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A MULTIPLE SENSOR RAINFALL ANALYSIS SYSTEM

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1. INTRODUCTION

A key factor used in issuing forecasts and warnings of river conditions affecting the Nation's safety and economic welfare is the quantitative measurement of the amount of rain that falls over a given area. The areal distribution of gages, used operationally to measure this rainfall, is typically spaced on a scale larger than the convective elements which contribute significantly to total rainfall. This inadequacy of reporting stations, along with the variability of precipitation, is one of the major problems in hydrology, in particular for flood forecasting. It is generally agreed by hydrologists working with rainfall runoff problems that there is more uncertainty in the measurement of rainfall with conventional rain-gage systems than with most other hydrometeorological variables. Sparse rainfall data cause frequent problems in routine river forecasting that become acutely severe as the scales of the event to be forecasted diminish. In a recent survey article on flash flood events, which addresses the importance of scales in reporting heavy rainfall events, Maddox, et al. (1979) state "Reports on the time of occurrence were often vague, while specific details on the timing, duration, and amount of precipitation were sometimes totally lacking."

This paper describes the plans for a Hydrologic Rainfall Analysis Project (HRAP) which was initiated to accomplish the research and development to produce reliable rainfall data operationally to partially fill this information gap, using surface, radar, and satellite reports.

1.1 Radar Rainfall Estimates

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 sparse station data, thereby making it possible to draw isohyets more accurately. Some early efforts in the operational hydrologic application of radar data are summarized by Greene and Flanders (1976), who outline the development of procedures for using radar as a tool to measure areal rainfall from the subjective manual techniques of the late 1940's, through the semi-automatic techniques, to the fully automatic techniques possible today.

Although there has been limited success in the operational application of digital radar data to the rainfall estimation problem (Greene and Saffle, 1978), the overall success has been disappointing. This has been primarily due to the lack of availability and reliability in radar-rainfall estimates.

1.2 Satellite Rainfall Estimates

In the mid-1960's cloud pictures acquired from polar orbiting satellites raised the hope that data sensed by satellite-borne radiometers could improve rainfall estimates in areas of sparse rain gage data. A complete review of the early attempts to estimate rainfall from satellite data is presented by Martin and Scherer (1973). Most of these methods were based on three ideas. First, the mere presence or absence of clouds in visible band imagery indicates the possibility or impossibility of rain. Second, if clouds could be categorized, then a certain average rainfall might be suggested based on a rainfall history developed in the area for different cloud types. Finally, infrared (IR) imagery, in addition to allowing coverage of an area during nighttime satellite passes, provides mapping of cloud top heights and hence the location of high cloud tops that often are correlated with deep convection.

These polar orbiting satellites, however, give only limited coverage to any particular location in the United States--generally only two images per day. Barrett (1970) concluded that this data frequency limits the usefulness of data sensed by polar orbiting satellites to synoptic scale applications.

In addition to using visible and thermal infrared imagery, efforts have been made to estimate rainfall using the Electrically Scanning Microwave Radiometer (ESMR) on board the polar orbiting Nimbus 5 and 6 satellites. However, this effort has been restricted mainly to over ocean areas (Adler and Rogers, 1977; Rao, et al., 1976; and Wilheit, et al., 1977).

With the advent in 1974 of geosynchronous or geostationary satellites, satellite imagery and digital data have been routinely available every half hour. This increase in the frequency of data encouraged the development of more sophisticated models to estimate rainfall. One of these was developed by Scofield and Oliver of the Applications Group of NOAA's National Environmental Satellite Service (NESS). This model uses IR and visible imagery. It is oriented toward convective storms, and uses a spatial enhancement of IR imagery to pick out cumulonimbus cores. The method follows a decision tree approach where, depending on storm development, the decision tree leads to numerical estimates of rainfall for the previous half-hour period at the particular points analyzed (Scofield and Oliver, 1977).

Another method was developed by Woodley and Griffith in conjunction with the Florida Area Cumulus Experiment (FACE) and the GARP Atlantic Tropical Experiment (GATE). Initially, this method was used in conjunction with radar and provided an estimate of a total volume of rainfall for a given radar echo and corresponding satellite image entity. The method includes a relationship between the growth curves of the cloud areas and the rainfall volumes. Additions have been made to distribute the rainfall within the storm so that rain at a point can be estimated. Work also has been done to automate this procedure. The status of work on this method is summarized in a paper by Griffith, et al. (1978).

The lack of ground truth rainfall measurements to compare with satellite rainfall estimates, as well as errors caused by navigation or registration uncertainties (i.e., assigning points in the imagery to points on the surface of the earth), have made it difficult to evaluate the worth of satellite rainfall estimates. Several investigators have used radar-rainfall estimates as ground truth and/or as a basis for determining empirical coefficients for the satellite techniques (e.g., Hudlow, 1975; Griffith et al., 1979). This need for high quality radar data has resulted in the comparison studies associated with data intensive projects such as GATE, done over the ocean, and FACE in southern Florida.

Although there have been some operational attempts to use satellite data to estimate rainfall, e.g., estimates of monthly precipitation over China and U.S.S.R. by Follensbee (1976), and the use of the Scofield-Oliver technique to estimate rainfall due to Hurricane Anita in 1978 for gage-sparse areas in the Mexican tributaries of the Rio Grande River, no technique yet has achieved the level of reliability and automation to be suitable for routine operational use.

2. HYDROLOGICAL REQUIREMENTS

Rainfall data needed for the production of flood forecasts are based somewhat on temporal and spatial requirements, depending upon application thereof to river stage forecasting or to flash flood warnings.

