, the amount of "earth-bound" circular-polarization data is considerably less than that for linear polarizations. It is usually assumed that if σ_{RR} is much less than σ_{RL}, the backscattering surface is smooth compared to a wavelength. This is not so. Hunter, et al., found that the circularly-polarized echoes were nearly equal for trees, seas at near-grazing incidence, and airplanes. Also discussed are previously published data[6] for a moderately heavy sea, normal incidence, and a transmitter wavelength of 1.2 cm. For these conditions, σ_{RR} is much less than σ_{RL}. Therefore, for earth-bound surfaces the condition σ_{RR} much less than σ_{RL} does not preclude rough surfaces.

THEORY FOR TRANSMITTING AND RECEIVING CIRCULAR POLARIZATIONS

In general, the polarization of an electromagnetic wave can be characterized by a vector. This vector consists of two orthogonal components which can be linear, circular, or elliptical. The change in polarization due to reflection from a target can be considered as a change in the components of the vector representing the wave falling on the target.[3-5] The new components are obtained by multiplying the incident wave vector by a matrix representing the target properties. In the case of a linear reference system, the relationship, suppressing range dependence, between the incident and reflected vectors and the transforming matrix may be given as follows:

$$\begin{pmatrix} E_x^r \\ E_y^r \end{pmatrix} = \begin{pmatrix} a_{xx} & a_{yx} \\ a_{xy} & a_{yy} \end{pmatrix} \begin{pmatrix} E_x^t \\ E_y^t \end{pmatrix} \tag{1}$$

Similarly, for the circular reference system:

$$\begin{pmatrix} E_1^r \\ E_2^r \end{pmatrix} = \begin{pmatrix} c_{11} & c_{21} \\ c_{12} & c_{22} \end{pmatrix} \begin{pmatrix} E_1^t \\ E_2^t \end{pmatrix} . \quad (2)$$

E_x and E_y, and E_1 and E_2 are orthogonal linear and circular components, respectively, of the electric vector lying in the plane perpendicular to the direction of propagation, and the superscripts t and r indicated transmitted and received components. Elements a_{ij} and c_{ij} are in general complex (phase factors). The first subscript designates transmitted polarization and the second designates received polarization. For most cases, the square matrices are symmetric, i.e., $a_{ij} = a_{ji}$ and $c_{ij} = c_{ji}$ (this may be visualized by interchanging the transmitting and receiving roles). For the derivations that follow, it is assumed that $a_{ij} = a_{ji}$ and $c_{ij} = c_{ji}$.

The matrix coefficients c_{ij} can be expressed in terms of the a_{ij} if the transmitted and received circularly-polarized waves are expressed in terms of the respective linearly-polarized waves. From Eq. 2, for the conditions E_1^t and E_2^t separately equaling zero, the c_{ij} can be obtained in terms of E_1^t, E_2^t, E_1^r, and E_2^r. For the equations that follow, E_1^t is defined as the circularly-polarized electric field that exists if $E_y^t = jE_x^t$ (for this case E_2^t is zero), and E_2^t is defined as the circularly-polarized electric field that exists if $E_y^t = -jE_x^t$ (for this case E_1^t is zero); $|E_1^t|$ and $|E_2^t|$ are equal to $\sqrt{2}\,|E_x|$. From reciprocity, a bilateral antenna receives the same polarization that it radiates. Therefore, upon reception the antenna outputs are proportional to

$$E_1^r = \frac{E_x^r + jE_y^r}{\sqrt{2}} \quad \text{and} \quad E_2^r = \frac{E_x^r - jE_y^r}{\sqrt{2}} .$$

E_x^r and E_y^r (for E_1^t and E_2^t each equaling zero) can be obtained from Eq. 1. One finally sees that

$$|c_{11}| = \left|\frac{a_{xx} - a_{yy}}{2} + ja_{xy}\right| ,$$

$$|c_{12}| = \left|\frac{a_{xx} + a_{yy}}{2}\right| , \qquad (3)$$

and

$$|c_{22}| = \left|\frac{a_{xx} - a_{yy}}{2} - ja_{xy}\right| .$$

The x and y directions applicable to Eqs. 3 are arbitrary. To discuss data for horizontal and vertical polarizations (denoted later by H and V), assume that the x and y directions point to the right and upward, respectively. Then, the definitions of E_1^t and E_2^t result in directions 1 and 2 being left circular and right circular, respectively. For most purposes, circularly polarized echoes are described simply as "same" and "opposite"; this means that the echo is rotating in either the same or opposite direction as is the transmitted wave.

