MEASUREMENT OF RAINFALL BY RADAR

by

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A. Characteristics of radar echoes from precipitation

The fact that a single radar installation can detect and locate precipitation over an area of several thousand square miles has made the possibility of measuring rainfall rates and amounts by means of radar appear very attractive. We would like today to examine its potentialities for such measurements and to consider its advantages and limitations as compared with a network of rain-gauges.

The radar was first devised as a tool for detecting and locating objects (especially aircraft) in the atmosphere. It accomplishes this by sending out short but very high-powered bursts of electromagnetic energy which are focussed by a large antenna into a narrow beam, often only one or two degrees in aperture. When the energy impinges on an object, be it an airplane or a raindrop, some of it is scattered or reflected from the object. The scattered energy travels in all directions and a small fraction of it comes back toward the radar and is received by the antenna as an echo. The bearing of the target is known from the direction in which the beam is pointed when an echo is received. The range is found by measuring the time interval between the emission of the pulse and the reception of the echo. Since microwaves travel with a known speed, the speed of light, the range of the target is directly proportional to the measured time interval, which is approximately 0.001 second for a target at 100 miles.

The echoes are displayed on the face of a cathode ray tube. The simplest type of indicator, called the A-scope, is shown in Fig. 1. At the time the pulse is transmitted a trigger pulse causes the electron beam to begin moving uniformly across the tube in a horizontal direction. An echo signal puts a voltage on the vertical sweep of the tube so that the beam is raised by an amount proportional to the intensity of the signal. In Fig. 1 the total length of the sweep corresponds to a range of five miles, the markers below the horizontal line being range markers. It can be seen that precipitation is occurring up to three miles since the trace is lifted above its normal position. By putting in a suitable delay between the triggering pulse and the start of the sweep, it is possible to view the echoes from a five-mile interval at any selected range. Signals displayed on the A-scope illustrate clearly an important characteristic of weather echoes - they have a very fuzzy appearance and fluctuate rapidly. These fluctuations arise because of the large number of scatterers which are in the illuminated portion of the beam. Scattered waves are received simultaneously from millions of hydrometeors and as the particles move relative to one another, interference between the waves produces rapid changes in signal intensity.

Although the A-scope shows the distribution and characteristics of the echoes in a selected direction, it cannot show the pattern of the precipitation. To obtain this we rotate the antenna at a low elevation angle and display the echoes on the PPI (Plan Position Indicator). At the time of pulse transmission the sweep starts at the center of the scope and moves outward toward the rim, the direction in which it moves outward being rotated in synchronism with the antenna. Any echo which is received causes an intensification of the beam so that the pattern of precipitation is mapped out as shown in Fig. 2. The pattern in the vertical is obtained in much the same way except that the scan is made over a sector instead of a whole circle. In the RHI (Range Height Indicator) the vertical scale is usually expanded with respect to the horizontal so that details of vertical structure may be more easily observed. On the RHI, the heavier height lines represent 10,000-foot levels, the lighter ones, 5,000 feet. The precipitation echoes in Fig. 2 are typical of general widespread rain associated with a warm front or coastal storm. It is clear that "general widespread rain" exhibits significant small scale variations in intensity. The RHI shows uniform snow between 10,000 and 20,000 feet. Just below the 10,000-foot level is a layer which produces an especially intense echo called the "bright band." The bright band is associated with melting snow which has a higher reflectivity than either dry snow or rain. Below the bright band the rain echoes are showery. The appearance of the snow illustrates another important characteristic of weather echoes - range attenuation. This means that the echo intensity depends not only upon the characteristics of the storm, but also upon the range at which it is observed; if all other factors are equal the signal intensity for weather echoes varies inversely as the square of the range. It is probable that uniform snow extended over the whole area, but as the echo grew progressively weaker with range it could not be detected beyond ten or fifteen miles.

An example of convective storms as they appear in a vigorous squall line is shown in Fig. 3. Even in this severe storm the areal coverage is small but the intensity of the storm is indicated by its height which is over 50,000 feet. Note that the horizontal scale is greatly compressed. Actually the horizontal and vertical dimensions of the storm were approximately the same.