2.1 River Stage Forecasts

a- Spatial Needs. Rainfall, especially that convective in origin, has been observed to have great spatial variability. The models used currently by the U.S. National Weather Service (NWS) in flood forecasting are known as lumped parameter models. This means that rainfall for a given basin is applied as a uniform rain over the entire area. It is assumed that the basin response to a representative mean rainfall will be similar to that of a uniform rainfall even though much of the rainfall, in reality, was concentrated in a fraction of the basin. A representative or suitable mean has been considered to be one where several gages, at least three to five, are weighted according to their effect on the watershed. However, such densities of gages are not always available operationally and, for convective events, representative areal rainfall cannot be determined from gages alone. Areal measurements from digital radar should significantly improve the representativeness of basin average rainfall under such conditions.

Generally, in nonmountainous areas, weighting of rain-gage data is based on the fraction of the watershed area each gage represents (NOAA, 1972). A large basin may require division into several subbasins, each with its own mean areal precipitation estimate, in order to properly model the flow from the basin. The detailed areal coverage provided by remote sensors will enable such basin subdivisions.

When mean areal estimates of precipitation are generated from areal measurements, such as from radar or satellite, rather than from point measurements, such as from rain gages, sufficient resolution and number of data samples should be retained to smooth or filter out noise in the measurement and to properly account for the spatial variability encountered at the watershed boundaries. The latter can be a problem in mountainous areas where narrow canyons and steep-sloped drainage areas exist.

b- Temporal Needs. The controlling factor on the frequency of reports is the time from the beginning of rain until the crest reaches the forecast point -- sometimes called the "period to peak." If the period to peak is on the order of several days, then six hourly or even daily rainfall reports are very likely to be adequate. When the time to peak for a basin is less than say, 24 hours, then precipitation reports should be gathered more frequently than six hourly.

In the past, the time taken to record and process data in a River Forecast Center (RFC) has limited the amount of data that could be adequately handled. With more automated procedures, reports may now be acquired and processed for "quick-peaking" basins every hour. Data from digital radar, geosynchronous satellites, and telemetered rain gages can be made readily available on hourly or shorter intervals.

2.2 Flash Flood Forecasts

In many impervious basins, or basins with steep slopes, the period to peak is very short. This is the condition in many urban watersheds. There is often insufficient time after heavy rains begin until "bankfull" runoff occurs to gather precipitation amounts, compute an areal average, and generate a forecast.

Preparations must be made in advance to: issue advisories as weather conditions indicate the possibilities of heavy rain; determine the amount of rainfall that can fall before flooding will occur; confirm that high intensities are being measured which are expected to cause flooding; and acknowledge immediately when measurement of the threshold quantities of rain have been received.

Flash flooding is most likely to occur on small basins (except for those cases resulting from dam failure when flash floods can occur below the dam). The quick rise is usually a direct result of either short travel times and/or steep slopes. When intense storms occur over areas where flooding is likely to be a problem, the precipitation sensor must have adequate resolution to resolve the mesoscale rainfall cores and locate them in the appropriate basins. A well calibrated radar equipped with a digitizer and data processing system is potentially the best state-of-the-art instrument for flash flood detection and warning. This was demonstrated during the 1977 Johnstown flash flood when radar rainfall estimates from the Pittsburgh D/RADEX system were the only real-time source of data available to the forecaster (Greene and Saffle, 1978).

3. HYDROLOGIC RAINFALL ANALYSIS PROJECT (HRAP)

Through cooperation with other elements of the National Weather Service, other research laboratories of NOAA, and the National Environmental Satellite Service, and using contractual support when feasible, the Hydrologic Rainfall Analysis Project (HRAP) will be directed toward developing objective techniques for preprocessing, quality controlling and optionally merging rainfall data from multi-radars, rain gages and, when feasible, satellites into a data base that may be accessed by any user having access to the distribution circuit of the Automation of Field Operations and Services, AFOS (Klein, 1978). The results from this research will provide immediate improvements in the accuracy and timeliness of the flood forecasts issued by NWS River Forecast Centers (RFCs) and should improve quantitative precipitation forecasting and result in better flash flood warnings issued by the Weather Service Offices.

HRAP is planned to evolve from the initial fixed scale rainfall analysis for limited areas, which are expected to be developed operationally within the next year, to the sophisticated national rainfall analysis system of the mid-1980's. The system is visualized as having the capability to produce rainfall analyses on a nested grid with zoom display capability to fulfill the fine scale resolutions requirements demanded by flash flood mesoscale applications up to larger regional and/or national scales required for quantitative precipitation updating.

In the early stages of the project these analyses will be limited to a single scale (a grid mesh of approximately 5 km) and to regions from which digital radar data are available. Therefore, one of the key factors affecting the future expansion of HRAP is the schedule of implementation of digital radar processors at NWS radar sites.

3.1 Data Sources

a- Rain gage data. Surface observed rainfall measurements (rain gage reports) are the backbone of the NWS operational flood forecasting program. The NWS routinely receives these data from a variety of observing stations, substation networks, and other sources. Most of the rainfall data that enters the NWS hydrologic forecasting system are obtained from:

- synoptic weather reports
- aviation weather reports
- automatic rain gage networks
- official substation reports
- volunteer cooperative observer reports

These rainfall reports are collected by various offices (NWS--weather forecast and observatory offices and RFCs; and other agencies--e.g., U.S. Army Corps of Engineers and U.S. Geological Survey) and relayed to the River Forecast Centers. The RFC in turn enters these data into the NWS River Forecast System (NWSRFS) data files which are located in the IBM 360/195 NOAA computer system located at Suitland, Maryland.

b-Radar-data. The NWS presently has a network radar system comprised of 51 WSR-57 and 5 WSR-74S weather radars, Figure 1. Supplemented by a number of WSR-74C local warning radars (not shown in Figure 1), this network provides nearly blanket radar coverage over the eastern two-thirds of the United States. The full potential of operational hydrologic use of data from these weather radars has been limited because the data from most of these sites are presented to the user in video output form that requires manual handling for applications. Faced with these shortcomings in the real-time application of radar data, the NWS began in 1971 the Digitized Radar Experiment (D/RADEX) with the goal of using automatic computer processing to enhance the usefulness of radar data. In D/RADEX, selected network WSR-57 radars were equipped with digitizing hardware including a minicomputer, and programs were developed to process the digital data into various products (Greene, 1975; Saffle, 1976) having application to both meteorology and hydrology.

