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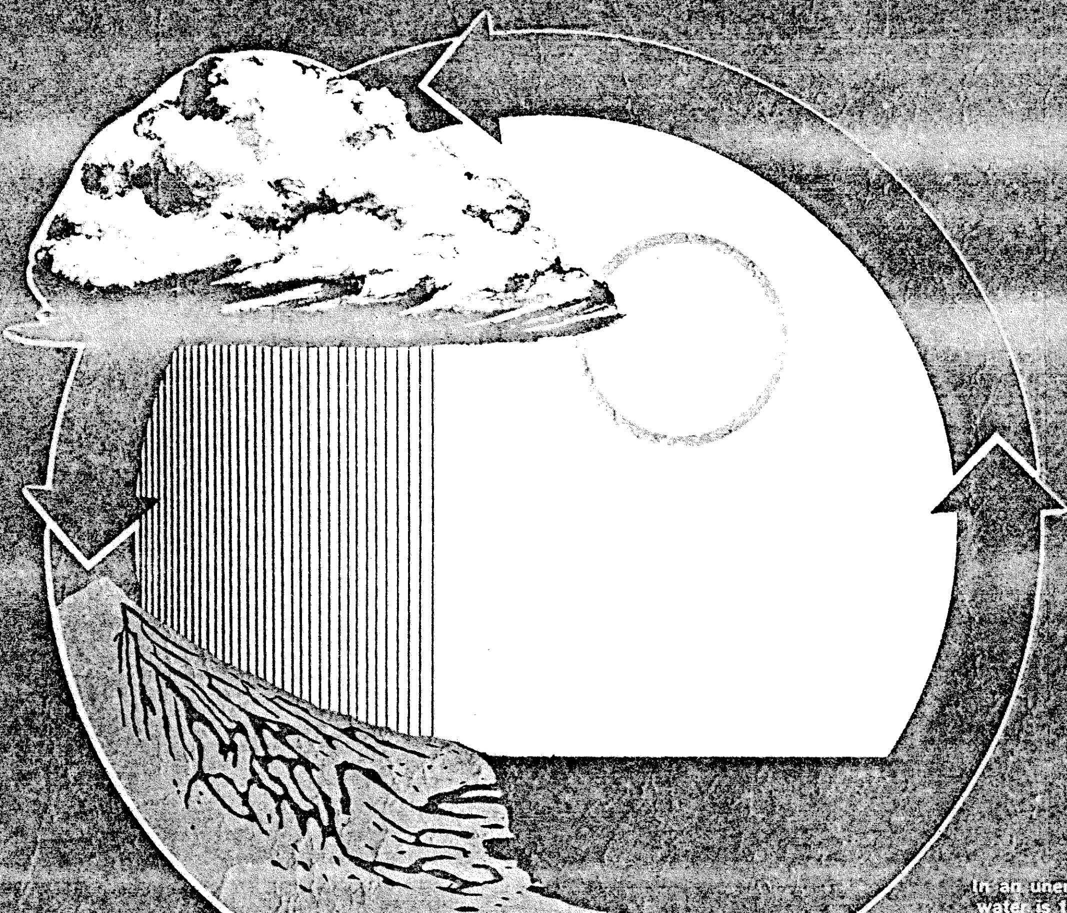

In an unending exchange, water is transferred from ocean to atmosphere, from atmosphere to land, and, finally, from land to sea. The diagram at left simplifies a complex cycle, showing only the large scale features of this exchange.

THE HYDROLOGIC CYCLE

AMERICAN METEOROLOGICAL SOCIETY

RADAR HYDROLOGY - THE STATE OF THE ART

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1. INTRODUCTION

Ninety percent of all significant weather occurs on a mesoscale. Severe storms having high rainfall potential, in this scale, cause great loss of life and property each year; thus it is imperative that these systems be detected, analyzed, and their movement predicted (Greene, 1971). This problem is complicated by the fact that in the United States even the most dense network of surface reporting stations are spaced on the order of 100 nmi, whereas the storm systems in question are distributed frequently on a much smaller spatial scale. This inadequacy of reporting stations, along with the variability of rainfall, is one of the major problems in hydrology. In fact, the distribution of rainfall as described by conventional rain gage observation is probably the least representative of any of the hydrometeorological variables. The problem is particularly acute in the case of death-dealing flash floods which by definition develop their course, and recede quickly.

