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NEXRAD - NEW ERA IN HYDROMETEOROLOGY IN THE UNITED STATES

by

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ABSTRACT

Introduction of the Next Generation Weather Radar (NEXRAD) System will usher in a new era of precipitation processing for the United States National Weather Service (NWS). Precipitation processing is performed in three stages. The first stage of processing occurs within the NEXRAD computer system and produces quantitative precipitation estimates, short-term forecasts of precipitation accumulations and flash-flood probabilities. Stages two and three, performed at NWS forecast offices external to NEXRAD, will further improve the quality of precipitation estimates through the use of satellite imagery, rain gage data, and eventually other hydrometeorological information. NEXRAD data, combined with rain gage and satellite data, will lead to large improvements in the accuracy of precipitation estimates.

INTRODUCTION

One of the most important steps in the process of making river forecasts is an accurate precipitation analysis. Precipitation is one of the primary inputs to the National Weather Service's River Forecast System. Accurate precipitation analyses are also extremely important to the meteorologist faced with a flash-flood situation. A rain gage network, even a fairly dense one, can miss significant rainfall, especially rainfall associated with intense convective storms. Another significant problem with rain gage networks is the inability to determine patterns of precipitation or to identify the heaviest amounts. Thus, there is a strong need for real-time precipitation analysis that is not totally dependent upon rain gage observations. This is especially important for remote areas where it is difficult to establish and maintain surface observing stations.

In the early 1970's an effort was begun to use the established NWS radar network to provide areal precipitation analysis. Development of procedures for using radar as a tool to measure precipitation has progressed from manual techniques, to semi-automatic techniques, to the fully automatic techniques employed by the Next Generation Weather Radar (NEXRAD) system.

NEXRAD is a joint Department of Commerce, Department of Defense and Department of Transportation effort to develop, procure, implement, and operationally maintain a Doppler weather radar system. It is a nationwide network of weather radars designed to meet the hydrometeorological service needs of the United States into the twenty-first century. The three agencies will acquire approximately 175 radars, 413 workstations, and associated equipment. For the continental United States, NWS plans to replace the existing weather radar network with 113 of the approximately 175 NEXRADs. Deployment of the NEXRADs is scheduled to begin in the spring of 1990 and continue into the mid-1990's. NEXRAD is a totally integrated system and consists of a 10 cm Doppler radar, a powerful computer to process the data and develop products, and a graphical workstation to display products.

The NWS hydrometeorological processing is performed in three stages. The first stage will be performed within the NEXRAD computer system. Processing for stages two and three is performed external to the NEXRAD computer system. Testing and evaluation of the Stage I hydrometeorological processing have been conducted by the Hydrologic Research Laboratory (HRL) in collaboration with the NEXRAD Operational Support Facility (OSF) in Norman, Oklahoma, and the Prototype Regional Observing and Forecasting Service (PROFS) located in Boulder, Colorado (O'Bannon and Ahnert, 1986; Kelsch, 1989). Testing and evaluation of Stages II and III are underway at HRL. Software for the three stages of hydrometeorological processing was developed by HRL. A schematic of the three stages of hydrometeorological processing is shown in Figure 1. The following sections will discuss the three stages of hydrometeorological processing. Particular emphasis will be placed on a more detailed description of the Stage I processing components as illustrated in Figure 2.

This paper concentrates on radar hydrology developments in the United States. However, other countries are pursuing similar directions in the development and operational implementation of radar hydrology applications (Joss and Waldvogel, 1989).

THE THREE STAGES OF HYDROMETEOROLOGICAL PROCESSING

Stage I

The Stage I processing within NEXRAD contains two major components: a Precipitation Processing System (PPS) and a Flash-Flood Potential (FFP) System (Figure 2). In Stage I the data are processed to a level of refinement that can be achieved with modest computer resources, yet provide an accuracy that make the precipitation estimates useful for local real-time applications.

