Hydrologic Forecasting Requirements for Precipitation Data from Space Measurements

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ABSTRACT

The requirements for precipitation measurements from space for hydrologic forecasting applications are discussed. The structure of the hydrologic forecasting service of the National Weather Service (NWS) is described, and an attempt is made to estimate the sampling and accuracy requirements for a range of spatial and temporal averaging scales corresponding to various NWS hydrologic applications. Finally, the data base requirements are addressed. The critical point is made that for the data sources to be most useful operationally at the NWS River Forecast Centers, the data must be available on-line in a format compatible with computer processing. Several data base systems are illustrated in a scenario for a multi-sensor rainfall analysis system (MSRANS). Actually, MSRANS is the softare existing within the various computer environments required to preprocess, process, and analyze rainfall information from multiple sources.

1. INTRODUCTION AND BACKGROUND

Hydrologic forecasting in its broadest sense covers the prediction of the quality and quantity of all components of the hydrologic cycle (Symposium on Hydrologic Forecasting, 1980). For the purposes of this paper, however, the scope will be restricted to the requirements for precipitation measurements from space as inputs to the forecasting of quantitative streamflow amounts for scales ranging from those required to diagnose flash floods to those needed for deriving seasonal water supply forecasts. Some of the material presented also may be relevant to water quality forecasting, since water quantities have a dire-- effect on pollutant concentrations and thus knowledge of the quantity of water and its transport is often a prerequisite to the diagnosis or prediction of streamflow quality.

Specifically, subsequent sections of this paper will briefly cover the structure of the hydrologic forecasting service of this country and will discuss the spatial and temporal requirements for precipitation data to support the various hydrologic forecasting procedures. Accuracy and data-base structure requirements also are discussed.

2. STRUCTURE OF U.S. HYDROLOGIC FORECASTING SERVICE

The Congressional Organic Act of October 1, 1890 and subsequent reorganizations assigned to the Weather Bureau [now the National Weather Service (NWS)] the duties of the forecasting of weather, the issuing of storm warnings, the display of weather and flood signals for the benefit of agriculture, commerce, and navigation, the gaging and reporting of rivers..." The NWS is the only federal organization legally authorized to disseminate river and flood forecasts and warnings directly to the public.

However, many other Federal and non-Federal organizations do become involved in various aspects of hydrologic forecasting. For example, the U.S. Army Corps of Engineers (a Federal agency) and the Salt River Project (a non-profit organization managed by landowners located in Central Arizona) produce their own specially-tailored river forecasts, which are used to supplement the NWS forecasts. These special forecasts are used in making decisions pertaining to the operation of their reservoirs and other riparian structures, but the forecasts are not disseminated directly to the public.

The hydrologic components of the NWS consist of headquarters elements and a research laboratory located in Silver Spring, Maryland; 13 River Forecast Centers (RFC's) located across the United States (Figure 1); and service hydrologists located in many of the Weather Service Forecast Offices (WSFO's). There are approximately 50 WSFO's located across the country with at least one in most states. For a further description of the relationships and interactions between the hydrologic and meteorological components of the NWS, see Clark (1977).

The current and future hydrologic procedures used by the RFC's are discussed by Ostrowski (1979). Several types of hydrologic models are currently used (Schaake, 1976). These include Antecedent Precipitation Index runoff models; conceptual hydrologic streamflow models, which use rainfall, and/or snowfall, and potential evapotranspiration as inputs to a soil moisture accounting system; streamflow routing models; reservoir operations models; and water supply forecast models. The total system of models, together with the data collection and data processing modules, is called the NWS River Forecast System (NWSRFS). Ostrowski (1979) also discusses the current types of data inputs that are available to NWSRFS. In the case of precipitation, sources range from manually read rain gages to remotely sensed measurements from land-based digital radars. In the future, the

