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THE OUTLOOK FOR PRECIPITATION MEASUREMENTS FROM SPACE*

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ABSTRACT

To provide useful precipitation measurements from space, two requirements must be met: adequate spatial and temporal sampling of the storm and sufficient accuracy in the estimate of precipitation intensity. Although presently no single instrument or method completely satisfies both requirements, the visible/IR, microwave radiometer and radar methods can be used in a complimentary manner. Visible/IR instruments provide good temporal sampling and rain area depiction, but recourse must be made to microwave measurements for quantitative rainfall estimates. The inadequacy of microwave radiometric measurements over land suggests, in turn, the use of radar. Several recently developed attenuating-wavelength radar methods are discussed in terms of their accuracy, dynamic range and system implementation. Traditionally, the requirements of high resolution and adequate dynamic range have led to fairly costly and complex radar systems. Some simplifications and cost reduction can be made; however, by using K-band wavelengths which have the advantages of greater sensitivity at the low rain rates and higher resolution capabilities. Several recently proposed methods of this kind are reviewed in terms of accuracy and system implementation. Finally, an adaptive-pointing multi-sensor instrument is described that would exploit certain advantages of the IR, radiometric and radar methods.

1. INTRODUCTION

The interest in measuring precipitation globally, and thus from space, has been intensified by recent international research activities aimed at understanding and predicting climate. The importance of precipitation in maintaining the mean global temperature structure and general circulation may be seen from the three principal sources of energy flux to and from the atmosphere over the globe: (1) IR losses to space at a rate of 5.1 x 10^{16} watts; (2) latent heating by precipitation of 4.4 x 10^{16} watts; and (3) heating by turbulent diffusion at about 0.7 x 10^{16} watts (Newell et al., 1974). As the key heat source, anomalies in precipitation, which are undoubtedly triggered by other anomalous boundary conditions (e.g., sea surface temperature, soil moisture) are strongly implicated in the chain of events responsible for climate variability. And of course precipitation is one of the key parameters which characterizes climate and must be predicted. We may cite an extensive list of other requirements for observations of precipitation, but the above should suffice for present purposes. We hasten to add that not all the needs may be met by spaceborne observations. Here we concentrate on those required to serve in climate monitoring and research and global weather prediction.

In spite of the extreme importance of precipitation, our knowledge of either the synoptic or climatological distributions of precipitation over more than 90% of the globe is abysmal. The question we address in this paper is the outlook for providing precipitation measurements of useful accuracy and or precision from space.

2. THE PRESENT SITUATION

Our present capabilities and future directions were recently reviewed in a workshop on "Precipitation Measurements from Space" (NASA/GSFC, 1981), hereafter referred to as P.W. At this writing, the report of the workshop is not yet available; thus, the following statements must be considered as preliminary, although we have attempted to reflect the concensus views faithfully.

2.1 Visible and IR Techniques

Visible and IR techniques of estimating rainfall work surprisingly well especially for large areas and durations for convective rainfall in the subtropics. For monthly precipitation, simple counts of highly reflective clouds provide remarkably good estimates. Even for 6 hour average rainfall, the fractional cloud cover at various IR thresholds and visible brightness appears to delineate the area of rain well, so that the use of known climatological rain rates provides volumetric amounts. More complex schemes involve both the area and its time derivative, again with some IR threshold. The P.W. working group found both advantages and disadvantages to the methods noted above and others not mentioned here, but concluded that no single visible and/or IR approach can perform adequately for climatic purposes in all regions.

Lovejoy and Austin (1979) argue persuasively that the skill of both visible and IR methods lies almost entirely in their ability to represent the rainfall area. Based on radar data, they find a correlation coefficient of about 0.9 between hourly rain areas and rain amounts in both Montreal and the GATE experiment, while area-rain rate correlations are negligible (see also Lovejoy, 1981). (We must be careful in distinguishing between a good "correlation" of radar rain areas and rain amounts and the ability of the satellite imagery to faithfully depict the rain areas.) This is reasonable because there is no direct physical link between either the visible or IR brightness and rainfall. (The exceptions are time derivatives of the latter, which reflect updraft velocities, or its minimum value, which is a measure of its maximum height.)