Precipitation Processing System (PPS)

PPS generates 1-hour running totals as well as 3-hour and running storm total precipitation accumulations. Five steps are performed to develop the best estimate of precipitation:

(1) Development of Sectorized Hybrid Scan
(2) Conversion to Precipitation Rate

(3) Precipitation Accumulation
(4) Adjustment using Rain Gages
(5) Product Update

Since radar indirectly measures precipitation rates, an emphasis on quality control of the data has been built into each of the processing steps of the PPS.

The first step produces a "sectorized hybrid scan", which is comprised of reflectivity data from the four lowest tilts of the radar volume scan. The choice of tilt is based on range and topography. Details of the sectorized hybrid scan are described within a companion paper from this symposium (Shedd et al., 1989). There are four reasons for multiple tilt processing:

(1) to minimize ground clutter and clear mountains or man-made obstacles,
(2) to reduce effects of abnormal beam refractions and losses,
(3) to improve range performance, and
(4) to maximize the use of data from a relatively uniform altitude.

NEXRAD reflectivity data are preprocessed prior to development of the hybrid scan to correct for several error sources. One source of error results from partial or complete beam blockages, generally from man-made objects (such as water towers). The form of the blockage correction depends upon the percent of the beam blocked and the radial width of the blockage. Reflectivity outliers can occur when the beam strikes high reflectivity objects such as planes. These data points are corrected using neighboring data points.

The final quality control check is to determine whether or not data from the lowest tilt will be used in building the hybrid scan. The low tilt is the one most likely to be contaminated by anomalous propagation (AP), ground clutter and other noise. The lowest tilt is rejected when more than a given percent of the echoes at the lowest angle disappear at the second elevation angle.

Following construction of the hybrid scan, reflectivity data from the Hybrid Scan step are converted to rainfall rates using the empirical relationship, $Z = aR^b$ where Z is the reflectivity factor, R is the rainfall rate, and a and b are constants. Two quality control procedures are performed in the Rate algorithm. First, temporal continuity of the total field volumetric water is checked to insure that spurious data have not introduced physically unreasonable rates of echo development or decay. Range effects resulting from signal degradation and partial beam filling may also unduly reduce precipitation estimates at further ranges; therefore, a range-dependent, site-varying correction will be applied to the precipitation rate data.

The third step is to perform precipitation accumulations. Two types of accumulations are generated. The first is a scan-to-scan accumulation which measures the precipitation accumulation from one instantaneous rate scan to the next. The second is a running hourly accumulation which is updated every volume scan. A temporal continuity test checks the data for

missing periods which might result from system malfunction or rejection of scans. If too much data are missing, no running hourly accumulation is performed.

An outlier check is performed on the hourly accumulations. This check is made in addition to the instantaneous reflectivity outlier check because clutter which passes the reflectivity test could, if it remains at a high level, produce impossibly large accumulations.

The fourth step is adjustment of the accumulations based on available rain gage data. In spite of efforts to maintain a high level of quantitative accuracy in estimating precipitation from radar data, there are sure to be errors in these estimates. In fact, errors of a factor of 2 or more can occur due to a wide variety of causes including hardware calibration, anomalous propagation, wet radome attenuation, inappropriateness of Z-R relationship for the particular storm system, and others. While some of these errors will be localized or perhaps range dependent, some will produce a generally uniform multiplicative bias in the radar estimated precipitation. In either case, a mean bias correction can be applied to the entire field in an attempt to insure that the estimate of total field volumetric water closely equals the true field volumetric water. In order to effect this correction, a procedure has been developed to compare hourly precipitation from rain gages to associated radar values and to estimate the mean-field radar bias.

The adjustment procedure is based on a discrete Kalman filter (Ahnert et al, 1986). The bias update is performed once per hour when sufficient real-time gage reports are available. If insufficient rain gage reports are available, the previous estimate of the bias is propagated forward.

