THOMAS J. SCHMUGGE
NASA Goddard Space Flight Center
Greenbelt, MD 20771

Microwave Approaches in Hydrology

Soil moisture condition in the surface layer of the soil can be monitored; and light and heavy snow cover can be discriminated, the presence of liquid water in snow can be detected, and snow water equivalent can be qualitatively estimated.

ABSTRACT: *The development of microwave sensors and the research on their application to the study of hydrologic problems has proceeded rapidly in the last few years. There are two primary reasons for this: first, the desirability of the all-weather capability of microwave sensors and second, the unique dielectric properties of liquid water cause it to be the dominant parameter influencing the microwave interactions at the Earth's surface. This is observed in variations of the microwave emissivity and radar backscatter. The particular hydrologic parameters that are being studied include soil moisture content, snowpack properties, surface water area, and the detection of precipitation over land. Both passive (radiometry) and active (radar) microwave approaches will be discussed with examples of results obtained from ground based, aircraft, and spacecraft platforms. Specifically, results will be presented which indicate that microwave systems can monitor the soil moisture condition in the surface (~0–5 cm) layer of the soil and that passive microwave systems can monitor snowpack conditions, e.g., discriminate between light and heavy snowcover, detect the presence of liquid water in the snow, and qualitatively estimate snow water equivalent.*

INTRODUCTION

AN INCREASING world population imposes greater demands on available water supplies. Variations in climate, leading to floods or drought, create havoc with the proper allocation of water in maintaining the present quality of life. Reasonable estimates of future water use and demand indicate a three to five times increase by the year 2000. To meet this increased demand, existing water supplies for a given region will have to be managed more efficiently, with intelligent transfers of water from regions having excess supplies to areas of scarcity. This improvement in water management efficiency will require better input data, in terms of accuracy and timeliness, for the decision making models used by hydrologists.

Since 1960 satellites have proved their worth by contributing data for water resources management. The early visible camera systems were later supplemented with infrared and near-infrared sensors. Unfortunately, these sensors are restricted by clouds from viewing the Earth and are limited in the number of hydrologic parameters they can adequately observe. Variables such as soil moisture, snowpack density, snow wetness, precipitation distribution, and timely observations of floods are not amenable to these shorter wavelength sensors.

The microwave portion of the electromagnetic spectrum offers potential for monitoring several of these parameters which are inputs to the models. For the purposes of this discussion the wavelength

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 46, No. 4, April 1980, pp. 495-507.

range from 0.3 cm to 50 cm will be considered the microwave portion of the spectrum.

The particular advantages of microwave sensing are (a) all weather capability, especially true at the longer wavelengths ($\lambda \gtrsim 5$ cm), which is important for any periodic observations from space of these surface parameters; (b) greater penetration depth into the soil or snowpack than with optical or infrared sensors; and (c) the large changes in the dielectric properties of media such as soil and snow produced by changes in water content.

In this paper we will present results indicating the current status of the use of microwave approaches for the remote sensing of parameters such as soil moisture, snowpack properties, and precipitation over land. Both active and passive microwave approaches will be discussed. The passive microwave approach (radiometry) involves the measurement of the thermal emission from the surface at microwave wavelengths. This emission depends on the temperature and emissivity of the surface medium. This is to be contrasted with the active microwave approach (radar) in which a pulse of microwave energy is transmitted by the sensor and the return or reflected signal is measured. The strength of the return depends on the surface roughness and dielectric properties of the terrain being studied, but not directly on the temperature of the medium. The *Manual of Remote Sensing,* published by the American Society of Photogrammetry, gives very complete descriptions of both these approaches (Reeves, 1975).

SOIL MOISTURE

The unique dielectric properties of water afford two possibilities for the remote sensing of the moisture content in the surface layer of the soil. The dielectric constant (ϵ) for water is an order of magnitude larger than that of dry soils at the longer microwave wavelengths, i.e., approximately 80 compared with 3 or 4 for dry soils. As a result, the surface emissivity and reflectivity for soils are strong functions of their moisture content. The changes in emissivity can be observed by passive microwave approaches, and the changes in reflectivity can be observed by active microwave approaches.

The dependence of the dielectric constant for a soil on its moisture content is shown in Figure 1, where the results of laboratory measurements at wavelengths of 21 and 1.55 cm are presented. The wavelength dependence is due to the difference in the dielectric properties of water at the two wavelengths and indicates that there is a greater dielectric difference at the longer wavelengths. At low levels there is a slow increase with soil moisture, but above a certain level there is a sharp increase in the slope of the curve. This bilinear result is due to the behavior of the water in the soil. When water is first added to a soil, it is tightly bound to the soil particles and in this state the water molecules are not free to become aligned and the dielectric properties of this water are similar to those of ice. As the layer of water around the soil particle becomes larger, the binding to the particle decreases and the water molecules behave as they do in the liquid, hence the greater slope at the higher soil moisture values. The transition depends on the soil texture, i.e., particle size distribution are lower for a sand and large for a clay. This effect has been demonstrated in laboratory measurements of the dielectric constant (Lundien, 1971; Newton, 1976; Wang and Schmugge, 1979).

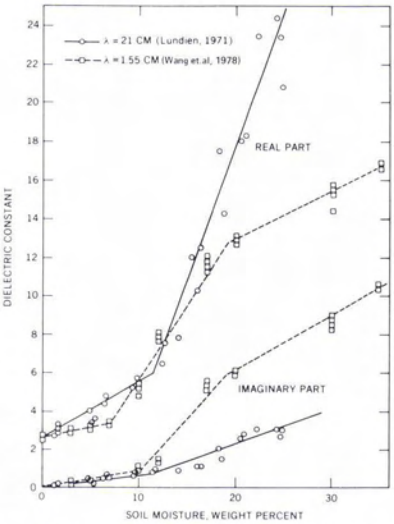

FIG. 1. Dependence of the soil's dielectric constant on its moisture content.

Recall that the dielectric constants of the medium describe propagation characteristics for an electromagnetic wave in the medium. Therefore, they determine the emissive and reflective properties for a smooth surface.