RIVER AND FLOOD FORECAST SERVICE

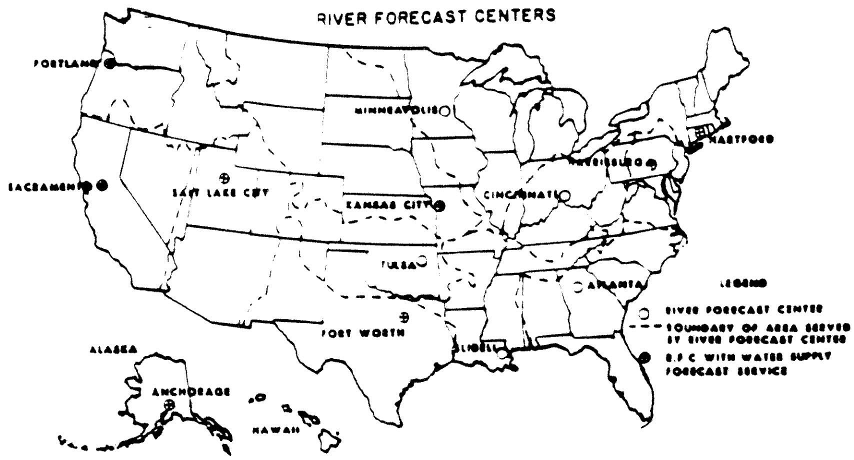


Figure 1. The 13 NWS River Forecast Centers and their respective forecast areas.

role of satellites potentially can become increasingly important if the requirements discussed in the subsequent two sections can be met.

3. SAMPLING AND ACCURACY REQUIREMENTS

As described by Kohler (1958), the operational problems confronted by the hydrologic forecaster can be partitioned according to the lead time of the forecast, which is related to the time scale for which the forecast applies. Kohler gives some of the purposes to be served by short-range hydrologic forecasts (referred to by Kohler as less than 10 days) and by forecasts for monthly or longer time periods. These include:

Short range forecasts -- usually less than 10 days

- Evacuating people and withdrawing movable property from the path of an oncoming flood.
- Fighting floods -- sand-bagging, closing of gates in levees and flood walls, planning for operation of pumps.
- Operating dams. Particularly valuable for flood control, navigation, and multiple-purpose structures.
- Planning for low-flow navigation.
- Scheduling diversion and distribution of irrigation water.
- Scheduling power production.
- Planning construction work in or near streams.

Monthly and longer forecasts

- Establishing long-range flood prevention and control operations.
- Planning for agricultural operations in irrigated areas.
- Establishing schedules of power operation.
- Planning municipal water supplies.
- Planning for long-range navigation activities.

In the short-range category, the flash-flood falls at the shortest end of the time scale, occurring in periods measured in minutes up to a few hours. At the other end of the time spectrum, it is feasible to predict with a fair degree of accuracy seasonal water supplies in those areas where a large fraction of the runoff is produced from snowmelt; for example, water stored in snowpacks provides as much as 70 percent of the water supply for the western states of the U.S. (Chang et al., 1981).

Most of the streamflow forecast models used by the NWS RFC's require precipitation averaged over a basin or sub-basin area as input. The size of the area, as well as the temporal period over which the precipitation is averaged, depend on the hydrologic application and on data availability. Quicker data availability can lead to improvements in the Mean Forecast Lead Time (MFLT) for a given size watershed; but, if the quicker data are less reliable, then the reliable MFLT can even decrease (Jettmar et al., 1979).

The frequency of samples required to achieve a desired accuracy for a given averaging domain will depend on the variability of the precipitation in time and, since rainfall generally is a nonstationary process, the variability in space is related to the variability in time. Furthermore, the precipitation variability is related to the type of precipitation which, in turn, may be related to season for a given locality. Figure 2 illustrates how the relative variability of average storm precipitation varies for a 400 mi^2 network in central Illinois (Changnon and Huff, 1980) for several different precipitation types. The relative variability would increase for all precipitation types for averaging increments less than those of the total storm periods.