In the final step of processing in the PPS, two basic types of products are generated. Graphical products will be displayed at forecast offices. Digital products will be used for subsequent numerical processing and input to forecast models.

The precipitation graphics products are displayed on a 2 km x 2 km grid to a range of 230 km from the radar site and have up to 16 color levels. These precipitation products are 1 hour, 3 hour, and storm total accumulations. The 1 hour and storm total products will be updated each volume scan. The 3 hour product will be updated once per hour.

Also produced is a digital array product of the running hourly accumulations. The product, updated every volume scan (approximately 5 minutes), will be mapped onto a 1/40th Limited-area Fine Mesh (LFM) grid (approximately 4 km x 4 km). Although this product has somewhat degraded spatial resolution, it will provide the same temporal resolution and far greater intensity resolution (up to 100 precipitation levels) than the graphical product. In addition, supplemental data such as instantaneous area averaged precipitation rates over a 1/4 LFM grid, bias estimate, missing periods, and rain gage data are appended to the digital array product. These supplemental data can be used for performing quality control and data adjustment steps in subsequent hydrometeorological procedures.

Despite all the quality control and data adjustment procedures in PPS, the products will not be perfect. PPS does not, for example, directly account for changes in the phases of precipitation from liquid to frozen or vice versa. The PPS products will, however, be of the highest quality possible given current technology and available resources. Further details are available in Ahnert et al. (1983, 1984). Ongoing and future research and development will enhance the performance of the PPS.

Flash-Flood Potential (FFP) System

The Stage I NEXRAD FFP System produces short-term forecasts of precipitation accumulations and flash-flood potential. The NEXRAD FFP System consists of a precipitation projection procedure and a flash-flood potential assessment procedure (Figure 2). The precipitation projection procedure forecasts precipitation accumulation up to 1 hour into the future. The forecasts are updated every volume scan (approximately every 5 minutes). The procedure also produces projected total precipitation accumulations and associated error variances. The projected total accumulation is composed of the previously observed accumulation and the projected accumulation. The observed precipitation data used by the FFP come from the NEXRAD PPS. The precipitation projection procedure consists of four steps:

(1) estimation of the mean, variance, and residual of the precipitation rate,

(2) estimation of localized storm velocity,

(3) estimation of the residual persistence, and

(4) projection of precipitation rates with subsequent conversion to accumulations.

In the first step, the precipitation projection procedure uses a spatial moving average for the mean, variance, and residual of precipitation rate. The mean is calculated by averaging over a region which roughly corresponds to a 20 km x 20 km area. The localized spatial moving average of the variance of precipitation rates over this region is computed similarly. The variance of observation error is assumed to be proportional to this variance. The residual is defined as the difference between the observed precipitation rate at individual bins in the 20 km x 20 km area and the mean value.

In the second step, the localized storm velocity and direction are determined by a pattern-matching technique. The technique involves comparing the current precipitation rate field with a previous precipitation rate field at every fifth box (1/40th LFM grid) for various offsets to determine the minimum sum of absolute differences. The offsets range from +2 to -2 boxes (1/40th LFM grid) in the X and Y directions which will account for storm movement in any direction and for storm velocities up to approximately 50 km/hr. The offset with the minimum sum of absolute differences provides the first estimate of the velocity and the direction at every fifth box (1/40th LFM grid).

These first estimates are in turn smoothed by weighted averaging with nearest neighbor first estimate velocities. Velocities are then interpolated for all the other boxes (1/40th LFM grid) using an inverse-distance-squared weighted average of the smoothed velocities. Simple persistence is assumed when projecting the storm velocity and direction into the future.

In the third step, the parameters of the residual process are estimated at each scan by translating the residuals of the previous scan according to the localized storm velocity and computing the lag-one autocorrelation of the translated previous residuals with the current residuals.