This paucity of data can be filled partially by weather radars which scan effectively a radius of more than 100 nmi. In some cases this is an entire storm producing area.

2. HISTORICAL BACKGROUND

The primary requirement of radar for hydrological purposes is to provide estimates of the amount and the temporal and spatial distribution of precipitation that falls over a watershed. Development of procedures for using radar as a tool to measure the areal distribution of precipitation have progressed from the subjective manual techniques, first used in the late 1940's, through the semi-automatic techniques, to the fully automatic techniques of today. Flanders (1969) presents a discussion of the requirements, specifications, and applications of each of these areas.

Shortly after World War II it was recognized that radar could be of significant value to the science of hydrometeorology through its capability of observing the location and areal extent of thunderstorm rainfall (Battan, 1973). An early application of radar data to rainfall assessment was made by Byers et al. (1948) who used radar data to determine the amount of rain falling over small areas. Hiatt (1956) suggested that radar data might be used to interpolate among the sparse station data, thereby making it possible to draw isohyets more accurately. Some early efforts in the <u>operational hydrologic application</u> of radar data are summarized below:

2.1 <u>Multiple Exposure Photo-Integrations</u>

The use of multiple exposure photography to integrate radar data over space and time was first investigated by Rockney (1954) at the Massachusetts Institute of Technology. The approach was to obtain a composite radar echo comparable to isohyetal analyses prepared from raingage data. This method was further tested, improved, and techniques developed for at the University of Miami by Hiser, et al. (1958) and at Texas A&M by Ligda, et al. (1956). In a demonstration of the usefulness of radar data to hydrologic problems, Tarble (1960) illustrated the difference in isohyetal maps drawn with and without the aid of integrated radar photographs. He shows that, with the assistance of radar, the river forecaster is able to determine the areal distribution of rainfall much more definitively and is able to concentrate his efforts on those areas where rainfall is of flood potential.

In 1961 an operational test of this procedure was made whereby the Wichita, Kansas, National Weather Service (NWS) radar staff made 2-hourly multiple exposure photographs of the radar PPI scope, encoded and transmitted these data to the Tulsa River Forecast Center (RFC). Although good results were obtained from the original film considerable loss in detail occurred when the radar exposures were encoded and transmitted because of the limitations in describing echoes in azimuth-range coordinates. The conclusion reached was that multiple exposure photographs could best be utilized on stations where a hydrologist has direct access to the film and comparative rainfall reports (Flanders, 1963).

2.2 <u>Radar Precipitation Integrator</u>

In 1959 the Stanford Research Institute (SRI) began investigations into estimation of rainfall by measuring the attenuation effects of rainfall on shortwave radio signals over predetermined paths. Based on these investigations, in 1962 SRI constructed a prototype Radar Precipitation Integrator (Collis, 1964). In this device rainfall is measured by means of the photoelectric sensing of the intensity-modulated PPI sweep, while the gain of the radar system is varied in steps. The rainfall was estimated at 141 locations for a selected time interval and the rainfall estimates transmitted to the user by telephone communications. Although the number of data points for which rainfall intelligence was derived was a factor of 10 greater than normally available from operational rain-gage networks, Kessler and Wilk (1968) report that the number of data points available from the Radar Precipitation Integrator System was still inadequate to define many thunderstorm rains and represented only a small fraction of the total information available from the PPI display.

2.3 Grid Tally Techniques

Manual gridding techniques were first employed in 1962 both by the NWS radar staff at Detroit, Michigan to estimate rainfall over Lake Erie (Flanders, 1963) and by the NWS radar staff at Missoula, Montana to obtain rainfall estimates for the remote mountainous regions of the Upper Columbia River Basin (Granger, 1963). In the Grid Tally Technique, a grid is superimposed on the PPI scope at various time intervals and a rainfall value is assigned to each grid box. Tallies are obtained by accumulating the values from the same grid box taken at successive times. Radar intensities were obtained for each box by use of the VIP or radar attenuators. One of the main drawbacks of these techniques is the large amount of time required for its operational use.

