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# "Polarization Effects in Millimeter Wave Propagation Through Rain: A Review of Present Theory and a Discussion of Current Experiments"

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## I. Introduction

Over the past 60 years the need for an ever increasing number of communications channels has steadily pushed the upper limit of usable frequencies from the tens of kilohertz region to about 12 GHz. Today, we are faced with the need to develop reliable systems at frequencies above 12 GHz to meet the communications needs of the present and the near future. However, the mastering of this part of the frequency spectrum will require overcoming difficulties more severe than those encountered at lower frequencies. The dominant factor affecting propagation along a ground path at frequencies above 12 GHz is rain. Rainfall attenuation and scattering increase so much as frequency is increased above 12 GHz that they are the greatest single problem facing the designer of communications systems to operate at these millimeter wavelengths. It is obvious that attenuation and scattering can greatly reduce the magnitude of a wave propagating through heavy rain but this is not the only effect. An arbitrarily polarized wave will be depolarized, or have its polarization changed, as it passes through a rain-filled space. The gross attenuation of millimeter waves as a function of rainfall rate has been studied in detail both theoretically and experimentally, but the dependence of attenuation on the polarization of the wave has received little attention. Semplak[1] at Bell Labs has measured the differential attenuation which rain produces between two orthogonal components of a linearly polarized wave and hence verified that rain causes depolarization of a wave which is transmitted with the particular polarization that he chose. However, the depolarization which would be experienced by a wave transmitted with any other polarization cannot be inferred from his measurements. As yet, no experiment has been done which provided data sufficient to calculate the depolarization by rain of an arbitrary linearly or elliptically polarized millimeter wave. It would be valuable to have actual data on how a wave with arbitrary polarization is affected by rain for several reasons as listed in Figure 1. First, a system could be designed utilizing a polarization for which the average attenuation is a minimum. Second, the two orthogonal polarizations exhibiting the minimum conversion of energy between them could be operated as separate communications channels and would have the least possible cross-polarization interference. Third, polarization diversity to increase reliability could be provided using the two polarizations whose respective fading levels have the least correlation. Fourth, a great deal could be learned about the rain itself.

## II. How Should Depolarization Effects Be Studied Experimentally?

In order to gain an insight into what measurements are necessary in order to completely define the depolarization properties of a medium such as rain we can turn to the general theory of depolarization as proposed by Beckmann.[2] This theory rests on the fact that a wave with any arbitrary polarization can be expressed as the sum of two waves with orthogonal linear polarizations. Therefore we will know how any wave is depolarized if we measure the depolarization of two orthogonal linearly polarized waves. As shown in Figure 2 $\overline{E}_T$ represents the electric field vector of a transmitted arbitrarily polarized plane wave at a particular instant of time. $\overline{E}_T$ can be resolved into components $\overline{E}_{Tx}$ and $\overline{E}_{Ty}$ along the x and y axes respectively. As $\overline{E}_{Tx}$ propagates toward the receiver, a part of its energy will be converted to a y-polarized wave which is called $\overline{E}_{Rxy}$. The remainder of the energy of $\overline{E}_{Tx}$ which reaches the receiver will still be x-polarized and is denoted by $\overline{E}_{Rxx}$. Similarly $\overline{E}_{Ty}$ produces a cross-polarization component $\overline{E}_{Ryx}$ and a direct component $\overline{E}_{Ryy}$. Hence each component of the received wave is composed of the sum of a direct wave and a cross-polarized wave. This relation is put into equation form in Figure 3. The x component of the received wave is called $\overline{E}_{Rx}$ and is equal to $\overline{E}_{Rxx}$ plus $\overline{E}_{Ryx}$. The y component $\overline{E}_{Ry}$ is equal to $\overline{E}_{Ryy}$ plus $\overline{E}_{Rxy}$. The $\Gamma$'s or polarization coefficients defined in Figure 3 allow these equations to be rewrittten in terms of the transmitted waves $\overline{E}_{Tx}$ and $\overline{E}_{Ty}$. The measurement of the polarization coefficients is straightforward. Making $\overline{E}_{Ty} = 0$ allows a direct determination of $\Gamma_{xx}$ and $\Gamma_{xy}$ while making $\overline{E}_{Tx} = 0$ permits measurement of $\Gamma_{yx}$ and $\Gamma_{yy}$.