Because the variability of rainfall varies with type and location, it is difficult to generalize the sampling requirements. However,

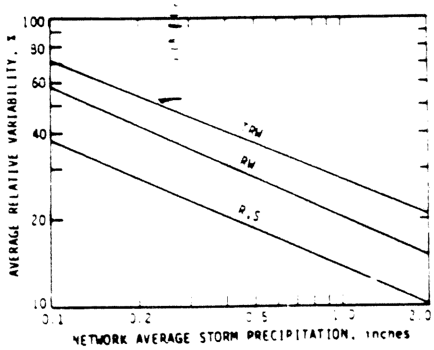


Figure 2. Relations between relative variability and precipitation type on a 400 mi^2 network in central Illinois (from Changnon and Huff, 1980, p.40). TRW = thunderstorm cases; RW = rain shower cases; R,S = continuous rain and snow cases.

for short-term forecasting applications, it is informative to examine some results presented in Figure 3 from Hudlow and Arkell (1978). Figure 3 gives estimates of the mean percent error that can be attributed to incomplete sampling (i.e., temporal sampling error) for various sampling intervals and size areas and for 1-hr, 2-hr, 3-hr, and 6-hr averaging intervals. The results shown in Figure 3 are based on digital radar data collected over the eastern tropical Atlantic Ocean during the GARP Atlantic Tropical Experiment (GATE). To consider these results is of value because the sampling requirements for tropical convection in the Intertropical Convergence Zone, where the GATE data were collected, may not be that dissimilar from those for thunderstorm convection in mid-latitudes and probably represent the limiting case to be met for precipitation sampling from space.

As mentioned above, the sampling frequency required depends on the application. For example, the detection of excessive rainfall at the smallest spatial scales that can produce flash floods will require samples spaced on the order of minutes while, as given by Johnson and Vetlov (1977), weekly observations are sufficiently frequent for mapping snow cover for most applications. Also, the wavelength and technique employed to estimate the precipitation may dictate even shorter sampling intervals than would be required to achieve the same accuracy from direct precipitation measurements. Negri and Adler (1980), for example, suggest that it may be necessary to collect infrared satellite data at high time resolutions (every 5 minutes) if thunderstorm-top ascent rates, estimated from the brightness temperatures, are used to infer rainfall rates. The reason for this is that the tops ascend rapidly over a short time period during the rapid growth phase of the developing stage of the storm.

Although there is very limited information available on sampling requirements for achieving necessary accuracies for various hydrologic forecasting applications, we have composited a rough summary of the requirements based on available information and the opinions of several hydrologists in the NWS Office of Hydrology (Figure 4). The mean percent errors given in Figure 4 were arrived at by first considering the magnitude of errors tolerable for current operational techniques using conventional data from land-based precipitation systems. These initial error values were then relaxed further after considering some of the practical and technical limitations likely to be encountered in estimating precipitation from satellite measurements. We feel that users of satellite information must be realistic in specifying accuracies; the "bottom line" to keep in mind is that the hydrologic forecaster will use the best quantitative precipitation information available. Currently, the availability of such information for computer computations often is very limited, especially in real or near-real time. Precipitation measurements from space offer the potential of significantly increasing the availability of rainfall information for operational hydrologic forecasting applications.

With the above philosophy in mind, the mean percent errors given in Figure 4 are those which roughly reflect the maximum acceptable error (which we can expect to achieve once satellite techniques have been calibrated for a specific geographic area and precipitation type) from satellite estimates alone over the range of spatial and temporal averaging scales indicated. The forecaster obviously would prefer the highest accuracy achievable. Conversely, precipitation estimates from satellite data with accompanying errors larger than those given in Figure 4 would still be quite useful if the errors in the satellite patterns are largely due to systematic biases and if other independent data are available for comparison and melding with the satellite data. An example of a multisensor precipitation analysis system is presented in Section 4.

Also included in Figure 4 are estimates of minimum temporal sampling frequencies required to achieve the corresponding accuracies. These sampling frequency requirements are rough estimates taken from Figure 3 (for the scales covered in Figure 3). The sampling frequency estimates for the larger scales, falling outside the domain represented in Figure 3, were obtained by extrapolating the results of Figure 3 and by referring to data from other authors (for example, Johnson and Vetlov, 1977).

