VIPOS: VAAL DAM CATCHMENT INTEGRATED PRECIPITATION OBSERVING SYSTEM

DE Terblanche • PJM Visser
MP Mittermaier • NJ Kroese

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VIPOS:
VAAL DAM CATCHMENT INTEGRATED PRECIPITATION OBSERVING SYSTEM

FINAL REPORT TO THE WATER RESEARCH COMMISSION FOR THE PERIOD JANUARY 1998 TO DECEMBER 2000

Deon E. Terblanche, Petrus J. M. Visser, Marion P. Mittermaier
and
Nico J. Kroese

METSYS, South African Weather Bureau,
Department of Environmental Affairs and Tourism

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INDEX

GLOSSARY OF ACRONYMS

AMF	Automatic Mains Failure
AGL	Above ground level
ARC	Agricultural Research Council
ASL	Above sea level
ATI	Area Time Integral
BPRP	Bethlehem Precipitation Research Project
CAPPI	Constant Altitude Plan Position Indicator
CIDD	Cartesian Interactive Data Display
CFAD	Contoured Frequency by Altitude Diagrams
CSIR	Council for Scientific and Industrial Research
DISPLACE	Digital Signal Processing for linear, quadratic and logarithmic responses
DSP	Digital Signal Prosessor
DVA	DISPLACE Variate Averaging
DWAF	Department of Water Affairs and Forestry
HKE	Hail Kinetic Energy
ITCZ	Intertropical Convergence Zone
LEWP	Line Echo Wave Pattern
MDS	Minimum Discernable Signal
MDV	Meteorological Data Volume
METSYS	Meteorological systems and technology section of the SAWB
MIPS	Million Instructions per Second
NCAR	National Center for Atmospheric Research
NPRP	National Precipitation Research Programme
PDF	Probability Density Function
PR	Precipitation Radar
PRF	Pulse Repetition Frequency
RDAS	Radar Data Acquisition System
RERV	Radar Estimated Rain Volume
SAWB	South African Weather Bureau
SIMAR	Spatial Interpolation and Mapping of Rainfall
SSS	Storm Severity Structure
TBR	Tipping bucket raingauge
TITAN	Thunderstorm Identification, Tracking, Analysis and Nowcasting
THKE	Total Hail Kinetic Energy
TRMM	Tropical Rainfall Measuring Mission
UPS	Uninterruptable Power Supply
UT	Universal Time
VIL	Vertically Integrated Liquid water
VIPOS	Vaal dam Integrated Precipitation Observing System
WAR	Wetted Area Ratio
WRC	Water Research Commission

EXECUTIVE SUMMARY

Apart from the use of radar information for precipitation monitoring in a quantitative sense in cloud seeding experiments in South Africa and in the work by the CSIR in the 1970s and 1980s on hail storms (and Doppler applications), the Vaal Dam catchment Integrated Precipitation Observing System (VIPOS) represents a first for South Africa. During the record floods in the Vaal Dam catchment in February 1996, the advantage of radar's high spatial and temporal resolution data under these conditions became clear. Furthermore, the comparison between the radar estimated rainfall during this event and rainfall measured by a dense raingauge network was excellent. Against the background of the dwindling number of reporting raingauges in South Africa, an opportunity was seen to develop a system that combines conventional raingauge information and modern remote sensing rainfall estimation by radar. The Vaal Dam catchment, with its high socio-economic profile, was an obvious candidate for such a system. At the inception of the project in 1998, the following aims were stated:

To develop an integrated precipitation observing system for the Vaal Dam catchment by:

- Further exploiting the capabilities of the MRL-5 dual-wavelength (S-and X-band) radar and related infrastructure at Bethlehem for refinement of the radar-based techniques for areal rainfall measurement.
- Transferring refined radar-rainfall measurement technology to other (C-band) radar installations potentially contributing to overall coverage of the Vaal Dam catchment, testing the technology and making necessary adaptations.
- Locating and calibrating other potentially useful rainfall-measuring devices in the Vaal Dam catchment and linking them, together with the radar installations, into a fully integrated precipitation observing system, specifically for hydrological applications.
- Developing appropriate software and communication systems needed to underpin the precipitation observing system and ensure operational reliability within the water resources management context.
- Design a spatial database in which data from the observing system, appropriately processed, can be stored and from which it can be withdrawn in near-real time for hydrological and modelling purposes.
- Ensuring the long-term sustainability of the observing system through the training and transfer of scientific and technical expertise.

The success of VIPOS is dependent on reliable data from the Water Research Commission's (WRC) MRL-5 S- and X-band radar at Witbanksfontein to the northeast of Bethlehem and the South African Weather Bureau's (SAWB) Enterprise C-band radar at Ermelo. The MRL-5 has since its installation in 1994 been subjected to extensive upgrades and performance testing to ensure reliable, quality data collection. Apart from these two radars, data from the Bethlehem and Irene Enterprise C-band radars also contribute towards the coverage of the Vaal Dam catchment.

One of the first steps in VIPOS was the upgrading of the SAWB Enterprise C-band radar at Ermelo with systems to ensure uninterruptable power supply and conformity in the calibration procedures and acquisition of data. During the first summer season (1997/1998) a preliminary data communication system using modems and telephone lines was implemented to ensure that radar-estimated hourly rainfall figures for the Vaal Dam catchment from both the MRL-5 and

Ermelo radars could be transmitted to Pretoria. During 1998 a considerable amount of planning went into ensuring the handling of future radar data in a manner that would support both research and real-time applications. It became obvious that a sound approach in this regard would be to use the TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting) system and its Meteorological Data Volume (MDV) data format developed by NCAR in the United States. In August 1998 Dr Mike Dixon from NCAR visited South Africa on invitation to provide training to users of the TITAN system. At that stage the Weather Bureau's Frame Relay data communication network was being implemented. It was now possible to initiate software development and implementation which utilized this communication system to transfer data from other radars to Bethlehem in the MDV format after each volume scan. During this visit, Dr Dixon also developed software that allows the merging of data from various radar systems in order to compile larger spatial rainfall fields in the MDV format. The 1998/1999 season could therefore commence with a state-of-the-art radar data communication, merging and display system that also included the generation of radar estimated rainfall fields for the quaternary catchments of the Vaal Dam. An efficient radar data archiving system formed part of these developments. Radar data and derived products are stored in a common data base that allows the same display and processing software to be used. The advantages and time savings to be gained from a well thought through data handling system when dealing with large quantities of complicated data have subsequently become apparent.

During the 1998/1999 and 1999/2000 seasons several studies were conducted to check and improve radar calibration methods, to evaluate rainfall estimation procedures and to identify key problem issues that affect the reliable collection of good quality data. In these studies data from the Liebenbergsvlei River raingauge network continued to play an important role. VIPOS also led to the development and testing of the first system in South Africa aimed at the integration of radar and rain gauge information. This system uses a new method in which the wetted area ratio is used to determine to what extent the radar rainfall fields should be adjusted by raingauge measurements.

The usefulness of daily raingauge information remains a problem in terms of its accessibility, reliability, coverage and the fact that the infrastructure is fragmented between various owners. Despite these problems, a prototype system is now in place to transfer daily raingauge data to Bethlehem where it is formatted to be compatible with radar rainfall estimation fields. VIPOS also clearly shows that radar estimated rainfall fields can be improved if adjusted by gauge measurements; however, quality of these gauge measurements is crucial, otherwise more harm than good is done through such adjustment. The existing raingauge infrastructure in South Africa needs attention at a high level to ensure quality data, a central real-time data base and the reviving of the infrastructure in areas where the coverage is no longer sufficient.

On the human resources and capacity building front the following events during the VIPOS project are significant:

- The merging of the Weather Bureau's radar scientific groups in Bethlehem and Pretoria during 1998.

- The creation during 1999 of the METSYS section within the Weather Bureau that resulted in the merging of Scientific and Technical groups at Bethlehem and Irene, creating only one entity with overall responsibility for the National Radar Network (and other electronic weather observing systems).
- The training and exposure VIPOS has given to young radar technicians and scientists and the opportunity created for close cooperation between scientists and technicians.
- The creation of data technologist posts in the Weather Bureau for electronic technicians and filling of these posts with individuals from different population groups.
- The interest generated at several South African Universities and the resulting support studies which have led to a better understanding and modelling of rainfall processes and patterns.

Other significant events included:

- The radar workshop in Pretoria at the end of 1998 where various stakeholders and potential users of the radar information were informed on the wide range of applications of this technology.
- The expansion of the MDV / TITAN radar networking system, developed as part of VIPOS, to the entire South African National Radar Network.
- The generation of products specifically for the Vaal Dam catchment and the extention of such products to the entire area covered by the National Radar Network; the making available of these products in real time on the internet (http://metsys.weathersa.co.za).
- The formation by VIPOS of the framework for new projects, including one which deals with the Caledon River (the potential application of radar rainfall estimates in hydro-electrical power generation) and the Spatial Interpolation and Mapping of Rainfall (SIMAR) programme, which is the new WRC umbrella programme having the ultimate aim to produce integrated radar/satellite/gauge derived rainfall fields for the whole of South Africa.

VIPOS achieved most of its aims and even exceeded these in terms of developing and implementing systems for the merging of data from all eleven radars in the National Radar Network. Although VIPOS did not succeed fully in delivering an operational system which integrates radar and gauge measurements in real-time, many of the components for such a system are in place and will be utilised by the Spatial Interpolation and MApping of Rainfall (SIMAR) project.

Issues that still require much work include the complex business of ensuring the quality and reliability of radar data within the context of a radar network. During the VIPOS project there were still periods of obvious data quality problems. Another issue that will have to receive urgent attention is the financial support available to maintain the national radar systems and improve their reliability; during the 2000/2001 financial year to less than 10% of the budget needed to operate this infrastructure in a professional and sustainable manner could be provided by the State. The applications of the National Radar Network and the systems developed as part of this project extend much further than water resources operations and research. This network is crucial to nowcasting of weather events, severe weather warnings, weather-related disaster mitigation, agriculture and the aviation sector. The project team ins convinced that the additional investment required to operate this network in a sustainable manner and expand it to crucial areas still not covered sufficiently, would be warranted.

The project team acknowledges the valuable support of the WRC and the SAWB in this project, which is the first in South Africa to produce radar-based products to a wide community of users in real time through the internet.

1. INTRODUCTION

Against the background of the dwindling conventional meteorological infrastructure over South Africa, new remote sensing technologies such as weather radar are of central importance. Radar's potential applications in hydrometeorology need to be capitalised on to ensure the sustainable monitoring and utilization of one of our scarce resources, namely water. In the context of the new Water Law, where great emphasis is placed on processes within catchment scale, the need to refine the spatial and temporal scale of rainfall measurements has becomes obvious. Furthermore, the bulk of the natural disasters in South Africa are weather related, many of which coincide with extremes of rainfall or the lack thereof. Previous weather radar research in South Africa has clearly shown the potential value of this technology. It is against the above background that VIPOS was initiated to lay the foundation of a proper framework in which to extend the radar research and development work in South Africa to real-time applications of value to the wider hydrometeorological audience.

The weather radar infrastructure in South Africa represents a capital replacement value of approximately R100 million Rand. The Water Research Commission (WRC) owns a dual-wavelength (S- and X-band) MRL-5 radar situated close to Bethlehem. The South African Weather Bureau (SAWB) operates nine Enterprise C-band radars of various ages; at Bethlehem, Irene, Ermelo, Bloemfontein, De Aar, Durban, East London, Port Elizabeth and Cape Town. Towards the end of the winter of 2000 another Enterprise C-band, that was in storage, was being prepared for installation at Pietersburg International Airport (Gateway). This radar will apart from supporting future rainfall enhancement studies in the Northern Province also expand the coverage of the National Radar Network to this province. Figure 1 shows the coverage of the National Radar Network at 200 km range. Also shown in this figure is the Vaal Dam catchment, clearly indicating those radars that are important in its coverage.

Successfully operating an extensive radar network to its full potential is no trivial matter with only a few of the developed countries of the world having accomplished this successfully. It is probably not surprising that South Africa has, especially prior to 1998, not been successful in optimizing the uses of its radar infrastructure for real-time applications. World-class radar related research and development work was, however, done in our country over a number of years utilizing data from individual radars. Prior to 1990 the CSIR, CloudQuest and the Bethlehem Precipitation Research Project (BPRP) (now part of METSYS) all contributed, using radar as a research tool, to a better understanding of storms and their characteristics. However, the hydrological applications of radar only started to receive attention in the 1990's after the formation of the National Precipitation Research Programme (NPRP), the success of the hygroscopic-flare cloud-seeding technique for rainfall enhancement and the arrival of the WRC's MRL-5 radar. The role radar could play in hydrological applications was probably best illustrated during the February 1996 floods in the Vaal Dam catchment. During this week-long rain event the radar-rainfall measurements were communicated to the Flood Control Centre of The Department of Water Affairs and Forestry (DWAF) on a regular basis. The comparison of radar rainfall measurements to those from a network of 45 gauges in the 4500 km^2 Liebenbergsvlei catchment came to within 3 % during this event (Mather et al., 1997).