2.4 NSSL - Fort Worth RFC Experiment

In 1966 a pilot study which involved digitized radar data, communications, and computer processing was conducted by the NWS RFC at Fort Worth, Texas and the National Severe Storms Laboratory (NSSL), Norman, Oklahoma. In this study digitized radar-echo intensity maps were produced semi-automatically at 30-minute intervals at NSSL and transmitted via low speed teletype communications to the Fort Worth RFC. These teletype data were converted to punched cards and input into a computer for hydrologic applications (McCallister, et al., 1966). This experiment demonstrated the operational feasibility of the concepts of hydrologic radar data processing that later formed one of the basics for the NWS Digitized Radar Experiment.

2.5 Manually Digitized (MDR) Programs

Moore and Smith (1972) developed a procedure in which data obtained from NWS WSR-57 radars are manually transformed into a grid representation by superimposing a coarse-mesh grid (a subset of the National Meteorological Center primitive equation model grid) over the radar PPI displays. These procedures, which have been implemented for the NWS WSR-57 network radars east of the Rockies, are being used operationally to update numerical precipitation guidance and to evaluate flash flood potential. Moore, et al. (1974) present excellent examples of the hydrologic applications of MDR data.

Although the grid is somewhat coarse, an approximate 40 nmi mesh, MDR has proven to be a valuable means of collecting and communicating radar data for further quantitative application not possible with previous plain-language radar reports. Plans are underway to replace the MDR and present coded message with a higher resolution (22 nmi mesh) code. Procedures or techniques developed in this program will be applicable to and aid in the transition into the fully automatic system. These systems, which are in the early implementation stage by the NWS, will be discussed in the next section.

3. AUTOMATIC OPERATIONAL SYSTEMS

These early techniques, although still applicable when dictated by economic, hardware and radar utilization (Flanders, 1969), are limited due to the fact that the original radar data are presented in the form of qualitative video scope displays. These highly perishable data at most stations must be reduced manually for forecast applications. Techniques for manual reduction of these data frequently are impractical because (1) the large quantities of data generated by the radar are too difficult to assimilate, and (2) the visual extrapolation of radar data is often difficult due to rapid changes in small-scale echo characteristics. The ultimate solution is "real-time" processing and analysis of radar data by automatic computer. This has been made possible by the development of the automatic radar-signal processing techniques pioneered by NSSL (Kessler and Wilk, 1968). Automatic processing techniques are currently undergoing operational testing in both the United States, the National Weather Service Digitized Radar Experiment (D/RADEX), and in the United Kingdom, the Dee Weather Radar Project (Harrold, et al., 1972). In both of these operational tests a prime objective is to improve hydrological forecasting techniques based on radar data.

3.1 D/RADEX

The National Weather Service Digitized Radar Experiment (D/RADEX) began in 1971 with the addition of automatic signal processing systems to four existing WSR-57 network radars - Kansas City, Mo., Monett, Mo., Oklahoma City, OK., and Fort Worth, Texas. In 1974 the Fort Worth radar was moved to Stephenville, Tex. and a special test site was established at Pittsburgh, Pa. Each of these 10-cm radars is equipped with a video integrator and processor (VIP), a data processing system consisting of a Data General Nova 1200 mini-computer, and various peripheral devices (McGrew, 1972). The integrator output of each of 115 one nmi range bins is quantized into one of 10 levels (digits 0 through 9) representing returned power bands varying in width from 4.5 to 6.5 db. These raw data are collected in a 2-degree by 1 nmi format corresponding directly to the radar reception process. For transmission and display these instantaneous intensity values (each digit corresponds to given reflectivity or decibel term which in turn is related to precipitation intensity) are transformed to a Cartesian format called an "I-J matrix", as shown in Figure 1. The exact configuration of the automated system and the derived and output products has continued to change as we have learned more about the system, improved output and display products, and employed efficient data compression techniques.

