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SATELLITE RAINFALL ESTIMATION FOR HYDROLOGIC FORECASTING

Richard K. Farnsworth and Raymond P. Canterford

Hydrologic Research Laboratory
National Weather Service, W23
Silver Spring, Maryland 20910

BIOGRAPHICAL SKETCH

Richard K. Farnsworth was born in Salt Lake City, Utah in 1934. He holds a BA and MS in Physics (Utah 1961 and Brigham Young 1966, respectively) and a Ph. D. in Natural Resources from Michigan 1976.

Raymond P. Canterford was born in Melbourne, Australia in 1948. He holds a B. Sc. (Hons) and a Ph. D. in Physics (Monash University, Australia, 1970, 1974). He is a Fulbright Fellow from the Australian Bureau of Meteorology currently assigned to the National Oceanic and Atmospheric Administration (NOAA).

ABSTRACT

Determination of an accurate areal extent and amount of rainfall is a primary requirement for issuing timely and effective flood forecasts. Estimation of these data using satellite imagery is potentially an important application of remote sensing. This paper presents a method for evaluating current rainfall estimation techniques in terms of the requirements for flood and stage forecasting of rivers. Since some of the techniques claim suitability (often inadequately supported) for hydrologic forecasting, an evaluation scheme has been developed based on "equivalent rain gage density" (ERGD). This scheme involves assigning ERGD's to the satellite techniques for specified time and space scales; down to the order of 3 hours and 1/4° x 1/4° latitude/longitude grids. The evaluation scheme allows not only intercomparisons among satellite techniques, but also a measure of their improvement, if any, over information from existing operational rain gage networks. The satellite techniques being investigated include those of Scofield and Oliver, Whitney and Herman, Woodley and Griffith, Arkin and Richards, and the University of Wisconsin.

1. INTRODUCTION

The use of satellite imagery has shown potential for producing accurate areal rainfall estimates. There are many satellite rainfall estimation techniques, currently available or under development, that are reported to provide estimates that are suitable for flood forecasting. However, variations in the techniques and their usage, and limitations on data suitable for adequate verification have prevented their evaluation for use in river forecast operations.

This paper proposes an evaluation scheme to provide a common system against which the various satellite rainfall estimation techniques can be compared to determine their suitability as input to operational flood forecasting. It also provides a measure of their improvement, if any, over rainfall estimates from existing operational rain gage networks.

2. SATELLITE RAINFALL ESTIMATION TECHNIQUES

A number of rainfall estimation techniques have been developed incorporating imagery from either geostationary or polar orbiting satellites. The latter satellites have poor resolution in time (once or twice daily). Consequently, most of the satellite techniques use infrared or visible data from GOES (Geostationary Operational Environmental Satellite) because of frequent imagery (half hourly). Techniques devised before 1973 are summarized by Martin and Scherer (1973).

Scofield and Oliver (1977) have developed a decision-tree method that enables estimation of "point" rainfall rates for the more intense rain situations, based on successive enhanced IR imagery. Moses (National Environmental Satellite Service (NESS), personal communication) is currently developing the technique further and incorporating automation as a "man-machine" mix. The Scofield/Oliver technique determines rain rate and areal extent by considering cloud top temperature, rate of cloud growth, cloud top temperature gradient, cloud cell mergers, etc.

The Griffith/Woodley technique (Griffith, et al., 1978, and Augustine, et al., 1979) has been developed over a number of years, initially in conjunction with the Florida Area Cumulus Experiment (FACE), and has recently been automated (computer requirements presently being rather large; Augustine, et al., 1979). Their technique estimates volumetric rain from convective cloud areas using a time dependent empirical relation incorporating cloud area (entities are tracked), maximum cloud area and cloud top temperature (through a weighting index). Distribution of this rain volume is made according to cloud top temperature. For the tropics 50% of the rain volume is apportioned within the coldest 10% of the cloud and the rest over the next coldest 40% of the cloud. The technique allows for the fact that most convective rainfall occurs during growth and mature stages.

Stout, et al. (1979), developed the University of Wisconsin (UW) technique which is a variant of the Griffith/Woodley technique discussed above. Both have been applied to GARP Atlantic Tropical Experiment (GATE) radar rainfall data.