In 1976 when the experiment officially ended, the NWS decided to convert the D/RADEX sites from experimental to operational and to run in this mode as long as parts and available maintenance would allow. At the time of this writing, spring 1979, four of the five D/RADEX sites are still operational. These sites (indicated by the stars in Figure 1) are Kansas City, Mo., Monett, Mo., Oklahoma City, Okla., and Pittsburgh, Pa. These sites will provide the digital radar data for the initial phase of HRAP.

Current planning within the NWS calls for the operational implementation of new automatic RAdar DAta Processor (RADAP) Systems at 71 radar sites. These include all 56 network sites (51 WSR-57 and 5 WSR-74S) and 15 local warning radar sites (WSR-74C's). Although scheduling of the purchase and installation of RADAP is contingent upon future NWS resources and contractual negotiations, the digital network should be in place by the mid-1980's.

c-Satellite data. The National Oceanic and Atmospheric Administration (NOAA) currently operates two different types of satellite systems, the NOAA polar-orbiting and the Geostationary Operational Environmental satellites (GOES) system of geosynchronous satellites (McGinnis, et al., 1979). Although the polar-orbiting satellites provide very high resolution spatial data, the observations are not frequent enough (once a day visible and twice daily infrared) to be used for estimating quantitative rainfall for flood fore-

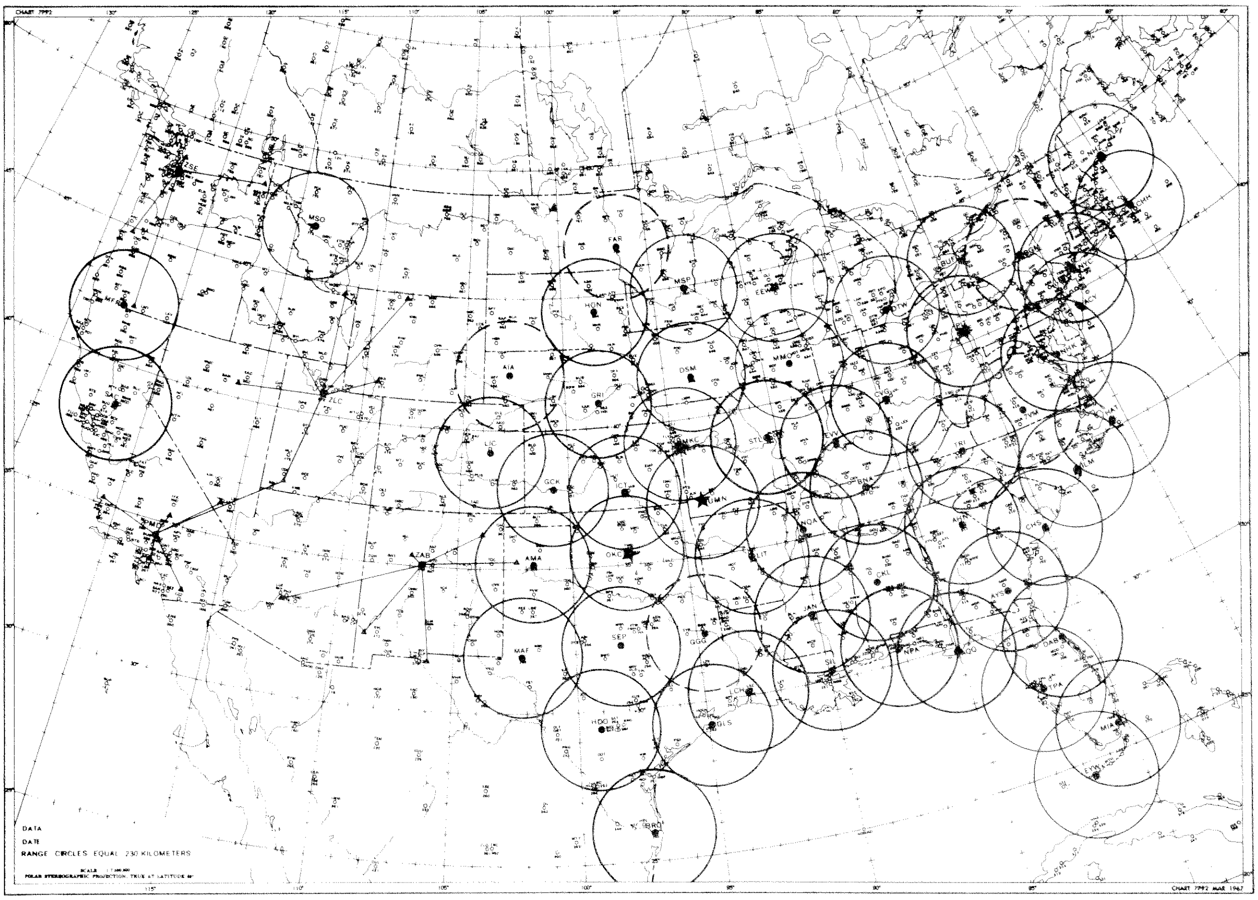

Figure 1.--Locations of the NWS network radars. WSR-57 radars are indicated in solid range circles (230 km) and the WSR-74S radars are shown in dashed range circles. The four D/RADEX sites are indicated by stars.

casting. Therefore the geostationary satellites, described in NOAA Technical Memorandum NESS 88 (NOAA, 1977), are the systems which meet the temporal and spatial data collection requirements for quantitative rainfall estimation.

NOAA currently has two geosynchronous satellites operational that sense data covering the United States. These are stationed in geostationary orbits over the equator at 75°W and 135°W longitudes. Briefly the imaging capability is provided by the Visible and Infrared spin-scan Radiometer (VISSR), which can sense in both the visible and thermal infrared regions. The highest imagery resolution, available at the nadir point (directly below the satellite) is 0.8 km for the visible data and 8.0 km for the infrared. Images are normally available at a 30 minute time interval (McGinnis, et al., 1979).