INTERPRETATION OF CIRCULAR-CIRCULAR DATA

As previously stated, the a's and c's are complex quantities that are proportional to the electric fields. To equate the various radar cross sections (proportional to electric field squared), care must be taken to account for phase appropriately. Considered below are three limiting cases for radar cross section, σ.

For a perfectly conducting surface having radii of curvature large compared with a wavelength, one would expect that a_{xx} is equal to a_{yy}. This means that at all times the phase and amplitude change upon reflection is the same for both polarizations. Then, Eqs. 3 would indicate that

$$\sigma_{11} = \sigma_{22} = \sigma_{xy}$$

and (4)

$$\sigma_{12} = \sigma_{xx} = \sigma_{yy} .$$

One expects that σ_{xy} would be small for a large, smooth scatterer. Edges might produce some depolarized echo — surfaces with radii small compared to a wavelength, such as sharp edges, are expected to be the major contributors to σ_{xy}.

Equations 4 are not, in general, valid for dielectric surfaces or poorly conducting surfaces because the reflection coefficient (magnitude and phase) for the air-surface interface will depend upon polarization and aspect angle. However, the complex reflection coefficients for the two linear polarizations (parallel and normal to incidence plane) at an air-water interface are, for angles near normal incidence, nearly equal and slowly varying functions of incidence angle. Wiltse, et al.,[6] reported results obtained at 24 GHz for σ_{HH}, σ_{VV}, σ_{VH}, and σ for receiving right- and left-circular polarizations when transmitting circular polarization (σ_{12} and σ_{11} or σ_{22}). The data, which were for a moderately heavy sea, indicated that σ_{12} for normal incidence was approximately equal to σ_{VV} and σ_{HH}, and σ_{12} was about 10 dB greater than σ_{11}. These are highly interesting data because, in combination with Eqs. 3 and 4, they indicate that a_{VV} and a_{HH} tend to be equal on an instantaneous basis (but not necessarily always equal). Thus, the polarization data strongly suggest that at normal incidence sea echo, even for a moderately heavy sea, is caused primarily by specular reflection.

For vegetation and for rough seas at grazing incidence, relative magnitudes and phases of a_{xx}, a_{yy}, and a_{xy} will depend upon the positions and orientations of the scatterers (leaves, twigs, ripples, and waves); therefore, it is expected that a_{xx}, a_{yy}, and a_{xy} would be statistically independent. Then Eqs. 3 indicate, on the average, that

$$\sigma_{11} = \sigma_{22} = \frac{\sigma_{xx}}{4} + \frac{\sigma_{yy}}{4} + \sigma_{xy}$$

and (5)

$$\sigma_{12} = \frac{\sigma_{xx}}{4} + \frac{\sigma_{yy}}{4} .$$

For scatterers of this type σ_{11} would, depending upon the magnitude of σ_{xy}, exceed σ_{12}.

Reported data[7] for vegetation indicate that on the average σ_{HH} and σ_{VV} are about equal, and the ratios σ_{HH}/σ_{HV} and σ_{VV}/σ_{VH} are 3-10 dB. All elements of foliage do not depolarize; therefore, because of different positions and orientations of the scatterers, the a_{xy} of individual scatterers are expected to be independent of the corresponding a_{xx} and a_{yy}. However, a_{xx} and a_{yy} may be equal for some surfaces (tree trunks, for example); therefore, Eqs. 5 are not completely valid for vegetation. The fact that substantial echo power for which a_{xx} is equal to a_{yy} (amplitude and phase) is confirmed by circular polarization data given by Gent, et al.[1] They found that for trees σ_{RR} was less than σ_{RL} by about $1\frac{1}{2}$ dB on the average. The reader may wish to review Eqs. 3 and recall that

$$\frac{\sigma_{11}}{\sigma_{12}} = \left|\frac{c_{11}}{c_{12}}\right|^2 .$$

For rough seas the depolarized echo might be 5 dB less than σ_{HH} or σ_{VV}; for calm seas σ_{VV} may be 10 dB greater than σ_{HH} and 15 dB greater than σ_{VH}.[8] Hunter and Senior[2] reported relative values for the averages of σ_{RR} and σ_{RL} for depression angles between 0.3° and 3°. The ratio of these averages, $\bar{\sigma}_{RR}/\bar{\sigma}_{RL}$, was between +1 and -2 dB for all available sea states and wind conditions (the experimental error was given as $\pm\frac{1}{2}$ dB). For high seas the mean values of σ_{RR} and σ_{RL} were found to be about equal, but instantaneous values were not. Thus, Eqs. 5 appear to be valid for high sea states and small depression angles; and a_{xx}, a_{yy} and a_{xy} are then, in essence, statistically independent. For low sea states σ_{RR} and σ_{RL} were reported to be equal on an instantaneous basis; this is consistent with the linear polarization data and Eqs. 3.

