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Some Effects of Measurement Errors on Rain Depolarization Experiments

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Measurements of rain-produced depolarization for linearly polarized 20- and 30-GHz satellite signals oriented vertically (V) and horizontally (H) and a few degrees either side of V and H are required to determine both the proper polarization orientation for future systems and the depolarization at that orientation. The polarization received from area-coverage satellite beacons will vary considerably for different measuring sites within the coverage area. Calculation of rain-produced depolarization of one pair of orthogonally polarized signals from measurements of depolarization, differential attenuation, and differential phase of a different pair of orthogonally polarized signals will be required. Some effects of measurement errors on these calculations are shown. Accuracies on the order of ±0.5 dB in differential attenuation and ±2 degrees in differential phase are required in the measurements. Cross-polarization isolation of 25 dB in the measuring system is inadequate.

I. INTRODUCTION

It is desirable to use two orthogonal polarizations to double the number of radio channels available in future 20- and 30-GHz satellite repeaters. Since rain-produced depolarization (cross-polarization coupling) is more severe for circular polarizations than for linear polarizations[1] oriented parallel to the raindrop axes (see Fig. 1), two properly oriented orthogonal (near vertical and horizontal) linear polarizations are the logical choice for such systems. The only measurements of rain-produced depolarization[1–4] above 10 GHz have been made on terrestrial propagation paths. Therefore, measurements of rain-produced depolarization for linearly polarized 20- and 30-GHz satellite signals oriented vertically (V) and horizontally (H) and a few degrees either side of V and H are required to determine both the proper polarization orientation for future systems and the rain-produced depolarization at that orientation.

There will be considerable variation, however, in the polarization orientation of linearly polarized signals received at different measuring sites within the coverage area of 20- and 30-GHz area-coverage satellite beacons.[5] For example, the polarization orientation will vary on the order of 40 degrees over the continental United States for a satellite in synchronous orbit. Thus, the orientation cannot be optimum at all receiving sites from the standpoint of collecting data for system design. Also, since the angular orientation of the raindrop axes with respect to V and H at a given site varies from storm to storm,[4] statistics of the polarization orientation that produces the minimum depolarization and of the minimum value of that depolarization are needed, as well as statistics of the depolarization for several fixed polarization orientations. These requirements imply the need for calculating depolarization at orientations other than the polarization transmitted by a satellite beacon to a given receiving site. In principle, this is readily done if signal attenuation, phase shift, and depolarization parameters are measured with sufficient accuracy. This paper shows some effects of measurement errors on the calculation of rain-produced depolarization for one pair of orthogonally polarized signals from measurements made on a different pair of orthogonally polarized signals that have a different angular orientation. This information is needed in determining the accuracy required for earth-based instrumentation used in depolarization-determining satellite-beacon propagation experiments.

II. PROBLEM DEFINITION

A propagation experiment for determining rain-produced depolarization can be defined as follows.

Transmit a linearly polarized signal, E_{1t}, through the rain. Measure the attenuation and phase of (*i*) E_{11}, the signal received with the same polarization as E_{1t}, and (*ii*) E_{12}, the depolarized signal received with polarization orthogonal to E_{1t}. Then transmit E_{2t}, the signal orthogonal to E_{1t}, and measure the attenuation and phase of (*iii*) E_{22}, the received signal with E_{2t} polarization, and (*iv*) E_{21}, the depolarized signal orthogonal to E_{2t}.

From these measurements, calculate (*v*) E_{y1}, the orthogonal depolarized signal that would be received through the same rain from E_{xt}, a linearly polarized signal transmitted at some orientation other than that of E_{1t} or E_{2t} and (*vi*) E_{x2}, the corresponding depolarized signal received from E_{yt}, a signal transmitted orthogonal to E_{xt}. Figure 1 illustrates the spatial orientation of the polarization vectors, E_1, E_2 and E_x, E_y, on a coordinate system referred to the axes of an elliptical raindrop.[6]

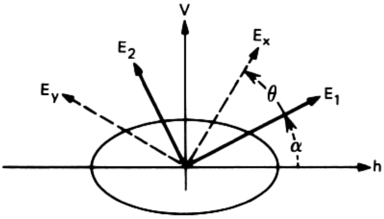

Fig. 1—Signal polarization vectors referred to elliptical raindrop axes.

A coefficient matrix for relating signals transmitted with polarizations 1 and 2, i.e., E_{1t} and E_{2t}, to signals received with the same polarization, E_{1r} and E_{2r}, can be defined as

$$\begin{bmatrix} E_{1r} \\ E_{2r} \end{bmatrix} = A_{12} \begin{bmatrix} 1 & b_{12} \\ c_{12} & d_{12} \end{bmatrix} \begin{bmatrix} E_{1t} \\ E_{2t} \end{bmatrix}, \tag{1}$$

where all coefficients and signals are complex and the phase reference for the transmission coefficients, b_{12}, c_{12}, and d_{12}, is the E_{1t} to E_{1r} coefficient.

The coefficients are obtained from the measurements described above as follows.

$A_{12} = \dfrac{E_{11}}{E_{1t}}$ is the absolute transmission coefficient (attenuation and phase) for the 1-oriented signal.

$b_{12} = \dfrac{E_{21}}{E_{2t}} \cdot \dfrac{1}{A_{12}} = \dfrac{E_{21}}{E_{11}} \cdot \dfrac{E_{1t}}{E_{2t}}$ is the depolarization coefficient for transmit 2 receive 1 normalized to A_{12}.