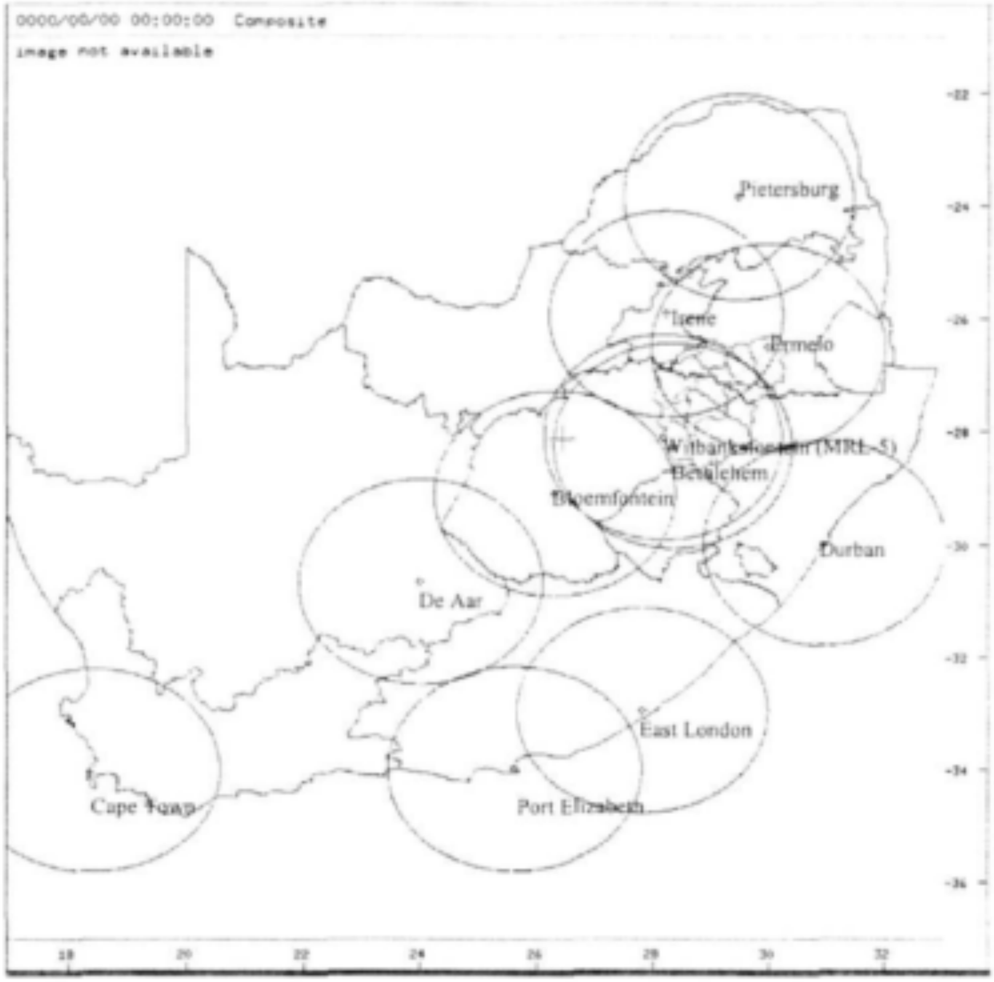


Figure 1. Coverage of the National Radar Network at 200 km range and the Vaal Dam catchment.

VIPOS (Vaal Dam Integrated Precipitation Observing System) is an attempt to extend these achievements and to accomplish the networking of radars on a regional scale in a manner that will address several potential real-time applications of radar data in South Africa. From its inception, planning within VIPOS was done to ensure that the methods developed and employed would be a prototype for other areas and/or the National Radar Network as a whole. Although the emphasis for VIPOS is on hydrological applications, including flood management within the Vaal Dam catchment, consideration is given to the meteorological and other potential uses of the data, which are addressed at the same time. VIPOS builds strongly on the radar related achievements and developments from the National Precipitation Research Programme which came to an end in 1997. These include further refinements and applications of:

- The in-house developed Radar Data Acquisitioning System (RDAS) consisting of hardware and software for radar antenna control, signal processing, data storage and simplifying radar calibrations (Terblanche et al., 1994). RDAS is a well proven system already in use on more than 30 radars in seven countries outside South Africa.

- The software using the DISPLACE processing technique for signal processing (Terblanche, 1996) and converting data from spherical coordinates into Cartesian coordinates (Mittermaier and Terblanche, 1997).

- The Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN) and related software developed by Dixon and Wiener (1993) and introduced to South Africa in 1995. TITAN is a modernised and real-time system based on software developed by Dixon and Mather (1986) as part of the rainfall enhancement experiments.

- Further strengthening and combining radar related scientific and technical experience and knowhow in South Africa.

The aims of VIPOS were formally stated as follows:

To develop an integrated precipitation observing system for the Vaal Dam catchment by:

- Further exploiting the capabilities of the MRL-5 dual-wavelength (S-and X-band) radar and related infrastructure at Bethlehem for refinement of the radar-based techniques for areal rainfall measurement.

- Transferring refined radar-rainfall measurement technology to other (C-band) radar installations potentially contributing to overall coverage of the Vaal Dam catchment, testing the technology and making necessary adaptations.

- Locating and calibrating other potentially useful rainfall-measuring devices in the Vaal Dam catchment and linking them, together with the radar installations, into a fully integrated precipitation observing system, specifically for hydrological applications.

- Developing appropriate software and communication systems needed to underpin the precipitation observing system and ensure operational reliability within the water resources management context.

- Design a spatial database in which data from the observing system, appropriately processed, can be stored and from which it can be withdrawn in near-real time for hydrological and modelling purposes.

- Ensuring the long-term sustainability of the observing system through the training and transfer of scientific and technical expertise.

2. PERSONNEL AND STRUCTURAL CHANGES

The VIPOS team consists of a group of Weather Bureau personnel (initially only from the BPRP) and a small separate "radar group" attached to the Weather Bureau's research section in Pretoria) working in close cooperation with contracted individuals and companies at Bethlehem. This group has built up a productive working relationship over more than a decade.

Internal re-organization within the SAWB in Pretoria in 1998 resulted in the disbanding of the "radar group" in the research section in Pretoria and the administrative transfer to the BPRP of the members of that group with the exception of Frank Adam, who joined the new Weather Forecasting Research group where, we trust, he will continue to play an important role in introducing products emerging from VIPOS to the SAWB's forecasters. Pieter Visser moved to Bethlehem early in 1999 and, apart from contributions to VIPOS, will make important contributions to radar meteorology in general. Frik Stuart joined the previous "radar group" in 1997 and gained wide experience in the use and software manipulation of radar data. The main thrust of his work was satellite-related under the guidance of Prof Pegram, utilizing the same data structures and display methods as that for radar data. Aspects of his work will be integrated in future remote sensing programmes. He was stationed in Pretoria until he left the Weather Bureau in 1999.

Nico Mienie joined the BPRP at the beginning of 1998 as part of VIPOS, specifically to be trained by Dennis Dicks of the contracted company Meteorological and Radar Technology (MRT) and Farren Hiscutt of the contracted company Electronic Systems Development (ESD), in the technical aspects of radar maintenance and upgrading. He has made good progress and received exposure and training on a wide range of radars (MRL-5, Enterprise and Pacer) and radar related issues. Since the beginning of 2000 Dennis Dicks, who now lives in Durban has only been called out to Bethlehem for specific issues to assist Nico Mienie who deals independently with the normal day-to-day maintenance and repairs of the radars and related systems. At the start of VIPOS one of the central concerns were the small number of experienced weather radar technicians in South Africa. This issue has been partially overcome through the formation of the METSYS section within the Weather Bureau during 1999. This is a major and important move within the Weather Bureau. Apart from combining the human resources from Bethlehem and Irene under one banner, a concerted effort was launched to attract new technical personnel to the section. This exercise was successful, primarily due to the creation of new salary structures that competed more realistically with the outside market. At the same time members of the previously disadvantaged groups were also appointed and a new era of close interaction between scientists and technicians has started. If anything, the human resources shortage issue has now moved from the technical towards the scientific side!

Apart from the loss of Frik Stuart, Marion Mittermaier left the Weather Bureau in September 2000 on unpaid leave to further her studies at Bracknell in the United Kingdom. At about the same time Izak Deyzel, previously from the Weather Bureau's Climate Section joined the group at Bethlehem. His main focus will be on satellite product development, as we believe that this technology, especially in the light of the Meteosat Second Generation to be launched later in 2000 will play an increasingly important role in complementing radar information.

Karel de Waal is continuing to play a central role in the development and maintenance of software and in the complex task of manipulating and archiving the large quantities of information resulting from this project and that from the National Radar Network as a whole. Deon Terblanche has been appointed as scientific manager of the METSYS section and Nico Kroese and Flip Pretorius are the administrative heads of the offices at Bethlehem and Irene.

During 2000 the additional pressures due to the agentization process of the SAWB could also be clearly felt within METSYS. In the preparation for this new dispensation the administrative load, on especially on the scientific component of METSYS has increased, but it is hoped that this will only be temporary.

The changes in the personnel situation and structure have in general been positive. It is believed that VIPOS played an important role in initiating some of these changes and placing radar meteorology on a much sounder footing in South Africa.

3. RADAR PRECIPITATION ESTIMATIONS

3.1 INFRASTRUCTURE

The Vaal Dam catchment is located on the eastern Highveld and includes parts of the Free State and Mpumalanga. The radar systems contributing to coverage over this catchment are the WRC's MRL-5 S- and X-band radar and the Weather Bureau's Enterprise C-band radars at Ermelo, Bethlehem and Irene. The MRL-5 and Ermelo radars are the most important. Figure 2 show the Vaal Dam quaternary catchments and the coverage of the various relevant radar systems.

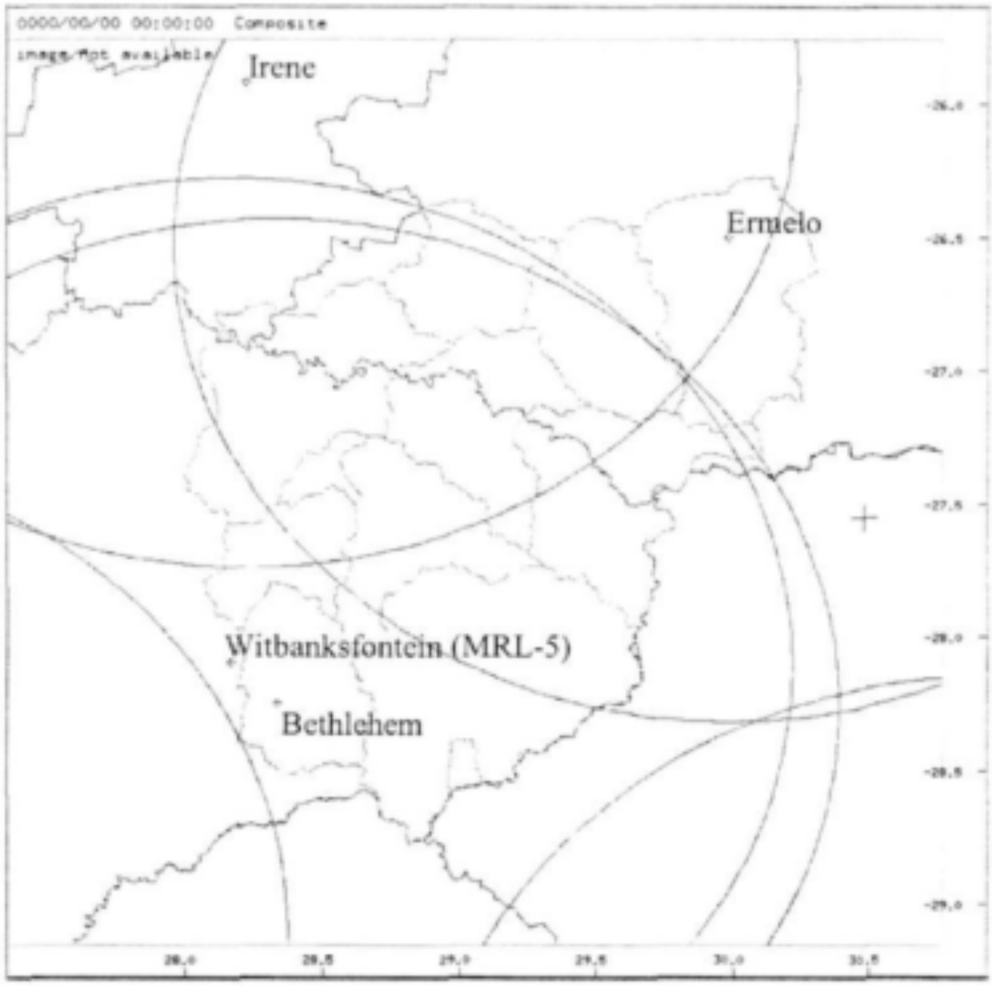


Figure 2. The Vaal Dam quaternary catchments and the sites and coverage of the MRL-5, Ermelo, Bethlehem and Irene radars (coverage of the Durban and Bloemfontein radars are shown in the southeastern and southwestern corners of the map).

