

Combining traditional and remote sensing techniques of rainfall measurement as a tool for Hydrology, Agriculture and Water Resources Management

Scott Sinclair⁽¹⁾ and Geoff Pegram⁽²⁾

(1) Civil Engineering, University of Natal, Durban, South Africa : sinclaird@nu.ac.za

(2) Civil Engineering, University of Natal, Durban, South Africa : peggram@nu.ac.za

ABSTRACT

The Hydrologist's traditional tool for measuring rainfall is the rain gauge. Rain gauges are relatively cheap, easy to maintain and provide a direct and suitably accurate estimate of rainfall at a point. What rain gauges fail to capture well is the spatial variability of rainfall with time (unless they form a very dense network), an important aspect for the credible modelling of a catchments response to rainfall. This spatial variability is particularly evident at short timescales of up to several days. As the period of accumulation increases to months, years and; finally, climatological timescales the expected spatial variability in rainfall is reduced and rain gauges do a better job of estimating spatial rainfall fields. Due to the fractal variability of rainfall in space, simple interpolation between rain gauges does not provide an accurate estimate of the true spatial rainfall field.

Weather radar provides (with a single instrument) a highly detailed representation of the spatial structure and temporal evolution of rainfall over a large area. Estimated rainfall rates are derived indirectly from measurements of reflectivity (electromagnetic energy reflected from raindrops in the atmosphere) and are therefore subject to errors that need to be corrected by some form of ground truthing. Rain gauges are commonly used to provide a ground truth but their point measurements are not directly comparable to the volume-averaged estimates of rainfall above the ground by weather radar.

Meteorological satellites provide a further source of rainfall estimates with lower spatial resolution than radar but far greater areal coverage. It is expected that the newly launched Meteosat Second Generation (MSG) will provide far superior rainfall products to those currently available.

A combination of these sources of rainfall estimation provides an attractive means of improving estimates of the true rainfall in space and time. The paper presents some rainfall estimation techniques combining information from each of the sources mentioned above and suggests exciting applications in the fields of flood hydrology, urban hydrology, water resource management and agriculture. The future is certainly not what it used to be.

1. Introduction

The solution to the problem of accurate rainfall estimation in space and time has important ramifications for the field of Hydrology as well as for many others. Hydrology is essentially a science that tries to quantify and explain the movement of water as it impacts on mankind. The starting point of this process is the driving input to the Hydrological system, precipitation. The hydrologic system is relatively forgiving in its smoothing of the noisy rainfall input to produce a less noisy (and more predictable) stream flow output (Dooze, 1973). It makes sense, however, that gross inaccuracies in the estimation of rainfall cannot be smoothed out by a hydrological model, no matter how good it may be. In fact poor rainfall inputs may result in flawed models as the models are fitted to stream flow data with the assumption that the rainfall input is perfect!

This paper presents a number of sources for spatial rainfall estimates and suggests that a combination of these sources of rainfall estimation provides an attractive means of improving estimates of the true (unknown) rainfall in space and time. Some rainfall estimation techniques are described that combine information from each of the sources making possible exciting applications in the fields of flood hydrology, urban hydrology, water resource management and agriculture.

2. Tools for rainfall estimation

This section of the paper describes some of the tools available to measure rainfall, outlining the strengths and limitations of each. A review of the South African scenario is also given.

2.1 Rain gauges

The rain gauge has been the Hydrologist's traditional tool for measuring rainfall. Rain gauges are relatively cheap, easy to maintain and provide a direct estimate of accumulated rainfall depth at a point. They are known to be subject to under-catch errors for heavy rainfall (Wilson and Brandes, 1979). The temporal resolution of a rain gauge ranges from daily read gauges providing daily totals through to tipping bucket type gauges which measure small depth increments, typically in the order of fractions of a millimetre. What rain gauges fail to capture well is the spatial variability of rainfall with time (unless they form a very dense network), this is an important aspect for the credible modelling of a catchments response to rainfall. This spatial variability is particularly evident at short timescales of up to several days. As the period of accumulation increases to longer timescales the expected spatial variability in rainfall is reduced and rain gauges do a better job of estimating spatial rainfall fields (Nagata et al., 2001). Due to the fractal variability of rainfall in space, simple interpolation between rain gauges does not provide an accurate estimate of the true spatial rainfall field, at short timescales.