$c_{12} = \dfrac{E_{12}}{E_{1t}} \cdot \dfrac{1}{A_{12}} = \dfrac{E_{12}}{E_{11}}$ is the depolarization coefficient for transmit 1 receive 2 normalized to A_{12}.

$d_{12} = \dfrac{E_{22}}{E_{2t}} \cdot \dfrac{1}{A_{12}} = \dfrac{E_{22}}{E_{11}} \cdot \dfrac{E_{1t}}{E_{2t}}$ is the transmission coefficient for the 2-oriented signal normalized to A_{12}.

The coefficient E_{1t}/E_{2t} can be measured in clear air (or before launch) so, in principle, all coefficients can be determined. Note that the absolute transmission attenuation and phase appear only in A_{12} so the absolute phase, which is not measurable in the beacon experiment, is not involved in the other coefficients. (It is not necessary for computing the rotated polarization coefficients either, as will be shown.) The coefficient d_{12} contains the differential attenuation and phase between the two polarizations, 1 and 2.

Table I — Representative differential attenuation and phase for vertical-horizontal polarization

Total Attn. (dB)	$\lvert A_{12}\rvert$	Differential Amplitude Ratio	Differential Phase (degrees)
10	0.32	1.25	17
20	0.10	1.6	33.5

The corresponding matrix relation for signals transmitted and received with orthogonal polarizations x and y (see Fig. 1) is

$$\begin{bmatrix} E_{xr} \\ E_{yr} \end{bmatrix} = A_{xy} \begin{bmatrix} 1 & b_{xy} \\ c_{xy} & d_{xy} \end{bmatrix} \begin{bmatrix} E_{xt} \\ E_{yt} \end{bmatrix}. \tag{2}$$

The problem stated at the beginning of this section then reduces to

Given: A_{12}, b_{12}, c_{12}, d_{12}, and θ, the angle between polarizations 1, 2 and x, y,
Find: A_{xy}, b_{xy}, c_{xy}, d_{xy}.

This is easily done since, from Fig. 1,

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} = [\theta_{12}] \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}$$

and (3)

$$\begin{bmatrix} E_1 \\ E_2 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} E_x \\ E_y \end{bmatrix} = [\theta_{xy}] \begin{bmatrix} E_x \\ E_y \end{bmatrix},$$

where, of course, $[\theta_{12}]^{-1} = [\theta_{xy}]$.

Table II — Rain-produced matrix coefficients determined from Table I and eqs. (6)

$\alpha = 0° =$ Vertical and Horizontal

Attn. (dB)	$\lvert A_{12}\rvert$	α deg.	d_{12} Mag.	d_{12} Ang.	b_{12} Mag.	b_{12} Ang.	c_{12} Mag.	c_{12} Ang.
10	0.32	0	1.25	17	0	0	0	0
10	0.32	45	1.0	0	0.1862	52.42	0.1862	52.42
10	0.32	20	1.188	13	0.1301	59.48	0.1301	59.48
20	0.1	0	1.6	33.5	0	0	0	0
20	0.1	45	1.0	0	0.3783	48.55	0.3783	48.55
20	0.1	20	1.448	25.38	0.2906	63.59	0.2906	63.59

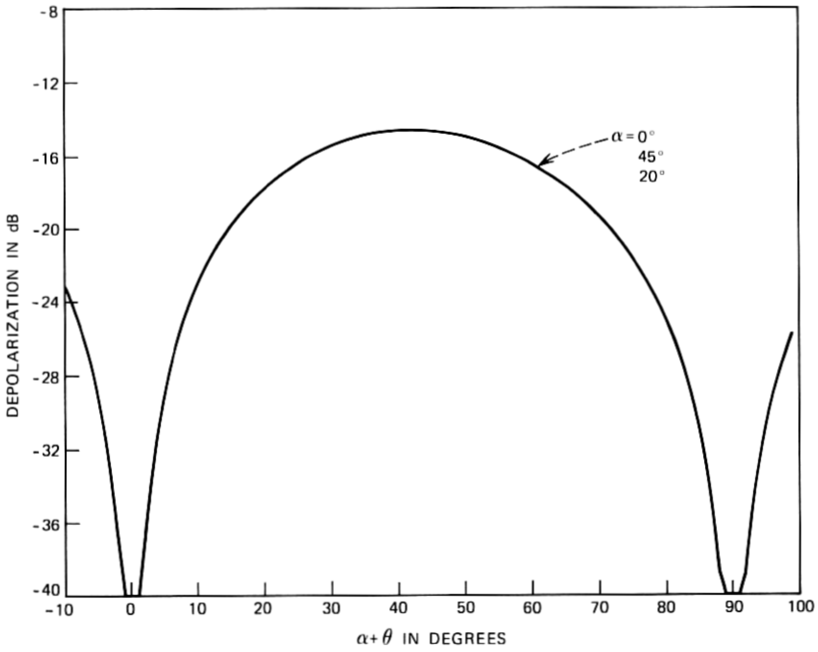

Fig. 2—Depolarization vs angle for 10-dB attenuation. No measurement errors for measurements at $\alpha = 0$, 20, and 45 degrees.