Apparently some aircraft, on the average, also satisfy Eqs. 5. Gent, et al.,[1] reported that at X-band σ_{11} and σ_{12} are equal within an accuracy of 2 dB or better. For these measurements σ_{VH} was approximately 10 dB less than σ_{VV}. Since the depolarization is small, this measurement indicates that a_{HH} and a_{VV} are not equal on an instantaneous basis, but that the average values of σ_{HH} and σ_{VV} are nearly equal.

Few actual surfaces are so smooth and symmetrical that a_{xx} is expected to be equal to a_{yy} over all angles. For example, in studies of backscattering of vertical and horizontal polarizations from flat rectangular plates, Ross[9] found that σ_{VV} and σ_{HH} are approximately equal for near-specular angles, but for near-grazing incidence, σ_{VV} is much greater than σ_{HH}. It is well known that σ_{VV} is also greater than σ_{HH} for a calm or moderate sea at near-grazing incidence. If

a_{yy} is much greater than a_{xx} and a_{xy}, Eqs. 3 indicate that

$$\sigma_{11} = \sigma_{22} = \sigma_{12} = \sigma_{yy}/4 . \tag{6}$$

For this case the various cross sections for circular polarization would be equal and 6 dB less than σ_{yy}.

THEORY FOR TRANSMITTING CIRCULAR AND RECEIVING LINEAR POLARIZATIONS

Equation 1 can be used to obtain the received linearly polarized components when the transmitted polarization is circular. Let $E_y^t = jE_x^t$, then it is seen that

$$\begin{aligned} E_x^r &= (a_{xx} + ja_{xy})E_x^t \\ E_y^r &= (a_{xy} + ja_{yy})E_x^t \end{aligned} \tag{7}$$

If the opposite circularity were transmitted ($E_y^t = -jE_x^t$), the equations for the fields corresponding to those above would be obtained by replacing j by -j in Eq. 7.

Radar cross section σ for any combination of transmitted and received polarizations can be expressed in terms of the a's. For example, since σ is proportional to the square of the ratio of the received to the transmitted electric fields, it may be seen that

$$\begin{aligned} \sigma_{xx} &= K \frac{|E_x^r|^2}{|E_x^t|^2} = K \, |a_{xx}|^2 \\ \sigma_{1x} &= K \frac{|E_x^r|^2}{|E_1^t|^2} = K \, \frac{|a_{xx} + ja_{xy}|^2}{2} \end{aligned} \tag{8}$$

where K is a multiplicative constant determined by over-all system parameters.

The x and y directions applicable to Eq. 1 are arbitrary. To discuss data for horizontal and vertical polarizations (denoted by H and V), assume that the x and y directions point to the right and upward, respectively.

Then, the definitions of E_1^t and E_2^t result in directions 1 and 2 being, respectively, left circular and right circular (denoted by L and R). Therefore, radar cross section for transmitting circular and receiving horizontal and vertical polarizations can be expressed as follows:

$$\begin{aligned} \sigma_{LH} &= K \left| \frac{a_{HH} + ja_{HV}}{2} \right|^2 \\ \sigma_{LV} &= K \left| \frac{a_{HV} + ja_{VV}}{2} \right|^2 \\ \sigma_{RH} &= K \left| \frac{a_{HH} - ja_{HV}}{2} \right|^2 \\ \sigma_{RV} &= K \left| \frac{a_{HV} - ja_{VV}}{2} \right|^2 \end{aligned} \qquad (9)$$

where

$$K \left|a_{HH}\right|^2 = \sigma_{HH},$$

$$K \left|a_{VV}\right|^2 = \sigma_{VV}, \text{ and}$$

$$K \left|a_{HV}\right|^2 = K \left|a_{VH}\right|^2 = \sigma_{HV} = \sigma_{VH} .$$

In general, none of the σ's are equal on an instantaneous basis because the phase and amplitude of each of the a's is a fluctuating function of time.