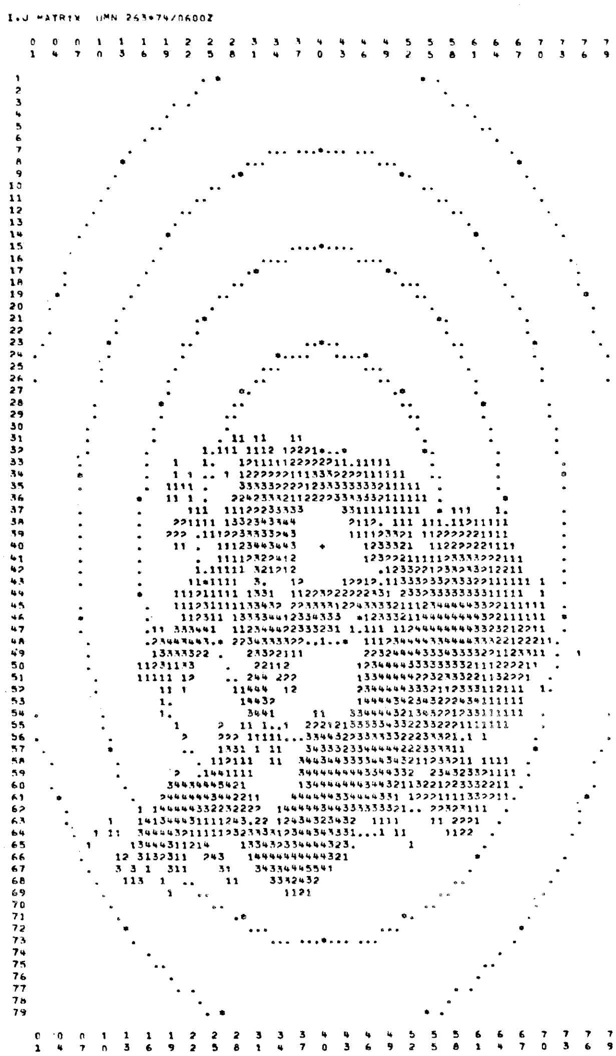

Figure 1. "I-J" matrix presentation of digital radar intensity values. Each display value represents the maximum digit falling within a 3 nmi by 3 nmi box.

D/RADEX has an overall objective to increase usefulness and to fully exploit weather radar data to both meteorological and hydrological applications. The hydrologic objective has been to test, evaluate, and improve hydrological forecasting techniques based in part or in whole on radar data.

Timely quantitative estimates of precipitation based on a continuous set of digital radar data have application to two important hydrologic forecast problems; flash flood warning and day-to-day river stage forecasting. The river stage forecast problem allows for a limited time delay for data collection and analysis, whereas the flash flood problem requires real-time data processing with alerting capabilities built into the system.

In the present context, the emphasis has been on the development of river stage forecasting techniques based on digital radar data at all RFC's served by a D/RADEX site; however, flash flood monitoring has been stressed only at the Pittsburgh, Pa. site. The reasoning behind this is that the Pittsburgh D/RADEX is a special test site where hardware and software procedures can undergo operational testing prior to implementation at other sites. The Pittsburgh location was influenced strongly by the seriousness of flash-flooding in that region. Quite naturally there is strong emphasis on the development of techniques to aid in the detection and forecasting of these phenomena. Sisk (1975) presents examples of the operational application of D/RADEX data to flash-flood forecasting at the Pittsburgh Weather Service Forecast Office.

3.1.1 Flash-Flood Monitoring. The objectives of the current operational development effort are: (1) to derive areal rainfall estimates from digital radar data each 12 min and to obtain accumulated totals on a 3 nmi x 5 nmi grid for the region within the effective hydrological range of the radar; and (2) to provide guidance to the forecaster by making a short period (2 h or less) prediction of spatially accumulated rainfall.

Objective (1) is accomplished by deriving areal radar-rainfall values, and accumulating and storing a three-hour running total of radar rainfall for each grid box. These amounts are updated at each radar scan (normally each 12 min). After an update each grid box is checked to see if the rainfall total exceeds a predetermined threshold value. When the threshold criteria are reached the radar computer automatically "dials-up" and transmits an alerting message to the Weather Service Forecast Office having watch and warning responsibility. In the present system these criteria are rainfall accumulations of 25 mm or more within a one-hour period and/or 50 mm within a three-hour period. Provision also has been made in this program to allow flash-flood guidance values provided by a RFC to be input and used as threshold values.