After combining (1) and (3), comparing with (2), completing the simple matrix multiplication, and defining

$$v = \cos^2\theta + d_{12}\sin^2\theta + (b_{12} + c_{12})\sin\theta\cos\theta, \tag{4}$$

then

$$\begin{aligned} A_{xy} &= vA_{12} \\ b_{xy} &= [(d_{12} - 1)\cos\theta\sin\theta + b_{12}\cos^2\theta - c_{12}\sin^2\theta]/v \\ c_{xy} &= [(d_{12} - 1)\cos\theta\sin\theta - b_{12}\sin^2\theta + c_{12}\cos^2\theta]/v \\ d_{xy} &= [\sin^2\theta + d_{12}\cos^2\theta - (b_{12} + c_{12})\sin\theta\cos\theta]/v. \end{aligned} \tag{5}$$

The absolute transmission attenuation and phase contained in A_{12} affects only the absolute attenuation and phase in A_{xy} and not the relative coefficients, b_{xy}, c_{xy}, and d_{xy}. The question of interest in the depolarization-determining propagation experiment is: What effect do errors in b_{12}, c_{12}, and d_{12} for specified α (orientation with respect to raindrop axes) have in determining the magnitudes of the depolarization coefficients, b_{xy} and c_{xy}, for $0 \leqq \theta \leqq 45°$? To proceed further, estimates of b_{12}, c_{12}, and d_{12} and of errors in measuring these quantities are needed.

III. ESTIMATES OF COEFFICIENTS AND MEASUREMENT ERRORS

Since direct measurements of most of the coefficients are not available, estimates must be obtained analytically using known properties of rain,[7–9] electromagnetic theory,[6,10] and the measurement data that are available.[1–11] The theoretical calculations are for paths through uniform rain. Setzer[10] calculates attenuation (db/km) and phase (degrees/km) constants for different rain rates assuming a Laws-and-Parsons drop-size distribution. Morrison et al.[6] calculate differential attenuation (db/km) and differential phase (degrees/km) for oblate spheroidal raindrops[7,8] with a Laws-and-Parsons drop-size distribution for two orthogonal linear polarizations oriented parallel to the axes of the elliptical cross section of the raindrops (see Fig. 1) at 18 GHz. The obvious difficulties in using this work are that actual rain is not uniform over the satellite path, the length of the rain-filled path is not known, the radio wave fronts will not be incident on the raindrops perpendicular to the raindrop cross-section axes with maximum ellipticity (as is more often the case for line-of-sight paths and is assumed in Ref. 6), and, of course, the drop-size distribution and raindrop ellipticity also vary from storm to storm.

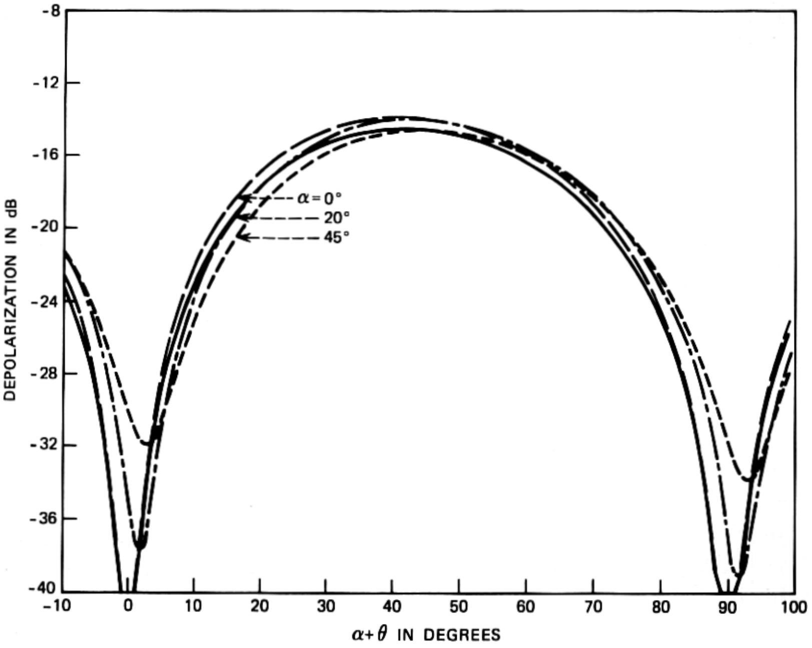

Fig. 3—Depolarization vs angle for 10-dB attenuation. Measurement error in d_{12} of +0.06 or +0.5 dB for measurements at $\alpha = 0$, 20, and 45 degrees.

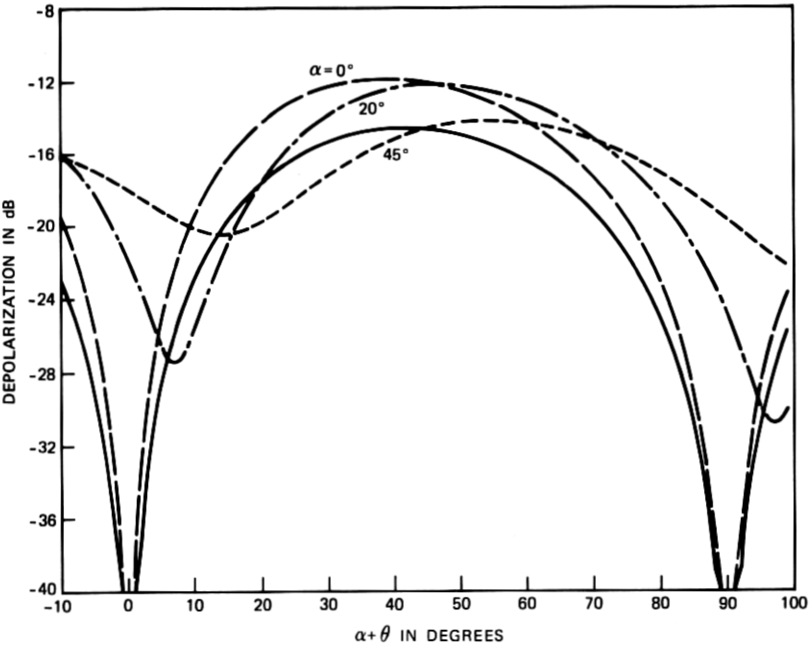

Fig. 4—Depolarization vs angle for 10-dB attenuation. Measurement error in d_{12} of +0.26 or +2 dB for measurements at $\alpha = 0$, 20, and 45 degrees.