PASSIVE MICROWAVE RESPONSE TO SOIL MOISTURE

A microwave radiometer measures the thermal emission from the surface, and at these wavelengths the intensity of the observed emission is essentially proportional to the product of the temperature and emissivity of the surface (Rayleigh-Jeans approximation). This product is commonly referred to as brightness temperature. All of our results will be expressed as brightness temperatures, T_B. The value of T_B observed by a radiometer at a height, h, above the ground is

$$T_B = \tau(rT_{\text{sky}} - (1 - r)T_{\text{surf}}) + T_{\text{atm}}$$

where r is the surface reflectivity and τ the atmospheric transmission. The first term is the reflected sky brightness temperature, which depends on wavelength and atmospheric conditions; the second term is the emission from the surface ($1 - r = e$, the emissivity); and the third term is the contribution from the atmosphere between the surface and the receiver. At the longer wavelengths, i.e., those best suited for soil moisture sensing, the atmospheric effects are minimal and will be neglected in this discussion.

The range of dielectric constant presented in Figure 1 produces a change in emissivity from greater than 0.9 for a dry soil to less than 0.6 for a wet soil, assuming an isotropic soil with a smooth surface. This change in emissivity for a soil has been observed by truck mounted radiometers in field experiments (Poe, 1971; Blinn, 1972; Newton, 1976), and by radiometers in aircraft (Schmugge, 1974; Estes, 1977; Barton, 1978) and satellites (Eagleman, 1976). In no case were emissivities as low as 0.6 observed for real surfaces. It is believed that this is primarily due to the effects of surface roughness, which generally has the effect of increasing the surface emissivity.

As can be seen in Figure 1, there is a greater range of dielectric constant for soils at the 21 cm wavelengths. This fact, combined with a larger soil moisture sampling depth and better ability to penetrate a vegetative canopy, makes the longer wavelength sensors better suited for soil moisture sensing.

In Figure 2a and b, the field measurements of Newton (1976) are plotted versus angle of observation, θ, for various moisture contents and for three levels of surface roughness. The horizontal polarization is that for which the electric field of the wave is parallel to the surface and the vertical polarization is perpendicular to it. These results indicate the effect of moisture content on the observed values of T_B and the effect of surface roughness, which is to increase the effective emissivity at all angles and to decrease the difference in T_B for the two polarizations at the larger angles.

For the smooth field there is a 100°K change in T_B in going from wet to dry soils, and it is clear that this range is reduced by surface roughness. The effect of the roughness is to decrease the reflectivity of the surface and, thus, to increase its emissivity. For a dry field the reflectivity is already small (<0.1) so that the resulting increase in emissivity is small. As seen in Figure 2b, surface roughness has a significant effect for wet fields where the reflectivity is larger (≈ 0.4). Thus, the range of T_B for the rough field is reduced to about 60°K. The smooth and rough fields represent the extremes of surface conditions that are likely to be encountered, e.g., the rough surface was on a field with a heavy clay soil (clay fraction > 60 percent) that had been deep plowed, which produced large clods. Therefore, the

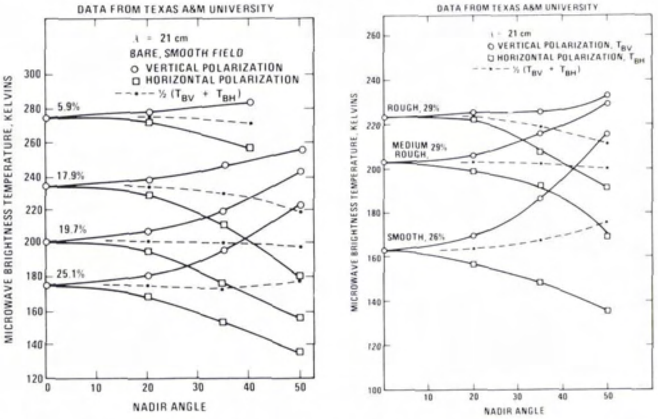

FIG. 2. Results from field measurements performed at Texas A & M University: (a) T_B versus angle for different moisture levels; (b) T_B versus angle for different surface roughness at about the same moisture level (Newton, 1976).

medium rough field, with a T_B range of 80°K, is probably more representative of the average surface roughness condition that will be encountered. Another important observation from Figures 2a and b is that the average of the vertical and horizontal T_B's is essentially independent of angle out to 40°. This indicates that the sensitivity of this quantity, $\frac{1}{2}(T_{BV} + T_{BH})$, to soil moisture will be independent of angle. This factor will be useful if the radiometer is to be scanned to provide an image.

When the brightness temperatures for the medium rough field are plotted versus soil moisture in the 0-2 cm layer, there is an approximate linear decrease of T_B, Figure 3a. As the thickness of the layer increases both the slope and intercept of the linear regression result also increase. This is because the moisture values for the high T_B cases increase, while it remains essentially the same for the low T_B or wet cases. This type of behavior was also seen in the results obtained from aircraft platforms and has led us to conclude that the soil moisture sampling depth is in the 2-5 cm range for the 21 cm wavelength. This is in agreement with the predictions of theoretical results for radiative transfer in soils (Wilheit, 1978; Burke *et al.*, 1979; Njoku and Kong, 1977).

The effect of a vegetative canopy will be that of an absorbing layer that depends on the amount of the vegetation and the wavelength of observations. In Figure 3b the results for a closely planted sorghum field (~1 m high) are presented.

The range of T_B is now about 40K compared to the 70K range observed for the bare field. While the sensitivity to the soil moisture variation is reduced, the correlation remains high (~0.9). At a shorter wavelength (2.8 cm) there was only a 10K range in T_B in going from wet to dry. While these measurements show that a radiometer operating at 21 cm still has good sensitivity to soil moisture variations, they suggest that radiometers working at longer wavelengths (30 to 50 cm) may have better sensitivity.

Significant improvements in the understanding of the effects of individual scene parameters on the relationship of brightness temperature to soil moisture have been achieved using ground-based measurements acquired during controlled experiments. However, demonstrations of the potential of passive microwave sensors for estimating soil moisture on an operational basis must be performed with aircraft and spacecraft sensors that integrate large areas of natural, non-idealized terrain. A series of aircraft experiments performed over the last several years by a number of investigators demonstrates the sensitivity of microwave radiometers to soil moisture in agriculture terrain. Skylab and Nimbus satellites have also provided significant results for very large areas of integration.