There is one question which often arises in connection with weather echoes: How can we get echoes from the back portions of storms or from storm areas which have showers between them and the radar? Actually we should not picture the process as one in which the transmitted power is reflected by the storm. The spaces between the hydrometeors are far greater than their dimensions, so that the amount of energy removed by each raindrop (or snowflake) is exceedingly small compared with the amount which goes on past it. In fact, under most conditions the total energy removed by all the raindrops is so small that the power in the beam is not measurably decreased. If the rain is heavy, however, and the wavelength of the radiation is relatively short, the energy taken out may become important and the back portions of intense showers may not be detected. If measurements are to be made in heavy rain, wavelengths of 10 cm or more should be used because in this case attenuation, even by heavy rain, is negligible.

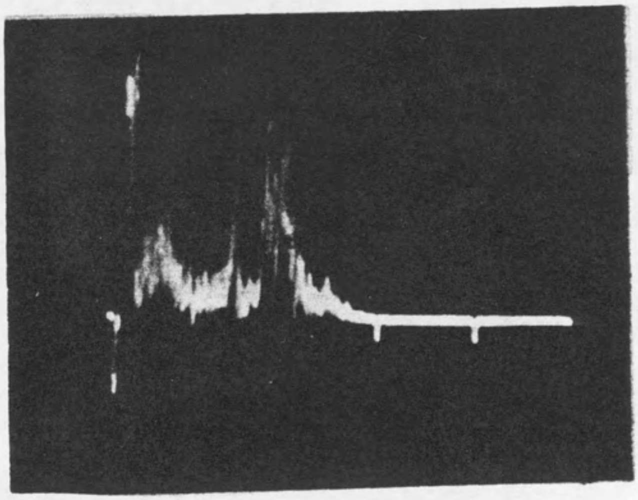
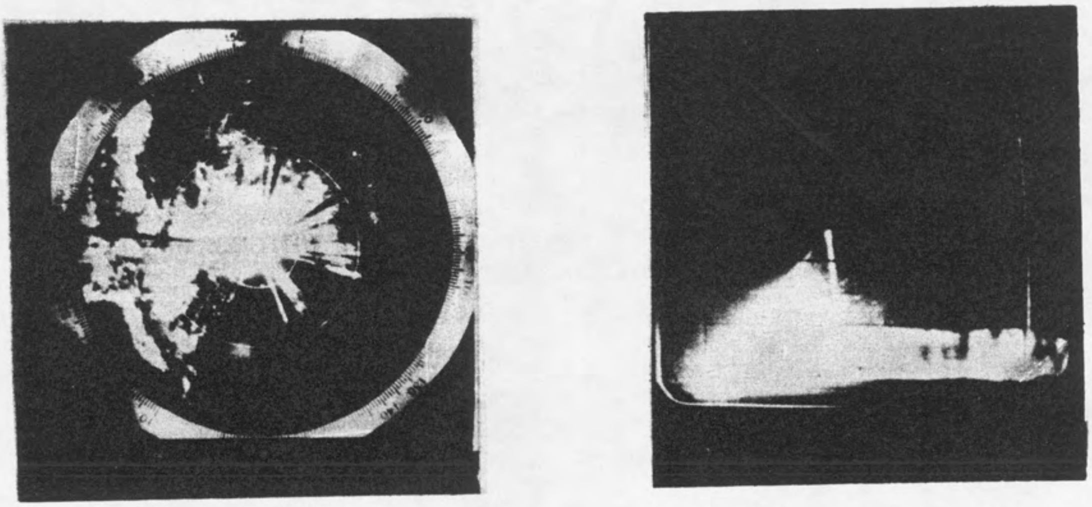