Successful application of radar data for hydrologic purposes depends upon minimizing errors inherent in radar measurements and their relationship to rainfall rates. One way of achieving this goal is to maintain data quality control by combining radar derived rainfall estimates with rain gaga data. To be responsive to the flash-flood problem this quality control function must be accomplished in near real-time. There are 10 DARDC (Device for Automatic Remote Data Collection) equipped rain gages under the Pittsburgh radar umbrella that may be interrogated for this purpose and interrogation will be accomplished by the NWS Automatic Data Acquisition System (ADAS) as reported by Schiesl (1975). ADAS will receive these data and retransmit them to the radar minicomputer on a scheduled or request basis.

The prediction of rainfall, objective (2), requires a mean pattern motion vector. It had been hoped that this motion vector could be obtained from the best pattern match between sequential radar derived precipitation patterns by use of cross-correlation techniques. The technique thought to be the most amenable to the radar mini-computer environment is a binary matching procedure (Greene and Clark, 1974). In the operational application of this technique pattern motion vectors were found to be quite unstable. A "global match" procedure, such as are most of the cross-correlation techniques, has stringent fixed boundaries of the radar umbrella. Motion vectors obtained through use of these "global match" procedures are contaminated by echoes moving into or out of the detection umbrella (Greene, 1972). To eliminate the instabilities in the computation of motion vectors a tracking procedure which uses a Lagrangian coordinate system will probably have to be used for echo displacement computations. Such a system, developed by Duda et al. (1972), uses clustering procedures to define and track echoes. The problem with the application of this procedure is that it requires storage and processing time requirements that do not lend themselves to the radar mini-computer environment.

3.1.2 River Stage Forecasting. Forecasting techniques based on digital radar data are being formulated semi-operationally at the RFC's by developing procedures and using radar data as inputs for streamflow synthesis in hydrologic models.

The D/RADEX processing system derives areal rainfall values, accumulates and transmits these totals via low speed dial-up telephone ASR 33 teletype writer communications system to the appropriate RFC each three hours (Hudlow, 1972, and Greene, 1975). These three-hourly rainfall estimates are furnished to the RFC in two forms: a grid form representing fictitious 3 nmi x 5 nmi watersheds under the radar umbrella and mean basin precipitation values for defined watersheds.

The grid message presents a coded value representing the average rainfall accumulated during a 3-hour period over a 3 nmi x 5 nmi (15 nmi^2) watershed. In the mini-computer the array used for these accumulations is the identical one employed for flash-flood monitoring. The only difference being that in the flash-flood version the accumulations are tested after each addition of a rain amount estimated from a radar scan.

The watershed portion of the data consists of basin average precipitation (in hundredths of an inch) for operationally defined watersheds, and precipitation totals for several control areas centered over rain gages (Hudlow, 1972). The control values are used for quality control purposes by comparing with rain gage recorded amounts on a quasi-real-time basis. In the field application these control values are used to adjust continually the radar-rainfall relationship to remove any consistent bias. Experience gained to date in the hydrologic application of digital radar data has demonstrated that rainfall rates obtained from the commonly used Marshall and Palmer (1948) relationship

$$Z = 200 R^{1.6} \qquad (1)$$

must be increased by a factor of 2.25 to be consistent with the observed data (Greene and Clark, 1974). Applying this factor to Equation (1) we obtain

$$Z = 55 R^{1.6} \qquad (2)$$

Note that in the development and application of Equation (2) no corrections are made for atmospheric absorption, rainfall attenuation, gradient bias, or radome losses.

Correlations obtained in comparing 6-hr radar, obtained by use of Equation (2), and rain gage accumulations are very good for ranges within 75 nmi of the radar, but at greater ranges correlations deteriorate rapidly (Greene, 1975). It is apparent that some type of range adjustment factor, such as suggested by Wilson (1971), or a rainfall optimization program based on the integration of radar and rain gage data as developed by Brandes (1974) will have to be used to improve rainfall estimates. In this vein, the Tulsa RFC is implementing the Brandes technique for operational testing this year (1976).

The HYDRO message is received automatically by the RFC every 3 hours from the radar sites by low speed telephone communications. The message is simultaneously printed on paper hard copy and punched onto 8-channel punched paper tape. Data in the paper tape form must be manually removed (in some cases converted to another medium) and input into a computer file for access by the operational hydrologic forecast programs (Greene, 1975). This manual editing and input step reduces the efficiency of the total system. Hopefully, these communications problems will be improved greatly when AFOS becomes operational [see paper by Clark (1976) in these Conference Preprints].