The results from aircraft experiments are summarized in Figure 4, where data from aircraft flights in February 1973 (Figure 4a) and March 1975 (Figure 4b) over Phoenix, Arizona are presented (Schmugge, 1976). The values of T_B at 21 cm and $\theta = 0°$ are plotted versus soil moisture expressed as a percent of field capacity in order to normalize the effect of soil texture differences. The agreement of the slopes for the three regressions indicates that the results are repeatable. The differences for the intercepts in Figure 4b are due to differences in soil

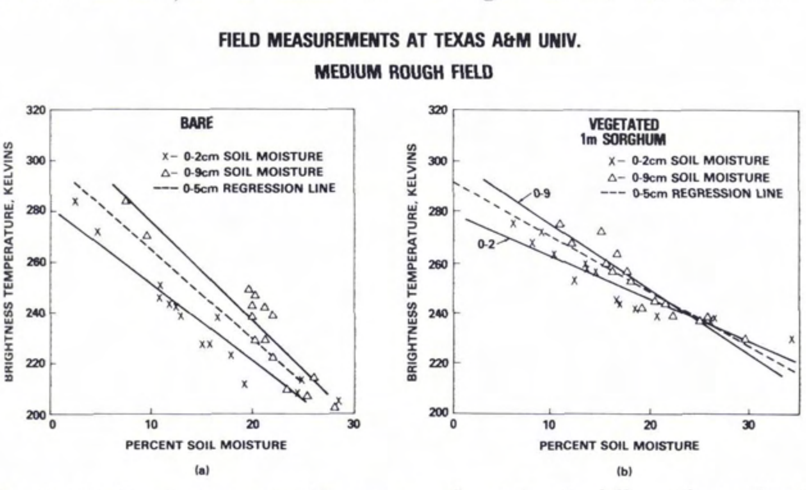

FIG. 3. Field measurements of T_B versus soil moisture in different layers for the medium rough field: (a) bare; (b) vegetated, 1 m of sorghum (Newton, 1976).

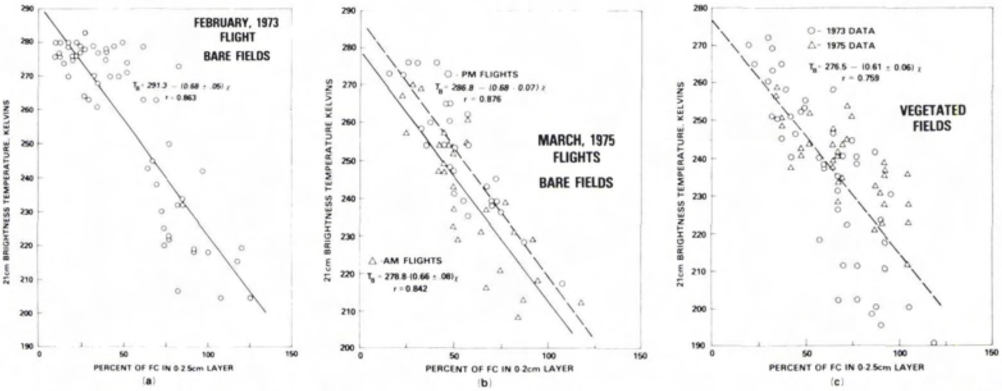

FIG. 4. Aircraft observations of T_B over agricultural fields around Phoenix, Arizona: (a) bare field results from 1973 flight; (b) bare field results from 1975 flights; (c) vegetated field results from both years (Schmugge, 1978).

temperature between the 1975 A.M. and P.M. results. Analysis of the roughness effects on these data (Choudhury *et al.*, 1979) indicate that these fields are approximated quite well by the medium rough situation of Figure 3.

In Figure 4c the results from vegetated fields for the two years are presented. The vegetation was either alfalfa or wheat with wheat being 20-30 cm high in 1973 and 50-60 cm high for the 1975 data. The slope of the curve is in good agreement with those for the bare fields. The intercept is lower due to the cooler soil temperatures. Thus, sensitivity to soil moisture is maintained through the moderate vegetative canopies considered here, which were approximately one half the height of the sorghum canopy considered in Figure 3b.

A further demonstration of the capability of the 21 cm radiometer is presented in Figure 5. Here the results at $\theta = 0°$ from six flights during 1976 and 1977 over a Hand County, South Dakota test site are compared with the regression result from the Phoenix data. The agreement is very good. These data were for a range of surface conditions including fallow fields, wheat, alfalfa, and pasture. The scatter in the aircraft data presented in Figures 4 and 5 arises from a number of sources, one of which is surface roughness as demonstrated in Figure 3b; another is the uncertainty of ground measurements. The standard deviation of the ground measurements is represented by the error bars in Figure 5. The number of samples ranged from 6 to 29 depending on the length of the fields. This difficulty of making accurate ground measurements has hampered the determination of the accuracy of this measurement technique.

Studies of the Nimbus-5 satellite Electrically Scanning Microwave Radiometer (ESMR) data at 1.55 cm wavelength have shown that it has limited applicability for soil moisture sensing. The limitation is primarily caused by a vegetative canopy over the soil. For situations where there is a significant amount of bare ground, the ESMR brightness temperature has shown significant correlations with soil moisture (McFarland and Blanchard, 1977; Schmugge *et al.*, 1977). These situations arise in agricultural areas before the crops are planted and during the early stages of growth.

Studies using the 21 cm data obtained by the S-194 instrument on board Skylab have

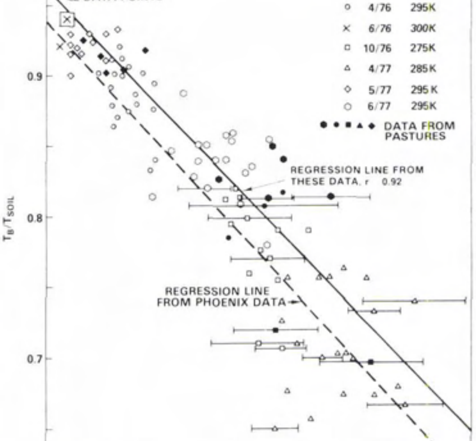

FIG. 5. Aircraft observations of T_B during 1976 and 1977 flights over agricultural fields in Hand County, South Dakota.

shown significant correlations with soil moisture variations. The latter were determined either by moisture budget models (Eagleman and Lin, 1976) or by using the antecedent precipitation index (McFarland, 1976). This was a limited data set and its interpretation was hampered by the coarse spatial resolution (~115 km) of the sensor. However, the results are encouraging for the potential use of a sensor operating at this wavelength for soil moisture sensing. Improved spatial resolution can be obtained by using larger antennas. The antenna on the Skylab instrument was 1 m square. In the future it should be possible to deploy much larger antennas from the space shuttle; for example, a 10 m antenna would yield resolutions in the 10 km range.