3.1.1 Data acquisitioning and processing

- *Radar data Acquisition System - RDAS*

The in-house developed Radar Data Acquisition System (RDAS), was first tested and installed on the Bethlehem Enterprise C-band radar (Terblanche et.al., 1994) in 1993, and after the necessary upgrades to accommodate data collection from both receivers, on the MRL-5 in 1994. This system consists of software and hardware running under DOS on a PC. Apart from digitizing the received signal at a rate of up to 10^6 Hz and the necessary averaging to reduce the large inherent variance of weather signals, this system also controls the antenna in a pre-programmed manner to do volume scanning. During 1995 and 1996 the DISPLACE processing algorithm was developed by Terblanche (1996a and 1996b) and implemented on RDAS for both the Bethlehem C-band and MRL-5 radars. The algorithm is a simple, time efficient signal processing technique that accomplishes pair-wise averaging of the logarithmic receiver output in a manner that simulates averages as if obtained from a quadratic receiver. This produces unbiassed power averages from weather signals making average bias corrections unnecessary and avoiding the large underestimations in received power (and rainfall estimates) that can occur in areas of steep reflectivity gradients typical of thunderstorms. Early in 1997 a major upgrade and redesign of the hardware of RDAS was completed to include software to assist during the receiver calibration procedures and to include the DISPLACE algorithm for signal processing from the radar's logarithmic receiver output as an integral part. In-house this version of RDAS is known as Version 4. RDAS outputs receiver calibration information and processed digitised information per radial to EXABYTE tape or via sockets to other computer systems.

- *Converting radar data from Spherical to Cartesian coordinates*

In order to transform the spherical data referenced to the radar site to a Cartesian coordinate system, Mittermaier and Terblanche (1997) developed software using a further development of the DISPLACE algorithm - the Displace Variate Averaging (DVA) technique. DVA was also designed to output radar information in the Meteorological Data Volume (MDV) format which conforms to the basic data and product structure of the Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN) system.

The "radar group" in Pretoria developed an interim system for merging radar data from the MRL-5 and Ermelo radars for the 1997/98 season. This was done before the SAWB's new Wide Area Network (WAN) become a reality during late winter of 1998. The development of the interim system was no small accomplishment as Pieter Visser, Frikkie Stuart and Frank Adam even had to develop a modem communication system to down load rainfall fields from Ermelo to Pretoria once an hour. The hourly rainfall field from the MRL-5 was sent to Pretoria via the network. The "radar group" acquired valuable experience in creating images on the web and using masks to extract sub-catchment rainfalls. The Vaal Dam catchment was demarcated into six "quaternary" catchments by the Department of Water Affairs and Forestry (DWAF) and the hourly (and 24-hour) sub-catchment rainfall figures were displayed on a rainfall field and made available on the Weather Bureau's web page.

- *Thunderstorm Identification, Tracking, Analysis and Nowcasting - TITAN*

There has been close contact between the BPRP and Dr Dixon, of the National Center for Atmospheric Research (NCAR) in the USA, over the eight years since the formation of the National Precipitation Research Programme (NPRP). This cooperation included the use of his original storm tracking and analysis software for all the analyses of the NPRP cloud seeding experiments (Dixon and Mather, 1986; Mather et al., 1997), the local introduction of his Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN) system (Dixon and

Wiener, 1993) within the NPRP during 1995 and the involvement of South Africans in the overseas installation of the RDAS and TITAN systems. The TITAN system and its supporting MDV data format has already become an integral part of rainfall enhancement research and operations in South Africa. The MDV data system is central to TITAN, its display system called RVIEW as well as other display systems. Of major importance for users is the fact that satellite data, model output, lightning position data and other gridded data can be converted into this format and displayed individually or as overlays using common display systems, including GIS. Non-gridded data (point measurements, aircraft positions etc.) can converted to an SPDB (Symbolic Product Data Base) format which is compatible with the rest of the system.

During Deon Terblanche's visit to NCAR in June 1998 planning of a workshop, to be held in South Africa, to address the development of a "MDV-based" networking system took place. A framework for developing a comprehensive networking system for South Africa was drawn up in such a way that the local VIPOS team members would take part in the system's design, be familiar with its components and capable of implementing and expanding it in the future. Obviously an MDV-based system would result in South Africa being part of a growing group of users and benefiting from a system that is continuously refined by some of the leading experts in the world, facilitating the exchange of data and information between researchers around the world.

During the period 3 to 14 August 1998 Dr Mike Dixon visited the project at Bethlehem and hosted the planned training workshop for members of the project and the Centre for Applied Statistics of UNISA. At the same time he was involved with the development of an inclusive radar system for South Africa and he specifically addressed the radar data processing, communication, merging and display needs of VIPOS. Prof Steffens was involved for the first three days, Lizelle Fletcher for the second and third day and Pieter Visser, Frikkie Stuart and Frank Adam for the first ten days.

The workshop was a success and the limited time was optimally used. This was in no small measure due to the professional guidance provided by Dr Dixon and the hard work and commitment of all involved.

The achievements of the workshop also related directly to the South African Rainfall Enhancement Programme (SAREP), concerning the storm-based analysis of operational rainfall enhancement projects. This was reported on in the internal SAREP progress report that became available in March 2000 (Terblanche and Mittermaier, 2000). The storm-analysis research tools have wider applications than those related to SAREP and include compiling storm climatologies and doing detail case studies on specific storm events.

- *The MDV-based radar networking system*

Figure 3 is a schematic diagram of the complete "MDV-based" radar system for South Africa that was designed during the workshop. This system provides data for operational and research applications and can be run in real time or retrospectively. In block A of this diagram the system at each radar site is shown. It consist of RDAS connected to the radar (for radar antenna control and signal processing, compiling volume-scan spherical data in 18 elevation steps, each per degree azimuth in 224 range bins, each 900 m long between the radar and 201.6 km in < 5 minute intervals) and the DVA system that generates MDV files (converting spherical radar data received from RDAS into Cartesian coordinates in a 1 km grid referenced to sea level, applying ground clutter removal (where necessary) using a clutter map and exporting the compressed reflectivity MDV files via the network to one or more remote computers). This system requires a PC (≥486, 8 MB RAM) for RDAS and a Pentium (200 MHz, 64 MB RAM)for the MDV generating system. Both these systems are South African developments, with the MDV generating system's code optimized, automated and re-organized by Dr Dixon to conform with established standards.

In block B of this diagram the system at Bethlehem is shown. This diagram includes processes that have not been implemented operationally but these are not central to the aims of VIPOS. In block B of the diagram the MDV files received from (local and) remote radars via the network are written into sub-directories from which the program *MdvMerge* creates merged reflectivity MDV files at specifiable time intervals in a specified latitude-longitude grid. The utility *MdvMerge*, written by Dr Dixon during his visit, can accommodate a network of radars and has been implemented to run on all the radars in the National Radar Network.

During the workshop Dr Dixon also assisted Pieter Visser and Frikkie Stuart in writing software to read and write MDV files and manipulate the data fields. Before leaving the workshop they were in the position to convert and dispay satellite data in MDV files and create MDV files containing the Storm Severity Structure (SSS) fields that Pieter Visser had developed as part of his MSc dissertation (Visser, 1999). Copies of this software were provided to Dr Dixon for potential use by NCAR.

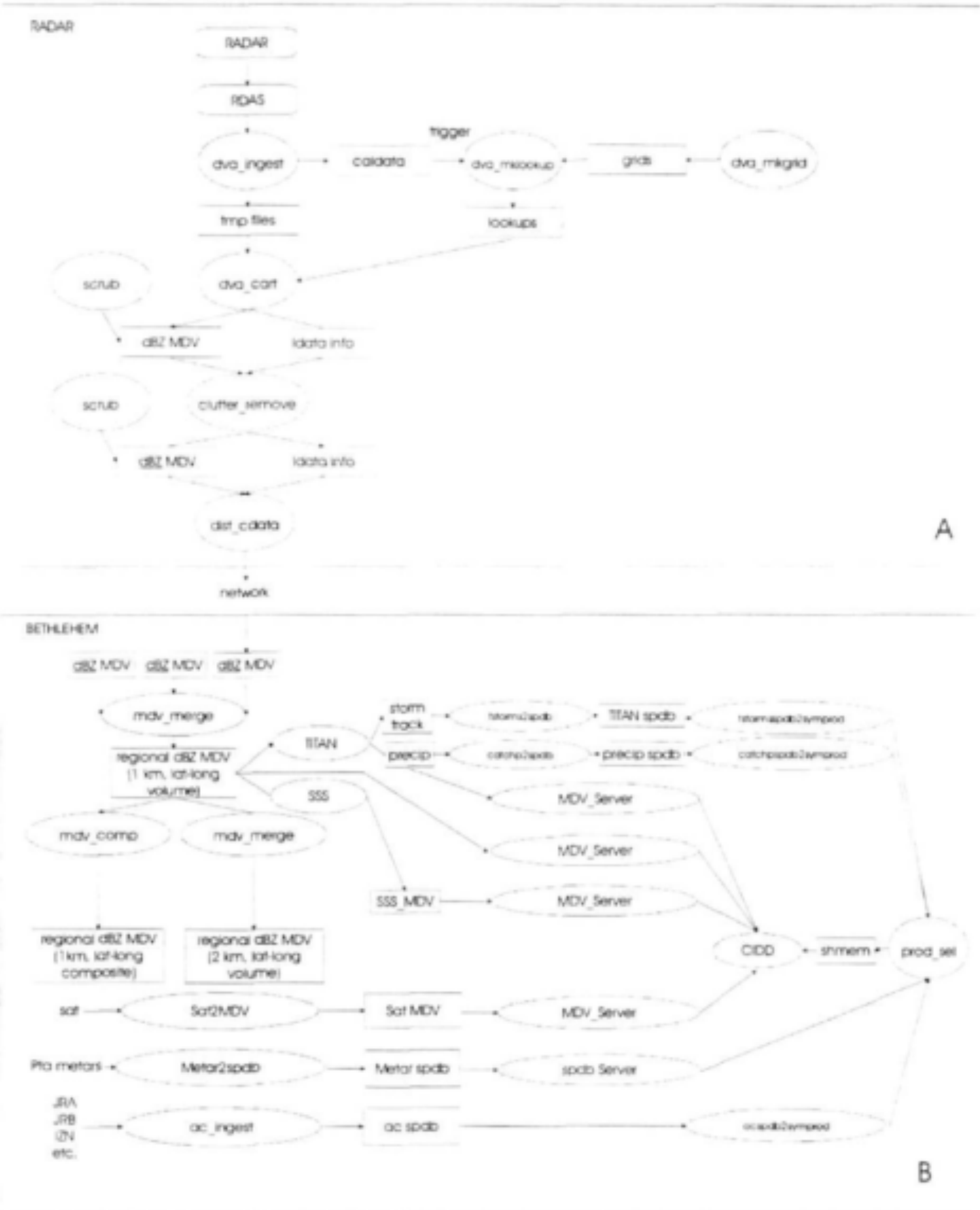


Figure 3. Schematic diagram of the MDV-based weather radar system.

The merged reflectivity MDV files from *MdvMerge* form the basis for several products and displays. TITAN tracks storms and computes the various storm and track properties, Vertically Integrated Liquid water (VIL) and precipitation accumulations over various time intervals from these files (as needed for VIPOS, flash flood warnings, rainfall enhancement research and operations, short term weather warnings and air traffic control). Pieter Visser also calculates SSS fields (short term weather warnings etc.) from these fields.

Dr Dixon, furthermore, also introduced the team to Cartesian Interactive Data Display (CIDD) system and the team got accustomed to using and configuring the system for displaying the various fields which can be generated. These displays include overlays and movie loops of satellite MDV files, merged reflectivity MDV files using *MdvMerge* on MRL-5, Bethlehem and Ermelo radar data, SSS fields, and TITAN generated precipitation accumulations and VIL fields as well as storm positions and forecast movement. Various combinations of overlays and background maps can be used. The movie loop option is ideal for the ultimate use at radar sites, weather offices etc.