Whitney and Herman (NESS) are working in conjunction with members of the National Weather Service (NWS) Office of Hydrology to develop a totally automated system oriented directly toward the needs of flood forecasting (Whitney and Herman, 1979). Their system involves estimating rainfall rates (6 hourly) on a grid network (0.3° x 0.3° latitude/longitude) using digital IR data and various meteorological parameters through the use of regression equations.

Lovejoy and Austin (1979) address the problem of delineating rain areas as well as rain amount, and distinguish sources of error in several of the above-mentioned techniques.

To determine a relationship between fractional cloud cover over a given area and the accumulated rainfall (6 hourly), Arkin (1979) used GATE radar rainfall as ground truth. He obtained a simple linear relationship dependent upon temperature threshold. It provides a benchmark accuracy which may be exceeded by more sophisticated satellite rainfall techniques.

3. HYDROLOGICAL REQUIREMENTS

It has been extremely difficult to determine the suitability for flood forecasting of the satellite rainfall estimation techniques discussed in Section 2. They have usually been applied to different data bases (i.e., specific areas and storms) and have often been verified against insufficient ground truth for flood forecasting requirements.

Agricultural and climatological requirements are different from those for accurate real-time stage and discharge forecasts on rivers. For instance, monthly and weekly values of rainfall are of value in climatology studies, while river forecasting requires estimates on a 6-hourly or shorter interval. Furthermore, river forecasting requires a finer spatial resolution of rainfall estimates; estimates are most important for headwater basins ranging from 200 to 400 square miles.

Rain gage data are the backbone of the NWS operational flood forecasting program, and therefore the evaluation system presented here includes a comparison of the satellite techniques with operational rain gage networks as well as the best available ground truth.

3.1 Flood Forecasting Spatial and Temporal Resolution Standards

Because of the variability of rainfall in space and time, it is necessary to define some practical standard resolutions that a rainfall estimation technique should have, to be of optimum value to operational flood forecasting. Headwater basins, for which estimates are critical, are often of the order of 300 square miles (approximately 1/4° x 1/4° latitude/longitude if considered on a grid basis). This is the standard for spatial resolution, adopted in this paper.

Temporal needs, or the frequency of rainfall reports, are controlled by the actual time interval, from the beginning of the rainfall until the flood crest reaches the forecast point, sometimes called the "period to peak." If this period to peak is less than say, 24 hours, then rainfall reports should be obtained at least every 6 hours. Currently the NWS flood forecast models are operated with 6 hourly rainfall reports, but developmental work has been carried out to adapt the models to intervals down to 1 hour. However, because of limitations in current satellite estimation techniques, a practical standard for temporal resolution is 3 hours. Since maximum flood warning time is the primary aim of a flood forecasting service, more frequent accurate rainfalls would nonetheless be advantageous.

In summary, the practical standards for flood forecasting that any satellite rainfall estimation technique should approach are 1/4° x 1/4° latitude/longitude spatial resolution and 3 hours temporal resolution.

3.2 Resolutions Considered in the Evaluation Scheme

While the preceding section outlines the specific standards of areal rainfall estimation for flood forecasting, many techniques do not currently approach these limits. Therefore, the proposed evaluation scheme is designed to accept techniques with coarser resolutions; spatial resolution out to 1° x 1° latitude/longitude and temporal resolution out to 24 hours. Techniques which provide accurate estimates within these bounds, but which do not approach the ideal standards of Section 3.1, still provide potentially useful rainfall estimates and should not be excluded from the evaluation scheme.

4. EVALUATION SCHEME CONCEPTS

The evaluation scheme proposed in this paper has been developed with the user requirements discussed in Section 3 as a basis. It should provide a means of comparison of the given technique's performance against other proposed satellite techniques and against the rainfall estimates from existing operationally reporting rain gage networks (which are almost always less dense than climatological or "after the fact" networks).