As a consequence of Beckmann's theory of depolarization, every medium will pass either one polarization unchanged, or two polarizations unchanged, or it will pass all polarizations unchanged; there are no other possibilities. If raindrops were spherical and if multiple scattering and sidescatter were negligible, then a rain-filled space would pass all polarizations unchanged. This result was obtained in 1908 by Gustav Mie whose work laid the foundation for later developments. Figure 4 shows the polarizations resulting from scattering from a single spherical raindrop. Note that in the direction of propagation linear polarization is produced when the incident wave is linearly polarized and therefore no depolarization occurs.

Although no depolarization would occur if raindrops were spherical, it has been established by high speed photography that raindrops are not spherical but oblate, and that the oblateness increases with drop size. Figure 5 represents a cross-sectional view of an oblate raindrop showing the major axis and the minor axis which are both perpendicular to the direction of propagation. This distorted raindrop will no longer pass all polarizations unchanged, but since the drop has symmetry about both its major axis and its minor axis it will not depolarize any wave with linear polarization parallel to either axis. Hence two polarizations are passed unchanged and the major and minor axes are called the principal axes of the drop since they define the incident polarization for which no depolarization occurs. In Figure 5 $\overline{E}_1$ and $\overline{E}_2$ will not be depolarized, but they will suffer unequal attenuation. The cross-section of the drop seen by $\overline{E}_2$ is larger than the cross-section seen by $\overline{E}_1$ and therefore $\overline{E}_2$ will suffer more attenuation by the raindrop than will $\overline{E}_1$. Oguchi[3] was the first to calculate the difference in attenuation suffered by waves polarized parallel to the principal axes of an oblate raindrop. The table in Figure 6 shows the expected attenuation at 8.6 mm wavelength for waves polarized parallel to the major and minor axes as a function of the rain rate in millimeters per hour. As can be seen, the difference increases from 0.4 db/km at 12.5 mm/hr to 4.6 db/km at 150 mm/hr. These theoretical predictions made by Oguchi have been verified experimentally by Semplak.[1]

Although, perhaps, it is not obvious at first, it is the difference in the attenuations along the principal axes of the drop which causes all polarizations not parallel to one of these axis to be depolarized. This is illustrated in Figure 7 where $\overline{E}_T$ represents a transmitted wave whose polarization is not parallel to either principal axis. $\overline{E}_T$ can be expressed as a component $\overline{E}_1$ along the major axis and $\overline{E}_2$ along the minor axis. As $\overline{E}_1$ and $\overline{E}_2$ propagate, they will be attenuated but their direction will not be changed since they are parallel to the principal axis. $\overline{E}_1'$ and $E_2'$ represent $\overline{E}_1$ and $\overline{E}_2$ at the time they reach the receiver. Since $\overline{E}_1$ has been attenuated more than $\overline{E}_2$, $\overline{E}_1'$ will be proportionally smaller than $\overline{E}_2'$ and the resultant $\overline{E}_R$ will not be parallel to $\overline{E}_T$. Hence $\overline{E}_T$ has been depolarized or rotated in the direction of the minor axis. The maximum depolarization of $\overline{E}_T$ will occur when $\overline{E}_T$ makes an angle of ± 45° with respect to the minor axis of the drop. This means that if the minor axis of the raindrop were vertical then the transmitted wave should be polarized at ± 45° from the vertical in order for the maximum depolarization to be observed. If the transmitted wave were vertically polarized then no polarization would be observed and the polarization coefficients could not be evaluated. The medium would appear not to depolarize when in fact any polarization except vertical or horizontal would be strongly depolarized.

In reality the minor axis of the raindrop is canted at some angle with respect to vertical and so a vertically transmitted wave would still be depolarized to some degree. However, since according to Thomas[4] the average raindrop canting angle is only about 15° a much greater depolarization would be observed for a transmitter at ± 45° from the vertical. Another conclusion can be drawn from the relation between the position of the principal axes and depolarization. Since the amount of depolarization depends on the position of the principal axes and since the canting angle is almost entirely dependent on wind velocity, depolarization should bear a strong correlation to wind velocity. There should be little or no correlation between depolarization and rain rate alone <u>unless</u> the position of the principal axes is taken into account.