3.1.2 The MRL-5 radar

- *Radar hardware*

At the start of VIPOS the MRL-5 dual-wavelength (S-and X-band) radar situated near Bethlehem had previously been operated over three summer seasons and a number of modifications had been effected to the radar to improve its performance and reliability. Antenna gains, beamwidth patterns and wave guide losses had been determined, to facilitate accurate calibration of the radar, with particular attention being given to the pointing accuracy of the antenna. The MRL-5 dual-wavelength radar, its characteristics and the upgrades performed to it have been described in some detail by Mather et al. (1997). At this point, with the radar having proven its reliability, it was decided that attention should be given to improving the sensitivity of both channels by installing low noise amplifiers. A amplifier installed in the X-band brought about an improvement in system sensitivity by some five dB. This sensitivity, together with the use of the 4.5 m antenna of the radar, resulted in a 49 dB gain and a beamwidth of 0.5 degree. This increases the ability to observe intensities of reflectivity from -20 dBZ at 10 km range to 0 dBZ at a distance of 100 km from the radar (See Figures 4 and 5 for typical calibration information on the S-and X-band). This, it is hoped, will allow the observing of clear air phenomena such as lines of conversion which are indicative of the onset of storm development. These data will shed light on areas of convergence, thunderstorm outflow and boundary layer fronts, like those often experienced over the northeastern Free State towards evening, which result in a marked drop in temperature and can trigger severe thunderstorms. This will open up new opportunities for atmospheric researchers and forecasters in South Africa and go a long way in compensating for the inherent limit on low noise figures at S-band and the lack of Doppler facilities on the MRL-5.

The BPRP was fortunate in acquiring a WSR-74 S-band radar transmitter and receiver unit which was scrapped from the USA National Weather Service and donated to the SAWB to be used as a source of spares. This radar was overhauled and then integrated into the MRL-5 S-band radar system and is now used as the primary radar with the Russian unit as standby, since the WSR-74 radar affords far easier maintenance and requires less attention. However, one problem with the WSR-74 is the exorbitant cost of replacing of the magnetron if it should fail in future. Funds should be found to acquire a spare magnetron.

Synchronizing the Enterprise S-band and the Russian X-band transmitter-receivers, using the standard MRL-5 timing circuitry, and supplying RDAS with a trigger with the correct timing, also received attention during 1998.

- *Data processing*

The MRL-5 radar was upgraded to version 4 of RDAS during 1997 and in August 1998 the upgraded DVA software was also introduced at the site.

Investigations into the option of increasing the Pulse Repetition Frequency (PRF) from 250 s^{-1} to 500 s^{-1} were also done. On the MRL-5 radar, with its dual transmitter-receivers, this results in 4-times the processing load on RDAS compared to a single channel radar operating at a PRF of 250 s^{-1}. Initial tests in this regard have been encouraging after replacing the 33 MIPS DSP chip on the card with a pin-compatible 40 MIPS chip.

An algorithm to compensate for the small deviations between the true calibration curve and the least square regression line fitted to the curve has also been developed but still needs to be implemented on RDAS. This correction will improve the accuracy of reflectivity measurements towards the lower end of the calibration curve as the Minimum Detectable Signal (MDS) of the receiver is approached. In previous studies (Mather et al., 1997; Terblanche 1996b) the importance of accurate measurements at these lower rain rates (in terms of the area covered and the rain rate themselves) during flood producing general rain conditions was shown.

- *Example of calibration information*

WITBANKSFONTEIN
MRL5_SE
1. 0
2. 74
3. 146
4. 2789
5. 342
6. -53
7. -98
8. 84
9. -171.16
10. 0.012
11. 25
12. 1.500000
13. 224
14. 8
15. 0
16. 4
17. 0

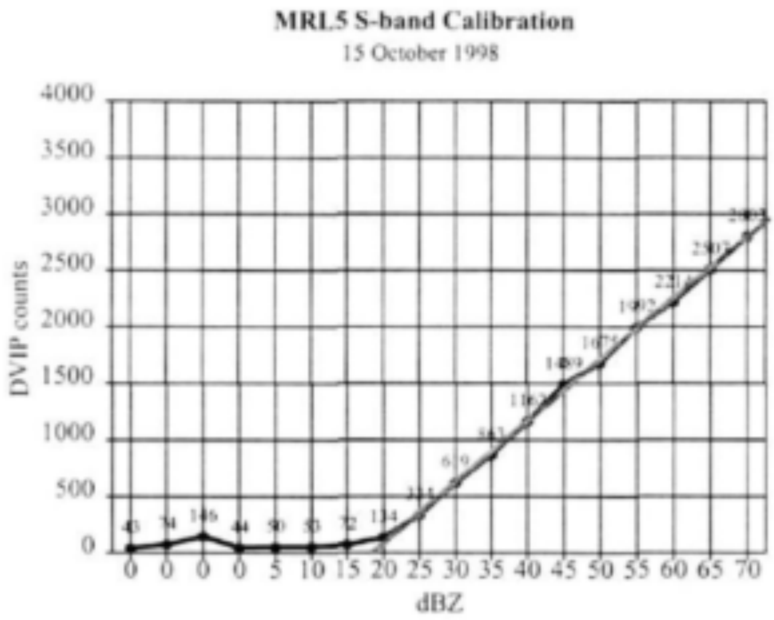


Figure 4. Example of the calibration curve for the MRL-5 S-band radar (Enterprise transmitter-receiver) relating reflectivity (in dBZ at 100 km) to digitised output from RDAS. Also shown is the file containing the calibration information as produced by RDAS during calibrations and subsequently used for data processing. The variables in the file are as follows:

1. Data storage medium (none, Exabyte, disk)
2. Minimum Detectable Signal (MDS)
3. Minimum Usable Signal (MUS)
4. RVPC high level (digitized output)
5. RVPC low level (digitized output)
6. Power high level (dBm)
7. Power low level (dBm)
8. Peak transmitter power (dBm)
9. Radar constant (dB)
10. 2-way atmospheric attenuation
11. Radar site #
12. Sample rate (µs)
13. # of bins
14. Time-azimuth averaging factor
15. Skip samples
16. Range averaging factor
17. Clutter filter on/off

WITBANKSFONTEIN
MRL5_X
1. 0
2. 76
3. 130
4. 2801
5. 469
6. -40
7. -95
8. 83
9. -150.96
10. 0.024
11. 1
12. 1.500000
13. 224
14. 8
15. 0
16. 4
17. 0

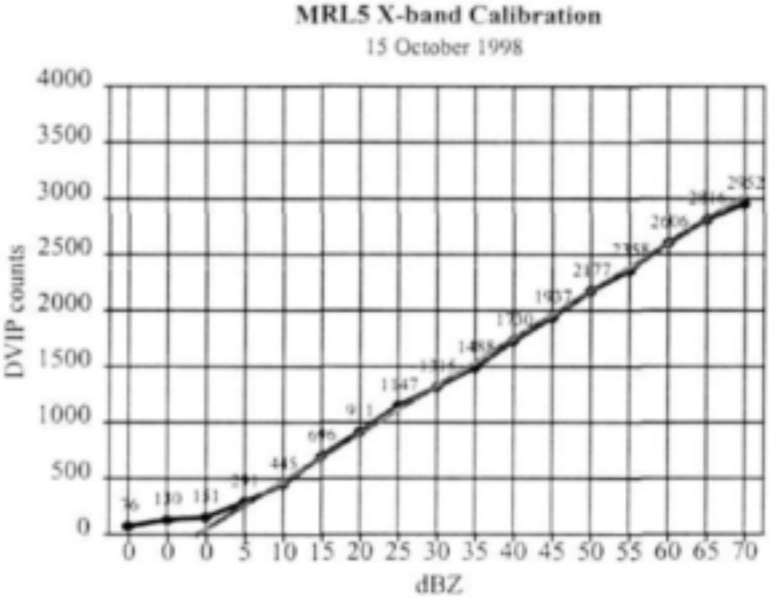


Figure 5. As in Figure 4 but for MRL-5 X-band radar.

At the start of VIPOS in 1998 these systems were in use on the MRL-5 and Bethlehem Enterprise radars and well proven. The challenge was to duplicate, upgrade and customize the various components of this system for use on other radars systems in order to achieve the coverage necessary for the Vaal Dam catchment.

3.1.3 The Ermelo C-band radar

- *Radar hardware*

The Ermelo C-band Enterprise radar is the same WSR-81 model as the Enterprise C-band radar at Bethlehem (Terblanche et al., 1994), except that a low-noise receiver was installed by the CSIR prior to it being bought second hand by the Weather Bureau. The radar had also previously been modified and used as a Doppler radar in the service of the CSIR and needed to be converted back to a conventional reflectivity measuring radar. These tasks were duly accomplished early in the project and with the usual routine alignments and calibration including the antenna pointing accuracy confirmed, the radar was placed into service at the beginning of the 1997/1998 summer. This radar is run almost continually, or at least for extended periods of time, throughout the summer seasons. For this reason, the emphasis on reliability cannot be emphasized enough. To date the only major failure to this radar has been the failure of the azimuth bearings, a known weakness of that specific model of Enterprise radar. A prototype modification has been made to the bearing system of the Ermelo antenna pedestal and installed in the another ex-CSIR radar, subsequently deployed at Pietersburg in October 2000. That radar's pedestal, which was hardly used, is now used in Ermelo but already suffered bearing problems in October 2000. It will be upgraded during the 2001 winter after the project team has verified that the prototype modification is successful.

Beam blocking by obstacles was also examined and found to be much less than that experienced with the Enterprise radar in Bethlehem. Figure 6 shows the beam blocking as a function of azimuth and elevation.

- *Data processing*

The Ermelo radar was upgraded to version 4 of RDAS for antenna control and data acquisitioning during the winter of 1997 in anticipation of the VIPOS project and as to facilitate data collection during the rainfall season from October 1997. This was a straight-forward exercise because of the previous version of RDAS already being in place in this radar and the similarity of this radar to the Enterprise at Bethlehem, used as the development platform for RDAS. During September 1998 the system used to convert radar data from spherical coordinates to Cartesian coordinates during the 1997/98 season was replaced with the DISPLACE variate averaging (DVA) system developed by Mittermaier and Terblanche (1997) and which now forms an integral part of the MDV-based system (see Section 3.1.1).

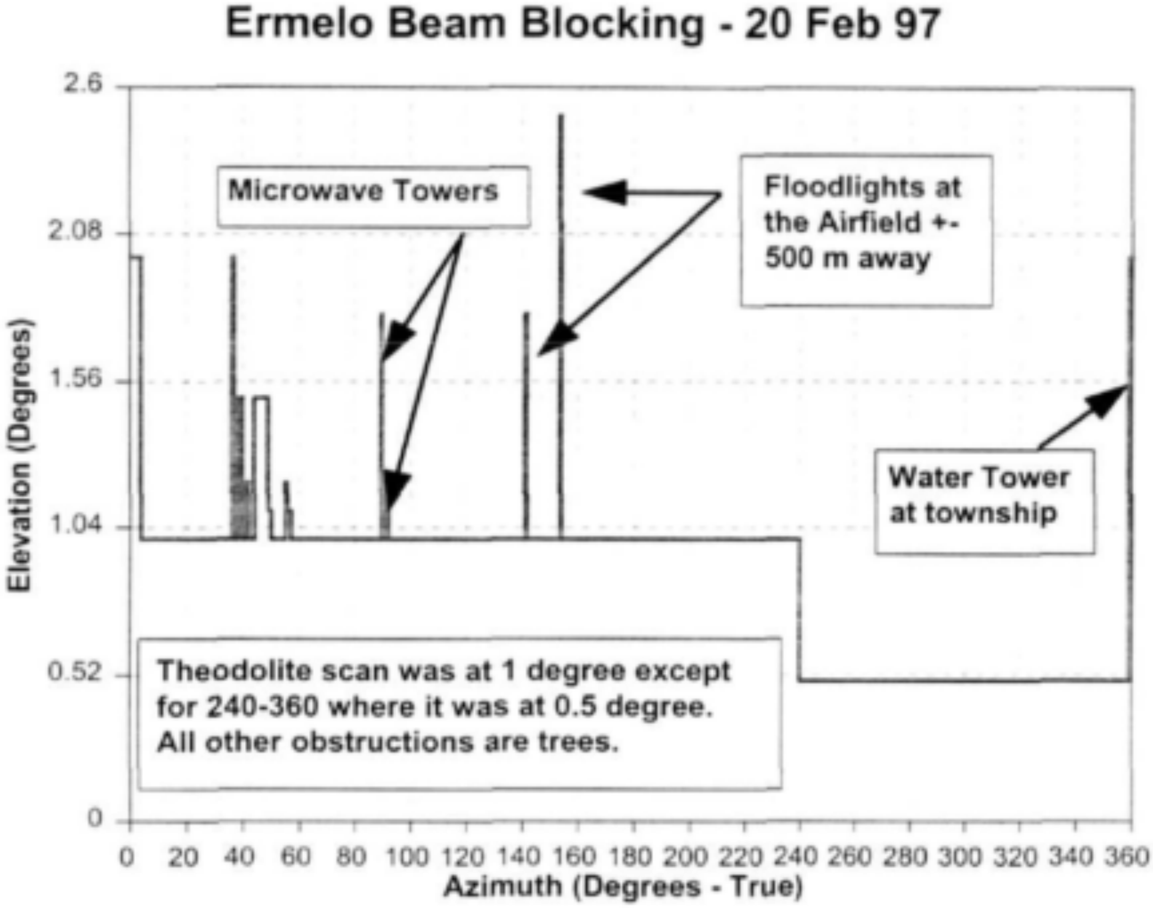


Figure 6. Beam-blocking at the Ermelo radar.

