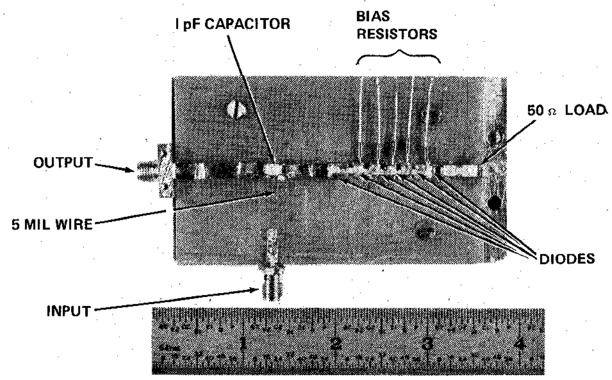

Fig. 5. Fabricated device on microstrip.

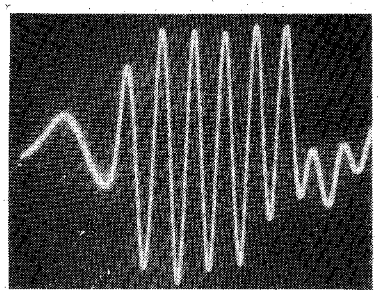

Fig. 6. *C*-band sequence-generator waveform. Vertical: 2 V/div; horizontal: 200 ps/div.

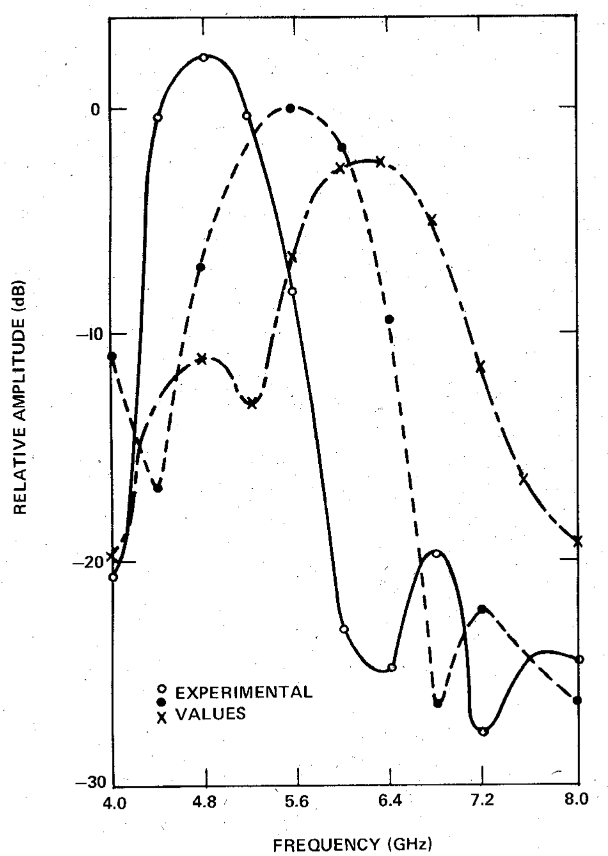

Fig. 7. *C*-band sequence-generator spectral amplitude for different biases.

waveform is found by summing all the reflected waves leaving the generator and is shown in Fig. 4(b). Note that the sequence can be modified by changing the bias currents. For example, if the bias is removed from diode 2, $t_{d2} = 0$, and the start of the reflection from diode 3 will follow the end of the reflection from diode 1 by a time $t' = 2(l_{12} + l_{23})/v$.