4. DATA BASE REQUIREMENTS

The National Research Council's Space Applications Board (1980) recently concluded that recommendations made in 1974 to the National Academy of Sciences on remote sensing applications to hydrology "remain valid but mostly unmet." The Panel on Water Resources, under the Space Applications Board, optimistically views the use of remotely sensed data for resource prediction. However, the panel states that "to be useful for prediction, remotely sensed data must be compatible with mathematical modeling of hydrologic systems." This is an extremely critical point to bear in mind for hydrologic forecasting applications. All of the NWS River Forecast Centers rely heavily on numerical models and automatic data

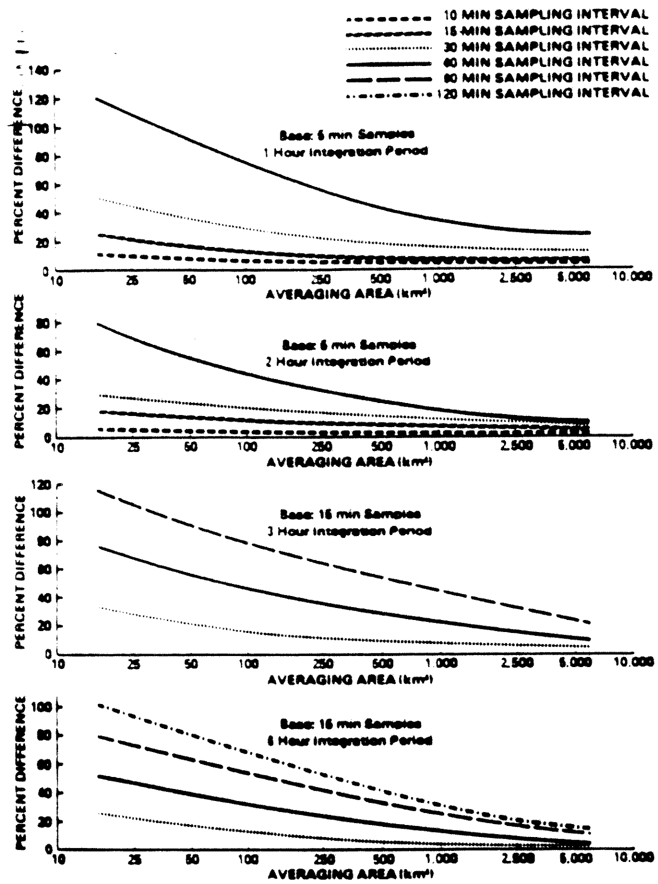


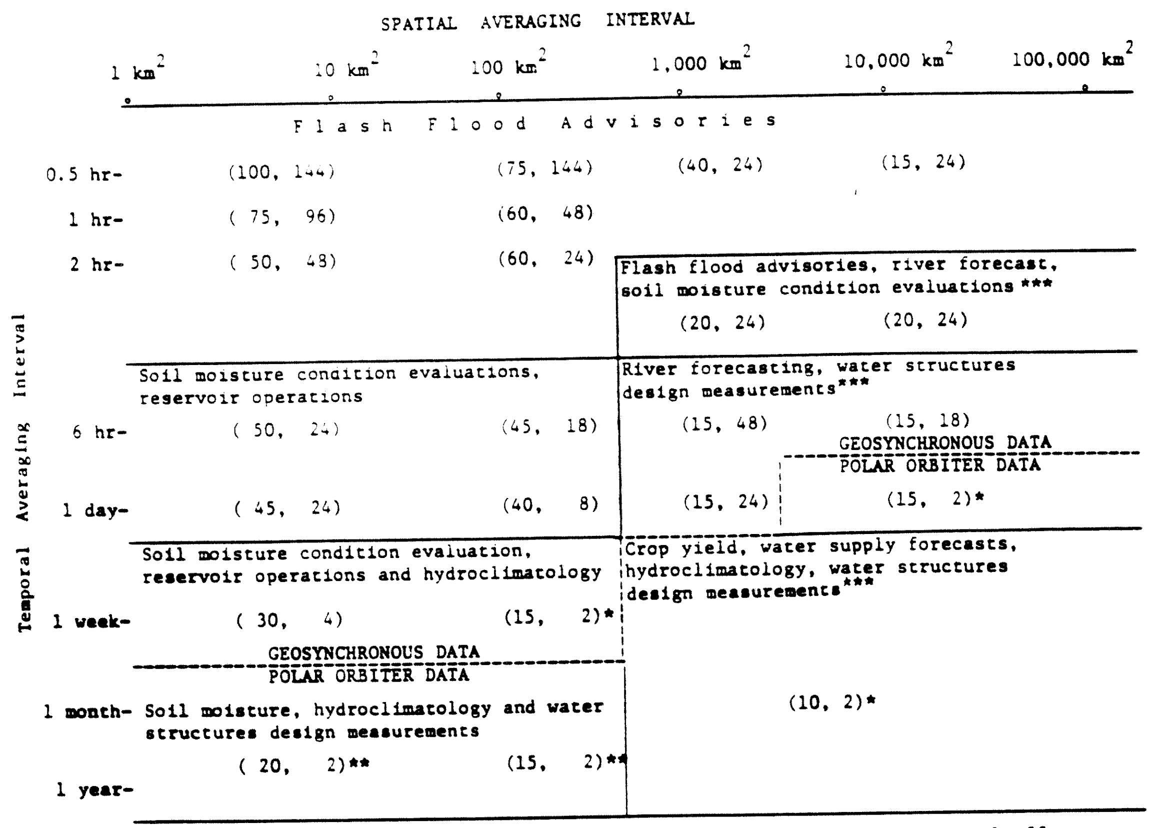
Figure 3. Upper two panels: Mean absolute percent difference between rainfall estimates using 5-min base sampling intervals and those using coarser sampling intervals for a range of spatial averaging and temporal integration scales. Lower two panels: Same as upper two, except a 15-min base sampling interval was used and longer integration periods were included. Based on analysis by Hudlow and Arkell (1978), who used digital radar data collected over the eastern tropical Atlantic Ocean during the GARP Atlantic Tropical Experiment (GATE).

processing procedures. For data sources to be most useful operationally, the data must be available on-line in a format compatible with computer processing. This becomes increasingly important as the scale of the phenomenon being forecast decreases and, correspondingly, the lead time between the occurrence of the precipitation and the hydrologic event decreases. Even for snow mapping for water supply forecasting, which usually pertains to relatively large scales (Figure 4), the large data volumes from the satellite sensors, and the informational flow that results, can be most effectively utilized only if we turn more to automatic (machine) processing of the imagery (Meier, 1980).