- *Example of calibration information*

ERMELO
ENTERPRISE
1. 0
2. 110
3. 134
4. 2676
5. 642
6. -45
7. -95
8. 85
9. -153.96
10. 0.014
11. 10
12. 1.000000
13. 224
14. 8
15. 0
16. 4
17. 0

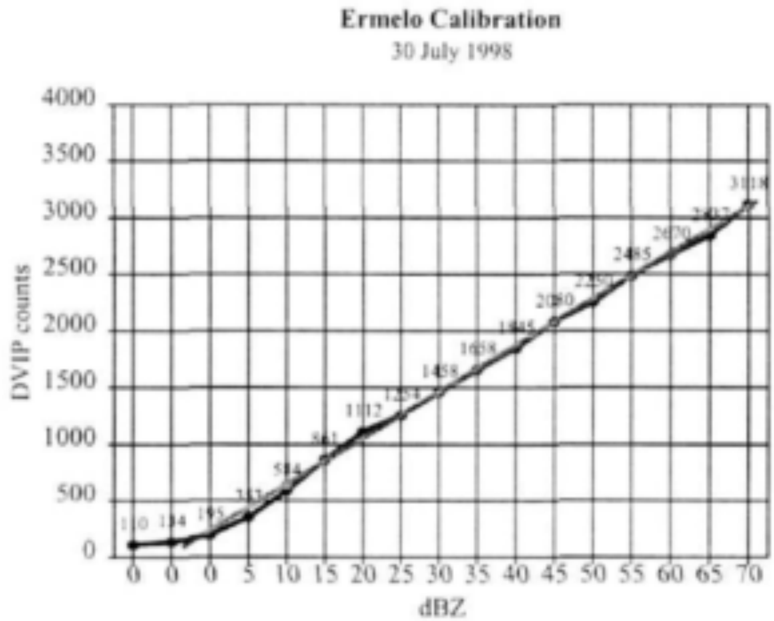


Figure 7. As in Figure 4 but for the Ermelo C-band radar.

3.1.4 The Bethlehem C-band radar

- *Radar hardware*

The BETHLEHEM C-band radar continues to play a role in the radar network as a backup to the MRL-5 radar and as a valuable and accessible unit in the training of radar personnel. It's secondary role stems from the siting of the radar which causes rather severe beam blockage in a number of areas, and the fact that the S-band frequency of the MRL-5 is superior in the penetration through precipitation than that of the C-band frequency. During the past year the only major problem encountered was failure of the azimuth bearings.

- *Data processing*

Version 4 of RDAS was first introduced to this radar in February/March 1997 and the radar is continuously used in tests and upgrades to RDAS.

- *Example of calibration information*

BETHLEHEM
ENTERPRISE
1. 0
2. 56
3. 71
4. 2619
5. 277
6. -42
7. -92
8. 84
9. -154.96
10. 0.014
11. 1
12. 1.00000
13. 224
14. 8
15. 0
16. 4
17. 0

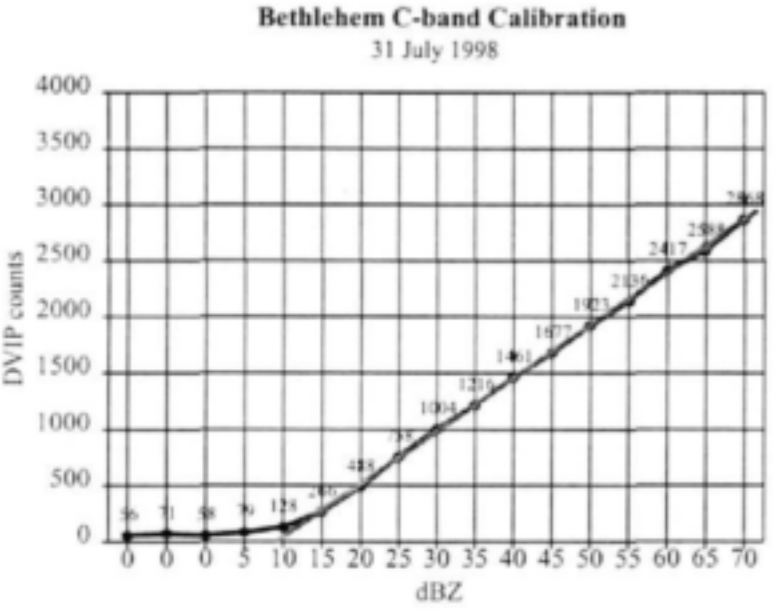


Figure 8. As in Figure 4 but for the Bethlehem C-band radar.

3.1.5 The Irene C-band radar

- *Radar hardware*

The Irene Enterprise C-band radar is the most modern radar in South Africa, being a 1993 model. It is also the only radar with Doppler capabilities contributing to the coverage of the Vaal Dam catchment. The Doppler capabilities are not used at present and do not have relevance to VIPOS. Of great importance is that during the VIPOS project period, the copper wire data communication links to Irene, that have always been unstable and susceptible to lightning damage, were successfully upgraded to microwave technology. The frequent interruptions to the electricity supply of this radar were also addressed by the installation of a uninterruptable power supply (UPS). Through close interaction between the scientific and technical components of the METSYS section, performance evaluation and testing of the radar continued into 2000. By the start of the 2000/2001 summer season this radar delivered data of a high quality.

- *Data processing*

Version 4 of RDAS was first introduced to this radar during 1998 and the systems installed for data transfer to Bethlehem. Due to its location this radar is of paramount importance and additional systems were installed to provide TITAN display systems in the Central Forecasting Office in Pretoria, as well as at the Weather Office at Johannesburg International Airport.

- *Example of calibration information*

IRENE
ENTERPRISE
1. 0
2. 59
3. 80
4. 2761
5. 146
6. -46
7. -106
8. 84
9. -158.96
10. 0.014
11. 5
12. 1.500000
13. 224
14. 8
15. 0
16. 4
17. 0

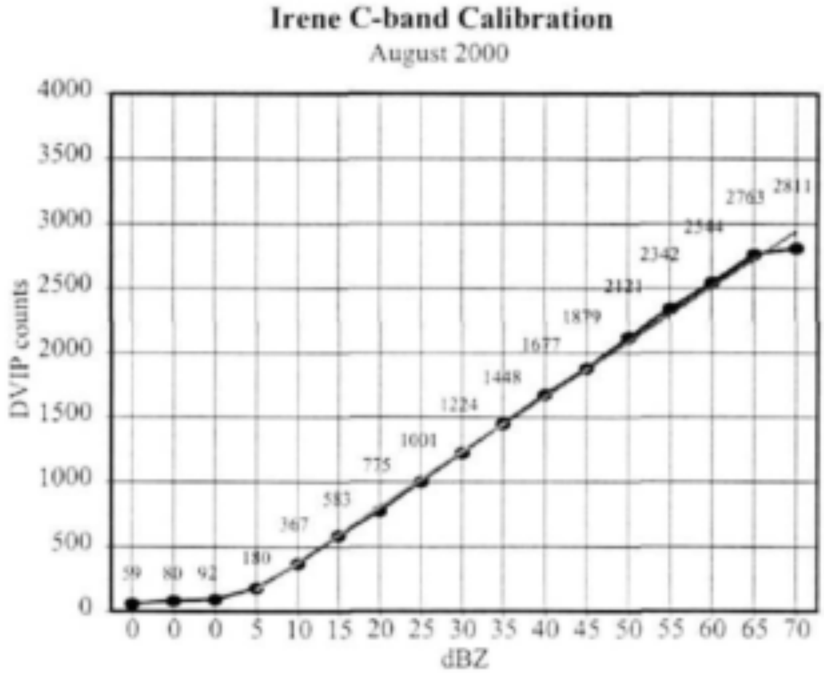


Figure 9. A s i n Figure 4 but for the Irene C-band radar.

3.1.6 Uninterrupted power supply to the MRL-5 and Ermelo radars

Due to the frequent interruption of Eskom power delivered to the MRL-5 radar site resulting in the loss of crucial radar data, a backup power unit was installed at the MRL-5 site during 1996 to ensure the continuous supply of utility power. The installation of a similar system at the Ermelo radar was high on the list of priorities when the BPRP took over the upgrading and maintenance of this radar as part of VIPOS. A schematic diagram of continuous power supply systems at the MRL-5 and Ermelo radars is shown in Figure 10.

The power consumption of the MRL-5 radar when in full dual-wavelength operation mode is of the order of 20 kW. In addition to making allowance for this consumpsion, consideration was given to the power consumption of the other utilities on site. It was decided that a 40 kVA UPS would be adequate for this purpose leaving a 40 % leeway for future expansion. This dictated the size of the generating plant which would need to be in the order of 80 kVA. To this end, an 85 kVA Leroy-Sommer generator driven by a 6 cylinder Perkins diesel engine was procured together with an Automatic Mains Failure (AMF) unit. As shown in Figure 10, the Eskom three phase power is supplied through the circuit breaker CB1 and is monitored by the AMF panel. On failure of the mains or any phase of the 3 phase supply, the AMF signals the generator to start. On obtaining the correct engine revolutions the contactor CB1 opens, isolating the mains, and contactor CB2 closes, supplying the alternator generated mains to the load. Protection against erratic mains pulses is provided by the inclusion of time delay switches. On restoration of the Eskom power the AMF panel opens CB2, isolating the generator supplied power, closes CB1 transferring the load to Eskom power and then signals the diesel to shut down. To ensure a continuous supply of power during transition from Eskom to stand-by power and vice versa it was necessary to install a UPS of sufficient power to supply the required current load. At all times the UPS remains on line. This means that the UPS receives the incoming AC power, converts it to DC backed up by the batteries and then reconverts it into AC which is then supplied to the load. On interruption of the incoming power the batteries, in the interim, continue to supply the DC power needed for the AC conversion until the generator power is applied. This cycle is repeated again on restoration of the Eskom mains. The wiring of the UPS is such that allowance is made to bypass the unit if necessary. The utility power that can tolerate short breaks in the supply (appliances, lights, air conditioners etc.) is routed to those facilities before passing through the UPS.

The Ermelo installation differed in that there was a requirement for stand-by power to be used to light the airfield landing lights in the event of a power failure. This was achieved by the provision of a feed from the generator through a contactor relay which is closed whilst the generator is running. This feed is then further switched through a sensing unit which senses whether the Eskom power or the standby power is to be used to light the landing lights and whether it is day or night. As the power requirements for the Ermelo installation are considerably less than those at the MRL-5 site, a John Deer 40 kVA diesel generator was purchased along with a 25 kVA Megaline UPS. Both these units arrived on site on 20 April 1998. The diesel generator was installed in a special sound-proofed room built in the corner of a store room.

Ermelo's standby supply is at present considerably overdesigned. This was done with intent, owing to the envisaged future of the site being rather fluid at the time and the need to rather err on the over-supply side. Aiding this decision was the fact that both the diesel generator and the UPS were acquired with considerable savings in cost.

The uninteruptable power systems installed at these radars and the specific components and layout used have proven to be robust. They form the basis of similar upgrades planned for other lightning prone radar systems in South Africa as funding becomes available.