## III. Description of a Current Experiment

At the present time an experiment funded by NASA is being constructed on the campus of Virginia Polytechnic Institute and State University to determine how a wave with arbitrary polarization is depolarized by rainfall. The experiment will be conducted at a frequency of 17.65 GHz and will measure the differential attenuation and cross-polarization levels of two orthogonal linearly polarized waves. The relative phase of both the direct and the cross-polarized component of each wave will also be measured although it is believed to be small.[5] From this data the polarization coefficients will be computed and a prediction of the depolarization of an arbitrarily polarized wave by rain will be possible.

For the experiment, a path length of 1.43 km was chosen since it is long enough for the desired effects to be observable, but short enough so that the rainfall will be likely to be constant along it. The ground clearance at midpath is 80 ft which represents an angle of about 2 degrees from the center of the beam. The antennas will be 48 inch parabolic dishes with a beam width of one degree and hence only the sidelobes will intercept the ground at midpath. This means that any multipath signal will be more than 50 dB below the main signal, and therefore multipath propagation will cause no errors in the cross-polarization measurements which should be no more than 40 dB below the main signal.

The transmitter for the experiment has an output of 50 MW which is divided by a 3 dB coupler and fed to separate transmitting antennas. The two transmitting antennas will be linearly polarized at +45° and -45° respectively in order to produce the maximum depolarization effect.

Two receiving antennas will also be oriented at ±45° and coupled to separate receivers. When both polarizations are transmitted simultaneously, the differential attenuation between them will be recorded. If, however, only one polarization is transmitted, the attenuation of the direct signal and the conversion to the orthogonal polarization will be recorded.

The rainfall will be measured with tipping-bucket raingauges in increments of 0.01 inches. Simultaneously, the number of raindrops falling per unit area will be recorded with a special sensing device. These two measurements will not only give the rainfall rate but will allow computation of the size of the average raindrop. This should eliminate errors due to the use of incorrect raindrop size distributions in the computations. Since a high correlation of wind velocity to depolarization is expected, three wind recorders will be provided along the path to record wind speed and direction. An additional weather measurement, the temperature of the rain itself, will be recorded since the complex permittivity of water is a function of temperature.

All the data generated by the experiment will be converted to digital form, preprocessed, and stored on tape by an on-line digital computer. The computer will also make periodic system reliability checks and will vary the switching speed of the transmitter as the rainfall rate changes.

Based on the computations by Oguchi[3] of the differential attenuation per kilometer encountered by waves polarized parallel to the principal axes of an oblate raindrop, we are able to predict the levels of the cross-polarization signals which will be observed for a frequency of 17.65 GHz and a path length of 1.43 km. According to Thomas[4] the ratio of the rainfall attenuation at 17.65 GHz to that at 35 GHz is as shown in part (a) of Figure 8. This ratio varies from 0.33 for a rain rate of 12.5 mm/hr to 0.44 for a rate of 150 mm/hr. Using these ratios Oguchi's differential attenuation at 35 GHz for a one kilometer path can be converted to the differential attenuation at 17.65 GHz for a 1.43 km path as shown in part (b) of Figure 8. Once the differential attenuation for waves polarized along the major axis and the minor axis is known, the expected conversion of energy from a polarization of +45° to a polarization of -45° can be computed as a function of the canting angle of the raindrops. The ratio of the cross-polarized signal received at -45° to the main signal received at +45° will determine one of the polarization coefficients. Figure 9 shows the method used to compute the expected level of the cross-polarized signal. $\overline{E}_T$ represents the polarization of the transmitted wave at an angle of +45° from the vertical. $\overline{R}_1$ and $\overline{R}_2$ denote the directions of the major and minor axis respectively of the raindrop. $\overline{E}_T$ is resolved into a component $\overline{E}_{T1}$ along $\overline{R}_1$ and a component $\overline{E}_{T2}$ along $\overline{R}_2$. Components $\overline{E}_{T1}$ and $\overline{E}_{T2}$ are attenuated by different amounts as they propagate and when the received signal components $\overline{E}_{R1}$ and $\overline{E}_{R2}$ are added to make the received signal $\overline{E}_R$, we find that $\overline{E}_R$ now has a cross-polarized component $E_{Rx}$ perpendicular to $\overline{E}_T$ and a main component $E_{RM}$ parallel to $\overline{E}_T$. Figure 10 shows the level of $\overline{E}_{Rx}$ in db below $\overline{E}_{RM}$ for several rainfall rates and for values of θ of 0° and +15°. As can be seen the expected level ranges from about -40 db to -15 db. We expect the cross-polarization discrimination of our antennas to be 35 - 40 db, so we should be able to measure depolarization for rain rates as low as 10 - 20 mm/hr. From our data we should be able to predict the depolarization of any arbitrarily polarized millimeter wave as a function of rainfall rate and wind velocity.