In a protracted and complex project such as HRAP one must attempt to gain insight into what future operational meteorological satellite systems may provide in the way of improved rainfall estimation. In a recent paper on the visions of future satellite systems of the 1990's, Atlas, et al., (1978) describes the concept of a system comprised of eight Low Earth Orbitors (LEOS) at 500 km height for global coverage at 3-hour intervals and three GOES types for Western Hemisphere stereo capacity. The impact by data from such combined satellite systems depends much upon state of the art developments in satellite rainfall estimation technology and in particular upon passive microwave and radar satellite systems.

3.2 Data Flow

The immense volume of data, the timeliness of the data, and the sophisticated processing required by various applications of digital radar data dictates that processing be done in two stages. Digital radar data have application to at least three important hydrologic problems; flash flood warning, river stage forecasting, and urban hydrology. Within the present framework of the NWS Office of Hydrology mission, only flash flood monitoring and river stage forecasting are presently being addressed. The river stage problem allows a limited time for data collection and analysis, whereas the flash flood problem requires real-time data processing that must be accomplished at the radar site. Based on these requirements, preliminary processing of digital radar data must be done on site in the radar minicomputer system and then will be transmitted to a central site having large-scale data processing capabilities. Figure 2 is a conception of the data flow and processing steps required in the marriage of multiple sensor data to a common rainfall analyses.

a- On-site Processing. On-site processing will

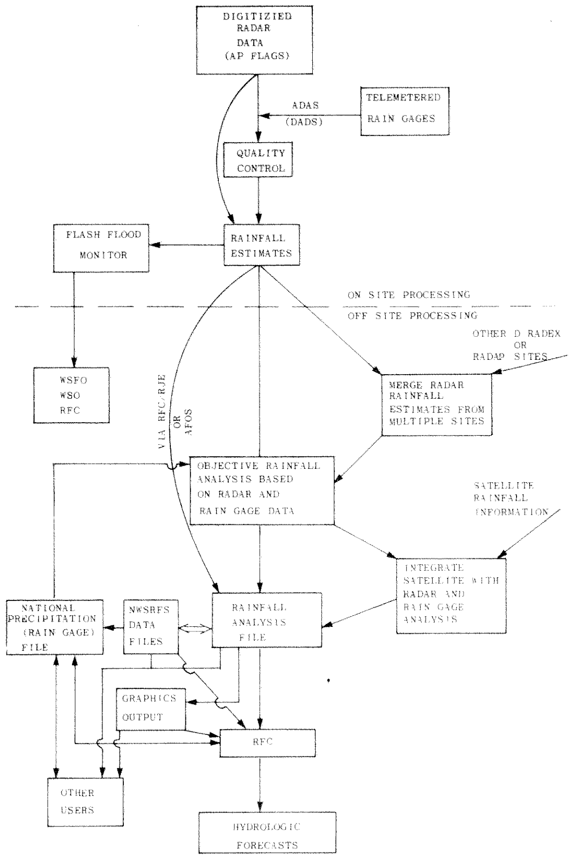

Figure 2.--Data flow for hydrologic applications.

include radar data collection and digitizing, anomalous propagation (AP) discrimination, real-time quality control, and derivation of rainfall estimates for flash flood monitoring and future hydrologic processing. The scenario for on-site processing functions is:

1) Collect and digitize data.
2) Flag data bins containing AP returns.
3) Perform the quality control function in near real-time by comparing radar rainfall estimates with selected rain gage data collected from automated rain gages under the radar umbrella. These data will be collected automatically through computer interrogation of the automatic gages by the NWS Automatic Data Acquisition System, ADAS (which is to be upgraded in the early 1980's by the new Data Acquisition and Distribution System, DADS). The ADAS/DADS computer will relay rainfall amounts to the radar computer. The procedure to be used to accomplish the quality control is described in the section on specific tasks.
4) Accumulate these initial rainfall estimates and at selected time intervals transmit these data to a central site for further processing.
5) Input rainfall estimates to an automatic flash flood alerting and monitoring routine.

b- Central Processing. Collection of radar-rainfall estimates at a central site makes these data available for sophisticated processing through the use of large scale computer systems. This processing will include conversion to a universal grid system, merging or compositing data from multiple radar sites, and combining with rain gage and/or satellite data by use of objective analysis techniques. The following processing steps are planned at a central location:

1) Collect radar-rainfall estimates from radar sites and store data on a disk file or other rapid recovery device for additional processing.
2) Assemble detailed rain gage data from all available sources and input to national precipitation file (to be discussed under section 3.3).
3) Obtain the optimal areal distribution of rainfall based on the integration of radar and rain gage data through the use of objective analyses techniques (to be discussed in section 3.3). A composite rainfall analysis will be developed from data collected from several sites or all sites within a region.
4) Supplement radar rain-gage analyses with satellite rainfall estimates (to be discussed in section 3.3).
5) Optimal areal rainfall analysis files will be structured for access by the NWS RFC's to be used as input into the appropriate hydrologic model computations also executed at a central computer site.

c-Communications. In the NWS D/RADEX one of the biggest problems encountered in the hydrologic application of digital rainfall estimates was the problem of transmitting these estimates from the D/RADEX site to the RFC or other processing site (Greene, 1975). It had been hoped that when the AFOS became operational this communications problem would be solved. Because of other data loading requirements, this may not be true with the present AFOS communications capabilities.