EXPERIMENTAL RESULTS

Several sequence generators have been constructed in microstrip in *L* and *C* band for use as RF pulse generators. A photograph of a 6-diode *C*-band generator is shown in Fig. 5. It was constructed on a 3/32-in polyolefin circuit board using Hewlett-Packard 5082-0335 SRD's spaced 0.17-in apart with 55-mil 100-pF ceramic capacitors. The bias to the first diode is supplied through the input SMA connector and 5-mil wire serving as an inductance in the input–output section. An output waveform (shown in Fig. 6) of this generator was photographed from a sampling oscilloscope. The spacing between and the amplitudes of the individual cycles can be varied by adjusting the bias. Fig. 7 illustrates the effects of different bias conditions on the spectrum computed from the Fourier transform of the time waveforms. Here, the individual biases were varied over a 2–20-mA range. A useful technique for adjusting the spectral peak of the waveform to a predetermined frequency f_0 is to make the time between the first and sixth positive peak equal to $5/f_0$ by varying the bias currents. In one application, this generator was used to obtain the transfer function of an isolated array phaseshift element over a 1-GHz bandwidth centered at 5.6 GHz. The spectrum was peaked to the desired center frequency by changing the bias currents to produce a 5/5.6 GHz = 890-ps period between the first and last peak. The unique features of the generator, the reasonable voltage amplitudes, and ease of tuning proved especially helpful for the foregoing application.

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Depolarization Measurements on the ATS-6 20-GHz Downlink: A Description of the VPI & SU Experiment and Some Initial Results

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***Abstract*—This paper discusses the depolarizing effects of precipitation at millimeter wavelengths and describes an experiment in which depolarization on the ATS-6 satellite 20-GHz downlink is measured. Data are presented for unexplained clear weather variations in the observed polarization and for depolarization by rain and snow. A preliminary analysis indicates that for a given attenuation level, a satellite path exhibits more severe depolarization than experiments with ground systems would predict.**

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I. INTRODUCTION

The VPI&SU ATS-6 experiment is primarily concerned with the depolarizing effects of precipitation at millimeter wavelengths. Since raindrops, snowflakes, and ice crystals are not spheres, they scatter electromagnetic waves anisotropically and change their polarization. This depolarization will produce crosstalk in communication systems which employ orthogonal polarizations for frequency reuse, and an understanding of atmospheric depolarization phenomena is necessary for the design of future earth–satellite systems.

Depolarization is described quantitatively by two related variables; these are illustrated in Fig. 1. The *cross-polarization ratio* (CPR) is the decibel ratio of the cross-polarized component of the received electric field to the copolarized component.

$$\mathrm{CPR} = 20 \log_{10} \left| \frac{E_{\mathrm{cross}}}{E_{\mathrm{co}}} \right|. \tag{1}$$

Since it is directly related to the electric field, the CPR is more frequently used by investigators studying the scattering process itself. Communicators are more concerned with crosstalk and the relevant parameter here is the *cross-polarization isolation* (CPI). In a two-channel communications system the CPI is the decibel ratio of the power received from the copolarized transmitter to the power received from the cross-polarized transmitter. Thus

$$\mathrm{CPI} = 10 \log_{10} \frac{\text{power received from copolarized transmitter}}{\text{power received from cross-polarized transmitter}}. \tag{2}$$

The relationship between CPR and CPI is discussed in the literature [1], [2]; in practice the CPI value is essentially the negative of the CPR value and the terms and numerical magnitudes are often interchanged.

Several groups are studying or have studied depolarization in terrestrial millimeter wave radio systems and at least two mutually consistent theoretical models have been developed [3], [4]. The theoretical problem is complicated, but if one assumes that all of the drops are aligned and that their size and shape distributions are known, it is possible to calculate CPR and CPI as a function of path average rainfall rate, path length, and canting angle (the angle between the minor axes of the drops and vertical). The predictions of the theoretical models agree well with experimental data taken on linearly polarized ground paths, but the extent to which the existing models must be modified to describe satellite path depolarization is at present unknown. Additional statistical data are needed and will be collected when the Communications Technology Satellite becomes operational.

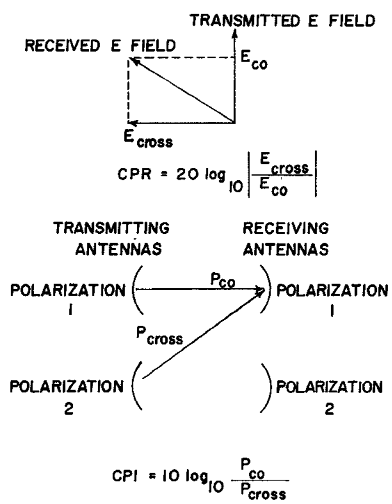

Fig. 1. Definition of depolarization parameters.