ACTIVE MICROWAVE RESPONSE TO SOIL MOISTURE

Analogous to the optical reflectivity of terrain, the backscattering coefficient, σ°, describes the scattering properties of terrain in the direction of the illuminating source. The scattering behavior of terrain is governed by the geometrical and dielectric properties of the surface (or volume) relative to the wave properties (wavelength, polarization, and angle of incidence) of the incidence illumination. Recall from Figure 1 that the dielectric constant of a soil-water mixture is strongly dependent on its water content. Thus, in general, σ° of terrain is dependent on the soil moisture content of an effective surface layer whose thickness is governed by the penetration properties of the terrain at the wavelength used; this thickness will be approximately the same for active and passive microwave approaches. In addition to its dependence on soil moisture content, however, σ° is also in general a function of the surface (or volume) roughness and vegetation or snow cover (if not bare). The variations of σ° with soil moisture, surface roughness, incidence angle, and observation frequency have been studied extensively in ground based experiments conducted by scientists at the University of Kansas (Batlivala and Ulaby, 1977) using a truck mounted 1-18GHz active microwave system. Some of their conclusions based on these investigations will be presented here.

To understand the effects of look angle and surface roughness, consider the plots of σ° versus angle presented in Figure 6 for five fields with essentially the same moisture content but with considerably different surface roughness. At the longest wavelength (1.1 GHz, Figure 6a), σ° for the smoother fields is very sensitive to incidence angle near nadir, while for the rough field σ° is almost independent of angle. At an angle of about 5° the effects of roughness are minimized. As the wavelength decreases, (Figure 6b and 6c) all the fields appear

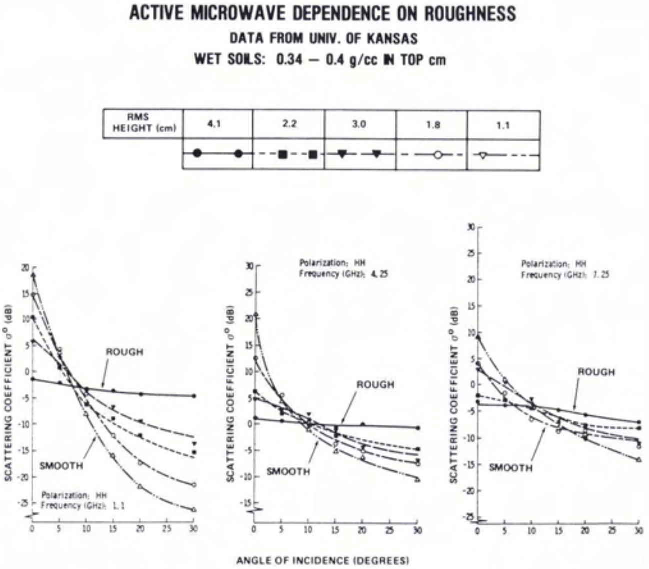

FIG. 6. Angular response of scattering coefficient for the five fields in high levels of moisture content: (a) L-band (1.1 GHz); (b) C-band (4.25 GHz); (c) X-band (7.25 GHz). 1975 soil moisture experiment (Batlivala and Ulaby, 1977).

rougher, especially the smooth field, and as a result the intersection point of the five curves moves out to larger angles. At 4.25 GHz the intersection occurs at 10°, and it was this combination of angle and frequency that yielded the best sensitivity to soil moisture independent of roughness. Based on these results, the following set of optimum parameters was determined: $\lambda = 6-7$ cm, $\theta = 7° - 17°$ from nadir, and horizontal transmit-horizontal receive polarization (Ulaby and Batlivala, 1976).

In addition to surface roughness, another soil variable that has exhibited an influence on the σ° response to moisture is soil texture. Figure 7b (Ulaby *et al.*, 1978) presents plots of two linear regression lines based on experimental measurements acquired in 1974 at a test site near College Station, Texas, and in 1975 at a site near Lawrence, Kansas. The 1974 soil was Miller clay with 49 percent clay content whereas the 1975 soil was Eudora silt loam with only 17.2 percent clay content. The two regression lines show a substantial difference in sensitivity (slope). A similar difference in sensitivity due to soil texture was observed by Schmugge *et al.* (1976) in their study of the passive microwave response to soil moisture. Airborne data acquired over test sites located near Phoenix, Arizona and in Imperial Valley, California showed a weaker sensitivity to moisture content of heavy soils (high clay content) than for light soils. To incorporate soil texture in the microwave response to soil moisture, the latter was expressed in terms of percent of field capacity, m_{fc}. The same conversion to percent of field capacity used by Schmugge *et al.* (1976) was applied to the radar data of 1974 and 1975, and the resulting regression lines, shown in Figure 7a, are in better agreement than those in Figure 7b. Although these results suggest that the dependence of σ° on soil texture can be removed by expressing moisture content in percent of field capacity, it is apparent that additional experiments are needed covering a wide range of soil texture.

Similar experiments were performed for fields with a variety of vegetative covers, i.e., wheat, corn, milo, and soybeans (Ulaby *et al.*, 1979). The vegetation heights ranged from about 0.5 m for the soybeans to over 2.5 m for the corn. They found that the correlations between σ° and the moisture in the 0-5 cm soil layer held up very well compared to those for bare soils, i.e., the slopes of the regression lines were equal to or, in a few cases, greater than those obtained for bare soils. Also, for the vegetated fields the best correlation was obtained between σ° and the moisture in the 0-5 cm layer, while for the

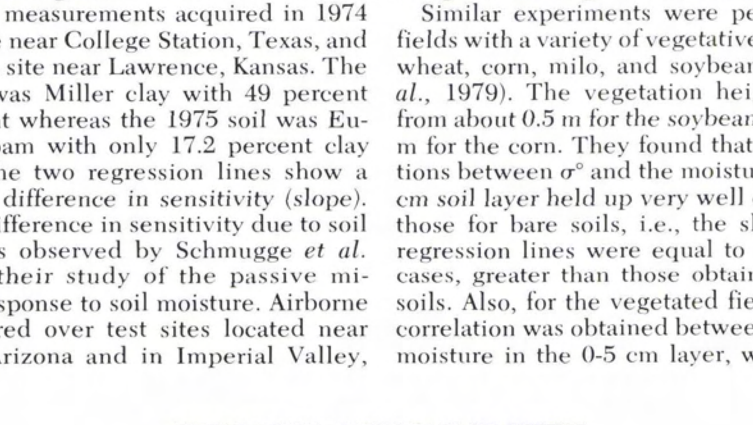

FIG. 7. Backscattering coefficient plotted as a function of soil moisture given (a) in percent of field capacity of the top 1 cm and (b) volumetrically in the top 1 cm. Data from bare soil experiments in 1974 (○) and 1975 (●) are combined (Batlivala and Ulaby, 1977).

bare soil cases the correlations were generally better with the 0-1 or 0-2 cm layers of the soil. This latter fact probably results from the more uniform profiles expected for vegetated fields. This good correlation between the microwave response and soil moisture for vegetated fields significantly enlarges the range of conditions for which microwave sensing of soil moisture is applicable.