The basic problem is to transmit digital radar rainfall estimates from the digital radar sites (either D/RADEX or RADAP) to the central processing site. Data loading problems are caused by the overwhelming quantity of data contained in the grid of radar-rainfall estimates. In D/RADEX, a grid point represents an areal rainfall estimate for a 5.5 km by 9 km box but in RADAP the mesh size will be decreased to approximately 5 km. Although the size of each grid record is a function of the rainfall event, since the grid is "cropped" to eliminate no rainfall sections, the grid transmitted from D/RADEX sites can contain as many as 3500 characters. When the installation of RADAP is complete, the number of digital radar sites will drastically increase. The increase in digital sites along with the finer resolution grid will significantly increase data loading. The finer data resolution will increase the size of the maximum grid record from 3500 characters to approximately 8000 characters and data will be transmitted from the radar sites at a 1-hr interval instead of the present 3-hr interval used in D/RADEX.

One alternative to transmitting digital radar rainfall estimates to the central processing site via the AFOS National Digital Circuit (NDC) is to use the RFCs as data interface and relay points utilizing the RFC remote-job-entry

(RJE) terminal data-link to the NOAA 360/195 computer system. This option, which is presently under study, will require in the worst case data from 12 radars to be relayed through a single RFC (the Atlanta RFC).

3.3 Specific Tasks

Several major tasks are involved in the development and implementation required to bring together data from multiple sensors to form an operational "optimal" rainfall analysis system. Some of the initial tasks that we plan over the next few years are:

a- On-site preprocessing and real-time quality control. The success in the application of radar data to rainfall estimation depends on minimizing errors inherent in radar measurements and their relationship to rainfall rates (Smith, et al., 1974). In 1975 the Office of Hydrology, NWS, contracted with the Institute of Atmospheric Sciences (IAS), South Dakota School of Mines & Technology, to investigate these uncertainties and develop a procedure for the real-time quality control of radar-rainfall estimates. Under this contract IAS developed a unique new technique for monitoring and identifying systematic biases in the calibration of digital radar rainfall estimates on the basis of comparisons with data telemetered in real-time from a few scattered rain gages (Smith and Cain, 1978). This technique, which applies the statistical method known as sequential analysis, has shown great promise when used with archived data. It remains to be tested in the real-time operational environment.

The NWS and IAS will conduct and evaluate a test of the sequential analysis procedure at the Pittsburgh D/RADEX site in the summer 1979. Such a test will establish the suitability of the procedure for quality control of radar rainfall measurements in an operational environment. If this test demonstrates operational feasibility, the research required to expand and, if necessary, modify the technique for use at other digital radar sites will be initiated.

The D/RADEX system at the Pittsburgh, Pa., Weather Service Meteorological Observatory was operational during the occurrence of the disastrous July 1977 Johnstown, Pa., flash flood. Figure 3 is an analysis of the total storm rainfall derived from the digital radar data sensed by the D/RADEX system during this storm. The radar-rainfall analysis gave an excellent definition of the time and space distribution of this flood-producing rainfall. But in comparison with rain gage measurements these radar estimates were too low. In the area of maximum rainfall, raingage measurements indicated accumulations of 12 inches while the maximum value obtained from the radar analysis is 8 inches (Greene and Saffle, 1978). If a real-time quality control program had been in operation in the Pittsburgh D/RADEX system it is quite possible that the quantitative radar-rainfall estimates for the Johnstown flood would have been better.

b- Communications and central processing. As discussed previously in section 3.2 various options must be considered to relay digital radar-rainfall estimates from the radar to a central processing site. HRAP will initially include rainfall

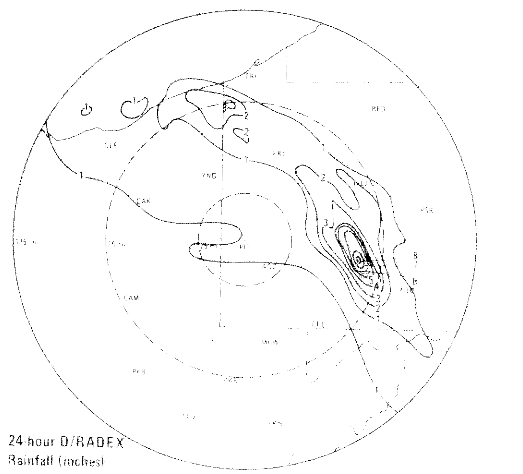

Figure 3.--Total storm radar-rainfall (inches) for the 1977 Johnstown flash flood derived from Pittsburgh D/RADEX data.

analyses for a limited area of the Midwestern United States in the Tulsa RFC area of responsibility where digital radar data are presently operationally available. This comprises digital radar data from three D/RADEX sites: Kansas City, Mo., Monett, Mo., and Oklahoma City, Okla. One way in which to get these data to the central processing site is to use the Tulsa RFC as a relay node. Digital rainfall estimates are presently transmitted to the Tulsa RFC from the three D/RADEX sites by commercial telephone lines and received via teletypewriter device. The teletypewriter at Tulsa is being replaced by a data terminal equipped with dual cassette tape drives. D/RADEX rainfall data will automatically be recorded at Tulsa and then relayed to the IBM 360/195 system at the NOAA computer site at Suitland, Md.

As a part of this effort the staff of the Tulsa RFC plan to assist in the formulation and evaluation of the techniques necessary to input these radar-rainfall estimates into the Tulsa hydrologic forecast procedures.

Processing tasks to be accomplished at the central processing site are:

1) Data merging and objective analysis. Part of the research is to determine how best to combine radar and rain gage data and to merge or composite data from multiple radar sites. A basic tool to be used in these procedures is objective analysis. Several objective analysis techniques to derive "optimal" rainfall distributions based on radar and rain gage data have been developed. These techniques have produced useful results in post facto case studies. However, additional tests and evaluation of these techniques must be made prior to operational implementation. In the early phases of HRAP, two candidate techniques [the Brandes (1975) and Crawford (1978), or variations thereof] will be tested and evaluated to determine their accuracy for various space and time scales and densities of gages.

2) National precipitation (rain gage) file. Rain gage data to be merged with the radar data are required in sufficient density to benefit from the use of sophisticated objective analysis procedures.