The experimental data yield path attenuation only for satellite paths[11] or differential attenuation for terrestrial paths.[2,3] The procedure that was followed in estimating satellite-path differential attenuation and differential phase was

(*i*) Choose total path attenuations,[11] 10 and 20 dB at 20 GHz, that represent rather severe conditions but that are exceeded for a significant time, ≈ 10 hours and ≈ 3 hours during a year.
(*ii*) Assume a uniform rain rate R falling over a path of length L and calculate a few R, L pairs that yield total attenuations of 10 and 20 dB using Setzer's[10] attenuation constants.
(*iii*) Calculate differential attenuation and phase between two linearly polarized signals oriented parallel to raindrop axes[6] (V and H in Fig. 1) using the calculated R and L.
(*iv*) Assume all raindrops oriented with their elliptical cross-section axes parallel and perpendicular to the signal polarizations, i.e., vertical V and horizontal H, so that, because of symmetry, the depolarization is 0.

The representative sets of estimated differential attenuation and phase (i.e., Section II matrix coefficients) obtained by this procedure are summarized in Table I.

These representative sets were selected from the different R and L combinations for total attenuations of 10 and 20 dB. The V and H matrix coefficients were then used in the polarization-rotation equations (5) to calculate coefficients for the two signal polarizations rotated 20 and 45 degrees with respect to the elliptical raindrop axes (i.e., $\alpha = 20°$ and 45° in Fig. 1). These coefficients used in later calculations are tabulated in Table II.

Methods available for estimating potential measurement errors are even less rigorous than those used in estimating the matrix coefficients, since measurement errors will depend both on carrier-to-noise ratios and on equipment-measuring accuracy. The three general types of measurement errors that are distinguishable are errors in (*i*) differential attenuation or phase between the two signals transmitted with different polarizations, d_{12}, (*ii*) relative attenuation and phase between depolarized signals and direct signals, b_{12} and c_{12}, and (*iii*) absolute amplitude and phase A_{12}. Since errors in absolute measurement do

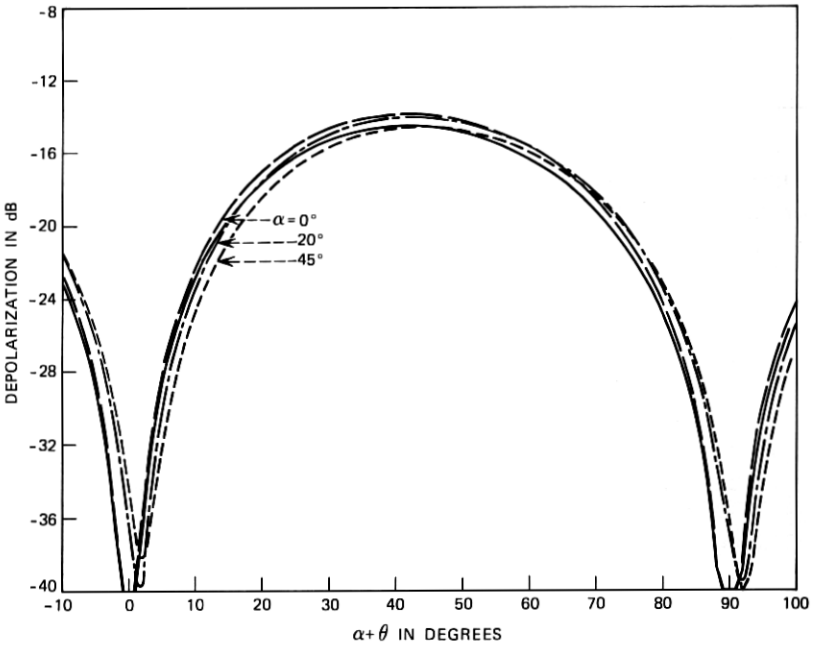

Fig. 5—Depolarization vs angle for 10-dB attenuation. Measurement error in d_{12} of +2 degrees for measurements at $\alpha = 0$, 20, and 45 degrees.