There have been several recent experiments studying the active microwave approach with airborne scatterometers, and the results should be available in the near future. In a preliminary report on an experiment consisting of a series of six flights over the same set of fields, Blanchard (1978) has concluded that, with repeated looks at fields which maintain the same level of roughness, it is possible to make estimates of soil moisture changes.

An opportunity to at least qualitatively test the active microwave approach from space will be provided by the synthetic aperture imaging radar on the Seasat satellite launched in June 1978. This radar, operating at a wavelength of 22 cm (L-Band), is capable of producing wide swath imagery with a spatial resolution of 25 m.

SNOWPACK PROPERTIES

The majority of the streamflow in most areas of the western United States is produced by the melting of the accumulated snowpack. In order to make efficient use of this snowmelt runoff, water resource agencies must be able to make early predictions of the total flow. In recent years satellite determinations of the snow covered area have been used to increase the accuracy of the early streamflow forecasts (Rango and Itten, 1976; Rango, 1975). An additional improvement could be made if it were possible to remotely sense the depth or water equivalent of the snow. At the present time this is not possible, but preliminary studies with microwave systems indicate that the potential may be there for doing this.

In contrast to the case for soils, the bulk dielectric properties of snow do not give an adequate prediction of the microwave response. For example, the dielectric constant of snow will be between that of air ($\epsilon = 1.0$) and ice ($\epsilon = 3.2$), the two components of snow, and can be estimated as a function of snow density using the standard dielectric mixing formulae. For a snow density of 0.5 gm/cm^3 this yields a dielectric constant of 2. The resulting emissivity for smooth surface would be approximately 0.98, and a T_B very close to the physical temperature should be observed. Indeed this is approximately observed for long wavelengths (>10 cm) and thick snowpacks, e.g., glaciers. For shorter wavelengths a more interesting phenomena is observed; volume scattering by the individual ice grains reduces T_B by scattering some of the radiation out of the sensor field of view. This has the effect of introducing some of the cold sky brightness temperature into the radiometer field of view, thus reducing the observed T_B. For the active microwave case, volume scattering greatly increases the backscatter from the snow. This effect will become stronger as the wavelength in ice approaches the grain sizes in the snow, typically on the order of a millimetre.

Experiments to date have indicated that the microwave response of snow is dependent on a number of parameters: depth, grain size, presence of liquid water, type and condition of the underlying media, and the wavelength of the observation. Examples of these dependencies are presented in Figure 8, where results from radiometers operating in the wavelength range 0.8 to 21 cm are given. The radiometers were on the NASA Convair 990 aircraft which flew over snow targets in the western United States. Three sites with different substrata were overflown. The first of these is Bear Lake, on the Utah-Idaho border, which had 15 cm of snow and 25 cm of ice over the water. The second site was a river valley south of Steamboat Springs, Colorado, which had 80 cm of snow over a wet soil. The third site was the South Cascade Glacier in the state of Washington, which had 5 metres of snow over ice. This was at a point neat the terminus or the end of the glacier.

In this figure T_B is plotted versus the wavelength of the radiometers. Note the large variation in brightness temperature ob-

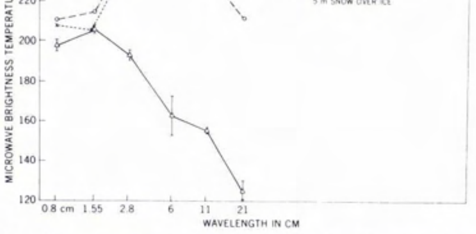

FIG. 8. Variation of microwave brightness temperature for snow with radiometer wavelength (Schmugge, 1973).

served by the longer wavelength radiometers, indicating their sensitivity to the media underlying the snow due to the transparency of snow at these wavelengths. The short wavelength radiometers, the 0.8- and 1.5-cm, displayed the least amount of variation and, in general, displayed a lower brightness temperature than the longer wavelength radiometers. This is due to the fact that they were responding primarily to the surface snow, which in general was dry with a density on the order of 0.2 g/cm³. The lower brightness temperature for these wavelength radiometers is due to a volume scattering effect caused by the snow grains.

At Bear Lake, the 21-cm radiometer has the lowest brightness temperature, indicating that it is seeing the low brightness temperature of water through the snow. As the wavelength decreases, the brightness temperature increases until the dry snow values for the 1.5- and 0.8-cm radiometers are reached. Similarly, at Steamboat Springs, the 21-cm radiometer has the lowest brightness temperature, indicating that it is able to see the wet soil through the snow.

At the glacier, the 21-cm and 11-cm radiometers had the highest brightness temperatures, and the values observed were in good agreement with those calculated using the known dielectric properties for ice and snow. As the wavelength decreases at the glacier, the brightness temperature also decreases until the low brightness temperature values for the 0.8- and 1.5-cm radiometers are reached, which indicates that these low brightness temperatures are in disagreement with the values calculated using the bulk dielectric properties for snow and ice.

SNOW WETNESS

Another important snow property that has a large effect on the microwave response at the shorter wavelengths is the presence of liquid water in the snowpack. For dry snow, volume scattering reduces the observed T_B by scattering some of the radiation out of the sensor field of view. When there is a film of liquid water on the ice grains, the scattering is reduced and the medium becomes lossy and behaves radiometrically like a blackbody. In Figure 9 the diurnal variations of both active ($\sigma°$) and passive (T_B) microwave systems are presented for a case in which there is some surface melting at mid-day. The snow temperature at 26 cm above ground (4 cm below snow surface) reached 0°C at 1030 hours and remained near 0°C until about 2200 hours, by which time the air temperature had dropped down to about −4°C, causing the pack to cool again. The ground was in a frozen state throughout the diurnal cycle. The wetness, or percent free water by weight, lags the air temperature which went above 0°C at 900 hours, and continues to increase during periods of positive air temperatures. The wetness was measured by a calorimetric technique. The reason for the dip in free water at 1100 hours is unknown but does to some extent follow the air temperature drop.