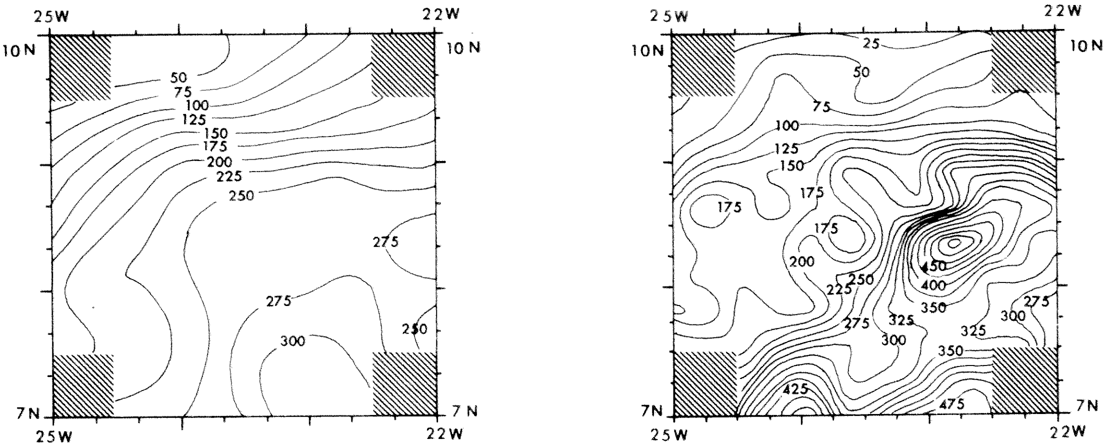

Figure 4.--Isohyetal contours (mm) derived from infrared satellite data (left) and digital radar data (right) for Phase I of GATE (from Griffith et al., 1979).

To gain the maximum number of gage reports for this purpose and to make these data readily available to the analysis program in a compatible format and coordinate system, a national rain-gage file will be developed based upon the reports available in the NWS River Forecast System (NWSRFS) files. Procedures will be developed to extract rain-gage data from the NWSRFS files, to quality control these data, and to pack these data in a central file designed for "efficient input" to the analysis program(s).

3)Satellite rainfall estimates. The strategy for this task is to identify techniques for using digital satellite data to complement and supplement data from rain gages and digital radar, with the overall objective of enhancing the quality of derived precipitation fields for use in hydrologic forecasting. Information from satellites should be very useful in gage-sparse regions and in regions not covered by digital radar. Also, satellites may prove especially useful in mountainous areas and for other areas as backup to the digital radar system. A significant part of this task will be accomplished through coordination of ongoing work with NOAA's National Environmental Satellite Service (NESS) and others. Also, some in-house testing of techniques probably will be required to determine suitable methods for use in supplying products to the RFCs on a 3-hourly to daily time scale for use with their hydrologic forecast models. Our intent is to adopt methods that will incorporate the strengths of the satellite data as part of a multi-sensor rainfall analysis system and to evaluate the biases that may be introduced into the hydrologic forecasts as a function of the input types. This will include sensitivity analyses of watershed model performance to different networks for calibrations versus operations.

A major objective of this task will be to evaluate the confidence that can be placed in rainfall estimates derived from various satellite techniques for various scales and types of rainfall. A simple technique that provides sufficient accuracy for climatological scales likely will be entirely inadequate for flash flood scales. Indeed the accuracy desirable, or achievable with various methods, must be compatible with the spatial and temporal scales being resolved. For a given method and type of rainfall, estimates for scales smaller than specific thresholds may contain intolerably large errors. To illustrate this point, Figure 4 shows a comparison of the isohyetal maps derived from satellite infrared data, using the Woodley and Griffith method (Griffith, et al., 1979), and from digital radar data (Hudlow and Patterson, 1979) for Phase I of GATE. Phase I consisted of 19 consecutive days during which a storm occurred on the average every four days. It is obvious from examination of the radar derived isohyetal map that considerable spatial variability (structure) persists in the rainfall patterns for this relatively long averaging period. However, inspection of the satellite derived rain fields shows that although the broad-scale features of the patterns compare very favorably with those from the radar, the satellite fields are much smoother and do not reproduce the mesoscale centers of heaviest rainfall accumulations.

The radar and satellite rainfall estimates averaged over the total 3° latitude x 3° longitude square are in close agreement (radar/satellite ratio of 1.09; see Griffith, et al., 1979). However, when the radar and satellite estimates are compared over smaller subareas of the square, the average correspondence diminishes.

Also using the digital radar and IR satellite data from Phase I of GATE, Richards and Arkin (1979) have computed linear correlation coefficients between the two for several space and time scales. Richards and Arkin made no attempt to isolate and track the satellite image entities, as is done with the Woodley and Griffith method; rather, correlations were made simply on a geometric grid basis. Figure 5 summarizes the average correlations for three spatial averaging scales (1/2° x 1/2°, 1 1/2° x 1 1/2°, and 2 1/2° x 2 1/2°) centered in the square shown in Figure 4 and for the three temporal averaging scales indicated. The satellite parameter used in the correlations was the fraction of the area covered by satellite image colder than the threshold temperature roughly corresponding to an altitude of 9 km. Clearly, Figure 5 shows that, unless additional information can be extracted from the satellite fields with more sophisticated techniques, there are limiting

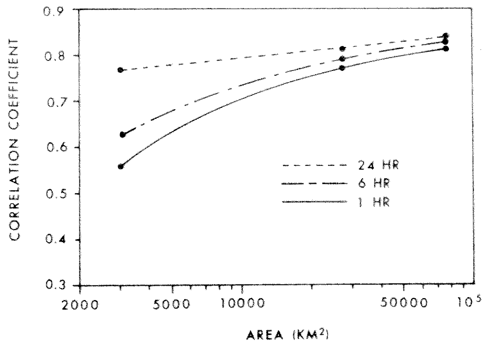

Figure 5.--Plot of linear correlation for Phase I of GATE between the fraction of area covered by high cloud (from infrared satellite) and rainfall amounts (from digital radar) for various spatial and temporal averaging scales.

space and/or time scales below which satellite IR data cannot accurately delineate convective rainfall quantitatively.