Of major significance to real-time applications of rainfall estimation is the immediacy of data availability from rain gauges and the automation of data collection. Logging gauges from which data are downloaded months after the event are of no use to the Hydrologist doing flood forecasting and are probably of little use to the Water Management Agency tracking the possible onset of drought conditions by monitoring the current seasons rainfall. This is not to say that historical data are of no use, as they certainly have their place in other applications such as scenario modelling and model fitting. Real-time applications, however, require immediacy of data availability in order to be viable.

2.2 Weather radars

Weather radars provide a highly detailed representation of the spatial structure and temporal evolution of rainfall over a large area with a single instrument. The radar network operated by the South African Weather Service (SAWS) gives a horizontal resolution of 1 km^2 and a temporal sampling resolution of between 4 and 5 minutes. The improvement in spatial detail compared to rain gauges and the immediacy of data availability makes radar an attractive tool for real-time rainfall applications. Unfortunately radars provide estimated rainfall rates that are derived indirectly from measurements of reflectivity (electromagnetic energy reflected from raindrops in the atmosphere) and are therefore subject to errors that need to be corrected by some form of ground truthing (Grecu and Krajewski, 2000). Rain gauges are commonly used as a ground truth but their point measurements are not directly comparable to the volume-averaged estimates of weather radar. A typical instantaneous radar image is shown in Figure 1. The data values (instantaneous reflectivity values) are artificially coloured using the scale shown to allow distinction between areas experiencing different rainfall intensities. The grey region indicates where no data are available.

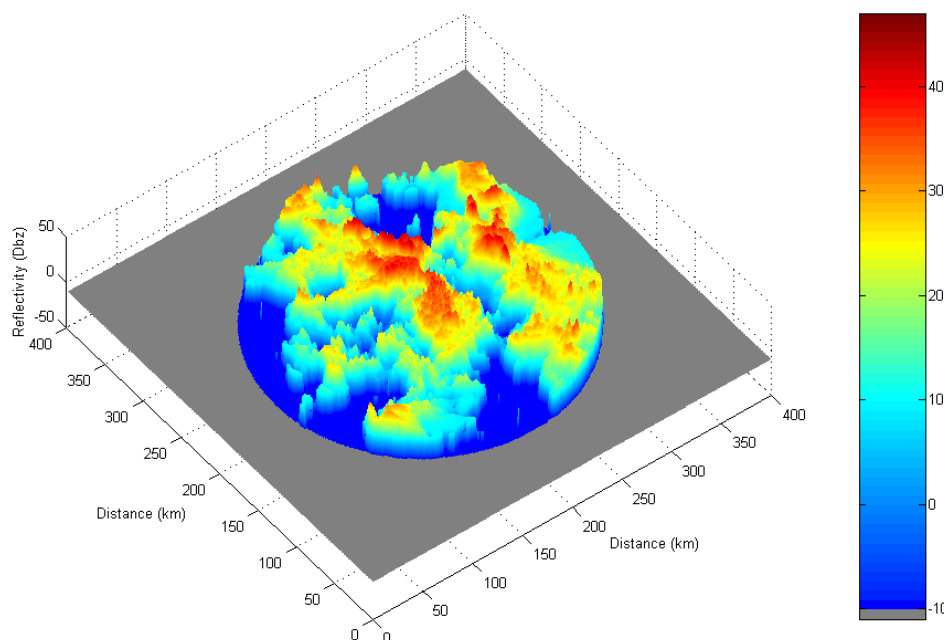


Figure 1: A typical instantaneous radar image showing reflectivity values

The instantaneous reflectivity values are converted to a rainfall rate using an appropriate variant of the well-known Marshall-Palmer relationship (Marshall and Palmer, 1948). In this manner sequences of instantaneous rainfall rate over specific areas can be obtained and accumulated over any required time interval depending on the application. Accumulation techniques will be discussed briefly in section 3.