For the active microwave case there is a large return for dry snow, positive at the 0.84

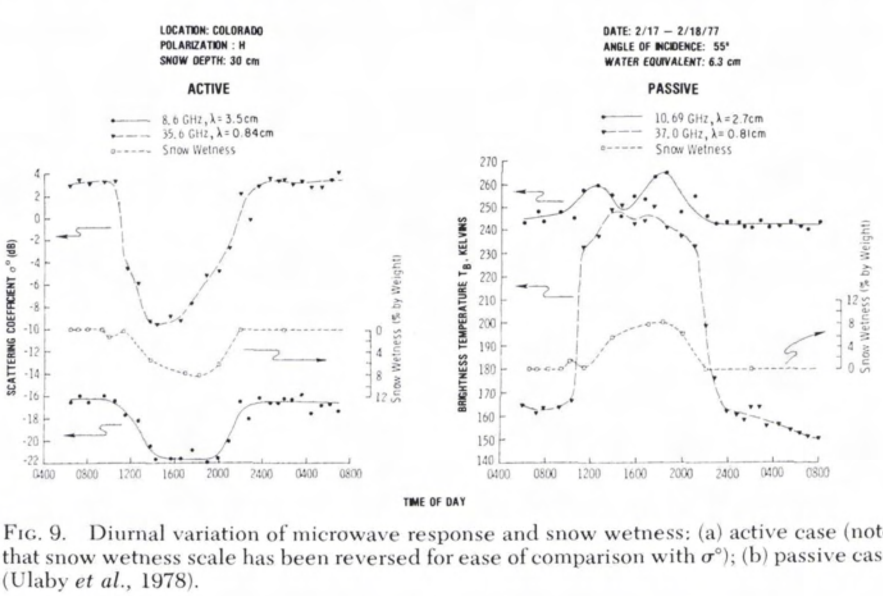

FIG. 9. Diurnal variation of microwave response and snow wetness: (a) active case (note that snow wetness scale has been reversed for ease of comparison with $\sigma°$); (b) passive case (Ulaby *et al.*, 1978).

cm wavelength where volume scattering is most effective. At the 3.5 cm wavelength the return is down by 20dB because the volume scattering effects are much smaller. For both wavelengths there is a dramatic decrease in the return when the snow becomes wet and absorption becomes dominant over scattering.

The situation for the radiometric case is similar; very low values of T_B are observed for the dry snow of the 0.81 cm wavelength, with a large, 80K, rise in T_B when the snow becomes wet. The rise in T_B at the 2.7 cm wavelength is much less, but T_B does come close to the physical temperature of the snow. From these results it is clear that microwave approaches can detect the presence of liquid water in the snow and, thus, the onset of melt in the pack; whether or not the amount of liquid water can be determined is a subject for further research.

SNOW WATER EQUIVALENT

The important question which remains is; Can the microwave approaches yield a determination of the depth and/or water equivalent of the snow? Some studies have shown that this lowering of T_B at the shorter wavelengths for dry snow is a function of snow depth (Edgerton *et al.*, 1971; Ulaby and Stiles, 1979). Figure 10 is a presentation of results from experiments conducted in Colorado by the University of Kansas, which give an indication of this possibility. The microwave responses were observed for snowpacks which were artificially piled. The snow and air temperatures were below 0°C during these experiments; therefore, the snow was dry. A change of 8 dB was observed as the snowpack was increased to a depth of 170 cm (Figure 10a). A T_B change of 50 K was observed at the 2.8 cm wavelength for snowpack changes of 140 cm (Figure 10b). At a shorter wavelength, 0.81 cm, there was a greater T_B change, but the curve saturated for water equivalents greater than 30 cm. The difference between the two curves in Figure 10b points up the difficulty in applying these results, namely, the dependence on snow density. There was a factor of two difference in the density between the two experiments, the first having been done with newly fallen snow while experiment three was done with twice as dense, older snow which presumably had larger grain sizes. Thus, there is a sensitivity of the microwave responses to snow water equivalent, but this sensitivity will depend on the snow's history and on the nature of the underlying medium.

The potential utility of microwave approaches is shown in Figure 11 where values of T_B observed by the Electrically Scanning Microwave Radiometer (ESMR) operating at a wavelength of 0.81 cm on the Nimbus 6 spacecraft are compared with the surface measurements of snow depth for the grass covered prairies in southern Alberta and Saskatchewan (Rango *et al.*, 1979). Snow depth values from ground stations were used to draw isohyets of snow cover, which were then averaged over 1° × 1° grid cells for comparison with the similarly averaged ESMR T_B's. An r^2 of 0.86 was obtained from the correlation, which is very encouraging. A similar result was obtained using the 1.55 cm data from the ESMR on Nimbus 5. In performing these analyses it is necessary that

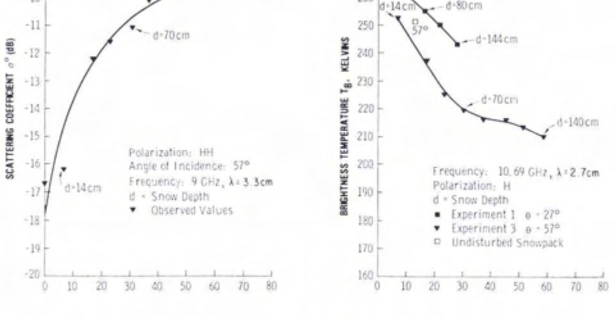

FIG. 10. Variation of microwave response with snow water equivalent for artificially piled snowpacks: (a) active case, (b) passive case (Ulaby and Stiles, 1979).