The following table gives an indication of the reliability of data capture by the MRL-5 and Ermelo radars during the 1999/2000 season:

	MRL-5	Ermelo
October 1999	68.2%	67.2%
November 1999	91.2%	Statistics not available
December 1999	98.2%	46.5%
January 2000	96.1%	85.2%
February 2000	99.9%	81.8%
March 2000	95.9%	97.0%

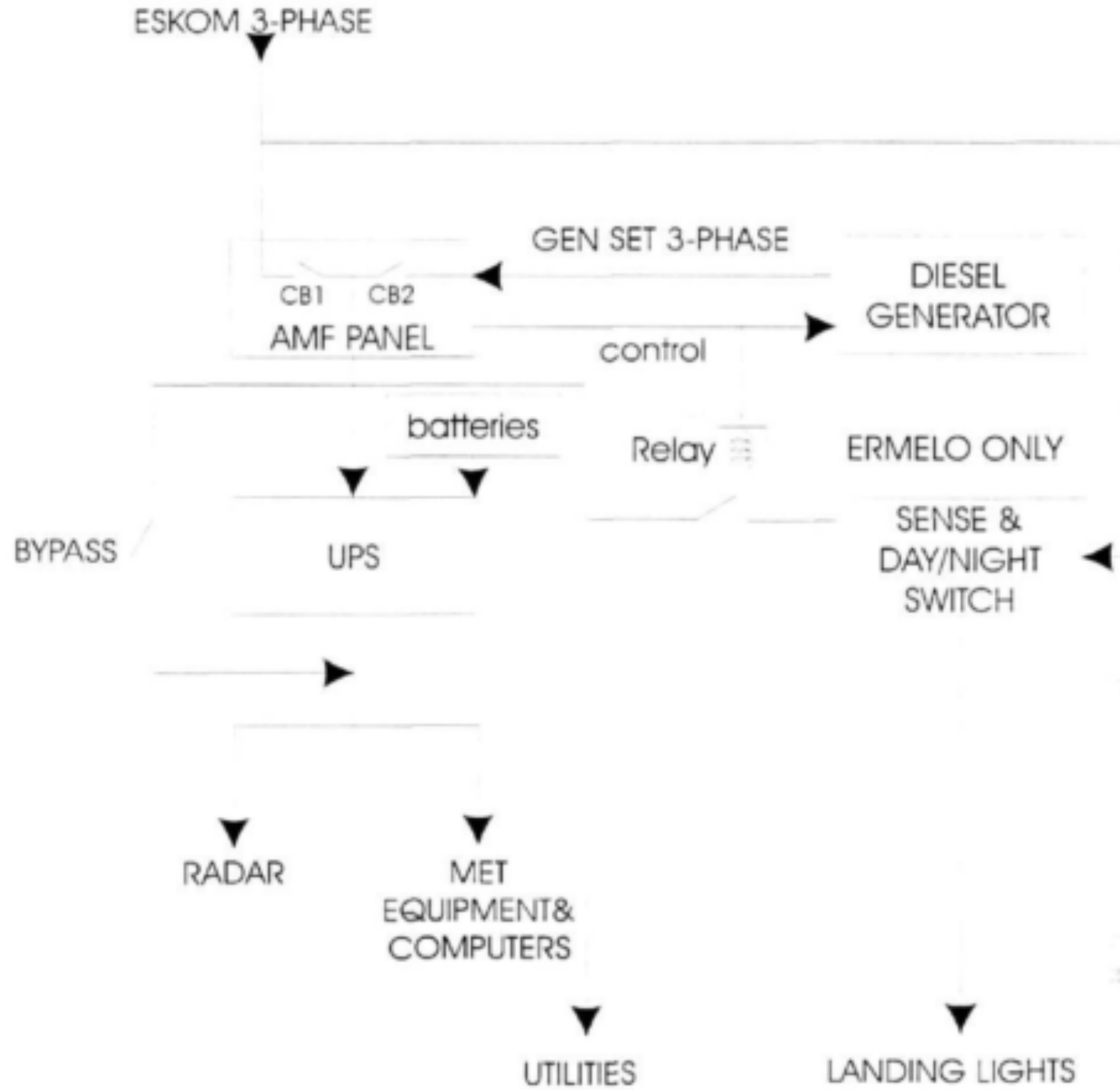


Figure 10. Schematic diagram of the continuous power supply system at the MRL-5 and Ermelo radars.

3.2 SPECIFIC RADAR STUDIES

3.2.1 Studying the overlaps of radar areas

- *24 September 1999*

During the afternoon of 24 September 1999, convective development occurred in the area of overlap between the MRL-5, Ermelo and Irene radars. This provided an ideal opportunity for comparing the measurements provided by the three radars. The merging program *MdvMerge* was applied to each of the radar's data in turn, as merging uses the maximum value detected in regions of overlap. The lowest common level of data for these 3 radars is the level 8 km ASL. All data in the overlap above this level were extracted for the purpose of this analysis for the volume scan at 16:58 UT.

The spatially aligned data series are plotted in Figure 11 using the MRL-5 data as reference. The regression lines for these series are also shown. From the differences in the slope of the regression lines and the regression coefficients (0.45 for Irene and 0.83 for Ermelo) it can be concluded that the antenna alignment between Irene and the MRL-5 is not as good as that between Ermelo and the MRL-5.

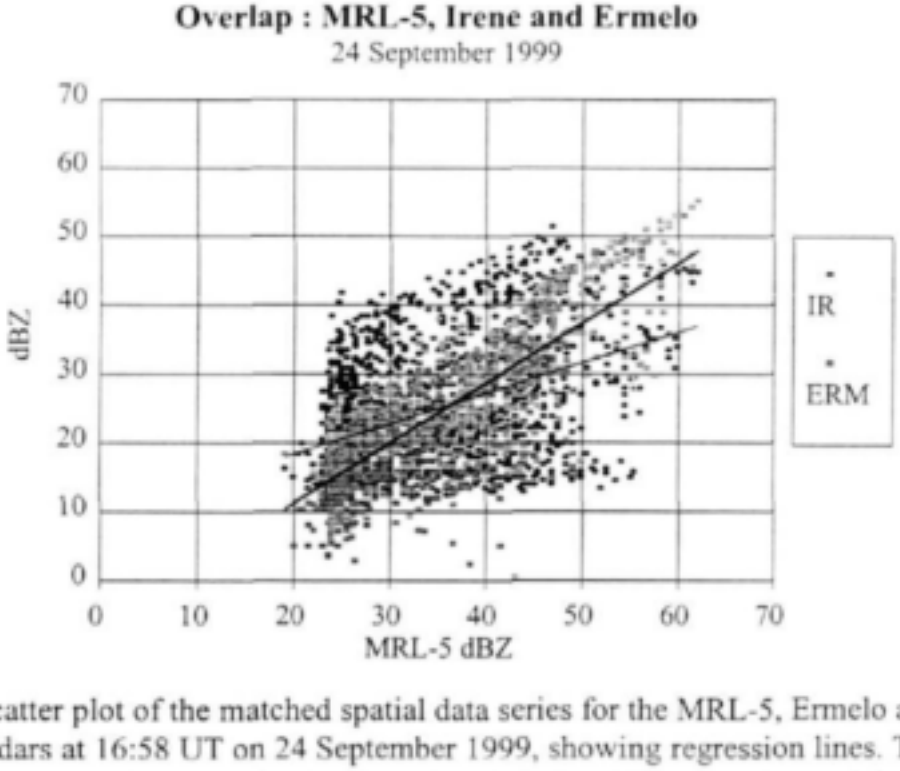


Figure 11. Scatter plot of the matched spatial data series for the MRL-5, Ermelo and Irene radars at 16:58 UT on 24 September 1999, showing regression lines. The thick line shows the regression between the MRL-5 and Ermelo radars and the thin line the regression between the MRL-5 and Irene radars.

The spatial constraints were removed from the data series by ranking each of the series in turn. These series were then plotted as shown in Figure 12. The correspondence found between the two C-band radars, Irene and Ermelo, is good although there is a discrepancy of ~ 10 dB between the reflectivity measurements of these two radars when compared to the MRL-5 S-band. More analyses and checks were done to determine the cause of this discrepancy but to date it has not been solved. To further investigate the data series independent of spatial constraints, the distributions of reflectivity for the different radars were expressed as frequency distributions as seen in Figure 13. Although the data sample is small and may not be representative, the figure would suggest that the Ermelo radar detected some reflectivity less than 10 dBZ, followed by Irene (with lowest reflectivity around 10 dBZ) followed by the MRL-5 radar with the lowest values just under 20 dBZ.

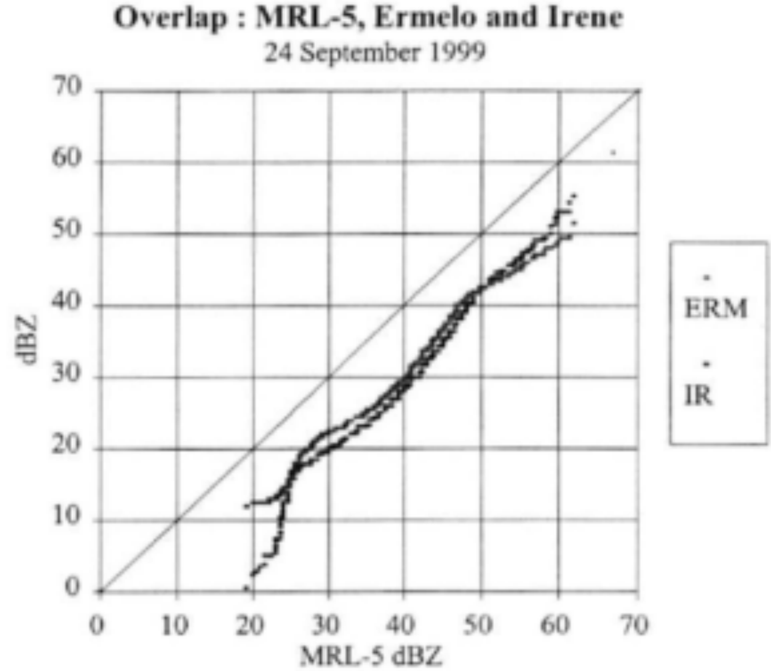


Figure 12. Ranked data series for the MRL-5, Ermelo and Irene radars for 16:58 UT on 24 September 1999. The 1-to-1 line has been drawn for reference.

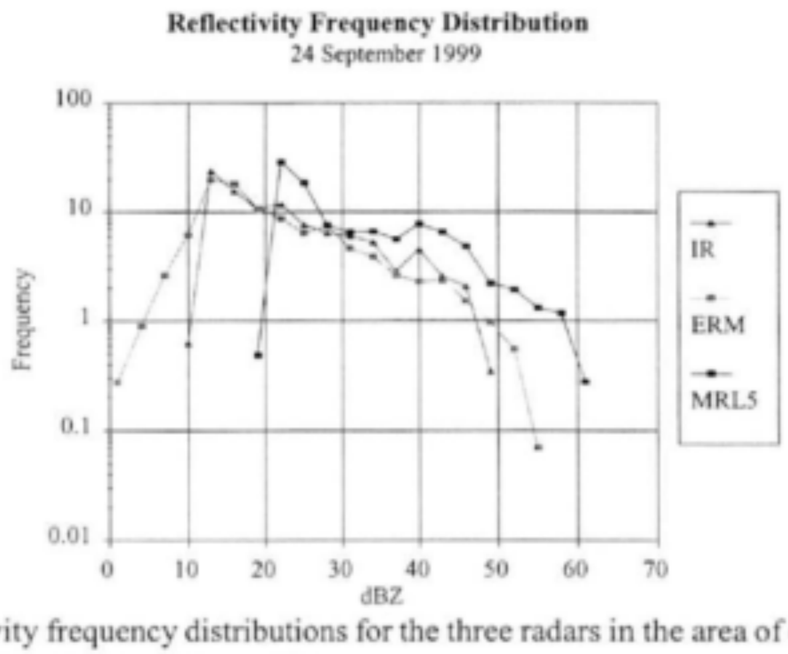


Figure 13. Reflectivity frequency distributions for the three radars in the area of overlap for 16:58 UT on 24 September 1999.

- *13 - 14 February 2000*

A similar study was done for the 24 hour period to 06:00 on 14 February 2000 after new calibrations on the MRL-5 and Ermelo radars. All in all there were in excess of 380 000 1' x 1' pixels that contained echoes during the 24 hour period. Due to the differences in sensitivity between these two radars radar, reflectivity frequency distributions were determined only for returns exceeding 18 dBZ within the ranges where the radars overlap.

As can be seen from Figure 14, very similar results were obtained to those for 24 September 1999. The calibration checks before the 2000/2001 summer season also did not shed any additional light on this discrepancy. This is a issue of major concern to the project team and has not been resolved at the time of writing despite lengthy debates. It is to be expected that the C-band data values will always be somewhat lower than those from the S-band but the magnitudes of the observed differences are worrying. It is for this reason that discussions have started with Dr Dixon to devise software that will be a integral part of the MDV-based networking system to automatically determine statistics on all the overlap areas in the network. Case studies of the type reported here are extremely computer and time intensive and just not good enough for the quick answers needed. This whole issue will be pursued vigorously until it is solved.