4.1 Correlation of Estimated Rainfalls Against Observed Ground Truth

a) Data Bases

A basic form of analysis, used by some authors to evaluate the performance of a satellite technique, is to determine the correlation coefficient relating the technique's rainfall estimates with the best available observed rainfall (whether radar, rain gage, or a combination), the "ground truth." Since the correlation coefficient is not a measure of the bias in a technique's estimates, it does not provide an absolute measure of performance. Further, the temporal and spatial resolution of the rainfall estimates is obviously limited by the resolution of the ground truth for such a comparison. To establish a set of estimated and observed rainfall values two approaches are adopted depending on the data set available. The first approach is used if estimates can be made for a single area only (e.g., 1° x 1° latitude/longitude box) but there are data for a series of storms over the area. In this case, the observed and estimated rainfalls are treated as a time series over the area. The other approach is the situation where only a single storm (such as a case study) is available, but it covers a large enough geographic area for a grid (in this example 1° x 1°) to be placed over the storm. This allows estimates to be made for each grid area over the storm. If there is more than one storm available, both approaches can be used in combination.

b) Correlation Diagrams

The evaluation scheme proposed includes correlations of estimated rainfalls against ground truth as a qualitative measure of performance only. Correlations for several spatial (grid size) and temporal (rainfall duration) resolutions should be determined to judge a satellite technique's performance. As outlined in Sections 3.1 and 3.2, grid sizes for 1/4° to 1° on side and durations from 3 hours to 24 hours are important. In this way it can be seen how a technique performs as spatial and temporal resolutions are reduced.

An example of this type of correlation diagram is given in Figure 1. It was determined by Greene, et al. (1979) from the work of Richards and Arkin (1979) on GATE rainfall (digital radar) ground truth using the first approach mentioned in a) above; as a time series of rainfalls over three spatial averaging areas (0.5° x 0.5°, 1.5° x 1.5° and 2.5° x 2.5°) and for the three temporal averaging scales shown. Their satellite method itself is discussed in Section 2. As can be seen from the figure which illustrates the properties of any satellite technique, the correlations become lower for smaller time and space scales. For hydrologic forecasting, correlations must be judged meaningful for the standard 1/4° x 1/4° and 3 hour resolutions discussed in Section 3.1. Simple extrapolation of Figure 1 to these resolutions obviously suggests this is not the case for this particular technique (which is only considered a "benchmark"), although it could provide useful information at the coarser resolutions. The proposed evaluation scheme would incorporate correlation diagrams to judge, qualitatively, if other techniques do in fact perform adequately at the finer resolutions.

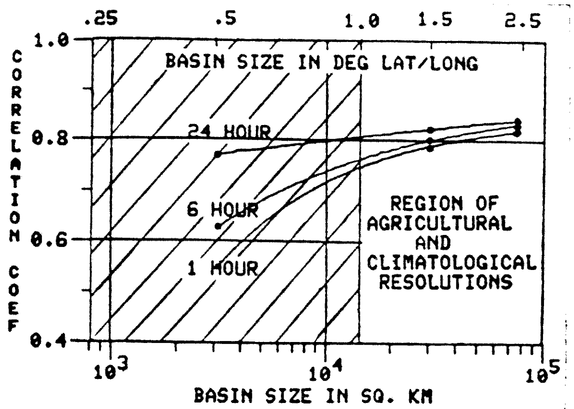

Figure 1.

Correlation Diagram: Correlation between the percentage of area covered by cloud (less than a threshold temperature) and areal rainfall for various spatial and temporal resolutions for Phase I of GATE. The hatched area is the range of spatial resolution considered in the evaluation scheme.

4.2 MAP Error Curves: Equivalent Rain Gage Density (ERGD)

A statistic that takes account of the spatial and temporal resolution and storm type (strongly convective, frontal, etc.) is required as a quantitative measure of estimates produced by a technique. Current literature does not provide such a direct statistic. Therefore, in the evaluation scheme presented in this paper, that statistic would be the "equivalent rain gage density" (ERGD). When a given satellite technique is compared against the best available ground truth, it provides areal rainfall estimates for specific time and space scales with inherent "mean areal precipitation" (MAP) errors. The ERGD is the density of rain gages that would yield the same MAP error when compared against the same ground truth. To expand on this concept further, some basic properties of MAP errors can be discussed by using MAP error curves, an example of which is shown in Figure 2.