And finally, in the fourth step, the projected precipitation rate at each box (1/40th LFM grid) is the mean precipitation rate plus the projected residual. The projected residual is the current residual times the residual persistence parameter raised to a power equal to the number of time steps into the future. These projected precipitation rates are then moved according to the projected local storm velocity and direction. The projected precipitation accumulations are based on these projected precipitation rates. These projections, accumulations, and error variances are the basic input for the flash-flood potential assessment procedure.

The flash-flood potential assessment procedure uses flash-flood guidance values developed by NWS River Forecast Centers (RFC) and observed and projected precipitation accumulations from the precipitation projection procedure to produce observed and projected Flash-Flood Probabilities. The Flash-Flood Probability is an estimate of the probability that the actual precipitation for some time during the rainfall event has exceeded (for observed Flash-Flood Probability) or will exceed (for potential Flash-Flood Probability) the flash-flood guidance value. The flash-flood guidance values are based on hydrologic models run by the RFCs. These guidance values are estimates of how much rainfall would be required over specified durations to produce flooding at one or more locations within a zone or county.

The FFP system generates digital, graphic, and alphanumeric products. The digital products are intended for numerical use at computer facilities external to the NEXRAD system itself. The digital data maintain the full dynamic range and full precision of the data used to generate the product. Just like the PPS, the digital data are mapped on a "universal" grid (1/40th LFM grid) so that data from multiple sites are compatible for mosaicking.

The digital data will be transferred to other computer facilities at the RFCs and forecast offices for use in automated forecasting models and procedures. The digital products consist of a projected precipitation and projected and observed error variance of the precipitation data array on a 131 x 131 1/40th LFM grid and is updated every volume scan. In addition, supplemental data such as projection parameters and storm velocity parameters are appended to the digital array product.

The precipitation graphics products will be displayed on a 4 km x 4 km grid to a range of 230 km from the radar site, are updated every volume scan,

and have up to 16 color levels. The three graphical products are projected precipitation accumulation for up to 1 hour into the future and observed and projected flash-flood probability displays.

The alphanumeric products are updated every volume scan and will provide flash-flood probability information in a form suitable for display on both graphic and alphanumeric display devices. The first alphanumeric product consists of a Flash-Flood Guidance Summary which will display the flash-flood guidance value, maximum observed precipitation accumulation for the zone, and maximum total storm (observed and projected) precipitation accumulation for each guidance value duration in each flash-flood guidance zone. The second alphanumeric product will display the maximum observed and projected flash-flood probabilities for each zone.

The products produced by the FFP System should be viewed by the user as useful guidance but not as definitive identification of flash flooding until interpreted together with other available information. The products generated, using the projection procedure, do not explicitly take into account storm systems moving faster than approximately 50 km/hr, curvilinear storm motions, individual cell dynamics other than that accounted for by the current residual field, or orographic effects.

Other limitations arise from the use of flash-flood guidance values which presently are not calculated the same way at all RFCs, are updated only once a day, and do not have an updating procedure to reflect changes brought about by multiple rainfall events. It is important that the user be aware of these limitations when interpreting and using products from the FFP System. Future research and development will be aimed at reducing these and other limitations experienced operationally. Further details on the FFP System are available in Walton et al. (1985, 1986, 1987).

Stage II

The Stage II Precipitation Processing program is used to compute hourly precipitation on a 1/40th LFM grid for the area covered by a single NEXRAD system. Input to Stage II includes hourly digital precipitation data from Stage I processing, GOES infrared imagery, rain gage data, and eventually other hydrometeorological information (Hudlow et al., 1983). Ultimately the Stage II program will run at the National Weather Service Warning and Forecast Office (WFO) collocated with the NEXRAD system (Figure 1). In the interim, a combination of Stage II and III processing will be done at several RFCs. Stage II precipitation analyses are used by the WFO in providing forecast guidance during periods of severe weather and as input to Stage III precipitation processing at RFCs.