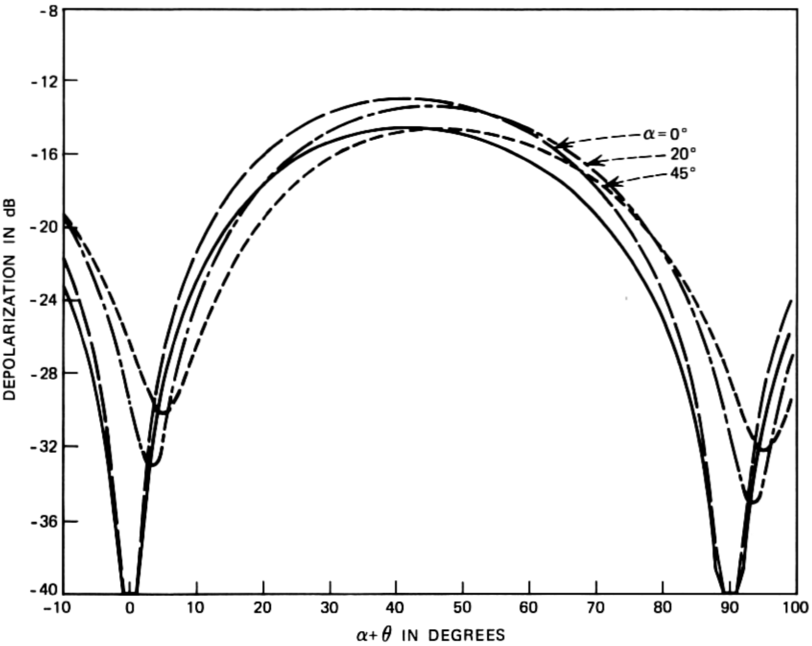

Fig. 6—Depolarization vs angle for 10-dB attenuation. Measurement error in d_{12} of +5 degrees for measurements at $\alpha = 0$, 20, and 45 degrees.

not affect the accuracy in calculating rotated coefficients, they will not be considered here.

Additive errors to d_{12} of ± 0.06 and ± 0.26 in magnitude and ± 2 and ± 5 degrees in angle were selected for assessing the effects of direct-signal differential attenuation and phase errors on rotated polarization coefficients. These values correspond to differential amplitude measuring errors of ≈ 0.5 and 2 dB. Such error values are likely to be contributed to by the measuring equipment or by noise, if the receiver carrier-to-noise ratio degrades sufficiently with attenuation of the signal by rain. Computing the rotated depolarization coefficients, b_{xy} and c_{xy}, in eq. (5) uses only the difference, $d_{12} - 1$, between the transmission coefficient so the magnitude error was added to d_{12} only.

Estimating errors for depolarization coefficients, b_{12} and c_{12}, is somewhat different for the V and H case than for the case of $\alpha = 45$ and 20 degrees because, for the assumed symmetric raindrop orientation, the theoretical V and H depolarization coefficients, b_{12} and c_{12}, are 0. Antenna cross-polarization isolation may be as low as 25 dB, resulting in a contribution of 0.06 to b_{12} or c_{12}. Since this overshadows noise contributions at reasonable signal levels, a spurious magnitude of 0.06 was assumed for b_{12}. In the VH case, this is the only contribution to b_{12}, and its phase angle is unknown. Error phase angles of 45, 90, 180, and 270 degrees were selected for b_{12}.

In the 45-degree case with rain attenuation of 10 dB, the rain contribution to b_{12} is $0.1862 \underline{/52.42}$ degrees (see Table II). Since the phase angle of the assumed error, 0.06, is unknown, several cases were considered for b_{12}: (*i*) no phase error, magnitude errors of ± 0.06, (*ii*) no magnitude error, phase error of ± 18 degrees, and (*iii*) phase error of ± 5 degrees, magnitude error of 0.06.

Similar considerations for the case of $\alpha = 20$ degrees resulted in the choice of errors in b_{12} of (*i*) magnitudes of ± 0.06, phase of ± 5 and ± 10 degrees, and (*ii*) magnitude of 0, phase of ± 30 degrees.

IV. RESULTS

It is obvious from Fig. 1 and eq. (2) that letting θ range over $0 \leqq \theta \leqq 90$ degrees and looking at $|b_{xy}|$ is equivalent to letting θ range over $0 \leqq \theta \leqq 45$ degrees and looking at both $|b_{xy}|$ and $|c_{xy}/d_{xy}|$.

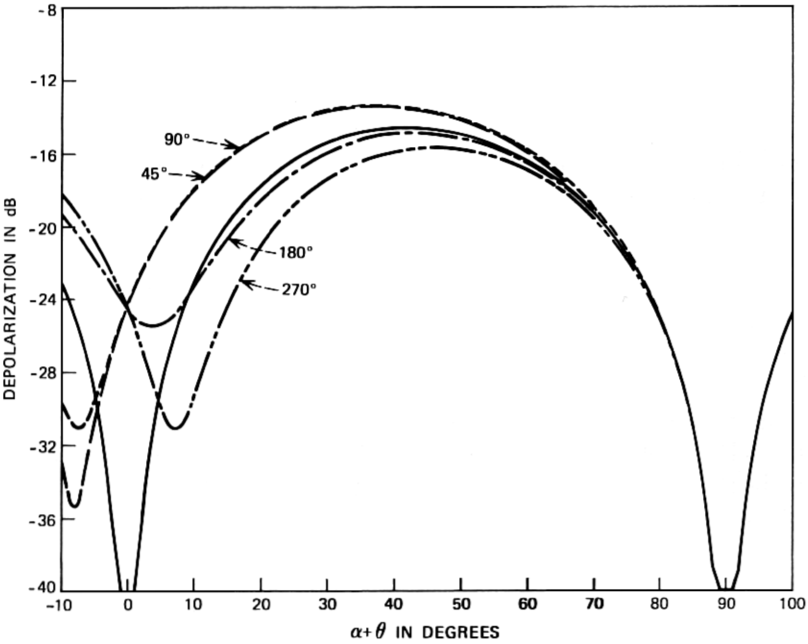

Fig. 7—Depolarization vs angle for 10-dB attenuation. Measurement error in b_{12} of $+0.06$ at phase angles of 45, 90, 180, and 270 degrees corresponding to cross-polarization contamination of ≈ -25 dB for $\alpha = 0$ degrees, i.e., V and H.