The above findings already suggest that VIS/IR techniques be exploited for their relatively good rain area depiction capabilities but that we use other methods such as microwave radiometry or radar to estimate the rain rates. Such a combination is also indicated if either of the latter instruments are to be flown on low orbitors, allowing only twice per day samples of rain rate. In that event, corrections for diurnal variability would have to be made through the use of the 24 hr sequence of cloud imagery from GOES.

2.2 Microwave Radiometry

The P.W. working group on microwave radiometry concluded that: (1) passive measurements in the 10-40 GHZ region represent a viable technique for measuring rain over the ocean, but (2) rain over land represents a much more difficult problem due to the highly variable background. The group also highlighted the following problems: (1) A negative bias (i.e., rainfall underestimate) and large variance due to the non-uniform distribution of rainfall or incomplete filling of the relatively large instantaneous fields of view (i.e., IFOV of 20 x 44 km at nadir on the Nimbus 6 Electrically Scanning Microwave Radiometer); (2) variability of the effective rain layer height, defined as the path integrated attenuation divided by the surface attenuation coefficient. This variability decreases with increasing area and is believed to be related climatologically to the freezing level, so it appears to remain a potentially serious problem only in intense convective storms; (3) significant and variable amounts of cloud liquid water content which introduce errors in retrieved rain rates and places a lower bound on the rate which can be detected. A significant factor omitted from the above is the presence of a mixture of hydrometeors of large drops, graupel, and hail in the more intense convective storms which will surely confound the relatively simple retrieval algorithms. Of course, unless it can be assumed that the rain begins at the freezing level, one gets only a measure of the effective integral with height and not of the rain intensity itself.

Of the above problems, it now appears that the unfilled IFOV dominates the errors in the ESMR data. However, a simulation by Lovejoy (1981) using an 8 x 8 km IFOV such as that anticipated for the LAMMR (Large Aperture Multichannel Microwave Spectrometer) has shown that the bias becomes neglible and random errors would be greatly reduced; i.e., $\pm$ 20% RMS for 12 hr accumulations; these would be reduced further for extended period climatological averages. We therefore conclude that microwave radiometry has an important role to play in space precipitation measurements over the oceans. Indeed, its failure over land is the key reason to consider spaceborne radar.

3. SPACEBORNE RADAR

The essential questions are: (1) can spaceborne radar provide sufficiently accurate observations of rain over both land and ocean? (2) can it replace or supplement the VIS/IR methods which are acknowledged to estimate rain area better than rate? and (3) how can we optimize a hybrid system which exploits the best features of the various methods? There is little doubt that radar could provide precision global distributions of rain rate given no constraints on the number of spacecraft, antenna size, and power. But what is achievable within realistic technological and monetary bounds? In what follows we outline several promising approaches. We note that some of these were previously proposed in the report of the Active Microwave Workshop (NASA, 1975). But let us first highlight some of the key obstacles which have hampered progress to date. These are briefly reviewed below.

3.1 Key Obstacles

One of the major problems encountered in previous proposed designs is the antenna size required to achieve beam filling and reduce the effects of surface clutter both in the main and side lobes. Both problems can be largely overcome by a sufficiently large antenna. To keep the antenna dimensions within bounds, we have frequently resorted to shorter wavelengths than we prefer to use in ground-based systems. This then results in large rainfall attenuation and potentially excessive errors in attempting to correct for the losses (Hitschfeld and Bordan, 1954). Proposed solutions have been either (1) to use two wavelengths, one attenuating and the other not, or two attenuating wavelengths as a means of controlling the errors. On the other hand, one can exploit the attenuation as a measure of path integrated rainfall (Atlas and Ulbrich, 1977; Eckerman et al., 1978). A hybrid system with microwave radiometry also appears valuable as a means of estimating total attenuation over the oceans.

A problem which is interwoven with antenna and beam size and which is intrinsic to all radar methods is the signal averaging time needed to obtain a reliable estimate of the echo power. This implies either a high pulse repetition frequency (PRF) or a very slow scan. The latter in turn reduces the attainable swath width. The trade-off between high resolution, scan time, and swath width is a related concern. Pulse to pulse frequency agility (Marshall and Hitschfeld, 1953) or a wide band "noise" pulse (Krehbiel and Brook, 1979) have been suggested solutions.