Stage II precipitation processing differs from Stage I in several ways. Additional quality control steps are carried out in Stage II processing. Satellite and rain gage data are used to detect and eliminate errors in NEXRAD data associated with clear-air anomalous propagation or other data contamination not detected or eliminated during Stage I processing (Fiore et al., 1986). From the satellite data it can be determined whether clouds are contained in a 1/4 LFM grid box. If radar detects rainfall in a 1/4 LFM grid box for which satellite data indicate no clouds are present and for which no rain gages record rainfall, then the radar rainfall estimates are replaced by zero values.

In Stage II processing, radar and rain gage data are "merged" to form an optimal "multisensor" estimate of the rainfall field. The merging procedure accounts for strengths and weaknesses of the two measurement systems. To estimate rainfall at a given location, a rain gage observation will be heavily weighted only if it is close to the location. The weight that a rain gage receives will also depend on characteristics of the rainfall field. For rainfall fields with large spatial variability, as is typically the case with convective storms, rain gage observations will generally receive lower weights than for more uniform rainfall fields, associated, for example, with stratiform rainfall.

The Stage II program will also produce estimates of rainfall based largely on rain gage data. In the "gage-only" rainfall analysis, radar and other data are used to delineate regions receiving no rainfall from precipitating regions. Graphical products will allow display of Stage II precipitation estimates at the WFO. Summary information, such as mean rainfall over the field and maximum point rainfall, will also be displayed by the Stage II program.

Stage III

The Stage III Precipitation Processing program (Stage III) provides two products. It provides hourly estimates of rainfall on a 1/40th LFM grid for the entire area of responsibility of an RFC. At an RFC it is necessary to combine information from a number of NEXRAD radars. The program also provides mean areal precipitation (MAP) values for basins specified by the RFC. MAP time series are provided at the time step required by the RFC (1 hour, 2 hours, 3 hours, 6 hours, or 24 hours) for operational hydrologic forecasting.

The Stage III program contains two basic steps: 1) quality control/mosaicking, and 2) MAP computation. The first step is an interactive quality control step in which the forecaster can replace the Stage II multisensor rainfall estimates by the Stage II gage-only estimates. The forecaster will base his decision on displays of preliminary mosaicked multisensor and gage-only fields for the entire forecast area. From these displays it should normally be clear to the forecaster if anomalous propagation errors, or certain other errors, are still present in the multisensor rainfall estimates. The product of the first step is an hourly mosaicked rainfall field for the entire RFC area of coverage. In the MAP calculation, hourly rainfall estimates on a 1/40th LFM grid are accumulated and averaged to the time and space resolutions required for hydrologic forecasting.

SUMMARY

The three stages of hydrometeorological processing will provide high-quality precipitation estimates over the conterminous U.S. The first stage will take place within NEXRAD and be used for real-time graphical displays and input to forecast procedures at the local forecast offices and RFC. Processing in stages two and three will further improve quality of precipitation estimates using satellite, rain gage data, and eventually other hydrometeorological information. The final optimal precipitation estimates will be input to hydrologic models and allow the user to monitor the accumulated precipitation for various durations up to the current time,

evaluate precipitation forecasts for short periods into the future, and assess flood potential. Using data from NEXRAD, combined with additional rain gage and satellite data, it should be possible to realize large improvements in the accuracy of estimating areal precipitation. These improvements should, in turn, lead to large economic benefits and better management of our increasingly precious water resources.

Space restrictions prevented inclusion of various sample products and test results herein. These may be obtained from references cited and/or by contacting the authors.

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REFERENCES

Ahnert, Peter R., Krajewski, Witold F., and Johnson, Edward R., "Kalman Filter Estimation of Radar-Rainfall Field Bias," Preprints of the 23rd Radar Meteorology Conference, Snowmass, Colorado, September 1986, JP33-JP37.