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1. Polarization with minimum attenuation could be used.
2. Polarization multiplexing could be employed using 2 polarizations with minimum cross-polarization interference.
3. Polarization diversity could be optimized by using 2 polarizations with the least simultaneous fading.
4. Data concerning the structure of rain would be obtained.

Figure 1. Benefits of a Depolarization Study of Arbitrarily Polarized Waves.

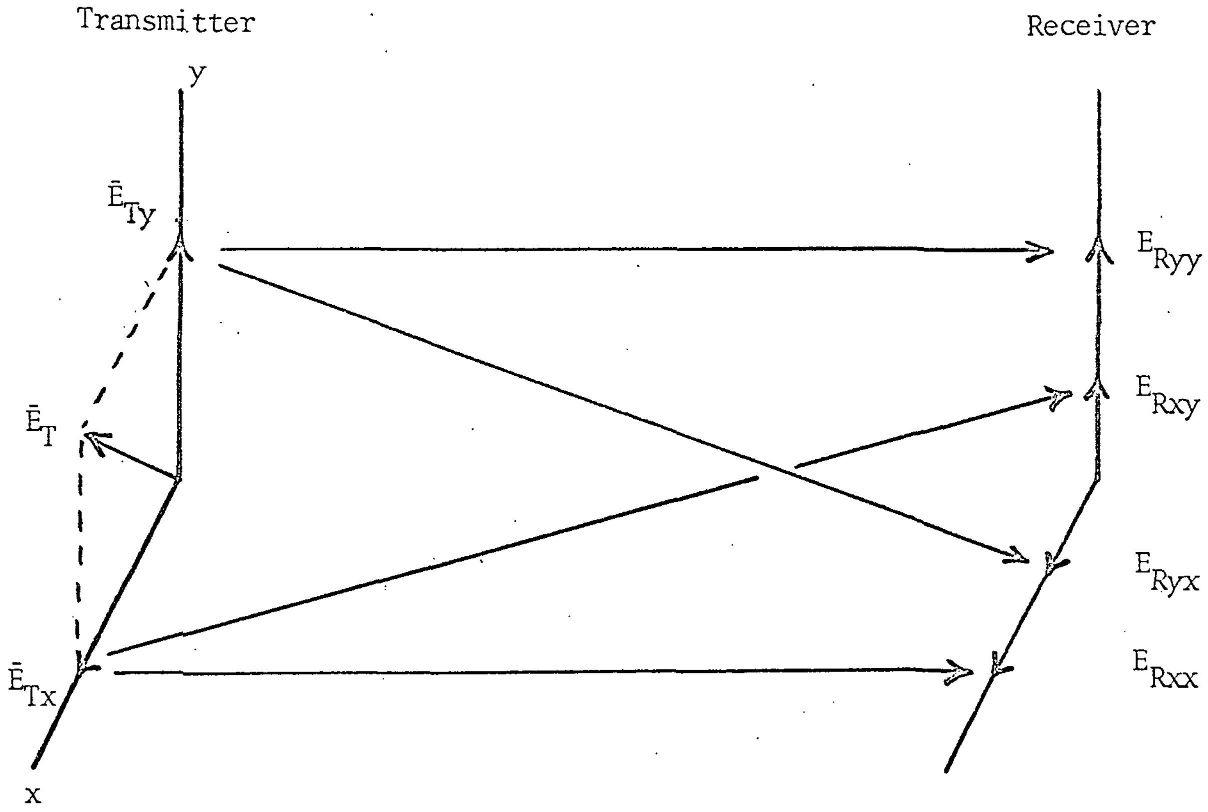

Figure 2 Expressing depolarization of an arbitrary wave as the sum of the depolarizations of two orthogonal linearly polarized waves.