A significant part of this task will be devoted to examining the feasibility of operationally deriving rainfall estimates from IR satellite data for a geometric grid network that is compatible with the standard grid adopted for HRAP. It is hoped that at least under many conditions, satellite estimates of usable accuracy can be obtained down to time and space scales of 6 hours and 1/4° x 1/4°, respectively, or better. Work recently reported by Waters and Green (1979) describing the VISSR data handling system shows that it is now possible through the use of the VISSR ingest computer and mass storage devices (Figure 6) to navigate and extract digital satellite data from the total earth disk, for all or part of the U.S., in near real-time and to produce a computer efficient VISSR data base. This VISSR data base should provide the basis for deriving satellite rainfall estimates operationally as a part of HRAP if the methodology can be refined to provide usable accuracies. This will probably require the integration of various forms of "ground truth" and calibration information.

4. CONCLUDING REMARKS

A rainfall data management and analysis system is under development by the NWS Hydrologic Research Laboratory in cooperation with other NWS, NOAA, and university groups. The objectives of HRAP are to acquire, process, communicate, and integrate multiple sensor precipitation data from radars, satellites, and rain gages into data files available to the operational components of the NWS. The primary goal is to improve the quantitative depiction of rainfall in space and time leading to better river stage forecasts and flash flood warnings; benefits also are anticipated in the areas of quantitative precipitation forecasting, agriculture, and other areas of water resources management.

The multiple sensor rainfall analysis system will reduce the reporting time interval, improve the capability to identify heavy rainfall centers having flash flood potential, reduce the nonrepresentativeness of converting point measurements to areal estimates, fill in rainfall estimates for many areas inadequately sampled by present gage systems, and structure these data in a form readily accessible to users. While limitations can be seen from the outset in theory, hardware, and software, it is felt that the system will significantly improve detailed areal rainfall estimates.

5. ACKNOWLEDGMENTS

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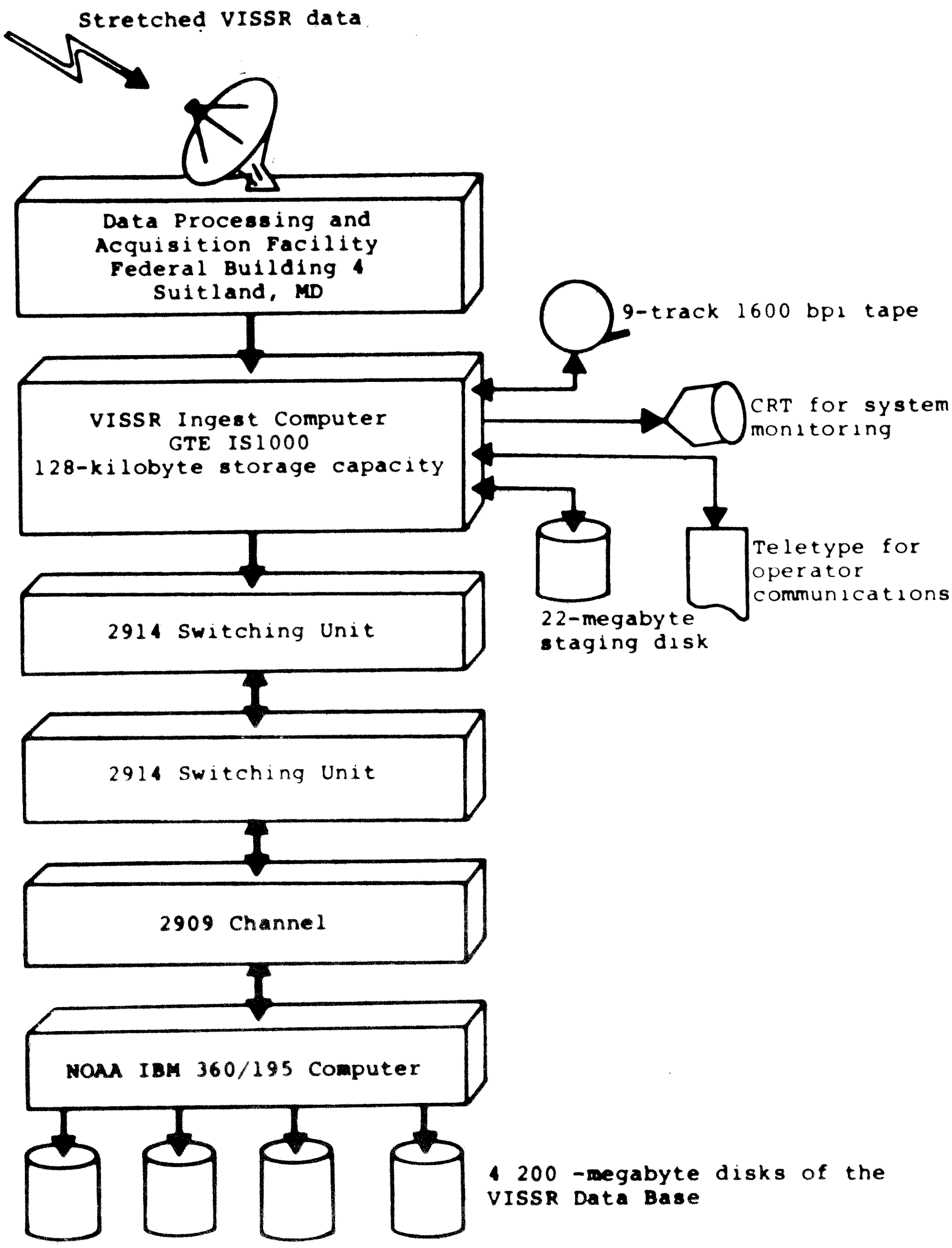

Figure 6.-- The VISSR Data Handling System used to build the VISSR Data Base (from Waters and Green, 1979).