Depolarization on a ground to satellite path may be different from depolarization along a ground path for three reasons. These are: 1) differences in size and shape distributions of the raindrops; 2) the presence of snow and ice in the freezing layer; and 3) the possible influence of cirrus cloud ice crystals. To investigate these factors and to study depolarization effects in satellite communications systems, several experiments are planned or in progress. The first measurements were made at 4 GHz by Taur [5] of COMSAT; our group and our colleagues at Bell Laboratories [6] are now working at 20 GHz with ATS-6, and later efforts are planned by AT&T [7], COMSAT, and NASA.

II. EXPERIMENT DESCRIPTION

The ATS-6 satellite transmits a linearly polarized signal at 20 GHz; in our experiment we are measuring the incoming power in the copolarized and cross-polarized components of the incident signal. From these we can compute the CPR. Under clear weather conditions, the CPR is small (−28 to −50 dB, depending upon antenna alignment); precipitation depolarization causes it to rise.

A block diagram of our experimental system appears in Fig. 2. In addition to the CPR of the incoming signal, it records attenuation and ground-level rain and wind data. A *Ku*-band radar is used to probe the weather conditions along the satellite path. All of the equipment is under the real-time control of a dedicated Raytheon PB-440 digital computer which updates the antenna pointing at 10-min intervals and performs initial data processing.

The receiver switches between the cross-polarized and copolarized antenna feeds once every 2 s.

III. CLEAR WEATHER EFFECTS

In the simplest kind of a dual-polarized satellite communication system, the ground antenna polarization would be aligned with the nominal clear weather polarization of the satellite signal and left for long periods without adjustment. With linear polarization, the proper antenna alignment may be found by rotating the receiving antenna until the cross-polarized signal components pass through a null. But even with perfect polarization alignment and clear weather, cross-polarization coupling in the transmitting and receiving antennas will cause the system to retain a finite level of cross-polarization isolation; this is called the residual isolation of the system (better than −40 dB for our station). The clear weather isolation observed in a dual-polarized satellite communications system depends upon the residual isolation and the accuracy of the antenna polarization alignment. Slightly misaligned "good" (high-isolation) antennas may be used to simulate aligned "poor" (lower isolation) antennas. If the satellite or ground antenna alignments change, the clear weather cross-polar-

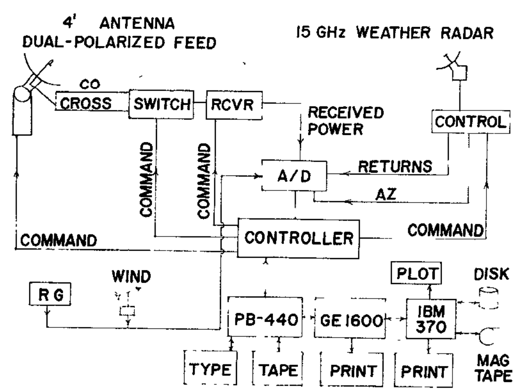

Fig. 2. Experimental system block diagram.

TABLE I
MEASURED CLEAR WEATHER POLARIZATION ANGLES WITH SPACECRAFT ANTENNA DIRECTED AT VPI&SU

Date (UT)	Time (UT)	Polarization Angle
6 February 1975	2100	−21.4°
7 February 1975	1900	−21.1°
20 February 1975	2200	−20.5°
28 February 1975	2230	−21.6°
4 March 1975	1917	−21.6°
10 March 1975	1800	−21.7°
20 March 1975	2005	−18.9°

ization isolation will change with them. This will raise the crosstalk level, and the designer must allow a crosstalk margin large enough to absorb the clear weather variations and rain effects or else develop some means for periodic polarization matching.