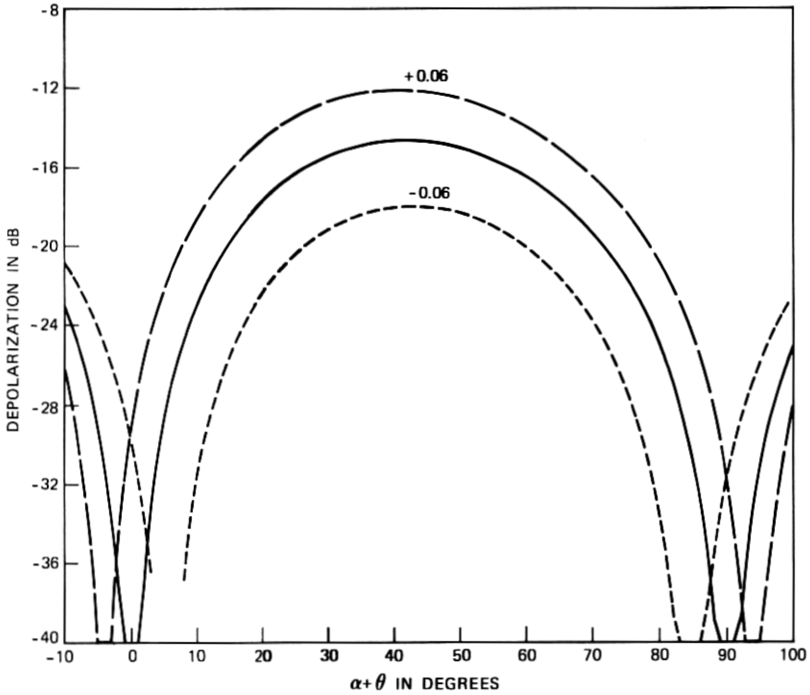

Fig. 8—Depolarization vs angle for 10-dB attenuation. Measurement error in b_{12} of ± 0.06 for measurements at $\alpha = 45$ degrees. Corresponds to cross-polarization contamination of ≈ -25 dB.

Also, any continuous 90-degree range of θ contains all values of $|b_{xy}|$. For the graphs in this section, then, $|b_{xy}|$ is plotted for the range of $0 \leqq \alpha + \theta \leqq 90$ degrees for all three initial polarization angles, $\alpha = 0$, 20, and 45 degrees. (Note that α is the orientation angle of the "measured" coefficients, 12, with respect to the axis of the elliptical raindrops and $\alpha + \theta$ is the angle of the calculated coefficients, xy, referred to the same elliptical axes and rotated an angle θ with respect to the measured coefficients, as in Fig. 1.)

Figure 2 is a plot of cross-polarization coupling (depolarization), $|b_{xy}|$, for $0 \leqq \alpha + \theta \leqq 90$ degrees computed using as starting points each of the three sets of coefficients in Table II for 10-dB attenuation with no measurement errors included. Without measurement errors, the rotated coefficients can be calculated without significant computation error. The 0 depolarization at 0 and 90 degrees is a result of the assumed perfect raindrop symmetry and orientation. In actual rain, random orientations and asymmetries will cause these nulls to fill in to some as-of-now unknown level.

Figures 3 to 10 are plots of depolarization, $|b_{xy}|$, for $0 \leqq \alpha + \theta \leqq 90$ degrees computed from the coefficients in Table II for 10-dB attenuation. The solid curve on each figure is the "no errors" curve from Fig. 2. Figures 3 to 6 each include measurement angles of $\alpha = 0$, 20, and 45 degrees and different errors in differential attenuation, $|d_{12}|$, and differential phase, $\underline{/d_{12}}$, indicated in the captions. In general, errors with the opposite sign of those in the figures produce error curves with approximately the same magnitudes but shifted in the opposite angular direction from $\alpha + \theta = 0$ degrees. Figures 7 to 10 include different measurement errors in depolarization, b_{12}, indicated in the captions. Each of these figures is for a specific α as indicated. Asymmetries in the error curves are a result of alloting all the measurement error to the one coefficient, b_{12}.

Figures 11 and 12 are similar plots of $|b_{xy}|$ computed from coefficients in Table II for 20-dB attenuation. They are for the different errors in d_{12}, as indicated.

Three overall effects of measurement errors on the calculated $|b_{xy}|$ near the regions of minimum depolarization that are indicated in