2.3 Satellite techniques

Satellites provide another attractive method for obtaining rainfall estimates. The particular advantage of satellites is that they are able to provide unsurpassed spatial coverage and can provide estimates of rainfall where there are gaps in the ground-based network of rain gauges and radars. The estimations are, however, indirect as the quantity actually measured by the instruments on board satellites is reflected, scattered and emitted radiant energy from the Earth (Cracknell, 1981). The satellite instrumentation is able to measure radiant

energy in a broad range of spectral (wavelength) windows making it possible to distinguish between different types and heights of clouds. Geo-stationary satellites such as the Meteosat Second Generation (MSG) satellite launched in 2002 (EUMETSAT, 2002) are able to produce data with a high temporal frequency (15 minute intervals in the case of MSG-1) making more accurate temporal estimates of rainfall possible. Figure 2 shows a false colour image generated from three of MSG-1's twelve spectral channels and figure 3 a rainfall estimation (scaled in mm) over South Africa using data from (the soon to be replaced) Meteosat-7.

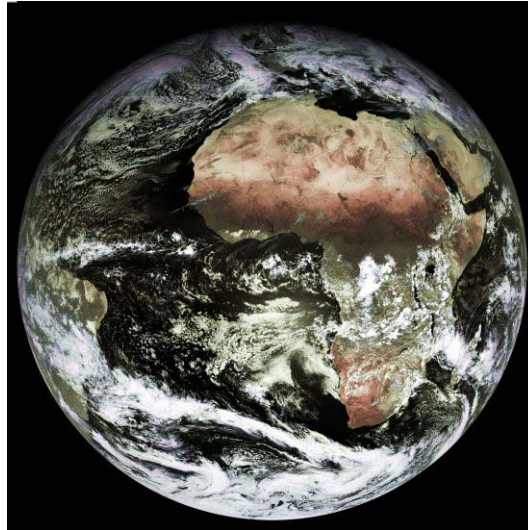


Figure 2: A false colour image from MSG-1

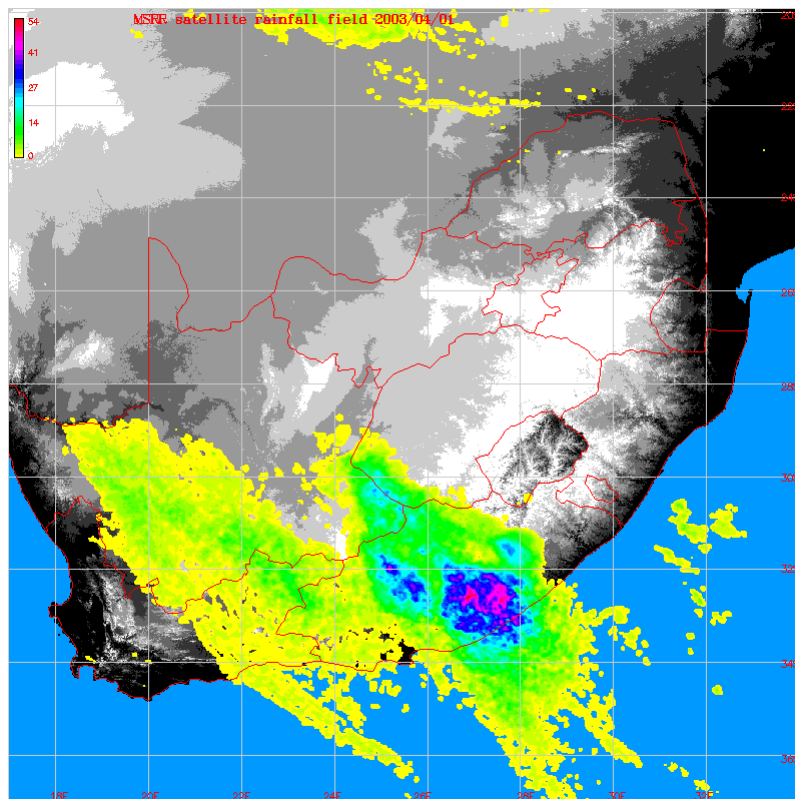


Figure 3: Daily rainfall estimate from Meteosat-7 (01 April 2003)

2.4 Alternative methods of rainfall estimation

There are several other methods that can be used to estimate rainfall or to help improve the estimates made by other techniques. Among these are the use of microwave attenuation between ground stations and the use of Disdrometers although these have a fairly limited area of influence (Ehret, 2002). A relative newcomer on the scene is the use of lightning detection networks for improving satellite rainfall estimations (Morales and Anagnostou, 2003) the principle is based on the observation that convective rainfall areas and regions of high lightning flash density coincide.