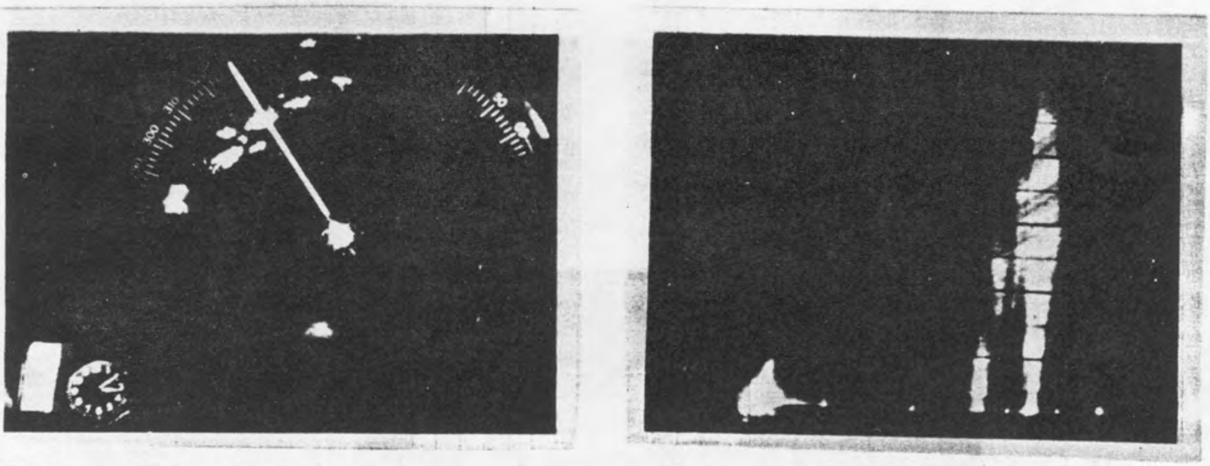
FIG. I. PRECIPITATION ECHOES ON A - SCOPE
VERTICAL POINTING 5 MILE RANGE



PPI 50 MILE RANGE

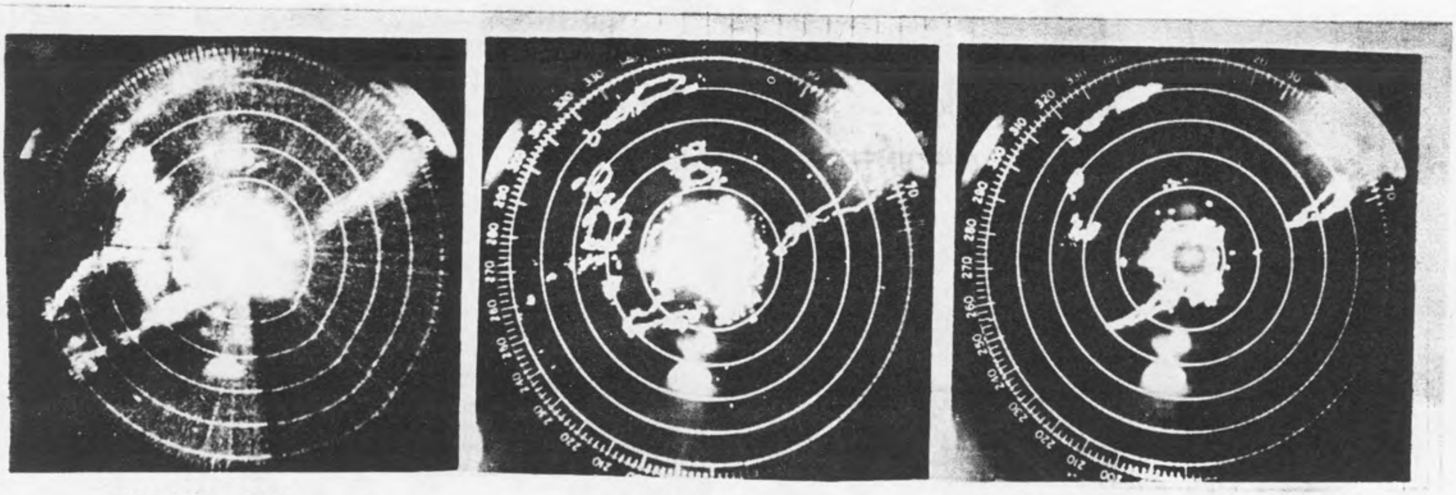
RHI 25 MILE RANGE

FIG. 2. WARM FRONTAL RAIN ON AN / CPS - 9 RADAR



PPI 120 MILE RANGE **RHI 100 MILE RANGE**

FIG. 3. RADAR ECHOES FROM A SQUALL LINE, JUNE 9, 1953.