When the ATS-6 experiment began, the consensus of NASA engineers was that the spacecraft attitude control system was so precise that no ground antenna polarization adjustments would be necessary to maintain a residual isolation close to optimum. The theoretical clear weather polarization of the ATS-6 signal at VPI (when the spacecraft antenna is pointed at VPI) is −17°, where the minus sign indicates a westward or right-hand tilt as seen by an observer standing at our station and facing the spacecraft. Our initial measurements indicated an actual value of −19.5°; given the uncertainties involved in making an absolute measurement of the polarization angle, this was acceptably close to the theoretical prediction and for about seven months we kept our antenna polarized at −19.5°.

In December 1974 and January 1975 our station was off the air for receiver repairs and modifications and after resuming operations, we rechecked the clear weather polarization angle. To our surprise, it had changed to −21.4°. We could find no reason for the change and began a program of measuring the clear weather polarization whenever the spacecraft was available. Table I presents the results of measurements made in February and March 1975. The values indicated have a mean of −20.97° and a standard deviation of 1°. A much larger sample is needed to more accurately establish the 3σ value.

The spacecraft yaw is supposed to be held to within 0.05°. A careful review of the spacecraft telemetry data by the satellite controllers and repeated checks of our antenna positioning system have shown no mechanical misorientations that could cause the observed polarization angle changes. Before each measurement our antenna pointing is carefully adjusted to maximize the received signal (to an accuracy of ±0.1°); hence, off-axis reception [8] would not seem to be at fault.

At present the cause of these clear weather variations is unknown. In all possibility they lie in some undetected error in the spacecraft control system or in the ephemeris data that go into it rather than any propagation phenomenon, but whatever the cause, variations like this would degrade any dual-polarized satellite communications system. With our equipment a 1° rotation in either direction reduces the clear weather CPR from about −40 dB to about −35 dB. This in itself would not be unacceptable for a commercial system, but the effect should be watched by other investigators.

IV. RAIN DEPOLARIZATION

On March 30, 1975, we recorded our first significant rain depolarization data. These appear in Fig. 3 which plots rainfall rate, CPR, and attenuation points which represent sample values taken at 1-min intervals; the blank spaces are times when our receiver lost phaselock and was searching for the satellite signal.

The rain gauge data in Fig. 3 are from three tipping bucket gauges. Gauge 1 (solid line) is directly beside the receiving antenna. Gauge 2 (dashed line) is 650 ft away and approximately 650 ft directly below

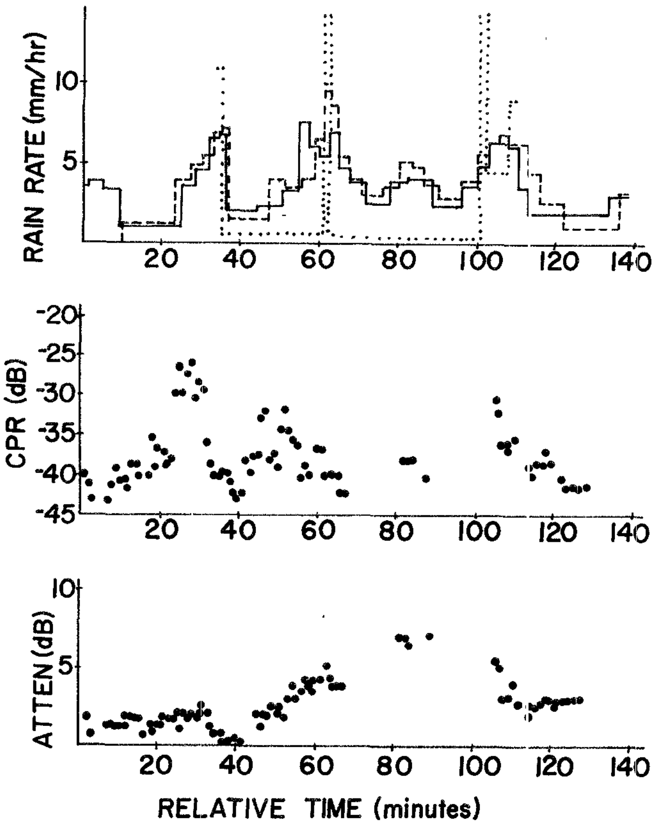

Fig. 3. Rain depolarization and attenuation data from the storm of March 30, 1975.