With all these problems in mind, Eckerman (1975) and Nathanson et al., (1975) proposed a very sophisticated radar with a multiplicity of receiving beams, thus achieving high resolution (1 km IFOV), low clutter, adequate signal dwell time, and a wide swath all simultaneously. The key problems with the latter were high cost and power consumption; these factors are constraints on any space system. In what follows we have therefore backed off from such a sophisticated system and consider a variety of less complex options. Another related consideration is to design the system as an add-on to a planned radar, thus accomplishing two purposes at little added cost.

3.2 Radar Options

3.2.1 Modified Altimeter

The simplest and least costly approach is to incorporate a rain measurement mode in the 13.5 GHZ (2.2 cm) SEASAT type radar altimeter (Goldhirsh and Walsh, 1981). The retrieval algorithms for recovering rain rate and an effective drop size distribution are discussed in the latter reference. In one form, one essentially measures echo power near the top of the rain where attenuation is negligible and assumes constant rain rate down to the surface. This is shown by the $\Delta h = 0$ curve in Fig. 1. Assuming constant rain rate with height, the decrease of signal level with depth is also a measure of rain rate. Under the same assumption, the authors show that the ratio of attenuation coefficient, k, to reflectivity, η, provides a unique measure of the slope or median volume diameter of the Marshall-Palmer drop size distribution; when this is used with the absolute value of either k or η, one also gets the intercept of the distribution. Of course, the assumption of constant rain rate with height facilitates the retrieval, but it is also a key weakpoint of the method. The authors also treat corrections for non-uniform beam filling. RMS rain rate errors over the range 10 to 100 mm/hr are about $\pm$ 5 and $\pm$ 2 mm/hr for an average of 45 and 220 pulses, respectively. Calibration uncertainties of $\pm$ 1 dB also result in bias errors of 13 to 20% between 10 and 100 mm/hr.

The SEASAT type altimeter would be modified by allocating 5% of the altimeter pulses to the rain mode; i.e., 50 pulses each of 3.2 μ sec or 500 m vertical resolution. (Note: the normal pulses are