NORMAL PPI **LEVEL 1** **LEVEL 5**

NOV. 30, 1957. 1700 EST

60 MILE RANGE

FIG. 4. COMPARISON OF RANGE-CORRECTED INTENSITY CONTOURS WITH NORMAL PPI PRESENTATION.

Time lapse photographs of the PPI show that individual precipitation areas tend to move in an orderly fashion in accordance with the upper-level winds and that they often show significant changes in intensity (building or dissipating) in periods less than one-half hour.

B. Accuracy of radar measurements of rainfall

Since the radar has clearly demonstrated the small scale variability of precipitation it has become obvious that only an exceedingly dense network of gauges can give an adequate description of the distribution of precipitation. However, there is quite a large gap to be bridged between the scope photographs which have been shown in the figures and quantitative measurements of precipitation rates and amounts. There are two major difficulties to be faced:

1. The technical problem of obtaining accurate measurements of the echo intensity from all points over a large area is rendered difficult by the fluctuating nature of the echoes and the large dynamic range of the signals (the most intense signals are on the order of a million times as strong as the weakest ones).

2. The average signal intensity is not uniquely related to the rainfall rate, but depends on the drop size distribution, a quantity which varies significantly from storm to storm.

The first of these problems is an engineering one. We will not dwell upon the various techniques which have been suggested, but will simply point out that it can be solved, and the complexity of the instrumentation which is required depends upon the degree of accuracy which is demanded. On the 10-cm SCR-615-B radar in the Meteorology Department of the Massachusetts Institute of Technology we have the following special instrumentation:

(a) A logarithmic receiver which provides the necessary dynamic range and makes it easy to correct for the range effect by adding an appropriate voltage.

(b) A quartz delay line whose delay time is synchronized with the time interval between pulses so that the echoes from a number of consecutive pulses can be superposed and thus provide an average of the fluctuating signal for each point without mixing the signals from various ranges.

(c) A contouring and leveling circuit which selects the points at which the signal crosses or reaches a selected signal intensity and displays them on the scope.

In Fig. 4 normal PPI presentation and two intensity contours are compared. Each level interval represents a factor of three in signal intensity so that level 5 indicates a signal (normalized in range) which is 100 times as intense as the signal at level 1. It is clear that the average signal intensity can be measured quite accurately over a large area and the data can be obtained with a reasonable degree of speed. However, this type of measurement is difficult and expensive and has only recently been achieved in a research radar; it is not yet in general operation work.

Let us go on to the second question: Once we have measured the radar signal intensity what does it tell us about the rain? Numerous observations have been made of drop size distributions in natural rain by various techniques. The theoretical value of the radar reflectivity for each distribution has been computed and plotted against the rainfall rate. The results show that, on the average, the radar echo intensity should be proportional to the 1.6 power of the rainfall rate, but the scatter is such that if the radar echo is used as a measure of the rainfall rate, we can expect an uncertainty of about a factor of two. An experimental check of this relationship, made by comparing simultaneous measurements of rainfall rate at the ground and radar signal intensity from the atmosphere just above the gauge, supports both the average dependence and the uncertainty factor predicted by theory. Significant variations in rainfall rate occur over very short periods of time and the radar follows these variations quite faithfully as shown in Fig. 5. It should be noted that such variations in rainfall rate cannot be observed on ordinary raingauges, but only on very large and sensitive ones. A difference of 5 db in signal intensity represents a factor of two in rainfall rate so that in the particular cases illustrated the agreement is somewhat better than the estimated factor of two. As the range increases, however, we must expect the accuracy to become poorer for two reasons. First, because of the curvature of the earth, the region sampled by the radar becomes progressively higher above the surface of the earth, so that the precipitation in volume sampled by the radar may not be representative of that which is reaching the ground. At 50 miles the radar horizon is a little over 1000 feet, but at 100 miles it is at 5000 feet. Second, the linear dimensions of the beam increase with range, so that the probability of having the whole beam filled with uniform precipitation becomes progressively smaller. At a range of 60 miles a 1° beam is a mile across; a 3° beam (as we have in our 10-cm radar) is three miles across. Many storms vary significantly in intensity over distances on the order of a mile especially in the vertical direction. We would estimate the uncertainty at 50 miles to be approximately a factor of three for a 3° beam and it becomes even worse at greater ranges.