Ahnert, P.R., Hudlow, M.D., Johnson, E.R., Greene, D.R., and Dias, M.P.R., "Proposed 'On-Site' Precipitation Processing System for NEXRAD," Preprints, 21st Conference on Radar Meteorology, AMS and Alberta Research Council, Canadian Meteorological and Oceanographic Society, Edmonton, Alberta, Canada, September 19-23, 1983, pp. 378-385.

Ahnert, Peter R., Hudlow, Michael D., and Johnson, Edward R., "Validation of the 'On-Site' Precipitation Processing System for NEXRAD," Preprints, 22nd Conference on Radar Meteorology (AMS), Zurich, Switzerland, September 10-14, 1984, 10 pp.

Fiore, J.V., Farnsworth, R.K., and Huffman, G.J., "Quality Control of Radar-Rainfall Data with VISSR Satellite Data," Preprints of the 23rd Radar Meteorology Conference, Snowmass, Colorado, September 1986, JP15-JP18.

Hudlow, Michael D., Farnsworth, Richard K., and Ahnert, Peter R., "NEXRAD Technical Requirements for Precipitation Estimation and Accompanying Economic Benefits," Hydro Technical Note-4, Office of Hydrology, National Weather Service, NOAA, Silver Spring, Maryland, December 1984 (Revised April 1985), 49 pp.

Hudlow, M.D., Greene, D.R., Ahnert, P.R., Krajewski, W.F., Sivaramakrishnan, T.R., Johnson, E.R., and Dias, M.P.R., "Proposed Off-Site Precipitation Processing System for NEXRAD," Preprints, 21st Conference on Radar Meteorology, AMS and Alberta Research Council, Canadian Meteorological and Oceanographic Society, Edmonton, Alberta, Canada, September 19-23, 1983, pp. 394-403.

Joss, Jurg, and Albert Waldvogel, "Precipitation Measurement and Hydrology - A Review," Contribution to the Battan Memorial and 40th Anniversary Conference on Radar Meteorology, American Meteorological Society, Boston, Massachusetts, to appear in conference proceedings, Summer, 1989.

Kelsch, Matthew, "An Evaluation of the NEXRAD Hydrology Sequence for Different Types of Intense Convective Storms in Northeast Colorado," Preprints, 24th Conference on Radar Meteorology, American Meteorological Society, Tallahassee, Fla., March 27-31, 1989, pp. 207-210.

O'Bannon, Timothy and Ahnert, Peter, "A Study of the NEXRAD Precipitation Algorithm Package on a Winter-Type Oklahoma Rainstorm," Preprints, 23rd Conference on Radar Meteorology, American Meteorological Society, Snowmass, Colorado, September, 1986, pp. JP99-101.

Shedd, Robert C., Smith, James A., and Walton, Mark L., "Sectorized Hybrid Scan Strategy of the NEXRAD Precipitation Processing System", Proceedings of the International Symposium on Hydrological Applications of Weather Radar, Salford, England, August 1989.

Walton, Mark L., Johnson, Edward R., and Shedd, Robert C., "Validation of the On-site Flash Flood Potential System for NEXRAD," presented at and published in the proceedings of the Twenty-First International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, October 26-30, 1987, 12 pp.

Walton, Mark L., and Johnson, Edward R., "An Improved Precipitation Projection Procedure for the NEXRAD Flash-Flood Potential System," Preprints of the 23rd Radar Meteorology Conference, American Meteorological Society, Snowmass, Colorado, September 1986, JP62-JP65.

Walton, Mark L., Johnson, Edward R., Ahnert, Peter R., and Hudlow, Michael D., "Proposed On-Site Flash-Flood-Potential System for NEXRAD," Preprint Volume, Sixth Conference on Hydrometeorology of the American Meteorological Society, Indianapolis, Indiana, October 29, 1985, pp. 122-129.