Theoretically based procedures for estimating the accuracy of MAP estimates (from rain gage networks) have been developed and compared with historical data from dense rain gage networks (e.g., Schaake, 1979 and Huff, 1970). Empirical relations determined from the dense experimental networks express the MAP errors in terms of the area over which the rainfall estimate is made (A square miles), the gage density (G square miles per gage), the storm duration (T hours), and the mean rainfall (P inches). Figure 2 is a graph of a relationship for the Muskingum, Ohio, basin derived by Schaake (1979):

$$CV_e = 0.055A^{-0.32}\ G^{0.60} \tag{4.1}$$

where CV_e is the coefficient of variation of MAP standard error and G and A are defined above. P is incorporated in CV_e and T is held constant.

Figure 2 illustrates the properties of the MAP error curves that form the basis of the ERGD determination. For the purposes of the figure, G in equation 4.1 has been redefined as gages per unit area (in this case 10,000 square miles) rather than area per gage. It can be seen that the MAP error increases as the gage density decreases. The MAP error curve (coefficient of variation of MAP error versus rain gage density) to be used in a particular situation would depend on the following features:

(1) The area A over which the rainfall estimate is to be made

(2) The storm duration

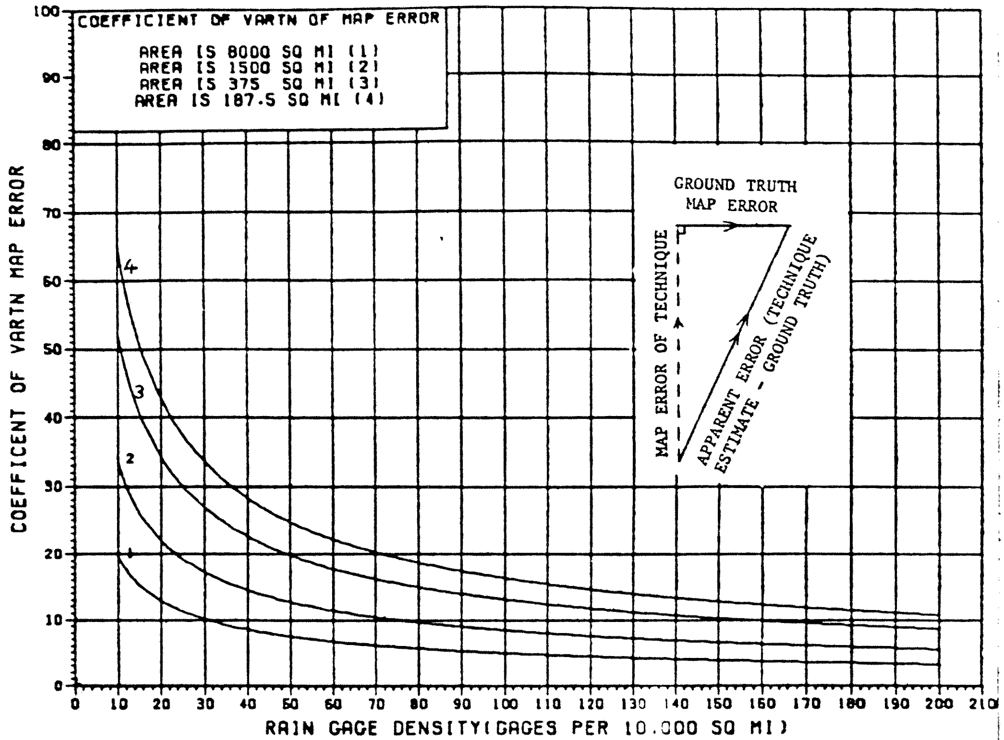

Figure 2. MAP Error Curve: Coefficient of variation of MAP error versus rain gage density. Derived from Schaake's (1979) empirical relation for Muskingum, Ohio. Inset to figure: Calculation of MAP error of a technique--see Section 4.2.

(3) The storm type (whether strongly convective, stratiform, etc.).