Progress has been made in recent years toward the computerized derivation of satellite rainfall estimates. For example, Griffith et al. (1981); Lovejoy and Austin (1979); Stout et al. (1979); Scofield and Oliver (1977); and Moses (1980) have developed procedures for estimating rainfall using data from visible and/or infrared geosynchronous satellites. Also, Wilheit et al. (1977) have developed a technique for mapping rainfall rates over the oceans using microwave data from the Nimbus polar orbiting satellite. However, none of these procedures are currently available on-line for hydrologic forecasting. The Oliver/Scofield technique has been used on a selected basis to provide accumulated rainfall maps to field offices during critical rainfall events, and plans exist to partially automate this technique using a man-machine interactive system (Moses, 1980). This system, called an Interactive Flash Flood Analyzer (IFFA) will be used in support of the NWS Flash Flood Warning Program.

Recognizing the need to automate the use of information from multiple rainfall sensors for hydrologic applications, the NWS Office of Hydrology, through its Hydrologic Research Laboratory (HRL), initiated the ongoing Hydrologic Rainfall Analysis Project (HRAP). HRAP is aimed at improving the acquisition, preprocessing,

Figure 4. Maximum acceptable mean percent error (first value in the parentheses) as a function of temporal and spatial averaging scales. Also estimates of the minimum temporal sampling frequencies (samples per day) required to achieve the accuracies are given as the second value in the parentheses. Larger errors would be acceptable if the errors in the satellite patterns are primarily due to systematic biases and if other independent data are available for comparison and melding with the satellite data.