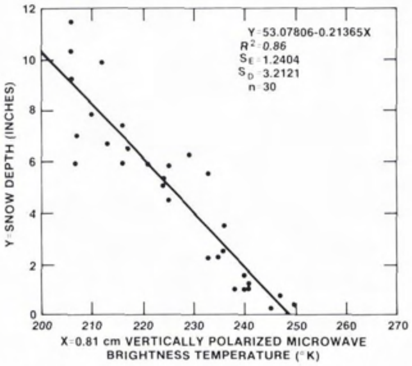

FIG. 11. Nimbus 6 vertically polarized microwave brightness temperature versus snow depth on the Canadian High Plains. Nimbus 6 data from daytime pass 15 March 1976 summarized by one degree Latitude-Longitude grid; snow depth data from 15 March 1976 summarized over same grid; data included from short and high grass prairie areas only.

the air temperatures be below 0°C in order to insure that the snow is dry, and to know something of the history of the snowpack. These requirements are complications which hinder the application of these space data for snowpack observations. Another complicating factor is the coarse 20 × 40 km spatial resolution of the Nimbus 6 ESMR.

These results are very encouraging for the possible use of microwave approaches to remotely monitor snowpack conditions for both total water content and the presence of liquid water. It is clear that the latter quantity can be observed with our current understanding while the former requires still further research to understand how the effects of the snowpack history on the water equivalent relationship can be taken into account.

PRECIPITATION

The measurement of precipitation is important for many applications such as streamflow and crop yield predictions and the understanding of the energy dynamics of the atmosphere. Almost everyone is familiar with the use of ground based radars as an operational tool for rainfall observations. However, not many people are familiar with recent attempts to measure rainfall from space with the ESMR's on Nimbus 5 and 6. These attempts have been rather successful over oceans but not so over land. This difference is due to the fact that the oceans provide a relatively constant, low T_B ($\leq$150K) background for observing the atmosphere. Over land the background is warmer, typically above 250K, and more variable. The effect of rainfall over the ocean is to increase the T_B observed from space up to 250 or 260K for high rain rates. The rate of increase in T_B depends on the wavelength. At the 1.55 cm Nimbus 5 ESMR wavelength, this maximum is reached for a rain rate of approximately 10 mm/hr (Wilheit *et al.*, 1977). This relationship has been used to determine rainfall rates over the oceans, thus providing information for regions of the Earth for which there were very few conventional data available. These data have been combined to produce an atlas of the monthly averages of rainfall over the oceans (Rao and Theon, 1977).

There have been recent attempts to make use of the dual polarization information of the 0.81 cm Nimbus 6 ESMR to distinguish between the emission of the rain from the emission coming from the ground. Theoretical studies have indicated that the upwelling emitted by the rain drops should be essentially unpolarized (Weinman and Guetter, 1977) while the emission from the ground should be polarized with the vertical component having a higher T_B than the horizontal. A statistical analysis was performed on the Nimbus 6 ESMR data to determine if the rainfall over land signatures could be differentiated from both wet ground and dry ground signatures (Rodgers *et al.*, 1979). The conclusion was that rainfall areas could be delineated provided that surface temperatures were greater than 5°C and the vegetation was bereft of dew. These results indicate that there is rainfall information in the microwave T_B's observed from space. Further research will be required to determine if quantitative rain rate information can be obtained. In particular, studies are planned at shorter wavelengths ($\lambda \simeq 0.3$ cm) which are expected to be more sensitive to rainfall over land.

SURFACE WATER AND FLOOD MAPPING

Mapping surface water bodies (ponds, lakes, reservoirs, rivers, etc.) is useful under the general framework of water resource management. In the absence of vegetation, the discrimination between water and land surfaces by passive microwave sensors is made on the basis of the large difference in emissivity between water and land at all microwave frequencies. Longer wavelengths are particularly appealing because of their superior vegetation penetration capabilities and because the difference in emissivity between water and land surfaces increases with wavelength. Likewise, radar can always map water bodies; in virtually all cases, water is observed to produce a much lower return (tone) on radar imagery due to the relative smoothness of the water surface. The ability of microwave sensors to map flood inundated areas under cloud cover conditions is extremely useful since such a capability can be used for conducting relief efforts, assessing loss of life and property, and delineating the extent of the flood plain.

CONCLUSIONS

Results have been presented which show that approaches are capable of monitoring the moisture content in the surface layer of the soil (5 cm thick), detecting the presence of liquid water in snow, and hold promise of being able to determine the water equivalent of snowpacks and delineating areas of rainfall over land. All these parameters are important for improved water resource management.

Our understanding of the basic physics behind these applications has proceeded to the point where microwave sensors can be defined which would be specifically for hydrologic applications. These microwave sensors would complement the information currently available from existing viable and infrared sensors, specifically in such areas as soil moisture and snowpack monitoring.

REFERENCES

Barton, I. J., 1978. A Case Study Comparison of Microwave Radiometer Measurements over Bare and Vegetated Surfaces, *J. Geophys. Res.*, 83, 3513-3517.

Batlivala, P. P., and F. T. Ulaby, 1977. Estimation of Soil Moisture with Radar Remote Sensing, In *ERIM Proc. of the 11th Intern. Symp. on Remote Sensing of Environment*, Vol. 2, 1557-1566.

Blanchard, B. J., 1978. *Measurement of Soil Moisture Trends with Airborne Scatterometers*, Report RSC 3458-2, Remote Sensing Center, Texas A&M University, College Station, Texas, 77843.

Blinn, J. C., III, J. E. Conel, and J. G. Quade, 1972. Microwave Emission from Geological Materials: Observations of Interface Effects, *J. Geophys. Res.*, 77, 4366-4378.

Burke, W. J., T. Schmugge, and J. F. Paris, 1979. Comparison of 2.8 and 21 cm Microwave Radiometer Observations over Soils with Emission Model Calculations, *J. Geophys. Res.*, 84, 287-294.

Choudhury, B. J., T. J. Schmugge, R. W. Newton, and A. Chang, 1979. Effect of Surface Roughness on the Microwave Emission from Soils, *J. Geophys. Res.*, 84, 5699-5706.

Eagleman, J. R., and W. C. Lin, 1976. Remote Sensing of Soil Moisture by a 21 cm Passive Radiometer, *J. Geophys. Res.*, 81, 3660-3666.

Edgerton, A. T., A. Stogryn, and G. Poe, 1971. *Microwave Radiometric Investigations of Snowpacks*, Aerojet General Corp., Final Report 1285R-4.

Estes, J. E., M. R. Mel, and J. O. Hooper, 1977. Measuring Soil Moisture with an Airborne Imaging Passive Microwave Radiometer, *Photogrammetric Engineering and Remote Sensing*, 43, 1273-1281.