It may appear at first glance that an inaccuracy of a factor of two or three is so great that radar measurements of rainfall would be useless. Let us, however, consider the uncertainties in the amount of rain measured by a network of gauges. Fig. 6 shows range-corrected signal intensity contours for a squall line and the distribution of recording rain gauges in New England. The intensity contours correspond, with the above-mentioned uncertainty, to the following rainfall rates:

Level number	1	2	3	4	5
Rainfall rate (mm/hr)	5	15	25	45	75
(in/hr)	0.2	0.6	1	2	3

It is obvious from the figures that the network of gauges, which are about 20 miles apart on the average, could not possibly give an adequate description of the distribution of precipitation since the most intense shower cells are usually less than five miles in horizontal extent. Let us consider as an example an idealized circular storm four miles in diameter in which it is raining at a rate of 2 in/hr. Assume that it moves along at a rate of 40 mph and lasts one hour, a lifetime which our observations have shown to be reasonable. During that hour it precipitates 10^{11} in^3 of water which is spread over an area of 160 square miles. The radar would show the area quite accurately but might be in error by a factor of three in amount. In the rain gauge network each gauge represents an area of 400 square miles. The storm might hit none, one, or two gauges, each of which might register any amount up to 0.2 inches depending upon whether the storm went directly over it or was somewhat off to the side. It turns out that the gauges might indicate rain over an area of zero, 400 or 800 square miles with a total amount from 0 to 6×10^{11} in^3. It appears that the total amount of rain indicated by the radar is at least as accurate as that deduced from most existing networks of raingauges and the distributional information is considerably better.

C. Conclusion

We have shown that the radar can be a very valuable instrument in describing the instantaneous distribution of rainfall. Although the accuracy of radar measurements of rainfall is inherently limited by natural variations in drop size distributions, improvements during the past few years in instrumentation and techniques have made it possible to obtain both a high degree of accuracy and rapid coverage in measuring the average signal intensity of fluctuating precipitation echoes from a large area. The problem of integrating the instantaneous data over periods on the order of an hour so that detailed maps of total rainfall may be plotted has not yet been solved satisfactorily. Because of the small areal dimensions of heavy showers high resolution is desirable. Some success has been achieved in the development of photographic integration techniques. Both scope tubes and films have adequate resolution, but they are rather severely limited by small dynamic ranges and nonlinear response. It seems clear that electronic techniques for data processing must be developed in order to maintain the degree of accuracy which has already been achieved in instantaneous measurements.