3. Temporal accumulation of spatial rainfall

Most applications of rainfall estimates require accumulations over discrete time intervals as well as over different spatial domains. It follows that before using rainfall estimates derived from instantaneous radar or satellite based observations care must be taken to accumulate correctly in time. This is not as simple as in the case of rain gauges where the rainfall is directly recorded as a depth over a given time period, accumulations over longer periods are obtained by adding together the depths recorded during each sub-period.

Accumulating the instantaneous spatial rainfall fields over the required time period can be done in a number of ways, with the choice of method having a significant effect on the resulting accumulated fields. Commonly a simple linear accumulation scheme (of averaging a sequence of images) is adopted. However, this is not necessarily the most appropriate option for accumulating rainfall caused by small scale and fast moving rain systems. The radar and satellite rainfall fields are sampled, instantaneously, at discrete time-steps, while the true rainfall field is evolving continuously with time. This evolution encompasses the growth and decay of the field's structures as well as complex field advection processes. If the sampling interval is not short enough to capture the dynamic changes in the field then simple linear accumulation techniques are inadequate and more sophisticated accumulations schemes are required to produce credible results.

Figure 4 shows some daily rainfall accumulations derived from the data set of the SAWS Bethlehem radar on two days in 1998 and a further two during 1999. The graduated colour scale indicates a range of rainfall depths from 0 mm (white) through to 100 mm (black). The first row of images (numbers 1-4) shows daily accumulations made using the simple linear scheme. Examination of the images shows obvious inconsistencies in the first, second and fourth images. The inconsistencies are manifested as "puddles" of rainfall with definite directional patterns and are caused by fast moving storms that move a significant distance between one observation and the next. Image number 3 does not show any evidence of these inconsistencies and was probably produced on a day characterized by slow moving rain systems.

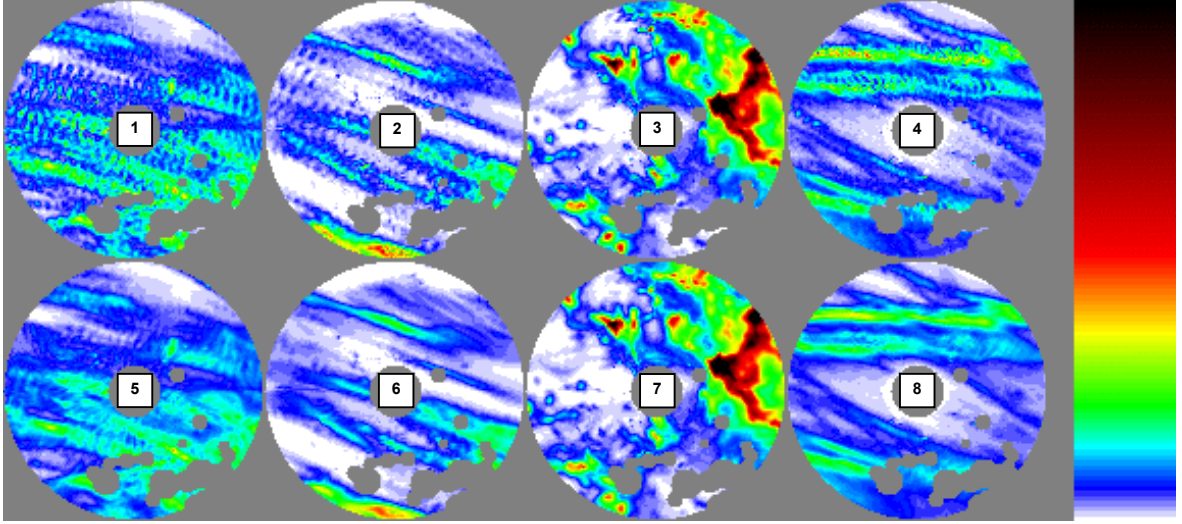


Figure 4: Comparison of daily accumulations

The second row of images (numbers 5-8) shows daily accumulations made on the same days using an accumulation scheme that takes into account the motion of the rainfall field between observations. The second accumulation scheme is based on the technique described by Hannesen (2002). The implementation used here computes a field of advection vectors which describe the transition between successive images using a fast optical flow algorithm (Bab-Hadiashar et al., 1996; Seed, 2001). The image is sub-divided into a number of sub-regions and a mean advection vector computed for each sub-region, the vectors are then interpolated onto the 1km x 1km pixel grid to produce a dense field of motion vectors. The accumulated rainfall between the images (A_p) may then be computed from Equation 1:

$$A_p = \frac{1}{V_p} \left[\int_{S_0}^P \frac{s - S_0}{\Delta s} R_0(s) ds + \int_{S_1}^P \frac{s - S_1}{\Delta s} R_1(s) ds \right] \quad (1)$$