One output from the hydrologic forecast program is the predicted flow hydrograph. Figure 2 is a comparison of the forecast hydrograph computed at the Tulsa RFC independently by use of rain gage data with the observed hydrograph. Although the radar forecast crest flow was low, the radar forecast was much more realistic than the forecast based on rain gage data. Personnel at the Tulsa RFC state that radar derived hydrographs compare favorably with those computed from rain gage data. Further, the radar forecast can be made and transmitted to the public in a matter of minutes versus a matter of hours needed to collect the data for making rain gage-derived forecasts (Tetzloff, 1974).

3.2 The Dee Weather Radar Project

In the Dee Project automatic processing systems have been implemented at three weather radar research stations; Castlemartin, Wales; Defford, Worcs; and Llangdegla, North Wales. These weather radar sites have been linked by computer to form an integrated network for the acquisition of data on precipitation systems (Taylor, 1975). The prime purpose of this system is to measure precipitation over several sub-catchments of the River Dee, located in a region of very hilly terrain in North Wales. These precipitation measurements are input, in the real-time, to hydrologic models of the River Dee for stream flow determination used for water management and river regulation. Radar data collection is complimented by a telemetry system

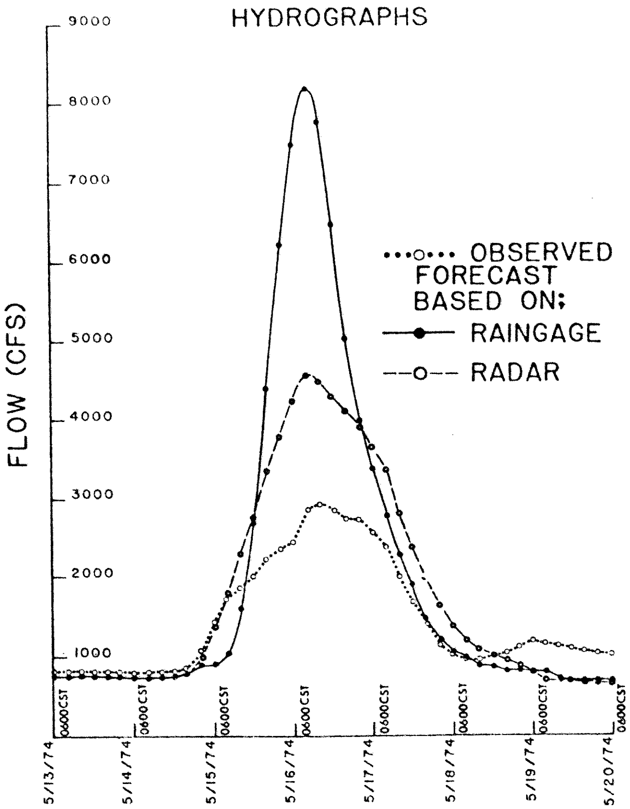

Figure 2. Comparison of predicted hydrographs based on radar and raingage data with the observed flow.

with computer acquisition of river stage and rain gage data from the Dee catchments. A detailed discussion of the hardward, data collection and processing systems, and hydrologic models used in the River Dee Project is presented in the Proceedings of the Symposium on Weather Radar and Water Management held in Chester, England, Dec. 1975.

4. FUTURE

4.1 Expansion

Scientists working in the field of meteorology and hydrology recognize that automatic computer processing of radar data in the real time adds a new dimension to hydrometeorology. Current planning within the NWS calls for the operational implementation of 71 digitizing systems. This includes all 56 network radar sites (51 WSR-57 and 5 WSR-74S) and 15 local warning radar sites (WSR-74C). Figure 3 illustrates the areal coverage provided by the network radars alone. Timing of the purchase and installation of the new automatic systems, called RADAP (RAdar DAta Processor), is contingent upon future NWS resources.

4.2 Research Activities and Developments

To increase the "state of the art", additional basic research and/or procedural developments is required for a number of problem areas. Some of them are:

a. Discrimination of non-precipitation echoes - both anomalous propagation (AP) and ground clutter.

b. Improvement of radar precipitation estimates - both liquid and solid.

c. Determination of the sensitivity of hydrologic models to radar data.