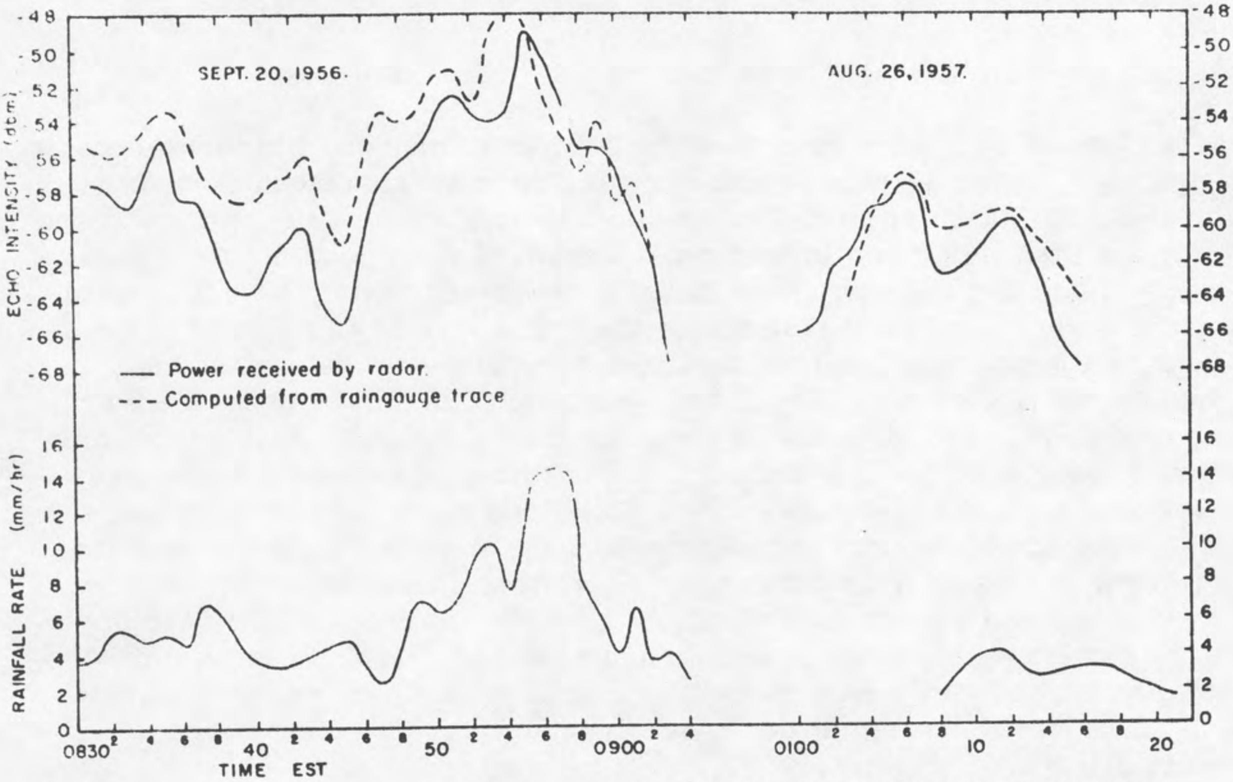


FIG. 5. COMPARISON OF DATA FROM SCR-615-B RADAR AND HUDSON-JARDI RAINGAUGE.

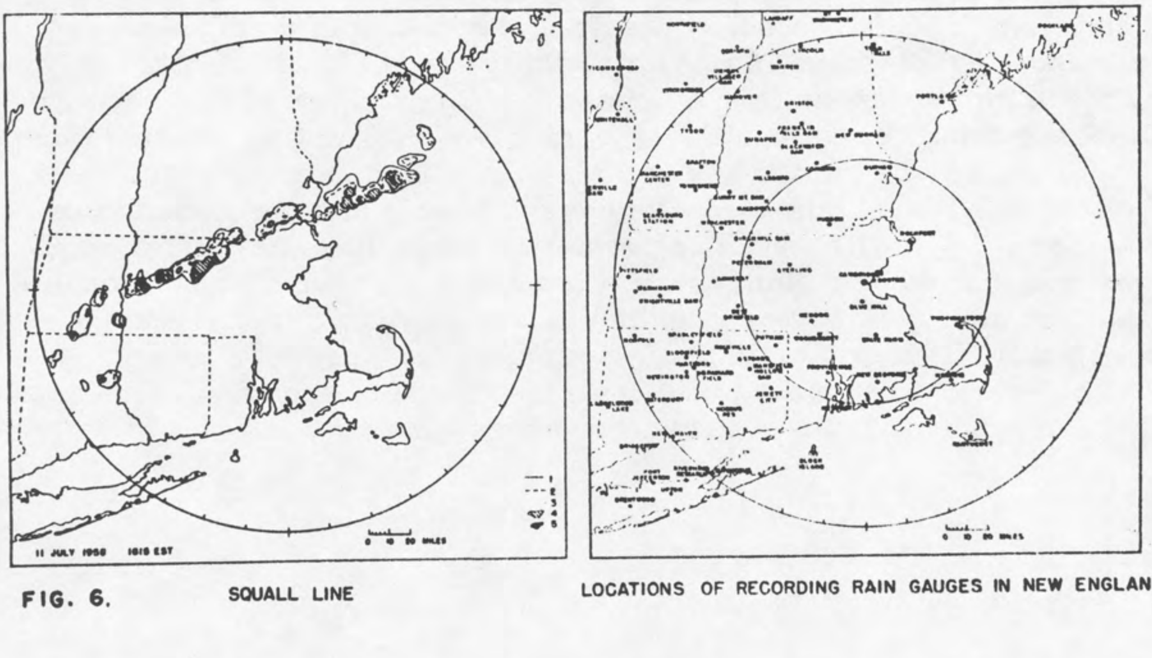


FIG. 6. SQUALL LINE

LOCATIONS OF RECORDING RAIN GAUGES IN NEW ENGLAND