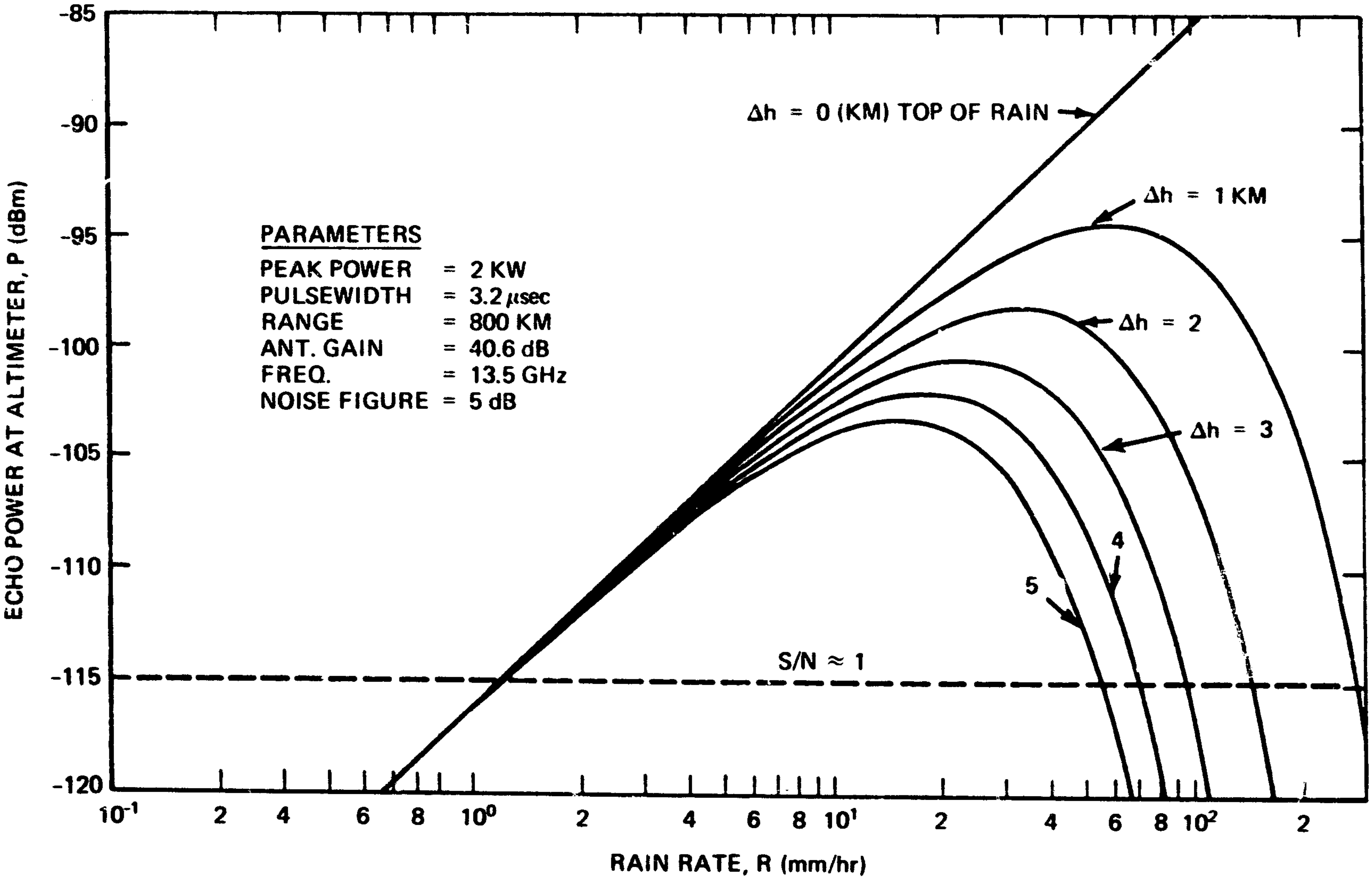

Figure 1. Echo power returned to the altimeter from various distances below the top of the rain rate (after Goldhirsh and Walsh, 1981).

"chirped" with 3.125 nsec or 0.47 m range resolution). Use of the SEASAT radar parameters also results in a minimum detectable rain rate of about 1 mm/hr from 800 km orbit. This is a marginal value for many purposes; a threshold rate of $\sim$ 0.1 mm/hr would be more useful.

Of course, the most serious limitation of the altimeter is its restriction to nadir measurements. Thus, it would have to be used in conjunction with a wide-swath IR or microwave radiometer. In either case, the radiometers would provide estimates of the rain areas while the radar would provide nadir rain rate calibration along the satellite track. The joint use of the altimeter with the microwave radiometer is preferable over the oceans because the radar provides an independent estimate of the total attenuation. Of course, a high resolution microwave radiometer also provides rain rate estimates off nadir so that in such a configuration, the radar should be considered as supporting the radiometer rather than vice versa.

3.2.2 Short-Wavelength Scanning Radar

This systems differs only slightly from the nadir radar altimeter in that it would scan cross-track to provide a wide swath measurement. A short wavelength (say 0.85 cm) would be used to attain the narrowest possible beams with a reasonable size antenna. A diameter to wavelength (D/λ) ratio of 400, or an antenna of 3.4 m would provide 2 km resolution from an 800 km orbit. Of course, we assume large enough power and PRF to get reliable measurements down to just below the melting level. Since attenuation is likely to reduce the signal below noise in moderate to heavy rain, one must assume constancy of rain rate with height below the $0^{o}C$ level as in the first method. Rain rate would be recovered from the reflectivity-rain rate relation adjusted to 0.85 cm and also from the attenuation rate. Over the ocean, retrievals would be greatly aided by a microwave radiometer. This would be especially useful in convective storms where either radiometer or radar alone is likely to be confounded by a variety of hydrometeors above the $0^{o}C$ level.

It should be noted that an approach which combines dual wavelength radar and dual wavelength radiometry in the 3 cm and 0.86 cm bands, is being pursued in Japan (Inomata et al., 1981). The method has been implemented in an aircraft with promising preliminary results.