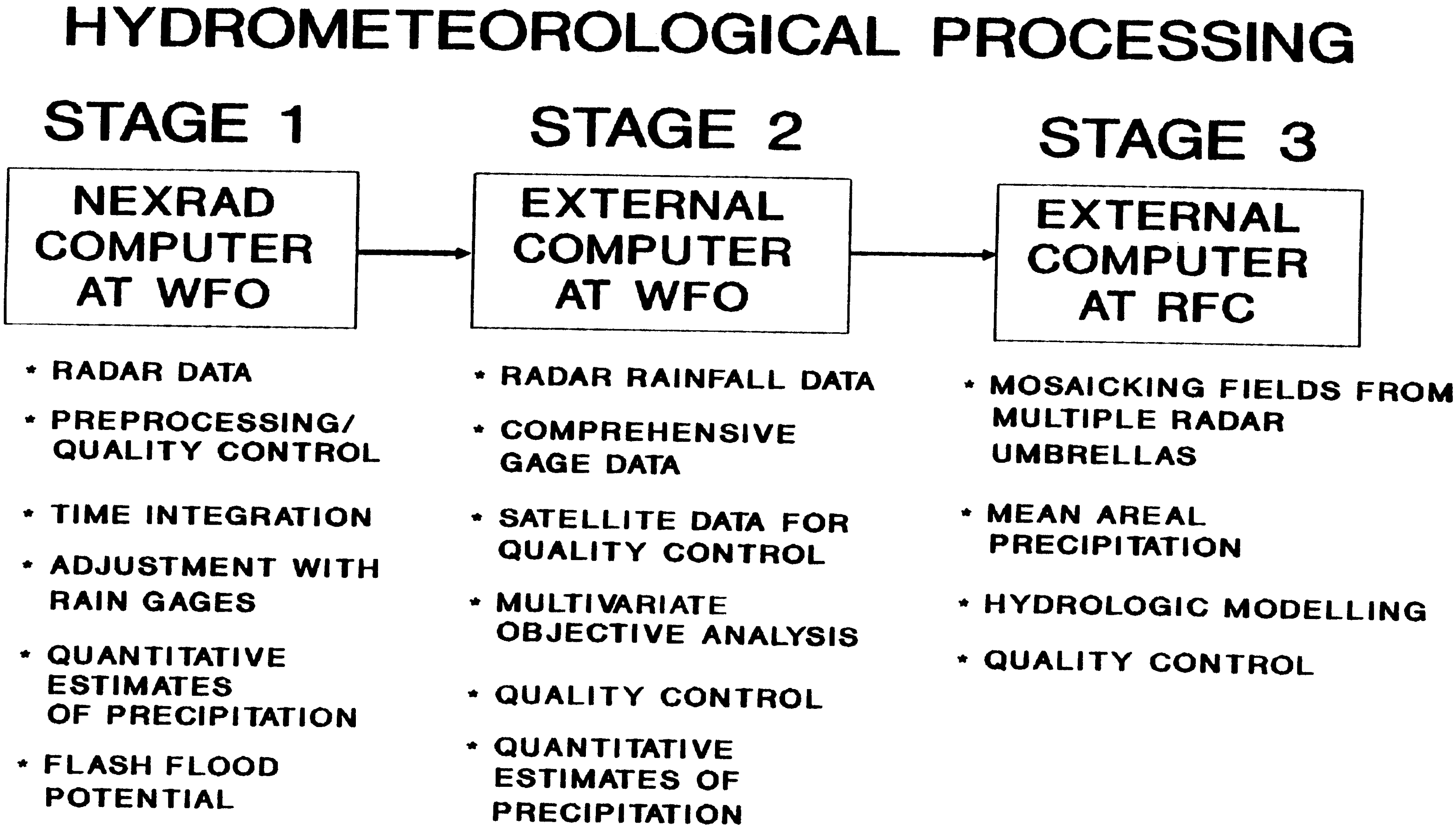

FIGURE 1 : Three Stages of Hydrometeorological