Here P is the pixel at which the rainfall accumulation is required and V_p is its velocity during the time between observations. R_0 is the initial observed field of rainfall rates at each pixel and R_1 is the observation at the end of the time interval. S_0 is the position that point P would have occupied at the beginning of the period on R_0 and S_1 is the position that P would have occupied on R_1 at the start of the period. Δs is the total distance that point P moves during the interval and s is a point along the path of the advection vector associated with P .

In order to compute the accumulations the continuous integrals in Equation 1 are replaced by a discrete numerical approximation of the integral using a fixed number of interior points (four points for the cases shown in Figure 4). Since the computational speed of the algorithm is directly related to the number of interior points required to accurately approximate the integral, future implementations of the algorithm will scale the number of interior points according to the length of the advection vector. This will allow the naive approximation to be applied for rainfall systems which are slow moving and therefore well captured by the radar's sampling frequency while the faster moving systems will be handled in more detail; the result will be useful accumulations with the minimum necessary computation.

4. Merging of rainfall estimates

In this section, “merging” refers to the synthesis of rainfall information provided by rain gauges, radar and satellite into a single estimate of the true (and unknown) spatial rainfall field. Merging techniques allow the Hydrometeorologist to take advantage of the strengths of each instrument’s estimate of rainfall while taking cognisance of and minimizing the effect of its weaknesses. As a result the best possible estimate of the spatial rainfall field (given the available information) is obtained.

Figure 5 shows an example of combining spatial rainfall fields to provide a merged daily field. These fields were produced as a product of the Spatial Interpolation and Mapping (SIMAR) project funded by the Water Research Commission (WRC) and can be found on the internet at <http://metsys.weathersa.co.za>. The different fields are merged by weighting each according to the explained variance at each point in the spatial grid covering the country. The explained variance of a rain gauge (for example) is at it’s maximum at the gauge and the merged field converges to the rain gauge values at the gauges with the other fields being given more weight in areas where the rain gauges do not provide much information.