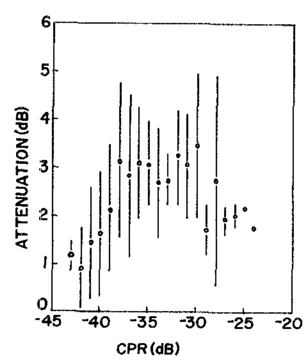

Fig. 4. Attenuation versus CPR for the storm of March 30, 1975. Each point represents the average attenuation at each 1-dB interval of CPR. The vertical bars extend ± one standard deviation from the average.

the radio path. Gauge 3 (dotted line) is approximately 2500 ft away in the general direction of the satellite and about 2500 ft below the path. Since our 15-GHz radar indicated the rain was about 9 mi deep (in the direction of the satellite) and 3 mi high, we suspect that gauge 3 may have malfunctioned and reported only during the most intense rain.

A striking feature of these data is the strong correlation between the rain rate peaks and the CPR peaks. The CPR peaks occurred slightly earlier than the rain rate peaks because of the time required for the raindrops to fall from the path to the gauges.

Unlike what we have observed on terrestrial radio systems, the attenuation and CPR are not well correlated with each other. The plot of attenuation versus CPR from terrestrial path data follows a well-defined curve. Peaks of attenuation and peaks of CPR occur simultaneously [9]. Fig. 4 shows average attenuation for each integer value of observed CPR. The attenuation does not continually increase with CPR. No explanation is offered for the lack of correlation between attenuation and CPR from satellite path data. More experimental observations are needed.

V. SNOW DEPOLARIZATION

A severe snowstorm lasting from November 30–December 2, 1974, yielded what we think are the first snow depolarization data for a satellite path. Snow and occasional freezing rain fell during most of this time interval, but from time to time there was considerable variation in the ground precipitation rate. The net snow accumulation was measured at 10 in by our local U.S. Weather Service observer.

Since the spacecraft operational restrictions prevented us from obtaining a continuous look at the signal from beginning to the end of the storm, we made a series of separate observations, each several hours in length. After the storm was over, we made clear sky calibration runs on December 3 and 6 to aid in data analysis.

Fig. 5 displays average measured values of attenuation and cross-polarization ratio versus time for the data runs between November 30, and December 6, 1974. Breaks in the time axis emphasize that this figure is a collection of data from five different runs spread over six calendar days.

The θ variable in Fig. 5 is the antenna polarization angle. Under clear weather conditions at the time of measurement the incoming signal was polarized at or near $\theta = -19.5°$, but with this antenna polarization the cross-polarized component was below the receiver phaselock threshold. Since then, we have improved the receiver sensitivity to the point that it maintains lock on the cross-polarized components. But at that time we normally operated the antenna at $\theta = -16.5°$; this provided a clear weather isolation of -28 dB and enabled the receiver to work properly. However, on December 2, the snow depolarization was such that we were able to make measurements at $\theta = -19.5°$.

On November 30, and the early part of December 1, heavy snow was falling. During the second run on December 1, the ground snowfall rate was negligible, but heavy cloud cover remained and surprising attenuation and CPR values were measured. On December 2, the satellite was available during an intense snow shower. As the hour progressed, the snow rate decreased and we saw corresponding changes in the attenuation and CPR. Unfortunately, we had to relinquish use of the satellite before the snow ended.

Snow depolarization is somewhat more difficult to analyze than rain depolarization because at present a theoretical model is nonexistent even for a terrestrial path and in addition, we have no handy "snow rate" parameter analogous to rain rate. One approach is to plot attenuation versus CPR and examine the result. This is done in Fig. 6 for all of the data presented in Fig. 5.