3.2.3 Surface Target Attenuation Radar (STAR)

This method, previously called "the surface reference technique," uses the scattering properties of the surface as a calibration point for meteorological attenuation measurements. The method depends upon both the fact that the path-averaged rainfall rate can be determined by means of a direct measurement of the attenuation (Atlas and Ulbrich, 1977) and the assumption that the fixed calibration target in the ground-based attenuation method can be replaced by the backscattering coefficient of the surface (Eckerman et al., 1978; Meneghini et al., 1981). Two variations of STAR can be distinguished: the surface comparison and the frequency agility methods. Both systems can utilize either fixed or scanning, real or Doppler azimuth sharpened beams. These systems operate at incidence angles of the order of 40^{o} in order to achieve a sufficiently wide swath.

3.2.3.1 Surface Comparison Method

To explain the method we first note that in the presence of rain the backscattered power from a range bin which intercepts the surface is proportional to the product of the backscatterng coefficient of the surface σ_1^0, (i.e., the scattering cross-section per unit area) and the attenuation factor, A, the two way fractional loss through the rain. If a second return power measurement is made either in the rain-free area adjacent to the storm cell or by a prior measurement at the actual target in the absence of rain, the power will be proportional to some new scattering coefficient, σ_2^0, say, where the difference between σ_1^0 and σ_2^0, will depend on the temporal or spatial inhomogeneities of the surface. A ratio of the two measurements approximately equals $A\sigma_1^0/\sigma_2^0$. The Skylab S-193 (Moore, 1974) and the University of Kansas (Ulaby, 1980) data have shown, however, that for a 10 km IFOV at K-band and incidence angles greater than 30^o, the ratio σ_1^0/σ_2^0 exhibits fairly small spatial fluctuations. Thus, the ratio of return power measurements provides an estimate of A from which the path-averaged rain rate is found by means of a k-R law and a measurement of the path length through the rain. The principal problems with this method are: (1) sensitivity of σ^0 to soil moisture and (2) lack of knowledge of the footprint size needed to achieve stability in σ^0.

The technique can be generalized to obtain the profiled rain rate. This is accomplished by starting with the equation for rain rate from an attenuating radar (Hitschfeld and Bordan, 1954) and using the attenuation, as determined above, to bound the total error of the estimate. An analysis of the method has brought out some of its major advantages and drawbacks. Moreover, for narrow beamwidths, the accuracy of the profiled rain rate is comparable to that of the path-averaged rain rate. For example, with a radar located on a low earth orbitor pointing at a 30^{o} incidence angle with respect to nadir and with $\lambda = 0.86$ cm, $P_t = 1$ kw, a storm height of 5 km and a standard deviation (s) in σ^0, of 1 db, the rain rate can be estimated within about 20% of the true value for rain rates from 2 to 12 mm/hr. For $s_o = 2$db the range extends from about 4 to 12 mm/hr. At longer wavelengths the range is shifted upward: e.g., if $\lambda = 1.87$ cm and $s = 1$ db then $R_{min} = 8$ mm/hr and $R_{max} = 55$ mm/hr.

To explicitly show the system performance, the mean return powers from the rain (R) and the surface (C) are plotted in Fig. 2 as a function of distance into the storm. Here, 0 km corresponds to the storm top and the region between 6 km and 9.5 km to the intersection of the range bin of the main beam with the surface. The gradual build up of the rain return (0 to 2 km) and the rapid decrease (7 to 9.5 km) represent regions where the range bins are only partially filled with rain. The decrease in the rain return power between 2.5 and 7 km is proportional to the total attenuation. Where the rms fluctuation of σ_1^0/σ_2^0 is comparable to this total attenuation, then the method will be unreliable; this is the major source of error at low rain rates. At high rain rates, the return power at the surface will be smaller than the noise, so that attenuation cannot be estimated reliably. Accordingly, a single wavelength STAR would yield a limited dynamic range. Thus STAR requires two wavelengths to cover a wide enough range. Also, at very low rain rates where attenuation cannot be measured accurately, one must rely upon use of the ordinary reflectivity-rain rate relations.