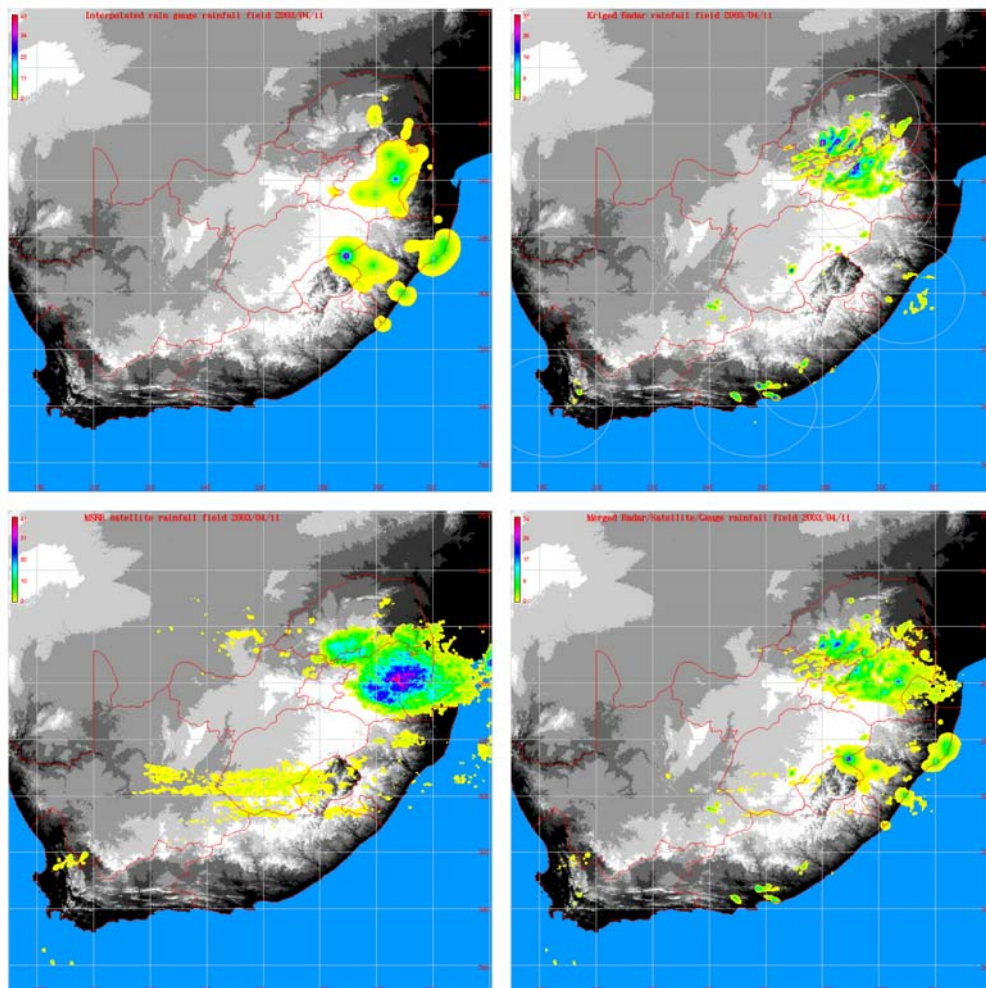


Figure 5: Individual and merged fields produced for SIMAR

The authors (under a recently completed WRC project “Umgeni Nowcasting – An integrated pilot study”) investigated the use of two newly proposed merging techniques for combining rain gauge and radar data. The techniques investigated were the Bayesian

merging technique proposed by Todini (2001) and the Conditional merging technique of Ehret (2002). A numerical experiment was carried out (over 256 km x 256 km regions) to compare the ability of each technique in reducing the bias and variance associated with radar estimates of rainfall in an objective way. Figures 6 and 7 show the results of that experiment and indicate that the conditional merging technique seems to be a good candidate for merging rainfall fields. The algorithms will need further development to include satellite data before they could be used as a possible alternative to the scheme used in SIMAR.