6. References

Adler, R.F. and E.B. Rogers, 1977: Satellite-observed latent release in a tropical cyclone. Mon. Wea. Rev., 105, pp. 956-963.

Atlas, D., W.R. Bandeen, W. Shenk, J.A. Gatlin, and M. Maxwell, 1978: Visions of the future operational meteorological satellite system. Proceedings EASCON '78 Electronics and Aerospace Systems Conference, September 25-27, 1978, Arlington, Va., 16 pp.

Barrett, E.C., 1970: The estimation of monthly rainfall from satellite data. Mon. Wea. Rev., 98, pp. 322-327.

Battan, L.J., 1973: Radar Observation of the Atmosphere, Univ. Chicago Press, Chicago, 324 pp.

Brandes, E.A., 1975: Optimizing rainfall estimates with the aid of radar. J. Appl. Meteor., 14, pp. 1339-1345.

Byers, H.R., and Collaborators, 1948: The use of radar in determining the amount of rain falling over a small area. Trans. Amer. Geophys. Union, 29, pp. 187-196.

Crawford, K.C., 1978: On the bivariate objective analysis of surface rainfall using optimum interpolation. Preprints 18th Conference on Radar Meteorology (Atlanta), AMS, Boston, pp. 336-341.

Follensbee, W.A., 1976: Estimation of daily precipitation over China and the USSR using sattelite imagery. NOAA Technical Memorandum NESS 81, 30 pp.

Greene, D.R., 1975: Hydrologic application of digital radar data. Preprints 16th Radar Meteorology Conference (Houston), AMS, Boston, pp. 353-360.

Greene, D.R. and A.F. Flanders, 1976: Radar hydrology - the state of the art. Preprints, Conference on Hydrometeorology (Ft. Worth), AMS, Boston, pp. 66-71.

Greene, D.R. and R.E. Saffle, 1978: Radar analysis of the 1977 Johnstown flash flood. Preprints Conference on Flash Floods: Hydrometeorological Aspects and Human Aspects (Los Angeles), AMS, Boston, pp. 176-180.

Griffith, C.G., W.L. Woodley, P.G. Grube, D.W. Martin, J. Stout, and D.N. Sikar, 1978: Rain estimation from geosynchronous satellite imagery - visible and infrared studies. Mon. Wea. Rev., 106, pp. 1153-1177.

Griffith, G.G., W.L. Woodley, J.S. Griffin, and S.C. Stromatt, 1979: Satellite-derived precipitation atlas for the GARP Atlantic Tropical Experiment. NOAA Atlas, (in preparation).

Hiatt, W.E., 1956: Radar in flood hydrology. Publication of the 42nd International Hydrologic Association, U. G. G. F., pp. 286-290.

Hudlow, M.D., 1975: Radar and satellite precipitation analysis of a 5 day BOMEX data sample, NOAA Technical Memorandum EDS BOMAP-18, 46 pp.

Hudlow, M.D. and V.L. Patterson, 1979: GATE radar rainfall atlas, NOAA Special Report, Center for Environmental Assessment Services, NOAA.

Klein, W.H., 1978: An introduction to the AFOS program. Preprints Conference on Weather Forecasting and Analysis and Aviation Meteorology (Silver Spring), AMS, Boston, pp. 186-189.

Maddox, R.A., C.F. Chappell, and L.R. Hoxit, 1979: Synoptic and meso-α scale aspects of flash flood events. Bull. Amer. Meteorol. Soc., 60, pp. 115-123.

Martin, D.W. and W.D. Scherer, 1973: A review of satellite rainfall estimation methods. Bull. Amer. Meteorol. Soc., 54, pp. 661-674.

McGinnis, D.F. Jr., R.A. Scofield, S.R. Schneider, and C.P. Berg, 1979: Satellites as an aid to water resource managers. Preprint 3486 ASCE Convention and Exposition Boston April 2-6, 1979, ASCE, 21 pp.

NOAA, 1972: National weather service river forecast system forecast procedures. NOAA Technical Memorandum NWS HYDRO-14.

NOAA, 1977: National environmental satellite service catalog of products. NOAA Technical Memorandum NESS 88, 102 pp.

Rao, M.S.V., W.V. Abbott III, and J.S. Theon, 1976: Satellite-derived global oceanic rainfall atlas (1973 and 1974). NASA SP-410, Scientific and Technical Information Office, NASA Goddard Space Flight Center, Greenbelt, Md., 186 pp.

Richards, F. and P. Arkin, 1979: Spatial and temporal variation in the relationship between satellite cloud coverage and precipitation. 12th Technical Conference on Hurricanes and Tropical Meteorology (New Orleans), AMS, Boston.

Saffle, R.E., 1976: D/RADEX products and field operation. Preprints 17th Conference on Radar Meteorology (Seattle), AMS, Boston, pp. 555-559.

Scofield, R.A. and V.J. Oliver, 1977: A scheme for estimating convective rainfall from satellite imagery. NOAA Technical Memorandum NESS 86, 47 pp.

Smith, P.L., Jr., K.R. Hardy, and K.M. Glover, 1974: Applications of radar to meteorological operations and research. Proceedings of the IEEE, 62, No. 6, 724-745.

Smith, P.L., Jr., and D.E. Cain, 1978: Application of sequential analysis to radar rainfall computations with D/RADEX data. Preprints, Conference on Flash Flood: Hydrometeorological Aspects and Human Aspects (Los Angeles), AMS, Boston, pp. 58-63.

Waters, M.P. III and R.N. Green, 1979: A merged satellite infrared and manually digitized radar product. Symposium on Machine Processing of Remotely Sensed Data, Purdue University, Lafayette, Indiana.

Wilheit, T.T., M.S. V. Rao, T.C. Chang, E.B. Rodgers and J.S. Theon, 1977: A satellite technique for quantitatively mapping rainfall rates over the oceans. J. Appl. Meteor., 16, pp. 551-560.