$$\bar{E}_{Rx} = \bar{E}_{Rxx} + \bar{E}_{Ryx}$$

$$\bar{E}_{Ry} = \bar{E}_{Ryy} + \bar{E}_{Rxy}$$

Define

$$\Gamma_{xx} = \frac{\bar{E}_{Rxx}}{\bar{E}_{Tx}} \qquad \Gamma_{yx} = \frac{\bar{E}_{Ryx}}{\bar{E}_{Ty}}$$

$$\Gamma_{yy} = \frac{\bar{E}_{Ryy}}{\bar{E}_{Ty}} \qquad \Gamma_{xy} = \frac{\bar{E}_{Rxy}}{\bar{E}_{Tx}}$$

Then

$$\bar{E}_{Rx} = \Gamma_{xx}\,\bar{E}_{Tx} + \Gamma_{yx}\,\bar{E}_{Ty}$$

$$\bar{E}_{Ry} = \Gamma_{xy}\,\bar{E}_{Tx} + \Gamma_{yy}\,\bar{E}_{Ty}$$

To measure coefficients

$$\Gamma_{xx} = \frac{\bar{E}_{Rx}}{\bar{E}_{Tx}}, \quad \Gamma_{xy} = \frac{\bar{E}_{Ry}}{\bar{E}_{Tx}} \qquad \text{when } \bar{E}_{Ty} = 0$$

$$\Gamma_{yx} = \frac{\bar{E}_{Rx}}{\bar{E}_{Ty}}, \quad \Gamma_{yy} = \frac{\bar{E}_{Ry}}{\bar{E}_{Ty}} \qquad \text{when } \bar{E}_{Tx} = 0$$

Figure 3. Definition of the polarization coefficients.