Processing

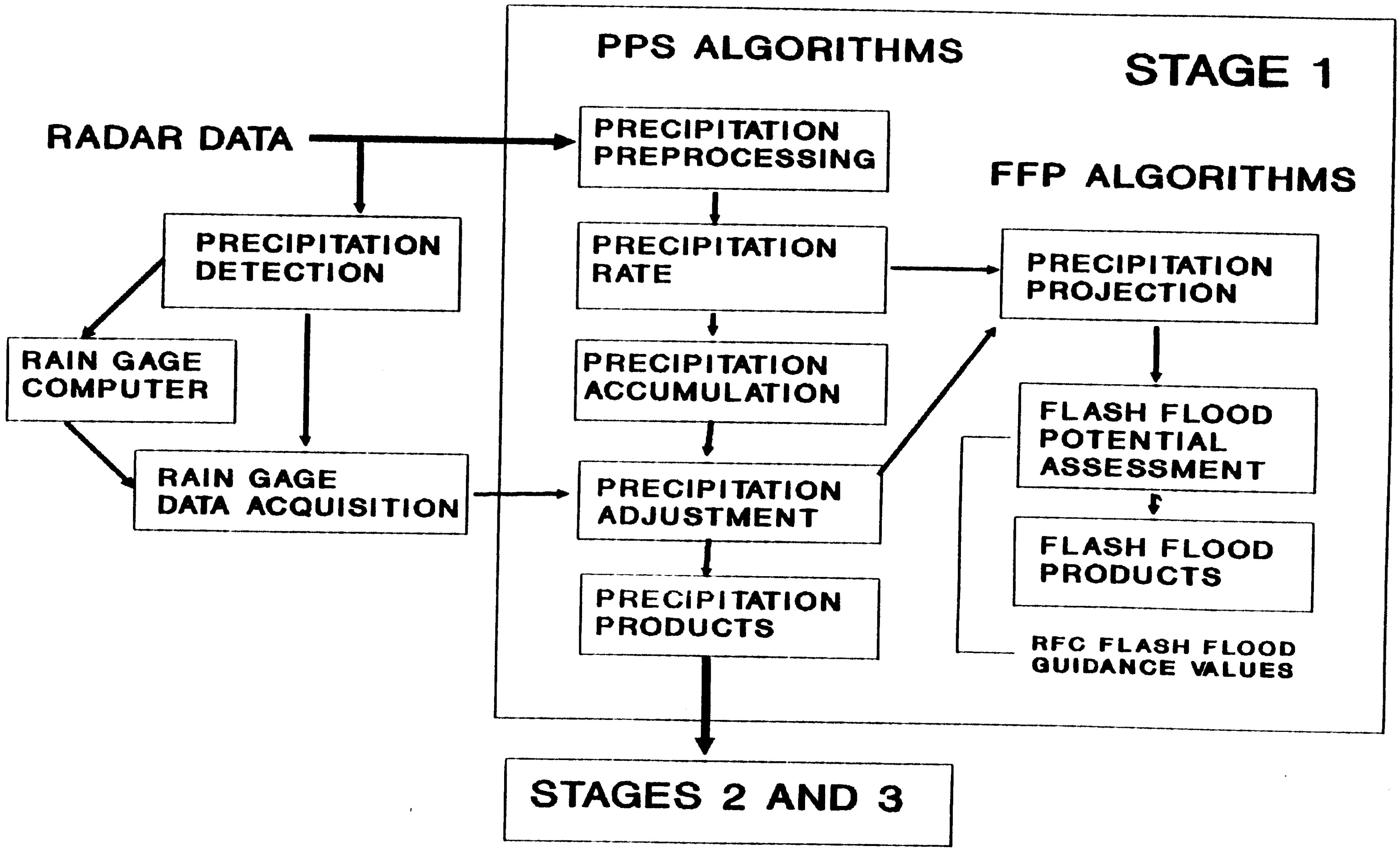

FIGURE 2 : Stage 1 Block Diagram