The data in Fig. 6 bear some resemblance to the attenuation versus

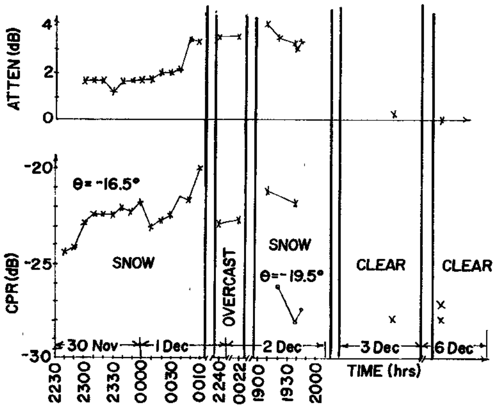

Fig. 5. Attenuation and CPR data for the snowstorm of November 30–December 2, 1974.

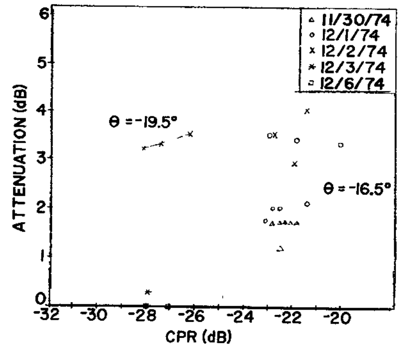

Fig. 6. Attenuation versus CPR for the November 30–December 2, 1974 snowstorm and subsequent clear weather calibration periods.

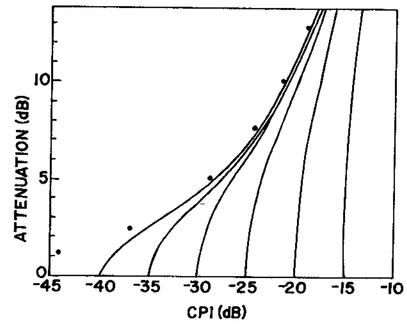

Fig. 7. Rain-induced fade versus cross-polarization level (including antenna effects). The abscissa intercepts are the residual (clear weather) antenna isolations. Points indicate scattering model theory for no antenna effects.

cross-polarization isolation plots calculated for rain depolarization in terrestrial radio systems using nonideal antennas [10]. Fig. 7 is a typical plot for a 19.3-GHz 1-km rain-filled path with 45° linear polarization and a variety of residual (clear weather) CPR values [10]. This is *not* a theoretical model for our 20-GHz snow data for the satellite path; it is introduced to show the trend of these curves and the effect on them of the residual isolation.

The effect of varying our antenna polarization angle is to change the residual CPR. At $\theta = -16.5°$, the clear weather CPR is -28 dB; the measured data at $\theta = -16.5°$ bear some resemblance to the -30-dB theoretical curve for rain.

A question to be resolved about all of this is where do the depolarization and attenuation occur? Is it in the obvious snowflakes near the ground, or is it in the clouds overhead, or do both play a part? Certainly our data of 2240 (UT) on December 1, through December 2, 1974, implicate the clouds, because little or no ground precipitation occurred during this time. On the other hand, the attenuation and CPR levels noted 1900–1950 on December 2, 1974, were correlated with the snow intensity at ground level by visual observation of the snow and the radar A-scope. When both clouds and snow were gone, the clear weather signal levels returned to their normal values. The obvious conclusion is that ground precipitation and higher altitude phenomena both play a role; the only sure way to separate the two is to compare snow depolarization data measured simultaneously on terrestrial and satellite paths.

Another potential source of error related to the antennas is apparent depolarization resulting from off-axis reception.[1] Ghobrial and Watson [8] first reported this as being caused by refractive effects on long paths; on a satellite path it could conceivably come from refraction or from antenna pointing errors. To eliminate both possibilities we made plots of CPR versus azimuth and elevation offset

[1] So far as could be determined, snow and ice accumulation on our antenna reflector and feed were negligible throughout the storm.

during the clear weather tests of December 6. These showed the CPR levels associated with off-axis reception to be well below the values measured during the storm (at least for the high residual CPR associated with $\theta = -16.5°$) and would seem to eliminate off-axis reception as a source of error in our data.