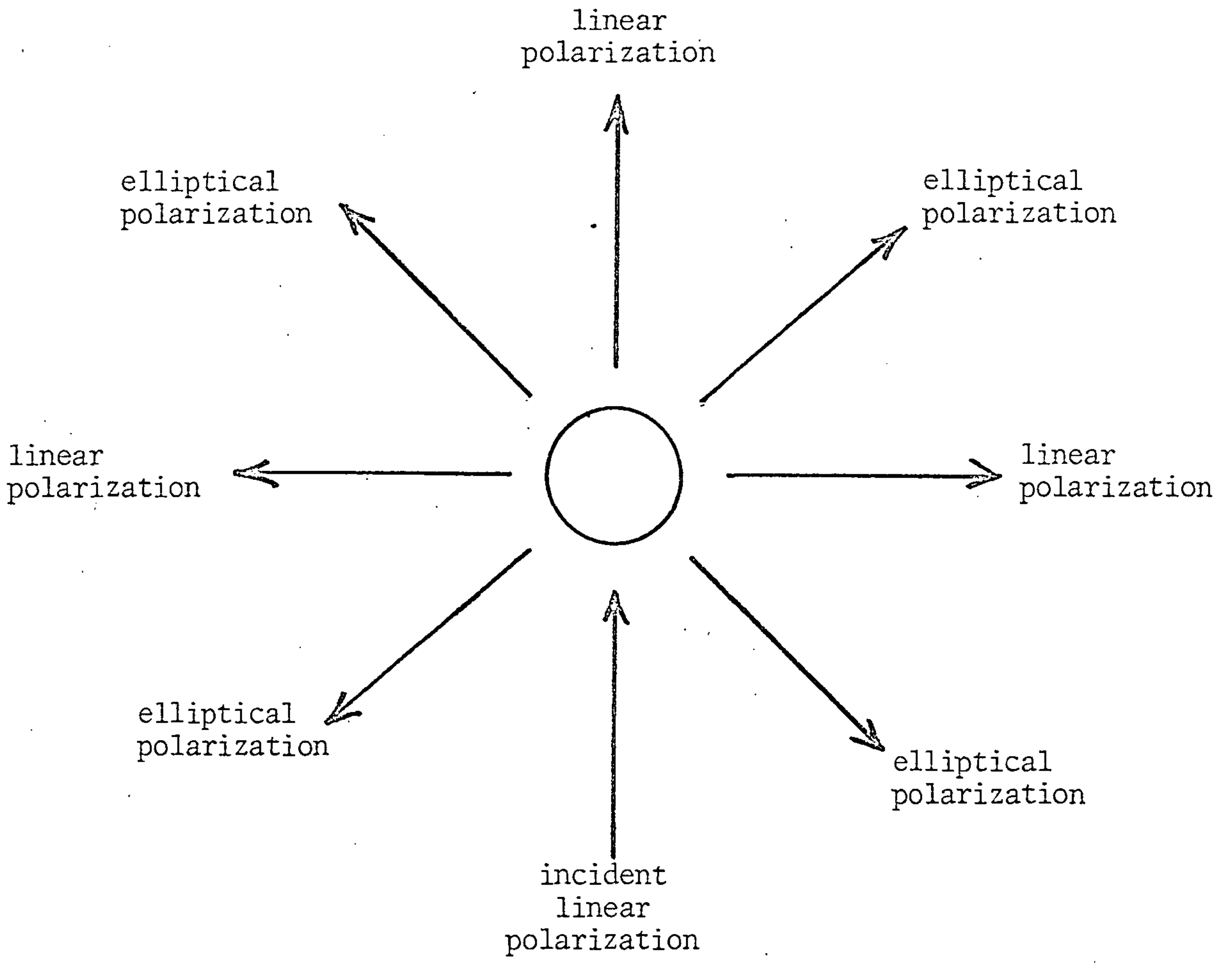

Figure 4 Scattering From a Spherical Raindrop

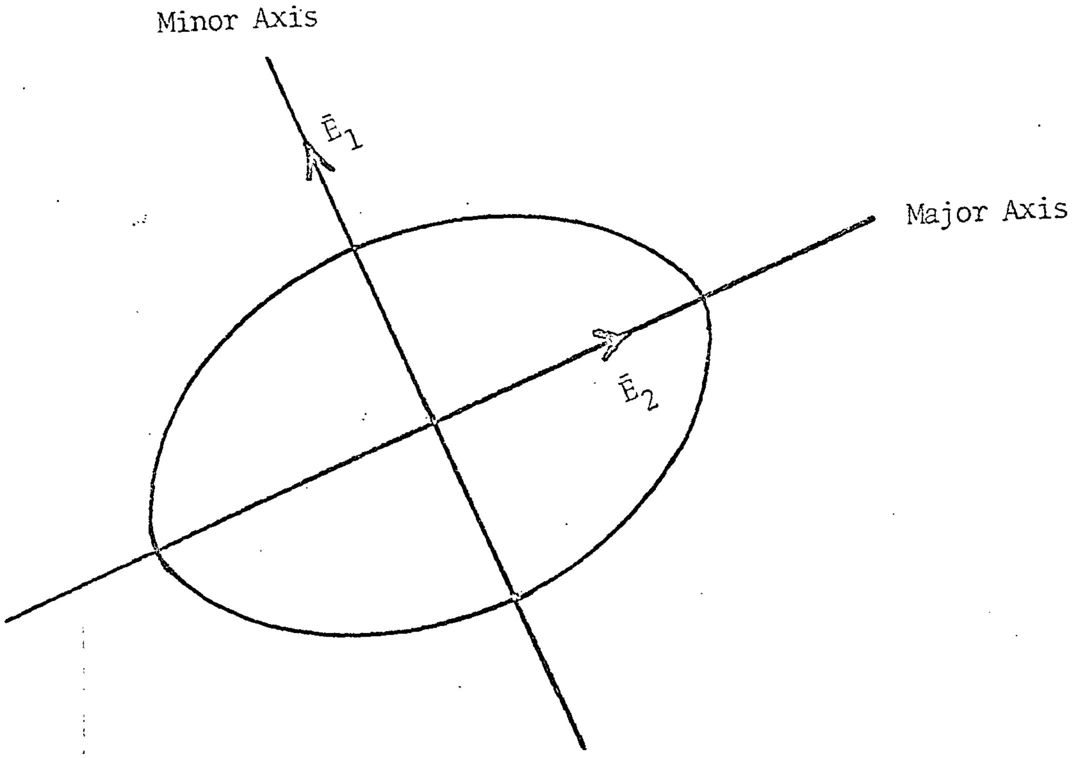

Figure 5 Oblate Raindrop

| Rain Rate mm/hr | Attenuation db/km Major Axis | Attenuation db/km Minor Axis |
|---|---|---|
| 12.5 | 3.21 | 2.81 |
| 25 | 6.20 | 5.46 |
| 50 | 12.0 | 10.3 |
| 100 | 22.1 | 18.9 |
| 150 | 31.6 | 27.0 |

Figure 6 Attenuation of waves polarized parallel to the major axis and the minor axis of an oblate raindrop.