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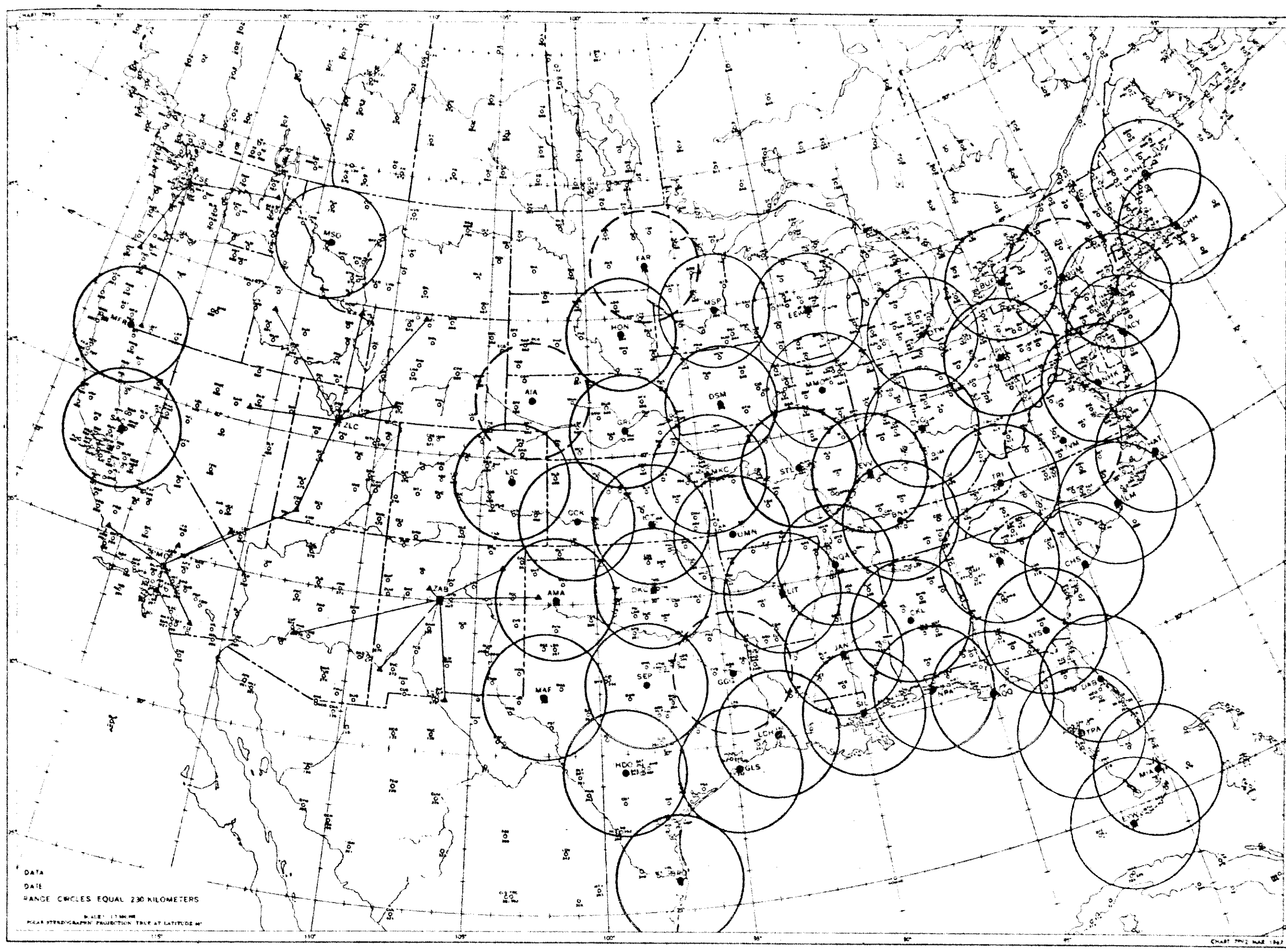

Figure 3. Locations of the NWS network radars. WSR-57 radars are indicated in solid range circles (230 km) and planned WSR-74S radars are indicated by dashed range circles.

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