The first feature (1) is illustrated in Figure 2--smaller areas have larger MAP errors overall. The other two features are not illustrated in Figure 2 since it was developed for a specific set of intense convective storms and only 6-hourly storm durations were considered. However, Huff (1970) included storm duration (1 hour to 48 hours) in his work on central and southern Illinois networks.

Feature (3), the storm type, can be discussed in terms of the spatial correlation structure of the storm and, in particular, the decorrelation distance, which can simply be defined as the mean distance between rain gages that correlation of their rainfalls drops to 1/e (for more detail, see Schaake, 1979). Clearly, the more convective the storm and the shorter the duration considered, the more rapidly the rainfalls decorrelate resulting in higher MAP error curves. For example, Huff and Shipp (1969) obtained some decorrelation distances of approximately 5 miles for 1 minute rainfall rates for storms in Illinois.

Objective analysis of observed rainfalls is carried out to provide the best available ground truth. It has as a basis this decorrelation distance in terms of the "radius of influence" of the point observations, and is used to analyze the point data onto a grid network for determination of areal rainfall (e.g., Barnes, 1964). In the evaluation of satellite rainfall estimation techniques, ground truth often consists of a low density rain gage network. It is important not to extrapolate ground truth rainfall to regions where there are insufficient data. The decorrelation distances of the storms define the extent of extrapolation allowable. These data-void areas should be omitted from any evaluation.

Often the best available ground truth rain gage network on which to evaluate techniques is the climatological daily rainfall network, and for shorter durations, the climatological hourly rainfall network (NOAA, Environmental Data and Information Service).

In summary, errors in the ground truth are determined from the MAP error curves. These curves would be developed from the best available ground truth rainfall or equations such as 4.1. The curves also allow the determination of the ERGD defined above. This is done by calculating the MAP error of the satellite technique, then reading from the MAP error curve the appropriate rain gage density that would have produced the same MAP error: the ERGD. To determine the actual MAP error of the satellite technique, the MAP error of the ground truth if subtracted vectorially (see inset to Figure 2) from the measured MAP error (error in satellite estimate minus the ground truth estimate) by assuming independence of the two contributing MAP errors (satellite estimate and ground truth).

5. EVALUATION SCHEME DECISION TREE

A decision tree has been developed to evaluate the suitability of satellite rainfall estimation techniques for operational flood forecasting. It provides both qualitative and quantitative measures of the relative performance of the various satellite techniques (Section 2), and compares the results of these techniques with those of operational rain gage networks. The decision tree (Figure 3, condensed here for space reasons) includes the basic steps of the evaluation scheme which will be discussed briefly for clarification. The basic underlying requirements and concepts have been presented in detail in Sections 3 and 4.

Given a specific satellite rainfall estimation technique that has been applied to a region with <u>ground truth rainfall data</u>, the process of evaluation is as follows (see Figure 3):

<u>Step 1</u>. Reject the technique if it does not satisfy the designated spatial and temporal resolutions.

<u>Step 2</u>. Identify the limitations of the given satellite technique. For example, if it is used for deep convection only, it must only be applied to suitable storm situations. Make a subjective judgment on the practicality of any dynamic calibration (e.g., radar or telemetered gages) the technique requires.

<u>Step 3</u>. Calculate the decorrelation distances for the ground truth data to classify its storm types. Determine the appropriate MAP error curves from the best available ground truth data or historical data.

<u>Step 4</u>. Determine as many points as possible on the correlation diagram (Section 4.1(b)) for the satellite technique. Do the same for the operational network if one is available for the area.

<u>Step 5</u>. The MAP errors of the satellite technique are calculated as discussed in Section 4.2.

<u>Step 6</u>. Determine the ERGD for each time and space scale by reading from the appropriate MAP curves the rain gage density corresponding to the satellite technique's MAP error (Step 5).