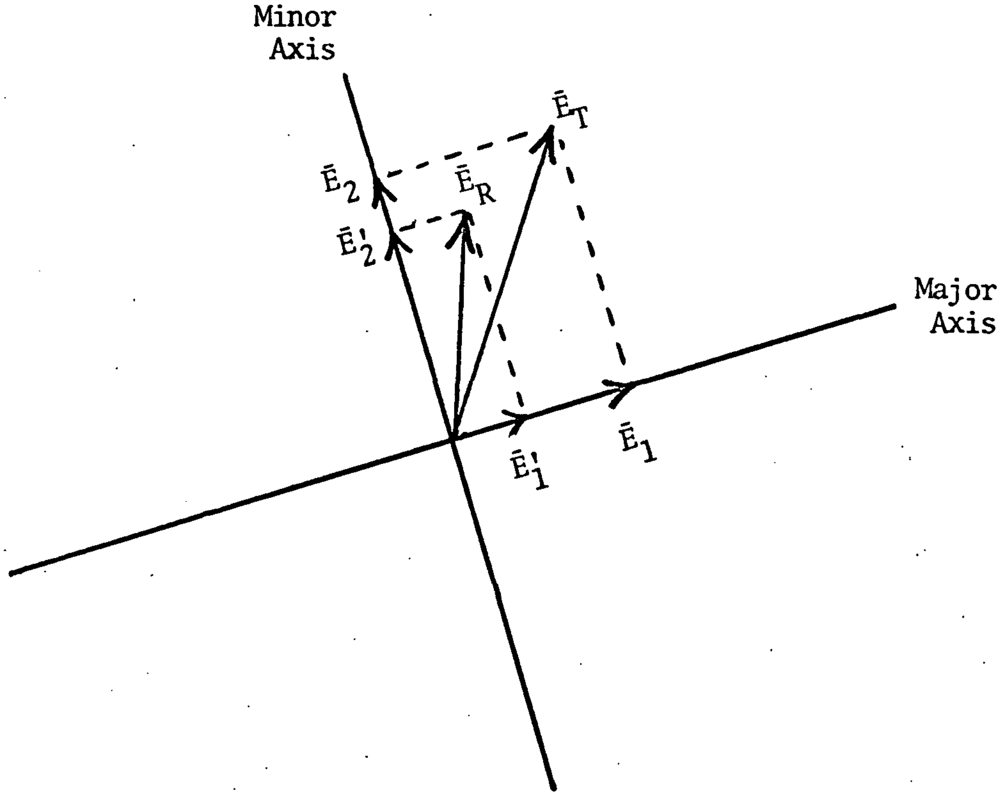

Figure 7 Depolarization by differential attenuation

| Rain Rate mm/hr | Attenuation db/km 35 GHz | Attenuation db/km 17.65 GHz | $\frac{\text{Attenuation at 17.65 GHz}}{\text{Attenuation at 35 GHz}}$ |
|---|---|---|---|
| 12.5 | 3 | 1 | 0.33 |
| 25 | 6 | 2 | 0.33 |
| 50 | 12 | 4 | 0.33 |
| 100 | 22 | 9 | 0.41 |
| 150 | 32 | 14 | 0.44 |

| | Attenuation at 35GHz $\frac{\text{dB}}{\text{km}}$ | | Attenuation at 17.65 $\frac{\text{dB}}{1.43\text{km}}$ | |
|---|---|---|---|---|
| Rain Rate mm/hr | minor axis | major axis | minor axis | major axis |
| 12.5 | 2.81 | 3.21 | 1.33 | 1.52 |
| 25 | 5.46 | 6.20 | 2.58 | 2.94 |
| 50 | 10.3 | 12.0 | 4.88 | 5.69 |
| 100 | 18.9 | 22.1 | 11.10 | 12.97 |
| 150 | 27.0 | 31.6 | 17.00 | 19.90 |

Figure 8 Computation of the differential attenuation at 17.65 GHz based on the attenuation at 35 GHz.