*Limited daily sensings (less than 4) can result in significant biases when diurnal effects are introduced either by meteorological or sensor effects.

**If significant diurnal effects do not exist, data from high spatial resolution satellites such as LANDSAT could be useful even with longer intersampling intervals.

***Estimates for these applications and corresponding scales require relatively smaller acceptable errors because they are more highly processed and are of a more quantitative nature.

quality controlling, and optimal merging of multi-sensor data bases for input to hydrologic forecasting models (Greene et al., 1979). In the foreseeable future, it seems likely that it will remain necessary to compare and combine the remotely sensed satellite data with data available from land-based remote sensors and/or in situ sensors (rain gages) in order to achieve the quantitative accuracies required for hydrologic forecasting. Also, rain-gage data are probably one of the better "ground truth" sources for evaluating the merits of various satellite rainfall estimation procedures. Farnsworth and Canterford (1980) propose the use of an "equivalent rain-gage density" for assessing the accuracy of satellite rainfall estimates as indicated by the gage density required to give equivalent accuracies.

Figure 5 illustrates the various data components and computer facilities currently envisioned to comprise a Multisensor Rainfall Analysis System (MSRANS). Actually, MSRANS is the software that exists within the various computer environments. Some of the individual components of MSRANS are on-line now [for example, the Manual Digitized Radar (MDR) file and the Visible/Infrared Spin Scan Radiometer (VISSR) file]. For an explanation of the data acquisition and the generation of the VISSR data base from the Geostationary Operational Environmental Satellite (GOES), see McClain (1980) and Waters and Green (1979). Other MSRANS components are not now on-line (for example, the RFC Gateway Computers), but all, or at least the essential, components should be in existence within a year or two. It will be a

MSRANS
(MULTISENSOR RAINFALL ANALYSIS SYSTEM)