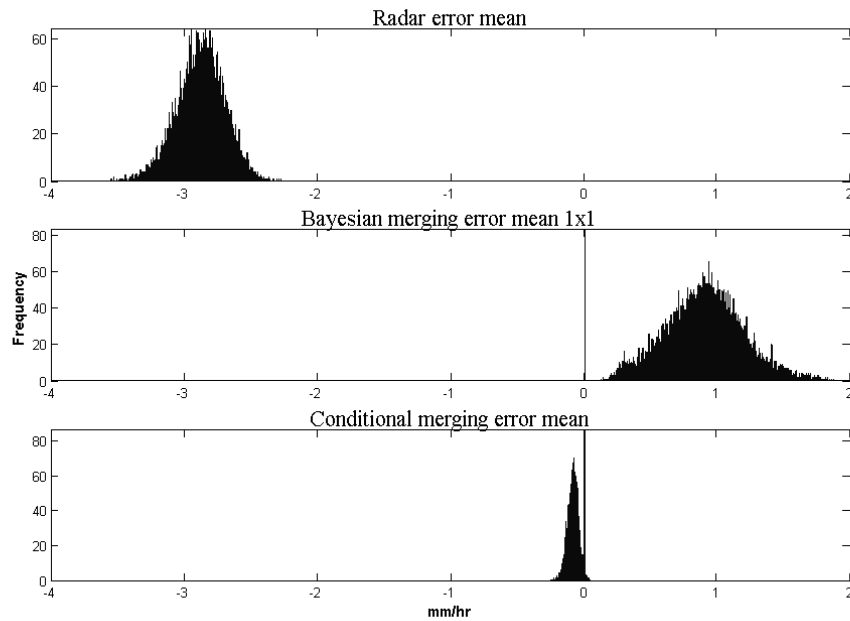


Figure 6: Reductions in mean errors from each merging technique

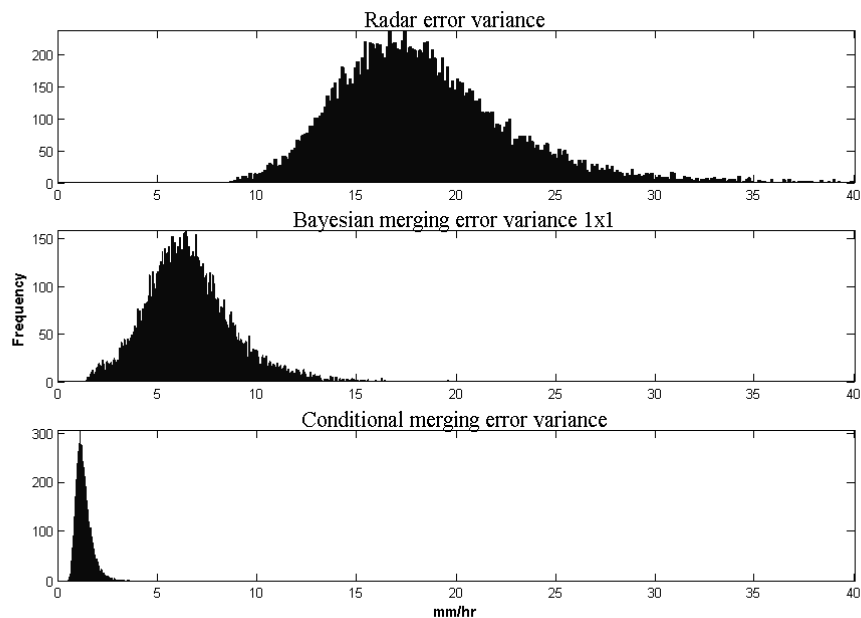


Figure 7: Variance reductions achieved by the merging techniques

5. Conclusions

This paper has described two remote sensing techniques for spatial rainfall estimation (weather radar and satellite) and compared them to the traditional tool of hydrologists, the rain gauge. An improved technique for accumulation of instantaneous rain-rate measurements has also been presented and examples of daily accumulations over the Bethlehem radar shown. Lastly, a description of merging techniques to combine each source of rainfall estimate into a single optimum field has been given with examples for daily rainfall accumulations produced as an output of the WRC funded SIMAR programme. Improved merging methods have been suggested for short timescales over targeted areas that will have application for activities such as flood forecasting and insurance assessment of claims due to storm damage.

6. References

- Bab-Hadiashar A., Suter D. and Jarvis R., 2-D Motion extraction using an image interpolation technique, *SPIE*, **2564**, 271-281, 1996
- Cracknell A. P., Remote sensing in Meteorology, Oceanography and Hydrology, *Halsted press*, Wiley, 1981
- Dooge J. C. I., Linear theory of Hydrologic systems, *Agriculture research service*, United States Department of Agriculture, Technical Bulletin No. 1468, 1973
- Ehret U., Rainfall and flood nowcasting in small catchments using weather radar, *PhD Thesis*, University of Stuttgart, 2002
- EUMETSAT, The EUMETSAT website, <http://www.eumetsat.de>, 2002.
- Grecu M., Krajewski W.F., A large-sample investigation of statistical procedures for radar-based short-term quantitative precipitation forecasting, *Journal of Hydrology*, 239, 69-84, 2000
- Hannesen R., An enhanced surface rainfall algorithm for Radar Data, *Progress report for MUSIC*, European Commission contract No. EVK1-CT-2000-00058, 2002
- Marshall J. S. and Palmer W. M., The distribution of raindrops with size, *Journal Meteorology*, **5**, 165-166, 1948
- Morales C., and Anagnostou E.N., Extending the capabilities of high-frequency rainfall estimation from geo-stationary based satellite infrared via a network of long-range lighting observations, *Journal of Hydrometeorology*, **4(2)**, 141-159, 2003
- Nagata K., Smith K. T., Nicol J. C. and Austin G. L., The effects of spatial variability on rainfall estimation, *Proceedings of the Fifth International Symposium on Hydrological Applications of Weather Radar – Radar Hydrology*, Kyoto - Japan, 2001
- Seed A.W., A dynamic and spatial scaling approach to advection forecasting, *Proceedings of the Fifth International Symposium on Hydrological Applications of Weather Radar – Radar Hydrology*, Kyoto - Japan, 2001
- Todini E., A Bayesian technique for conditioning radar precipitation estimates to rain-gauge measurements, *Hydrology and Earth System Sciences*, 5(2), 187-199, 2001.
- Wilson J.W., Brandes E.A., Radar measurement of rainfall – A summary, *Bulletin of the American Meteorological Society*, **60(9)**, 1048-1058, 1979