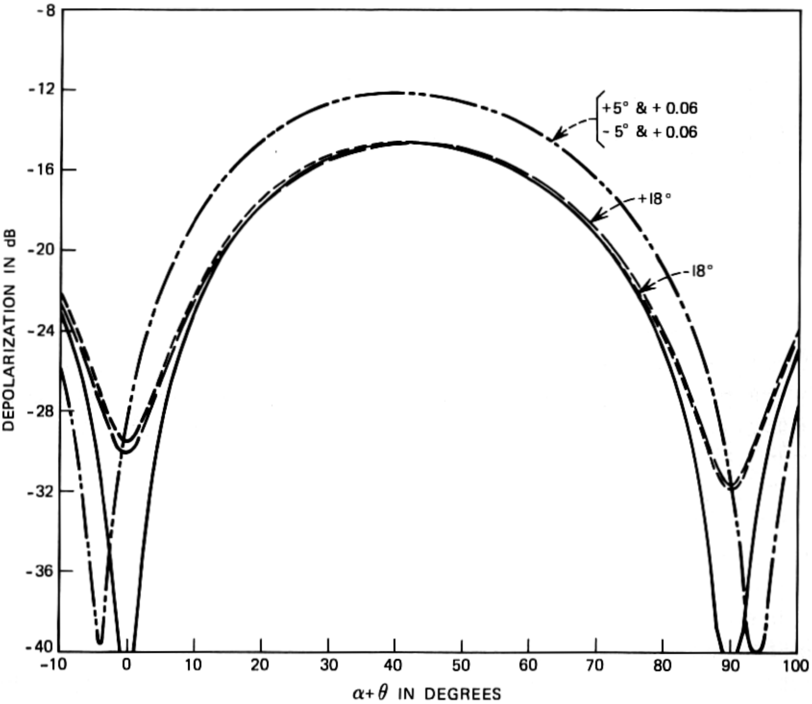

Fig. 9—Depolarization vs angle for 10-dB attenuation. Measurement error in b_{12} of ± 18 degrees and of $+0.06$ with ± 5 degrees. Corresponds to cross-polarization contamination of ≈ -25 dB.

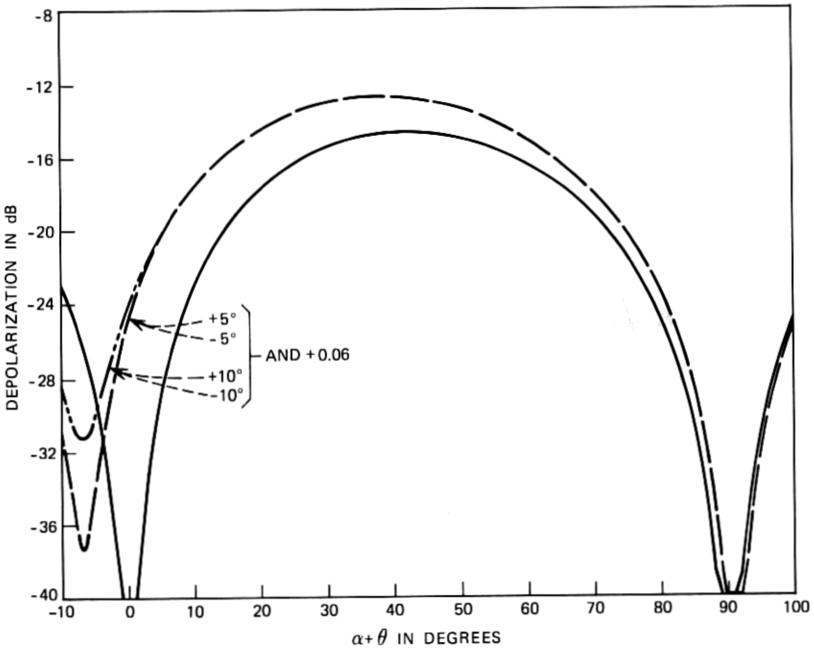

Fig. 10—Depolarization vs angle for 10-dB attenuation. Measurement error in b_{12} of +0.06 with ±5 degrees and of +0.06 with ±10 degrees for measurements at $\alpha = 20$ degrees. Corresponds to cross-polarization contamination of ≈ -25 dB.

Figs. 3 to 12 are (*i*) the $|b_{xy}|$ at $\alpha + \theta = 0$ and 90 degrees become nonzero in all cases, (*ii*) the minima of the $|b_{xy}|$ vs $\alpha + \theta$ curves shift in angle from the no-error 0 and 90-degree positions, and (*iii*) at the minima the $|b_{xy}|$ also become nonzero. These effects are tabulated for each separate error for initial angles, α, of 0 and 45 degrees and total attenuation of 10 dB in Table III.

From the figures and Table III, it appears that errors in measuring $|d_{12}|$ at $\alpha = 45$ degrees on the order of ±2 dB or ±5 degrees produce unacceptable errors (min > -30 dB and offset of min $\geqq 5°$) in $|b_{xy}|$ at the vertical and horizontal orientation, $\alpha + \theta = 0$ and 90 degrees, from the standpoint of use in evaluating future systems performance. An error of ±2 degrees in $|d_{12}|$ at $\alpha = 45$ degrees produces acceptable errors in $|b_{xy}|$ at $\alpha + \theta = 0$ and 90 degrees. An error of ±0.5 dB in $|d_{12}|$ at 10-dB attenuation produces errors in $|b_{xy}|$ at 0 degrees that are marginally acceptable.

V. SUMMARY

The deficiencies in the methods used to estimate the rain-produced differential attenuation and phase and the measurement errors are