A striking feature of the snow data displayed in Fig. 6 compared to rain data from a terrestrial link [2] is the large depolarization observed for a given attenuation. To get a CPR of −28 dB (the leftmost $\theta = -19.5°$ point in Fig. 6) with rain on a ground path would require at least 7-dB attenuation and possibly as much as 20 or 30 dB, depending on path length and raindrop canting angle.

Some theoretical case may be made for associating small attenuation and severe depolarization with scattering by bodies which are relatively lossless but lack rotational symmetry. Certainly snowflakes and high-altitude ice crystals fit this description, but the very fragmentary data available for snow do not necessarily support this conclusion. Watson [11] working at 11 GHz with a 13.7-km path reported a huge fade (24 dB) in wet snow accompanied by a CPR of −22 dB. On the other hand, a rain fade of only 8 dB on the same path was associated with a −20-dB CPR. Since our frequency is almost twice that of Watson's and his snow was wet while ours was dry, it is very possible that he could have been dealing with scatterers that were relatively more isotropic than ours were. Some Russian work [12] at a much higher frequency also indicates that, for the same water content, snow attenuates more highly than rain, but this tells us nothing about depolarization. Clearly more research is needed. We should operate a terrestrial path link and a satellite downlink simultaneously, and also study the high-altitude conditions with a polarization diversity radar.

ACKNOWLEDGMENT

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Microwave Scattering from the Ocean Surface

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***Abstract*—This paper reviews current aircraft and satellite programs which use microwaves to measure ocean wave and surface wind conditions. These particular measurements have been identified by the user community as offering significant economic and technological benefits. Active microwave remote sensing techniques for these applications have been described theoretically and verified experimentally. The results of recent aircraft and satellite experimental programs are presented herein along with plans for the SeaSat-A satellite scatterometer (SASS).**

INTRODUCTION

For many years many industrial and government groups have expressed interest in measuring a variety of oceanographic conditions. However, the great area of the sea and its harsh environment have prevented effective monitoring with sufficient observational density to satisfy most of their requirements. A recent study conducted for NASA has shown that significant economic and technological benefits would result from a satellite able to measure ocean waves and surface winds on a global scale. Even though many desired oceanographic parameters cannot be inferred from satellite measurements, data from a spacecraft can be combined with other surface measurements to construct a more general view of the ocean. Furthermore, surface observations are quite useful by themselves to bolster the library of measurements of the ocean/atmosphere interaction. Several active microwave techniques have been shown, both theoretically and experimentally, to be applicable for aircraft and/or satellite ocean measurements. Other radar techniques in earlier stages of development promise improved or expanded ocean remote sensing capabilities. This short paper reviews several of the foregoing techniques including recent aircraft and satellite ocean measurements and presents plans for the SeaSat-A satellite scatterometer (SASS).

WAVE MEASUREMENTS

An extensive real-time data collection network with rapid dissemination of data to users does not currently exist for the global ocean wave conditions. Moreover, existing quantitative techniques utilize *in situ* instrumentation and frequently involve laborious data analyses. Radar techniques, however, have exhibited potential for rapid and accurate measurements of ocean wave conditions over large areas.

A dual-frequency correlation technique has been developed by Weissman [1] for measuring the root-mean-square (rms) wave height averaged over an area of the sea that is much greater than typical horizontal wavelengths, of the wind-generated waves. Implementation of this technique on commercial and/or military aircraft while on transoceanic flights would provide routine observations of rms wave height over major shipping lanes. This technique of measurement involves a near-nadir looking radar that transmits and then receives two monochromatic plane electromagnetic waves simultaneously. At the receiver the two radar returns are correlated as a function of their variable frequency separation Δf. The resulting cross correlation $R(\Delta f)$ depends primarily on the rms wave height.

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