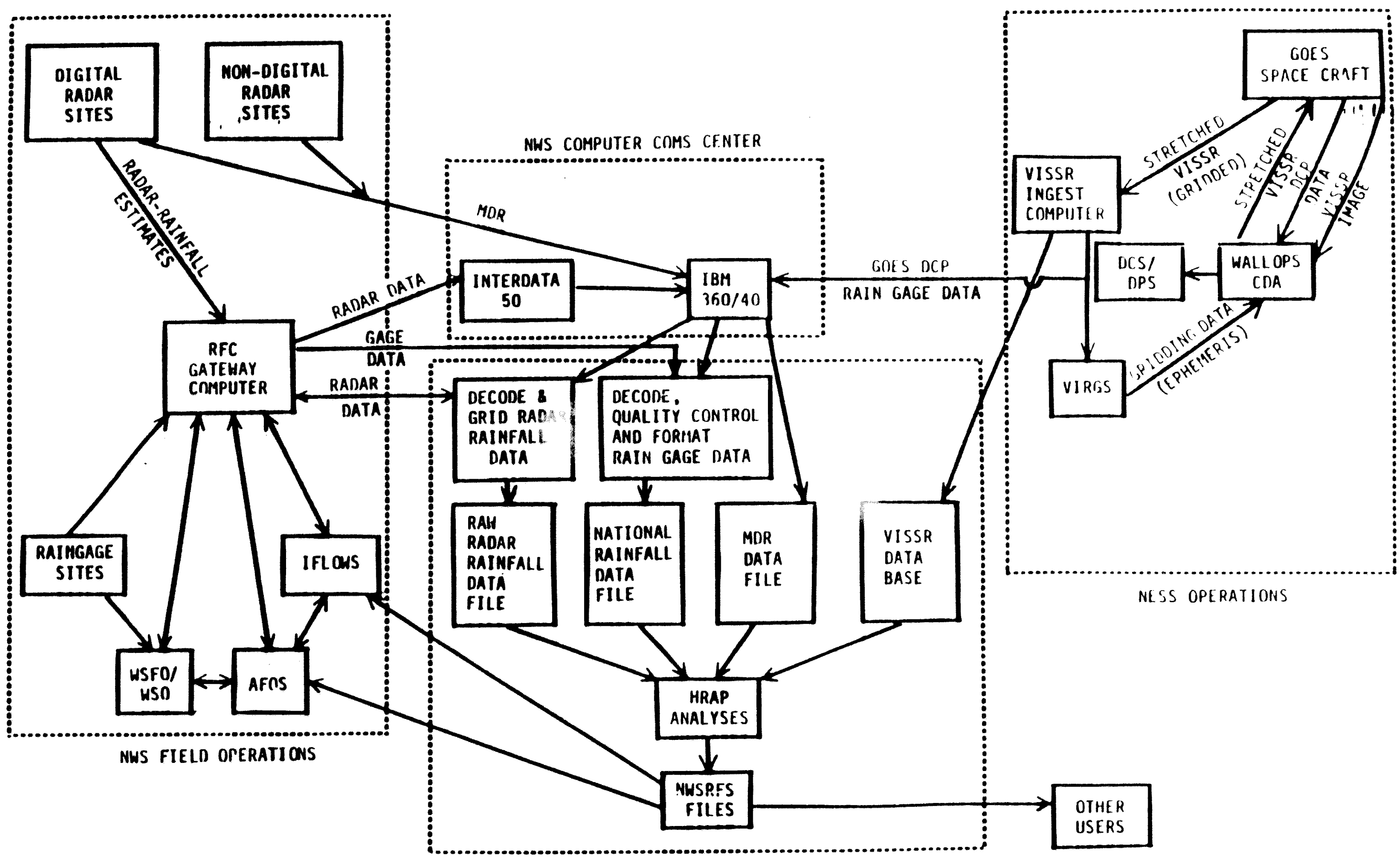


Figure 5. MSRANS -- See text for explanation of operational status of various components.

considerably longer period, however, before the total system will be functioning in an optimal multisensor analysis mode. Achieving this goal requires ongoing research and development over the next several years to implement multivariate objective analysis procedures such as those described by Crawford (1978). This is one of the objectives of HRAP (Greene et al., 1980). A similar project is under way in the United Kingdom (Collier, 1980). Satellite data base structures in the future should be planned to accommodate the types of numerical multivariate analyses being developed as part of these projects.

5. CONCLUDING REMARKS

In the planning for future satellite sensors and data bases, it is important to keep foremost in mind the ultimate applications for the data. In the case of most hydrologic forecasting applications, it is critical that the data bases be made available on-line in the computer environment being used by the hydrologic forecasters to perform their hydrologic computations. Achieving this will allow the strengths of the remotely sensed data to be most effectively utilized, since they can be used with data from in situ sensors in a multivariate analysis mode. As indicated in Section 3, this approach should significantly relax the accuracy requirements for the satellite precipitation estimates if the errors in the satellite patterns are largely due to systematic biases.

6. ACRONYMS

AFOS	--	Automation of Field Operations and Services
CDA	--	Command and Data Acquisition Station
DCP	--	Data Collection Platform
DCS/DPS	--	Data Collection System/Data Processing System
GARP	--	Global Atmospheric Research Program
GATE	--	GARP Atlantic Tropical Experiment
GOES	--	Geostationary Operational Environmental Satellite
HRAP	--	Hydrologic Rainfall Analysis Project
HRL	--	Hydrologic Research Laboratory
IFFA	--	Interactive Flash Flood Analyzer
IFLOWS	--	Integrated Flood Observing and Warning System
MDR	--	Manual Digitized Radar
MFLT	--	Mean Forecast Lead Time
MSRANS	--	Multisensor Rainfall Analysis System
NWS	--	National Weather Service
NWSRFS	--	National Weather Service River Forecast System
RFC	--	River Forecast Center
VIRGS	-	VISSR Interactive Registration and Gridding System
VISSR	--	Visible/Infrared Spin Scan Radiometer
WSFO	--	Weather Service Forecast Office
WSO	--	Weather Service Office

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