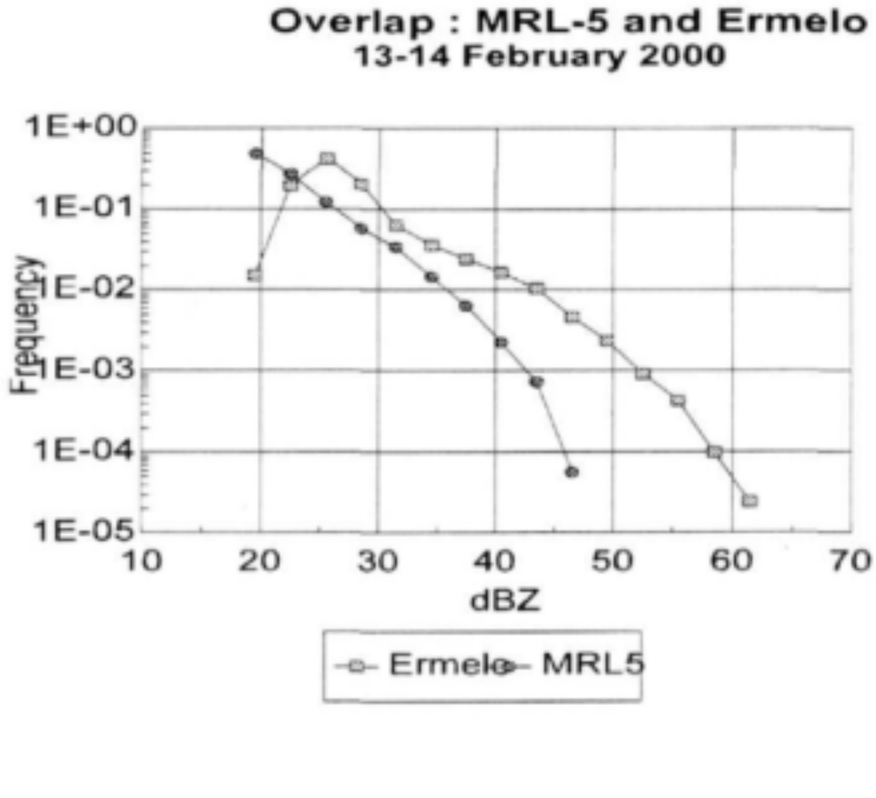


Figure 14. Comparison of the MRL-5 and Ermelo radar reflectivity distributions in the area of overlap between the two radars for the 24-hour period from 06:00 on 13 February 2000 to 06:00 on 14 February 2000.

3.2.2 *The Tropical Rainfall Measuring Mission (TRMM) satellite*

The Tropical Rainfall Measuring Mission (TRMM) is a joint project between NASA and the Japanese National Space Development Agency (NASDA). The TRMM satellite was launched in late 1997. The project was designed to have a lifetime of 3 years. TRMM is designed to measure tropical rainfall between 30° N and S at an altitude of 350 km at an inclination of 35°. Figure 15 is an example of the TRMM orbits for one day.

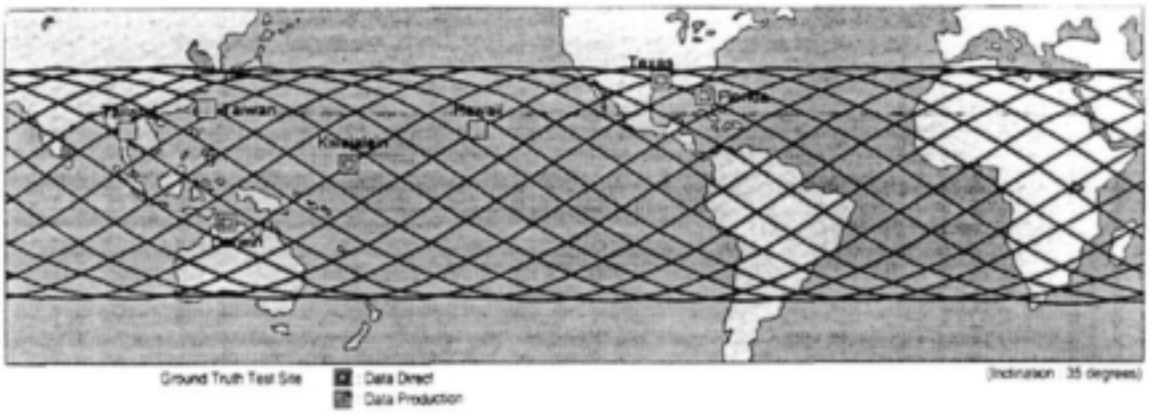


Figure 15. Example of the TRMM orbits for one day and ground validation (GV) sites.

TRMM has 5 instruments on board :

- The first space-borne *Precipitation Radar (PR)* which provides a 3-D distribution of rainfall over land and ocean. It is an electronically scanning radar operating at 13.8 GHz with horizontal polarization, using a 128-slotted waveguide antenna and solid state power amplifiers to develop an active phased array. The PR provides an horizontal resolution of 4.3 km at nadir, with a bin resolution of 250 m and a scanning swath width of 220 km.

- The *TRMM Microwave Imager (TMI)* - a multi-channel microwave radiometer providing detailed information on the integrated columnar precipitation content, areal distribution and intensity.

- The *Visual Infrared Scanner (VIRS)* which provides high resolution data on cloud coverage, type and cloud top temperatures.

- The *Lightning Imaging Sensor (LIS)* which can investigate the global incidence of lightning, its relationship to the global electric circuit and through measurements from the other instruments, the correlation with rainfall.

- The *Clouds and Earth's Radiant Energy System (CERES)* which is a visible and infrared sensor designed to measure the emitted and reflected radiative energy from the Earth's surface, atmospheric constituents (clouds and aerosol).

The primary objective of TRMM was to understand the role of latent heat in driving the global atmospheric circulation. It provides the first opportunity to estimate the vertical profile of latent heat that is released through condensation. Equatorial and tropical precipitation and heating is concentrated in the so-called Intertropical Convergence Zone (ITCZ). Rainfall data obtained from TRMM is important for global hydrological cycle studies and for validating global climate models, especially their ability to simulate and predict climatic conditions on the seasonal time scale. TRMM was designed to increase the extent and accuracy of rainfall measurements in the tropics. For more background information refer to Simpson et al. (1996).

To validate TRMM 10 ground validation sites representative of different rainfall regimes were chosen, none on the African continent. Table 1 summarizes these locations and the radar specifications. The locations can also be seen in Figure 11.

Table 1 Official TRMM Ground Validation (GV) sites (which represent different tropical rainfall regimes) and their radar specifications.

Site	Radar Specification
Darwin, Australia	5 cm Doppler radar 5 cm multi-parameter radar
Melbourne, Florida, USA	10 cm WSR-88D NEXRAD Doppler radar
Houston, Texas, USA	10 cm WSR-88D NEXRAD Doppler radar
Kwajalein Atoll, Rep. Of Marshall Islands	10 cm DWSR-93 Doppler radar
Tel Aviv, Israel	5 cm EEC conventional radar
Sao Paulo, Brazil	10 cm conventional radar to be replaced with 10 cm dual-polarization Doppler radar
Guam, Marianas Islands	10 cm WSR-88D NEXRAD Doppler radar
Kaohsiung, Taiwan	10 cm WSR-74S/81S conventional radar to be replaced with 10 cm WSR-88D NEXRAD Doppler radar
Om Koi, Thailand	10 cm DWSR-93 Doppler radar
Phuket, Thailand	10 cm DWSR-93 Doppler radar
Molokai, Hawaii	10 cm WSR-88D NEXRAD Doppler radar

The Precipitation Research sub-directorate located at Bethlehem has embarked on an independent validation study with a slightly different focus. The main research and operational objective of using TRMM PR data is to compare the radar calibration performance of the different ground based radars of the South African network to an independent source in a relative and objective manner.

The composite reflectivity field (the maximum value detected in a vertical column) is extracted from the TRMM PR swath data and processed into a regular 3' by 3' latitude-longitude grid for the block extending from 24°S 24°E to 32°S 32°E. This field is stored in the standard MDV format, which simplifies the comparative process immensely.

Typically there are two over-passes per day for this latitude-longitude window, either approximately 5 or 24 hours apart. The times regress, so that over-passes occur about an hour earlier each time.

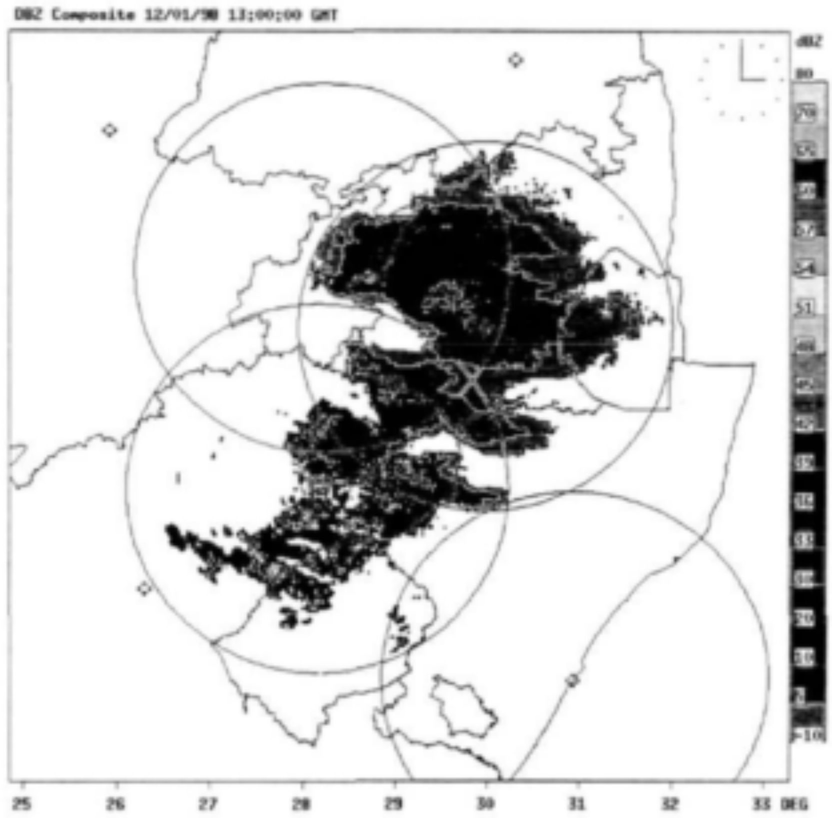
3.2.3 Radar network inter-calibration checking using TRMM PR measurements

As has been shown, as soon as data from different radars are merged, discrepancies between the data sources become more apparent. These can be hardware dependent (i.e. one radar's sensitivity is better than another's) or calibration dependent. Although some improvements can be made regarding a radar's sensitivity, the latter aspect is where the potential of using TRMM PR measurements is the greatest. Using an independent data source, all ground-based local platforms can be compared, in a relative manner, to determine how well the calibrations of the individual radars match.

The results shown here focus on the region of overlap between the Ermelo and Witbanksfontein (MRL-5) radars. Figure 16 a and b show the merged reflectivity composite and the TRMM maximum reflectivity fields respectively.

A scatter plot of all the retrieved data points from the MRL-5 radar and the TRMM PR in the overlap area is shown in Figure 17. A regression performed on these series showed that the slope (0.77) is close to 1-to-1. Despite the scatter, which is the result of the different spatial resolutions and sensitivities of the two radars, it is evident that the MRL-5 radar's S-band reflectivity measurements compares favourably with those obtained from space.

a.



b.

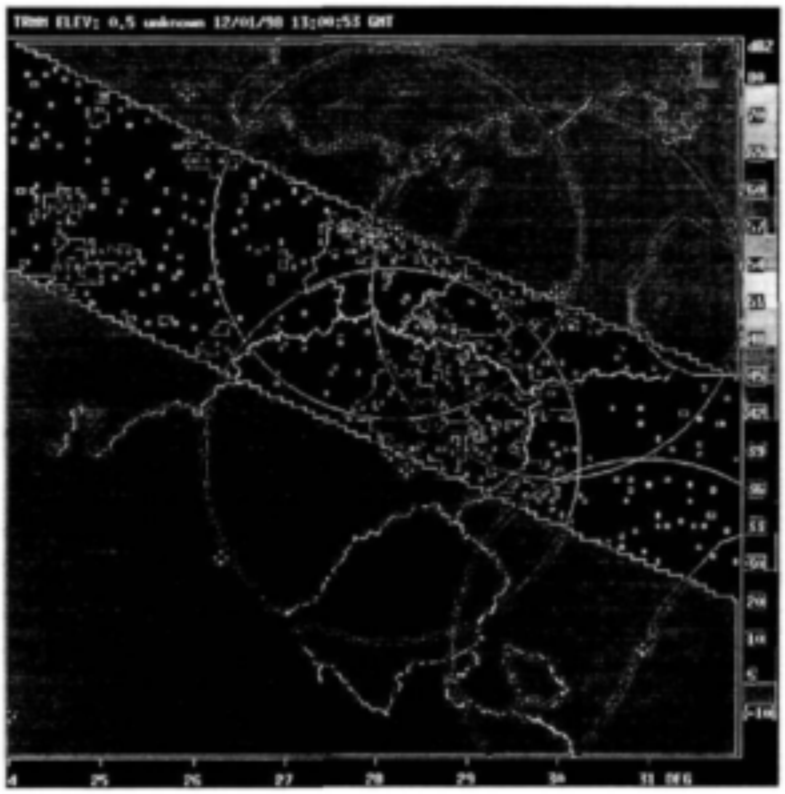


Figure 16. (a). The merged reflectivity field and (b). the TRMM PR field for 1 December 1998 at 13:00 GMT.