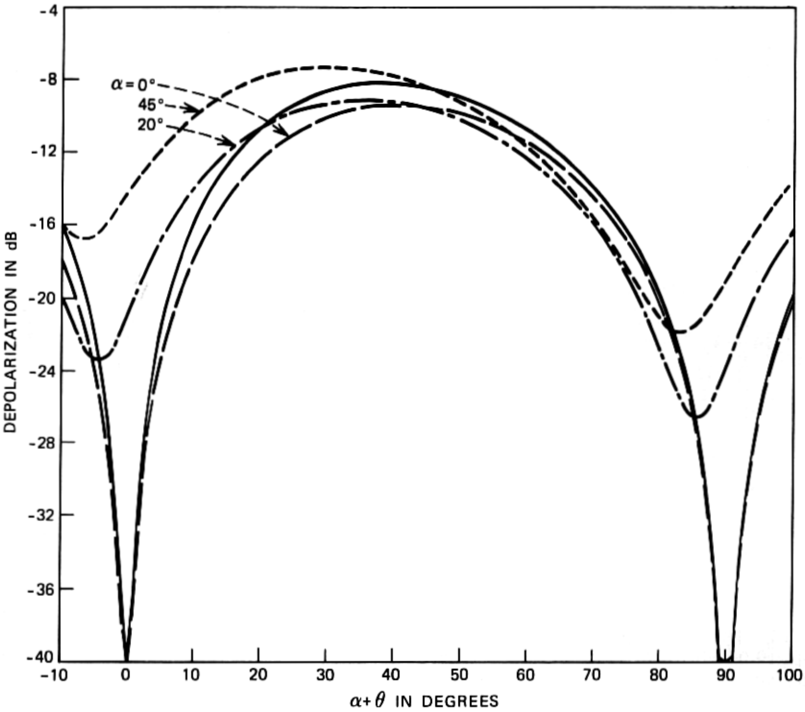

Fig. 11—Depolarization vs angle for 20-dB attenuation. Measurement error in d_{12} of -0.26 or -2 dB for measurements at $\alpha = 0$, 20, and 45 degrees.

obvious. However, a range of 20-GHz attenuation and rain rate and of measurement errors were considered, so the estimates of the effects of the errors illustrated in the figures and in Table III should be representative of those to be encountered in an actual experiment.

Calculation of rain-produced depolarization of one pair of orthogonally polarized signals from measurements of depolarization and differential attenuation and phase of a different pair of orthogonally polarized signals is quite sensitive to measurement errors. Therefore, it is better to measure the propagation parameters for the polarization orientation for which the parameters are desired. Considering future system applications, the optimum polarizations are linear, oriented horizontally and vertically (i.e., perpendicular to horizontal and the propagation path) at the receiving site, since this combination is expected to produce the minimum depolarization on the average. Measurement at the desired orientation produces the best results at the desired orientation and can produce at least partial results during partial equipment failure. Useful depolarization information can be

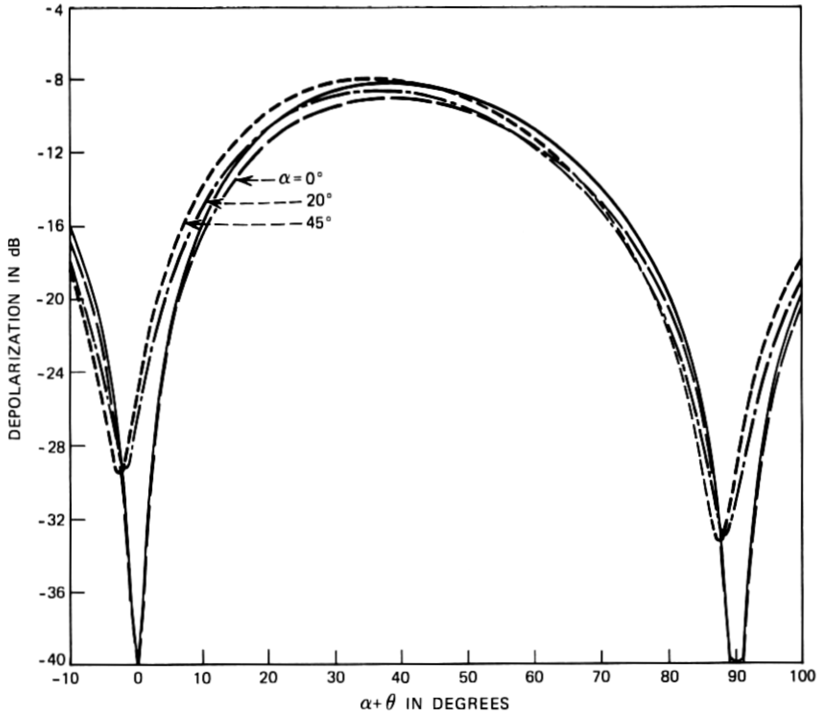

Fig. 12—Depolarization vs angle for 20-dB attenuation. Measurement error in d_{12} of -5 degrees for measurements at $\alpha = 0$, 20, and 45 degrees.

Table III — Summary of effects of measurement errors on $\lvert b_{xy}\rvert$ for 10-dB rain attenuation and $\alpha = 0°$ and 45°

Error	Max $\lvert b_{xy}\rvert$ at $\alpha + \theta = 0°$ or $90°$		Max Angular Shift of Min of $\lvert b_{xy}\rvert$		Largest Min of $\lvert b_{xy}\rvert$	
	$\alpha = 0°$	$\alpha = 45°$	$\alpha = 0°$	$\alpha = 45°$	$\alpha = 0°$	$\alpha = 45°$
	dB	dB	deg.	deg.	dB	dB
$\lvert d_{12}\rvert$						
±0.5 dB	0	−30	0	4	0	−32
±2.0 dB	0	−18	0	15	0	−20
$\underline{/d_{12}}$						
±2 degrees	0	−34	0	2	0	38
±5 degrees	0	−26	0	5	0	30
Cross-polarization of −25 dB	−25	−29				
at max shift of min			7°	4°	−31	−40
at largest min			4°	0°	−26	−29

obtained by calculation if the satellite configuration requires measurement of propagation parameters at a polarization orientation other than the optimum discussed above.

The accuracies required in the measuring system to ensure adequate accuracy in the calculated propagation parameters (particularly depolarization) are (*i*) error in differential attenuation between the transmitted polarizations $< \pm 0.5$ dB, and (*ii*) error in differential phase for the same two signals $\leqq \pm 2$ degrees. Cross-polarization isolation of 25 dB in the measuring system is inadequate.

VI. ACKNOWLEDGMENTS

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