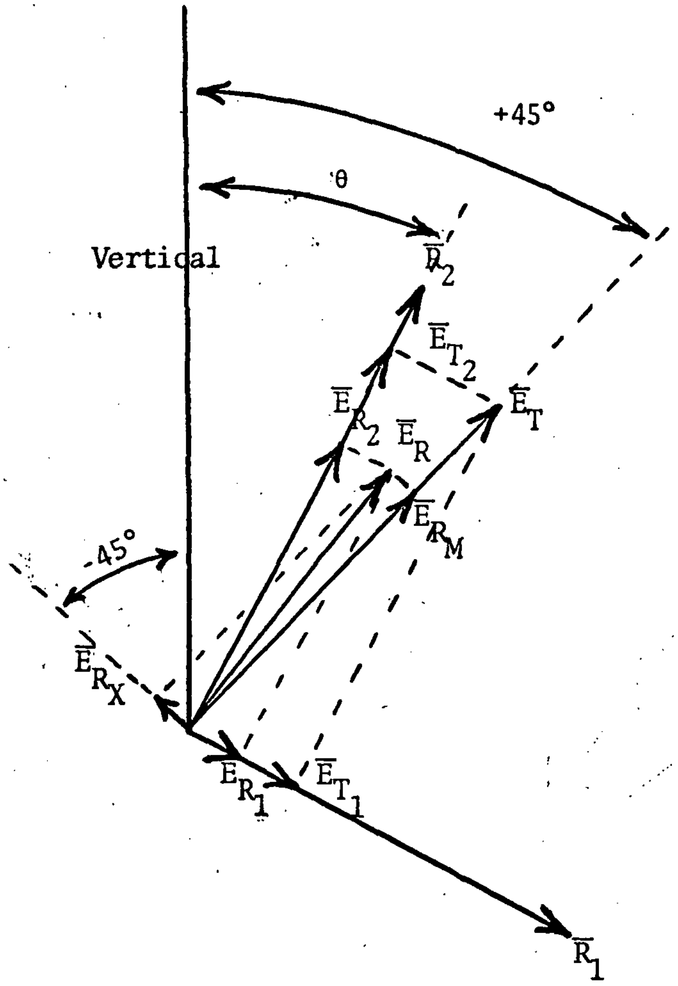

Figure 9 Method used in computation of cross-polarized signal level

Canting angle = θ = 0°

| Rain Rate | $E_T$ | $E_{T_1}$ | $E_{T_2}$ | $E_{R_1}/E_{T_1}$ | $E_{R_2}/E_{T_2}$ | $E_{R_1}$ | $E_{R_2}$ | $E_{RM}$ | $E_{RX}$ | $E_{RX}/E_{RM}$ db |
|---|---|---|---|---|---|---|---|---|---|---|
| 12.5 | 1.41 | 1 | 1 | 0.858 | 0.840 | 0.858 | 0.840 | 1.20 | 0.012 | - 40.0 |
| 25 | 1.41 | 1 | 1 | 0.743 | 0.713 | 0.743 | 0.713 | 1.03 | 0.021 | - 33.8 |
| 50 | 1.41 | 1 | 1 | 0.570 | 0.520 | 0.570 | 0.520 | 0.770 | 0.036 | - 26.6 |
| 100 | 1.41 | 1 | 1 | 0.279 | 0.225 | 0.279 | 0.225 | 0.356 | 0.038 | - 19.4 |
| 150 | 1.41 | 1 | 1 | 0.142 | 0.101 | 0.142 | 0.101 | 0.171 | 0.029 | - 15.5 |

Canting angle = θ = 15°

| Rain Rate | $E_T$ | $E_{T_2}$ | $E_{T_1}$ | $E_{R_1}/E_{T_1}$ | $E_{R_2}/E_{T_2}$ | $E_{R_1}$ | $E_{R_2}$ | $E_{RM}$ | $E_{RX}$ | $E_{RX}/E_{RM}$ db |
|---|---|---|---|---|---|---|---|---|---|---|
| 12.5 | 1 | 0.866 | 0.5 | 0.858 | 0.840 | 0.429 | 0.726 | 0.843 | 0.008 | - 40.4 |
| 25 | 1 | 0.866 | 0.5 | 0.743 | 0.713 | 0.371 | 0.616 | 0.719 | 0.014 | - 34.2 |
| 50 | 1 | 0.866 | 0.5 | 0.570 | 0.520 | 0.285 | 0.450 | 0.532 | 0.023 | - 27.2 |
| 100 | 1 | 0.866 | 0.5 | 0.279 | 0.225 | 0.139 | 0.195 | 0.238 | 0.024 | - 20.0 |
| 150 | 1 | 0.866 | 0.5 | 0.142 | 0.101 | 0.071 | 0.087 | 0.110 | 0.010 | - 16.2 |

Figure 10 Expected Cross-Polarization Levels