INTERPRETATION OF CIRCULAR-LINEAR DATA

The facets of a sea surface that are comparable in size to a wavelength or larger are not expected to depolarize (a_{VH} and a_{HV} negligible), but would in general contribute to a_{HH} and a_{VV}. The contributions to a_{VV} and a_{HH} for such nondepolarizing scatterers may or may not be equal.[5] Asymmetric scatterers, such as ripples, that have dimensions small compared with a wavelength, are expected to depolarize. Ripples will, of course, also produce contributions to a_{VV} and a_{HH}. Since relative magnitudes and phases of the a's for a given illuminated patch of sea will depend on the positions and orientations of the various scatterers (ripples and waves), a_{HV} (or a_{VH}) will be statistically independent of a_{HH} and a_{VV}.

For computing average values, certain simplifications can be made for targets for which the a's are statistically independent. Let a bar denote a time average. Then from Eq. 9, average cross section for sea echo may be expressed as

$$\bar\sigma_{LH} = \bar\sigma_{RH} = \frac{\bar\sigma_{HH} + \bar\sigma_{HV}}{2}, \quad \text{and}$$
$$\bar\sigma_{LH} = \bar\sigma_{RV} = \frac{\bar\sigma_{VV} + \bar\sigma_{HV}}{2} \qquad (10)$$

Hunter and Senior give results[2] obtained at X-band for transmitting right-circular and receiving H and V polarizations. They reported that, for a limited series of measurements, the ratio $\bar\sigma_{RV}/\bar\sigma_{RH}$ was found for practical purposes to be equivalent to $\bar\sigma_{VV}/\bar\sigma_{HH}$. Thereafter, comprehensive measurements were made using a circularly-polarized transmission, which permitted simultaneous ($\bar\sigma_{RV}$ and $\bar\sigma_{RH}$), as opposed to sequential ($\bar\sigma_{VV}$ and $\bar\sigma_{HH}$), measurements. The importance of a simultaneous determination of $\bar\sigma_{VV}$ and $\bar\sigma_{HH}$ cannot be overemphasized. For example, radar cross section of sea echo has been observed to increase by as much as 10 dB in a one-minute interval.[8]

As may be seen from Eq. 10, $\bar\sigma_{RV}/\bar\sigma_{RH}$ is not, in principle, equal to $\bar\sigma_{VV}/\bar\sigma_{HH}$; the difference may or may not be negligible, depending on relative magnitude of σ_{HH}, σ_{VV} and σ_{HV}. However.

$$\bar\sigma_{VV} = \bar\sigma_{HH} \text{ if } \bar\sigma_{RV} = \bar\sigma_{RH}$$
$$\bar\sigma_{VV} > \bar\sigma_{HH} \text{ if } \bar\sigma_{RV} > \bar\sigma_{RH}, \text{ and} \qquad (11)$$
$$\bar\sigma_{VV} < \bar\sigma_{HH} \text{ if } \bar\sigma_{RV} < \bar\sigma_{RH}.$$

Therefore, the technique of measuring the ratio $\bar\sigma_{RV}/\bar\sigma_{RH}$ is a valid means for determining whether $\bar\sigma_{VV}$ is less than, equal to, or greater than $\bar\sigma_{HH}$.

Relative magnitudes of $\bar{\sigma}_{HH}$, $\bar{\sigma}_{VV}$, and $\bar{\sigma}_{HV}$ depend on many factors including sea conditions and transmitter wavelength. Results at 6.3 GHz and 35 GHz for small depression angles are given elsewhere.[8] Progressing in the direction of calm to rough sea conditions, $\bar{\sigma}_{VV}$ and $\bar{\sigma}_{HH}$ at 6.3 GHz might exceed $\bar{\sigma}_{HV}$ by 13 dB and 6 dB, 10 dB and 6 dB, and 6 dB for both, respectively. From Eqs. 10, $\bar{\sigma}_{LH}$ and $\bar{\sigma}_{RH}$ will be raised by 1 dB or 0.4 dB by contributions from $\bar{\sigma}_{HV}$ that are, respectively, 6 dB or 10 dB less than $\bar{\sigma}_{HH}$. The $\bar{\sigma}$'s at 35 GHz are more nearly equal to one another than at 6.3 GHz. Therefore, at X-band it is expected that $\bar{\sigma}_{RV}/\bar{\sigma}_{RH}$ would usually differ from $\bar{\sigma}_{VV}/\bar{\sigma}_{HH}$ by less than 1 dB. The 6-dB figure was purposely selected so that estimates of errors would be conservative. A more typical value, but it depends on sea state and azimuth, would be 9 dB instead of 6 dB. This means that, on the average, the errors will be smaller than indicated above.