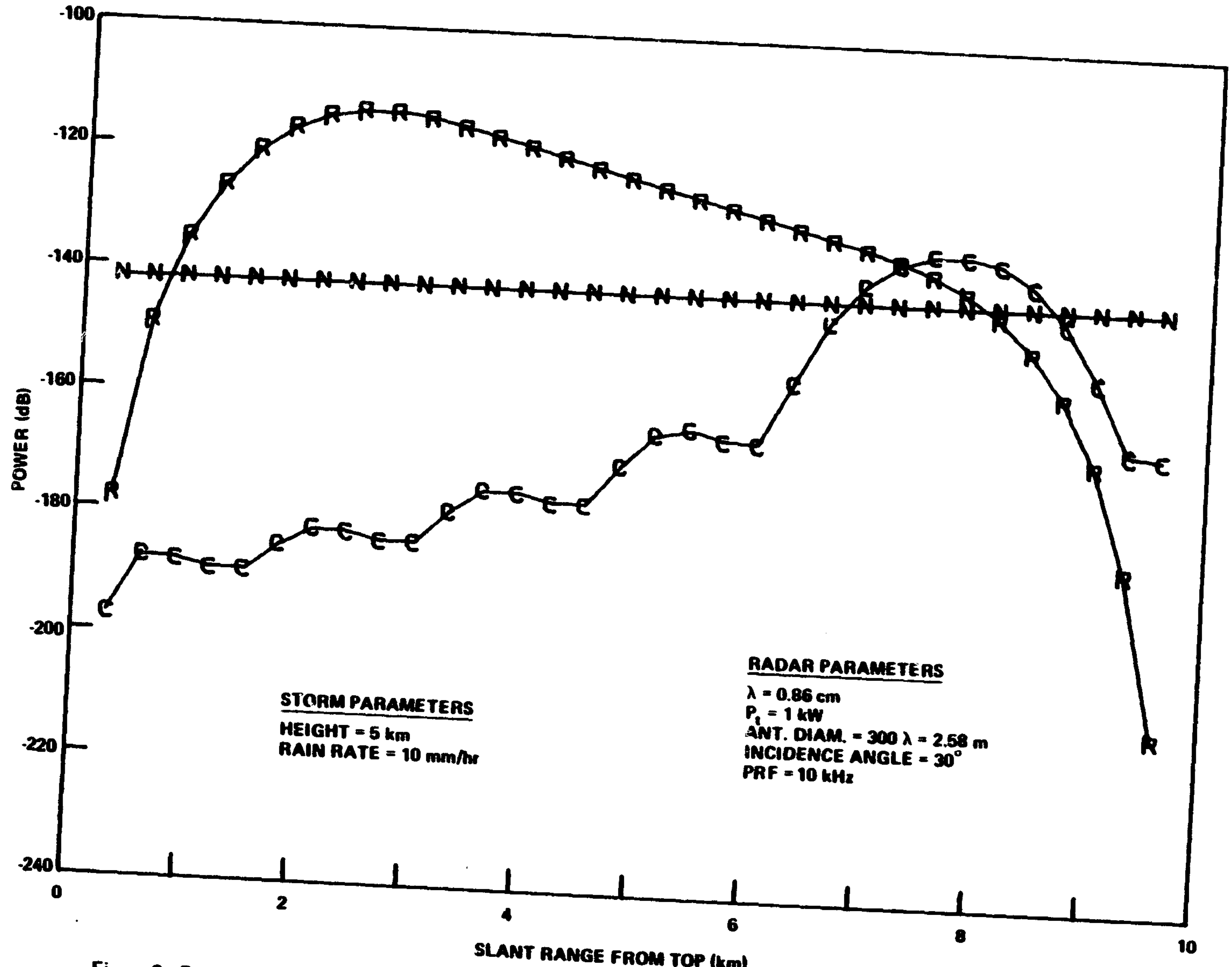

Figure 2. Radar return from rain R, noise N, and ground clutter C for the STAR radar (after Meneghini et al., 1981).

It is worth noting that the STAR method has been analyzed primarily for rain over land. Over ocean it is expected to be less accurate because of the dependence of σ^0 on wind speed for angles other than 10^o. For measurements over ocean, a radar-radiometer sensor appears promising. In this mode the total attenuation would be obtained from the radiometry while the radar would provide a measure of the storm height and the range profiled reflectivities. From these data the path-averaged and profiled rain rates could be obtained readily. In principle, a radar scatterometer which measures σ^0 to estimate near surface windspeed over the ocean could also be used to obtain σ^0 for use with STAR. Indeed one can use STAR itself as a scatterometer, but this approach has not been studied.