Lundien, J. R., 1971. *Terrain Analysis by Electromagnetic Means*, Technical Report No. 3-693. Report 5. U.S. Army Waterways Experiment Station, Vicksburg, Mississippi.

McFarland, M. J., 1976. The Correlation of Skylab L-Band Brightness Temperatures with Antecedent Precipitation, Preprints *Conf. on Hydrometeorology*, Fort Worth, Texas, April 1976.

McFarland, M. J., and B. J. Blanchard, 1977. Temporal Correlation of Antecedent Precipitation with Nimbus-5 ESMR Brightness Temperature, Preprints *Second Conf. on Hydrometeorology*, Toronto, Ont., Canada, October 1977.

Newton, R. W., 1976. *Microwave Sensing and its Application to Soil Moisture Detection*, Technical Report RSC-81 of the Remote Sensing Center at Texas A & M University, College Station, Texas. Available from Univ. Microfilms order No. 77-20-398.

Njoku, E. G., and J. A. Kong, 1977. Theory for Passive Microwave Sensing of Near-Surface Soil Moisture, *J. Geophys. Res.*, 82, 3108-3118.

Poe, G. A., A. Stogryn, and A. T. Edgerton, 1971. *Determination of Soil Moisture Content Using Microwave Radiometry*, Final Report No. 1684 FT-1, DOC Contract 0-35239 Aerojet-General Corp., El Monte, California.

Rango, A., (ed), 1975. *Operational Applications of Satellite Snowcover Observations*, National Aeronautics and Space Administration, NASA SP-391, Washington, D.C. 430 pp.

Rango, A., and K. I. Itten, 1976. Satellite Potentials in Snowcover Monitoring and Runoff Prediction, *Nordic Hydrology*, 7, 209-230.

Rango, A., A. T. C. Chang, and J. L. Foster, 1979. The Utilization of Spaceborne Microwave Radiometers for Monitoring Snowpack Properties, *Nordic Hydrology*, 10, 25-40.

Rao, M. S. V., W. V. Abbott, and J. S. Theon, 1976. *Satellite-Derived Global Oceanic Rainfall Atlas* (1973 & 1974), NASA SP-410.

Rao, M. S. V., and J. S. Theon, 1977. New Features of Global Climatology Revealed by Satellite-Derived Oceanic Rainfall Maps, *Bull. Amer. Meteor. Soc.* 58, 1285-1288.

Reeves, R. G., (Ed), 1975. *Manual of Remote*

Sensing, American Society of Photogrammetry, Falls Church, Virginia, 945 pp.

Rodgers, E., H. Siddalingaiah, A. T. C. Chang, and T. Wilheit, 1979. A Statistical Technique for Determining Rainfall over Land Employing Nimbus-6 ESMR Measurements, *J. Appl. Meteor.*, 18, 978-991.

Schmugge, T., 1973. Microwave Signature of Snow, *Proc. of the Annual Science and Technology Review GSFC*, National Aeronautics and Space Administration, NASA SP-361, pp. 193-195.

————, 1978. Remote Sensing of Surface Soil Moisture, *J. of Appl. Meteor.*, 17, 1549-1557.

Schmugge, T. J., P. Gloersen, T. Wilheit, and F. Geiger, 1974. Remote Sensing of Soil Moisture with Microwave Radiometers, *J. Geophys. Res.*, 79, 317-323.

Schmugge, T. J., J. M. Meneely, A. Rango, and R. Neff, 1977. Satellite Microwave Observations of Soil Moisture Variations, *Water Resources Bull.*, 13, 265.

Schmugge, T. J., T. Wilheit, W. Webster, Jr., and P. Gloersen, 1976. *Remote Sensing of Soil Moisture with Microwave Radiometers-II*, NASA Technical Note TN D-8321. NTIS Order No. N76-32625.

Stiles, W. H., and F. T. Ulaby, 1979. The Active and Passive Microwave Response to Snow Parameters, Part I: Wetness. Accepted for publication in *J. Geophys. Res.*, Oceans and Atmosphere Section.

Ulaby, F. T., and P. P. Batlivala, 1976. Optimum Radar Parameters for Mapping Soil Moisture. *IEEE Trans. Geo Electron.*, GE-14, 81-93.

Ulaby, F. T., and W. H. Stiles, 1979. The Active and Passive Microwave Response to Snow Parameters, Part II: Water Equivalent of Dry Snow. Accepted for publication in *J. Geophys. Res.*, Oceans and Atmospheres Section.

Ulaby, F. T., A. K. Fung, and W. H. Stiles, 1978. *Backscatter and Emission of Snow: Literature Review and Recommendations for Future Investigations*, RSL Tech. Report 369-1, University of Kansas Center for Research, Lawrence, Kansas.

Ulaby, F. T., P. P. Batlivala, and M. C. Dobson, 1978. Microwave Backscatter Dependence on Surface Roughness, Soil Moisture, and Soil Texture: Part I–Bare Soil, *IEEE Trans. Geo. Electron.*, GE-16, 286-295.

Ulaby, F. T., G. A. Bradley, and M. C. Dobson, 1979. Microwave Backscatter Dependence on Surface Roughness, Soil Moisture, and Soil Texture: Part II–Vegetation-Covered Soil, *IEEE Trans. Geo. Electron*, GE-17, 33-40.

Wang, J., T. Schmugge, and D. Williams, 1978. *Dielectric Constants of Soils at Microwave Frequencies–II*, NASA Tech. Paper TP-1238.

Wang, J. R., and T. J. Schmugge, 1979. An Empirical Model for the Complex Dielectric Permittivity of Soils as a Function of Water content. Accepted for publication in *IEEE Trans. Geo. Electron.*

Weinman, J. A., and P. J. Guetter, 1977. Determination of Rainfall Distribution from Microwave Radiation Measured by the Nimbus-6 ESMR, *J. Appl. Meteor.*, 16, 437-442.

Wilheit, T. T., A. T. C. Chang, M. S. V. Rao, E. B. Rodgers, and J. S. Theon, 1977. A Satellite Technique for Quantitatively Mapping Rainfall Rates over the Oceans., *J. Appl. Meteor.*, 16, 551-560.

Wilheit, T. T., 1978. Radiative Transfer in a Plane Stratified Dielectric, *IEEE Trans. Geo. Electron.*, GE-16, 138-143.

(Received 12 April 1979; accepted 25 September 1979; revised 24 October 1979)

Journal Staff