Hunter and Senior give results on the dependence of $\bar{\sigma}_{RV}$ and $\bar{\sigma}_{RH}$, for small depression angles, on azimuth. For these measurements, over-all accuracy for relative magnitudes was given as $\pm$ 0.5 dB. They found that the ratio $\bar{\sigma}_{RV}/\bar{\sigma}_{RH}$ depends on sea state and azimuth, but that $\bar{\sigma}_{RV}$ nearly always exceeds $\bar{\sigma}_{RH}$. An exception to this was for a medium sea state when looking crosswind (in general, along the troughs in the waves). In this case it was found that $\bar{\sigma}_{RH}$ may be slightly larger (1 dB according to an idealized curve given) than $\bar{\sigma}_{RV}$. In view of Eqs. 11, it would appear that $\bar{\sigma}_{HH}$ exceeds $\bar{\sigma}_{VV}$ under those conditions. Further, the ratios $\bar{\sigma}_{RV}/\bar{\sigma}_{RH}$ and $\bar{\sigma}_{VV}/\bar{\sigma}_{HH}$ are necessarily very nearly equal if $\bar{\sigma}_{RV}/\bar{\sigma}_{RH}$ is close to unity.

COMMENTS

Under sea conditions for which σ_{RH} exceeded σ_{RV} a more or less typical ratio was 1 dB, but from personal discussions with Hunter it appears that on occasion σ_{RH} may have exceeded σ_{RV} by nearly 2 dB. The sea conditions under which σ_{RH} exceeds σ_{RV} are of importance because this is not admissable under the classical interference theory. However, there is no doubt that the average of σ_{RH} will, on occasion, be greater than the average σ_{RV} for crosswind conditions; this necessarily implies that the average σ_{HH} will, on occasion, exceed the average σ_{VV}.

A type-setting error exists in reference 2 regarding the notation $\delta V - \delta H$; this should read σ_{RV}/σ_{RH}.

CONCLUSIONS

The accurate measurements of Hunter, et al., represent a significant contribution to the literature, and the results should help to provide further insight into the scattering mechanisms of complex surfaces. The following has been learned from the observations tabulated in the Introduction:

1. For rough seas at near-grazing incidence, fields for transmitting and receiving horizontal, transmitting and receiving vertical, and transmitting a linear and receiving its orthogonal component are, in essence, statistically independent.

2. For seas at near-grazing incidence, the average of σ_{VV} nearly always exceeds average of σ_{HH}, because averages for σ_{RH}/σ_{RV} are shown to be nearly equal to averages for σ_{HH}/σ_{VV}. In a sense this is new information, because the ratio σ_{HH}/σ_{VV} had not previously been acquired in a single measurement.

3. For seas at near-grazing incidence, average σ_{HH} sometimes exceeds average σ_{VV}. This was shown to be so, because if σ_{RH} is greater than σ_{RV}, then σ_{HH} is necessarily greater than σ_{VV}. It had previously been observed (on rare occasions) that σ_{HH} exceeds σ_{VV}, but conditions for this anomaly had not been established, except it was known to have occurred for rough or moderately rough seas. Hunter, et al., found that when it exists, it consistently occurs looking crosswind and, in general, along the troughs in the waves.

4. For trees a substantial portion of the echo power is in fields for transmitting and receiving horizontal, transmitting and receiving vertical, and transmitting and receiving orthogonal linear components that are, in essence, statistically independent. However, there is a discernible amount of return from trees for which fields for transmitting and receiving horizontal and for transmitting and receiving vertical are equal both in amplitude and phase.

5. For airplanes measured by Hunter, et al., instantaneous values of σ_{HH} and σ_{VV} are not equal. Since the major scattering surfaces are comparable in size to a wavelength or larger, it would have been expected that σ_{HH} and σ_{VV} are, in general, equal on an instantaneous basis.

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13. ABSTRACT

Information on electromagnetic scattering is obtained by comparing data for various polarizations obtained at the Royal Radar Establishment with data obtained elsewhere. Equations are developed that express scattering for transmitting circular polarization and receiving circular or linear polarizations in terms of scattering for transmitting and receiving linear polarizations.

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13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*.

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