3.2.3.2 Frequency Agility Rain Radar (FARR)

This variant of the surface reference technique exploits the weak frequency dependence of ground radar reflectivity σ^0 (0.25 dB/GHz at horizontal polarization). Two approaches should be considered, pulsed and CW.

With the pulsed FARR the radar ranges on the ground range bin. As with the ground comparison method, the received power from the surface range bin in the presence of rain is proportional to the product of the reflectivity, the attenuation and the radar constant. When volume scattering from the rain is negligible compared with surface scattering, the method is simplified. The ratio of received power from two simultaneous observations with slightly separated frequencies is proportional only to the product of the ratio of the radar constants and the attenuation factors at the two frequencies.

The calibration constant ratio can be considered as known since it can be measured often during non-raining intervals. Thus, the measured power ratio is proportional only to the logarithm of the differential attenuation, which is proportional to the rain rate. The advantages of this approach are the simple algorithm, independence from variability of the drop size distribution, and the fact that the required storm height is also obtained by the measurement. The disadvantage (compared with CW) is the high peak power. With the CW FARR approach, the radar signal contains contributions from both the attenuated ground return and the attenuated volume scatter of the rain within the beam. The markedly different frequency dependence of the ground reflectivity, precipitation attenuation and precipitation scatter offers the potential for separation of these factors. Rain rate can be determined from either the attenuation or volume reflectivity coefficients. Three measurements are required since there are three unknowns. The advantage of the CW approach is the lower peak power than with the pulse radar. However, the rain retrieval algorithm is complex, and the drop size dependence of the volume reflectivity may introduce significant uncertainty into the measurement. Further study is required to determine the feasibility of these concepts and to assess their relative merit.

The main advantage of the frequency agility method over the comparison method is its applicability to ocean and land scenes. It is feasible to use both methods over land to cross-check the validity of the assumptions and models.

3.2.4 Adaptive Pointing Beam

Many microwave antenna configurations can be used to image precipitation in storms, each having advantages and disadvantages depending on the required range of rain rate, resolution, swath width and accuracy. The systems proposed include: mechanical, conically scanned, single beam (Skolnik, 1974) and a pushbroom, fixed simultaneous multibeam phased array (Nathanson, et al., 1975). Contiguous coverage is obtained from these systems; however, it is necessary for the transmitter to be functioning continuously. Since precipitation normally covers limited areas, scanning time is being wasted while average power and data rates are higher than needed, and dwell time is too small to attain accurate samples. A solution to this problem is an Adaptive Pointing Beam which functions only over precipitating clouds (Atlas, 1981).

The key to such an adaptive approach is either an infrared or microwave radiometer which scans the horizon ahead of the spacecraft and identifies those cloud systems which are probably precipitating. It is only necessary for the look-ahead radiometer to sense the presence of rain and control the subsequent beam position to sample the rain areas in some optimal fashion.

The radar receiver and transmitter antennas are preferably phased arrays which electrically scan cross-track through nadir. There is a complete system for each side of the track. Several strategies are feasible including: a single pencil transmit and receive beam; multiple fixed receive beams; or multiple stepped pencil receive beams and scanned broad transmit beams. Scanning rates and beam multiplicity must be selected during tradeoff studies. However, the possibilities extend from a detailed high resolution snapshot of the storm to characterization of features such as boundaries and peaks.

The adaptively pointing concept is applicable to any of the measurement algorithms since it solves problems common to all. Of course, the major concern with this approach is that of adequate sampling. Can we find a passive detection scheme which adequately identifies all significant precipitation regions, and can we then devise a set of radar sampling scenarios which insures sufficiently accurate estimates of the total precipitation?