<u>Step 7</u>. The given technique is compared with other techniques that may have been analyzed, using the decision tree and with any

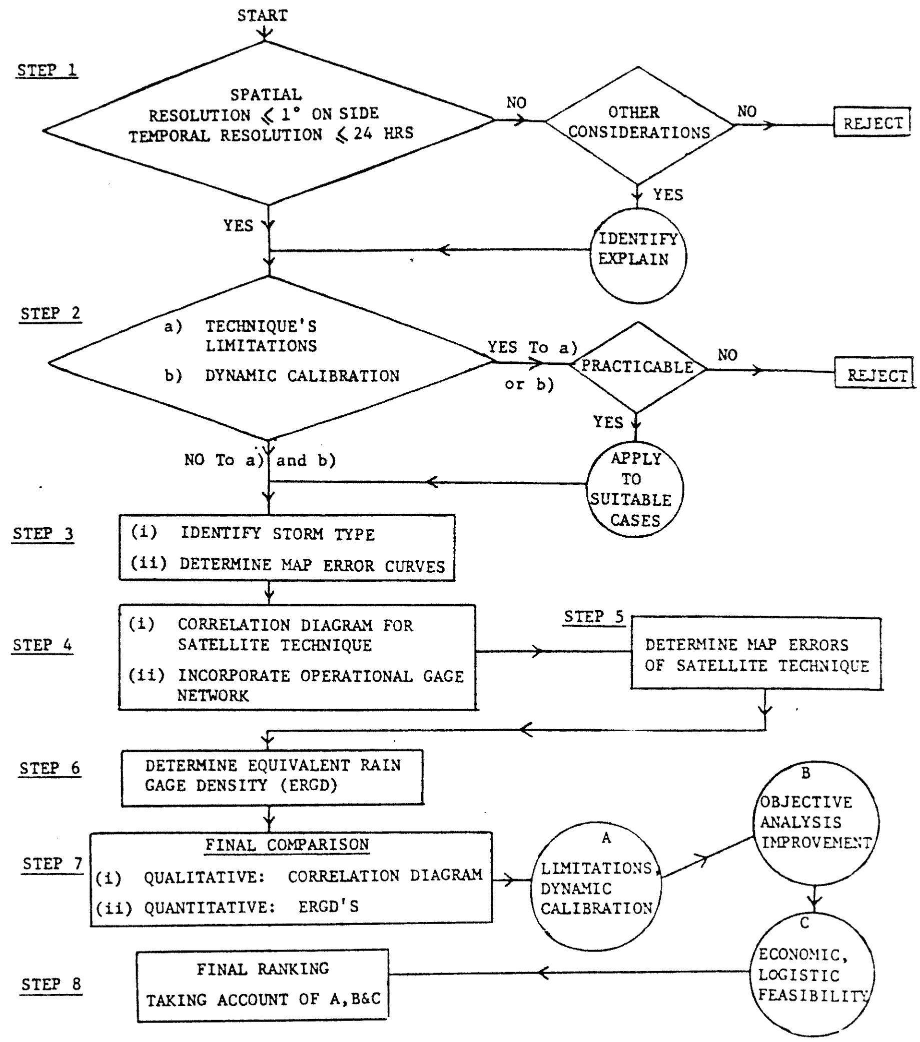

Figure 3. Decision tree for evaluation of rainfall estimation techniques.

operational network. Questions to be answered by these comparisons include: Does the given technique perform well for the required space and time scales and storm types? Does the technique show improvement over any operational rain gage network that may be available for the region under study?

Step 8. Undertake a final ranking of the technique. This must include subjective judgment on the practicality of its limitations, the feasibility of any calibration required, and whether it is economically and/or logistically feasible. Another important consideration is whether objective analysis techniques, as used for merging radar and rain gage data, could substantially improve any or all of the techniques in the final ranking.

6. CONCLUSIONS AND RECOMMENDATIONS

An evaluation scheme for satellite rainfall estimation techniques has been presented. It is basically oriented to operational flood forecasting needs, and should provide valuable information in determining the suitability of any proposed satellite rainfall estimation technique. The primary techniques that should be evaluated with this scheme are those of Woodley/Griffith, Scofield/Oliver, University of Wisconsin, and Whitney/Herman.

Proposers of practical rainfall estimation techniques should include, in the results of future case studies, data concerning ground truth, time and space scales of their estimates, and a numerical rating such as ERGD.

The evaluation scheme enables potential users to not only become familiar with a given technique, but also have a practical understanding of how that technique blends with current rainfall information.

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