Initial thinking about the antenna suggested that we use a real aperture in the vertical direction and synthetic (SAR) in the along track direction. In order to attain a sufficiently narrow vertical beamwidth, a diameter/ wavelength (D/λ) ratio of about 300 is desirable, giving a nadir beamwidth from 600 km orbit of 2km with a 6 meter high antenna at $\lambda = 2$ cm. With a real aperture, the antenna would thus be a 6 x 6 m array with face oriented normal to the track. For certain scan-track patterns, the horizontal dimension of the array can be reduced and the resolution improved by the use of Doppler beam-sharpening techniques. For Doppler beam-sharpening to be effective, the bandwidth used to achieve resolution should be about 5 times the bandwidth due to random motions of the hydrometeors; this places a limitation on the minimum pixel dimension that is much more stringent than that due to the radar motion itself. However, in directions within, say, 60° of the side, resolutions of 2 to 3 km due to Doppler beam-sharpening can be achieved, depending on spacecraft height, provided a spectral width for the random motions of 2 m sec^{-1} is assumed reasonable. Mean velocities of the hydrometeors will provide mean Doppler shifts that will appear as horizontal displacements of their apparent position. Use of this technique, however, would allow scanning a wide area of the ground with a fixed conical antenna beam from an antenna, say, 25 cm (horizontal) by 6 m (vertical).

4. DISCUSSION

It is clear that the solution to the measurement of precipitation with a spaceborne radar is not yet certain. However, the new concepts presented here provide considerable promise and deserve to be studied more carefully both theoretically and in aircraft trials.

We have not discussed the use of long wavelength ($\lambda \geq 5$ cm) scanning systems which are essentially free of attenuation because they would require excessively large antennas to achieve narrow beam widths and IFOV's (i.e., 2-3 km at nadir). On the other hand, larger beam widths introduce virtually insuperable problems with surface clutter and unfilled IFOV's. Even with narrow beams, however, the retrieval algorithm rests on the existence of a well defined Z-R relation; aside from the large scatter about such relations, we know that they vary markedly with precipitation type and thus with climatic region.

Neither have we dealt with dual wavelength methods such as proposed by Eccles and Atlas (1973) or Goldhirsh and Katz (1974) because: (1) the non-attenuating wavelengths are subject to the same criticisms discussed above, and (2) at the attenuating wavelengths, it is difficult to achieve the kind of accuracies required in short range intervals, especially at the lower rainfall rates which contribute most to the global rainfall. Furthermore, we have excluded 1 km IFOV sophisticated multibeam systems (Eckerman, 1973; NASA, 1975) largely on the basis of anticipated costs.

Despite the sampling deficiencies of the modified SEASAT-type altimeter and some concern about the basic algorithm, its simplicity and economy speak highly for it. Moreover, the probability of an ocean radar altimeter mission in the next 5 years seems high.

The hybrid approach which combines the surface reference technique (STAR), the frequency agility system (FARR), the short wavelength reflectivity schemes, and the adaptive pointing approach, all supplemented by microwave radiometry over the oceans appear attractive for an initial system. Of course, forward looking IR imagery is implicit in adaptive pointing. Adaptive pointing of the STAR would enhance its accuracy considerably through signal averaging. Over the oceans, microwave radiometry would provide an independent estimate of total attenuation, also improving accuracy. Where excessive rain rates cause loss of surface targets the STAR automatically becomes the short wavelength system in which rainfall is estimated through both reflectivity and the attenuation rate just below the bright band assuming uniformity from there down. Finally, the short wavelengths and sensitivities involved in all of the above provide for detecting and estimating rates of snowfall, also an important climatological requirement which has not been adequately addressed before.

We again note that sampling considerations are critical with any orbiting precipitation system. If the orbitor is sun synchronous, the diurnal variability will have to be accounted for through proxy measurements of clouds from a synchronous satellite. However, for climatological purposes we can choose an inclined orbit such that the local observing time varies over the month to provide a reasonably accurate monthly mean. Much more needs to be done on sampling and orbital considerations.

5. CONCLUSIONS

This paper does not pretend to define the ultimate solution to the problem of precipitation measurements from space. However, we have identified several new promising avenues of attack which go a long way toward overcoming the most serious obstacles which have impeded progress in the past. The role of precipitation in climate, and its accurate specification for use in regional and global weather prediction impel us to move forward with a serious effort to further assess and develop some of the more hopeful approaches described here and elsewhere (NASA, 1975).

6. ACKNOWLEDGEMENT

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