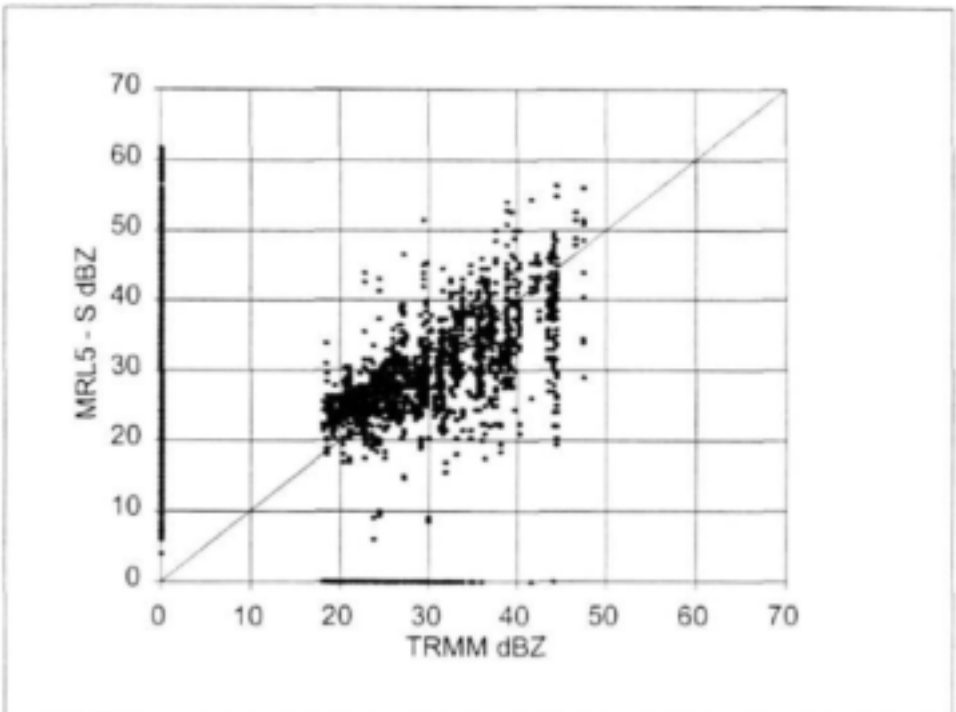


Figure 17. Matched data points for the overlapping region with the TRMM PR data forming the basis of comparison. A 1:1 line has been included for reference.

When the spatial and temporal constraints on the data are removed by converting the data into reflectivity frequency distributions it can be seen from Figure 18 that there is a good correspondence in the shape of the distribution function between the MRL-5 and TRMM PR measurements, keeping their respective noise thresholds in mind.

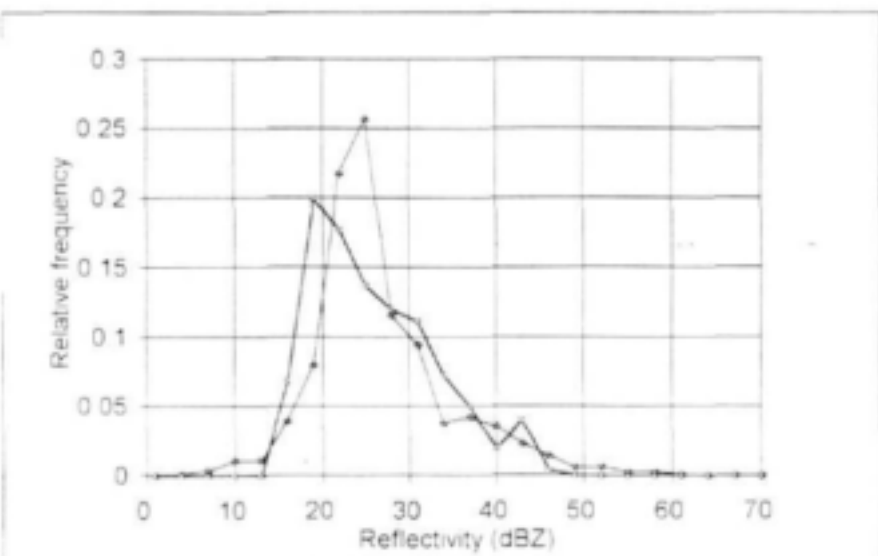


Figure 18. Reflectivity frequency distributions for the TRMM PR and MRL-5 S-band data for the scan at 13:00 GMT.

3.2.4 The use of composite reflectivity in rainfall estimation

This section is of relevance to investigations to extend the usable range of radar data through the use of the vertical reflectivity profile obtained through volume-scan data collection.

In radar rainfall studies in the NPRP it has become customary to use the ~ 2 km above ground CAPPI radar reflectivity values in radar rainfall measurement in South Africa. This level was chosen as it represents a sound compromise between the maximum range covered and relative closeness to the ground. However, due to the combined effect of the lowest elevation normally set at 1° or 1.5° and the curvature of the earth on the height of the radar beam above the ground, a severe limitation is placed on the range of useful 2 km CAPPI data (~75 km). At NCAR and specifically in the rainfall accumulation routines used in TITAN the maximum reflectivity value within the vertical column is used in rainfall calculations. Obvious potential advantages of this method include a much larger useful range for radar rainfall measurement and less sensitivity to partial beam blocking effects at less ideally sited radars (two examples in South Africa being the Bethlehem C-band and Tzaneen C-band radars). Disadvantages could include even larger sensitivity to overestimation in rainfall in the presence of the bright band or hail. Conceptually there is also the difficulty in relating the maximum reflectivity in the vertical column to rainfall falling on the ground, especially if one is concerned with short time interval measurements. However, in the light of the less than ideal spacing for rainfall measurement of radars in South Africa and the fact the maximum reflectivity algorithm is a standard feature of the TITAN software, the method warrants verification. Time did not allow a detailed study in this regard but a case study of one of the significant flood events in the data base is presented here to compare the established method and the new method.

A detailed description of the radar-rain gauge study for 24-25 January 1996 is given in Mather et al. (1997). The rain gauges in the Liebenbergsvlei catchment measured a 24-hour average area rainfall of 62 mm. From the 2 km CAPPI data 48 mm was estimated for the same period. Using the maximum reflectivity value the 24-hour accumulated catchment rainfall was found to be 65 mm. These three accumulated time series are shown in Figure 19. This would seem to indicate that the Marshall-Palmer Z-R relationship $Z = 200R^{1.6}$ was accurate enough under the prevailing conditions with the use of composite reflectivity data.

The rain rate exceedance probabilities for the radar-derived rain rates and the rain gauge rain rates are shown in Figure 20. The smoothness of the 2 km AGL radar curve as compared to that of the rain gauges was pointed out in Mather et al. (1997). The exceedance probability curve for the maximum values does not show the same smoothness but shows interesting variability in the occurrence of rain rates between 25 and 45 mm.h^{-1}. Using the Marshall-Palmer Z-R relationship this related to reflectivity values between 45 and 49 dBZ. Upon further investigation of the three-dimensional CAPPI data it was found that substantial regions of stratiform rain surrounded the intense convective cores. The stratiform regions had embedded elevated shower cores with maxima situated at heights above 2 km AGL, verifying the presence of a bright band at a height between 3 and 4 km AGL.

In Figure 21 the cumulative rain rate contributions to the total rainfall are illustrated. Once again the region of enhancement due to the presence of an elevated bright band are evident. It is perhaps significant to note the shift in the median contributing rain rate from 15 $mm.h^{-1}$ for the 2 km CAPPI data to 27 $mm.h^{-1}$ for the composite data, which is close to the 24 $mm.h^{-1}$ of the rain gauges, albeit if somewhat exaggerated due to bright band effects.

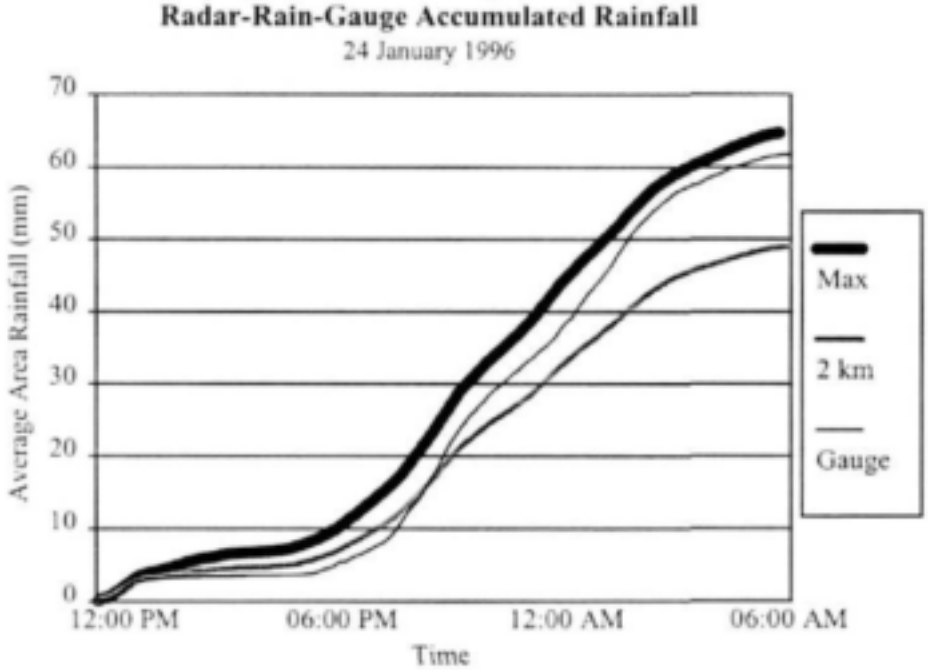


Figure 19. Accumulated rainfall using the rain-gauge network, 2 km CAPPI radar reflectivity and the maximum in the vertical column over the Liebenbergsvlei River catchment during the night of 24 January 1996.

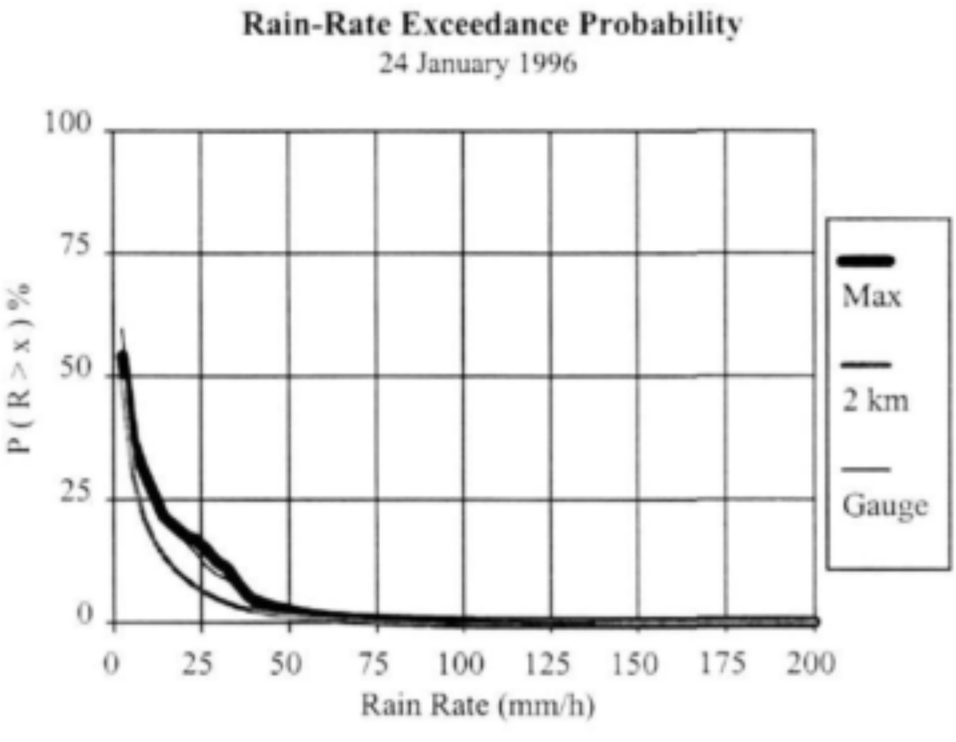


Figure 20. Exceedance probabilities for the frequency of occurrence of rain rates for 24 January 1996 as measured by the Liebenbergsvlei rain gauges and the radar.

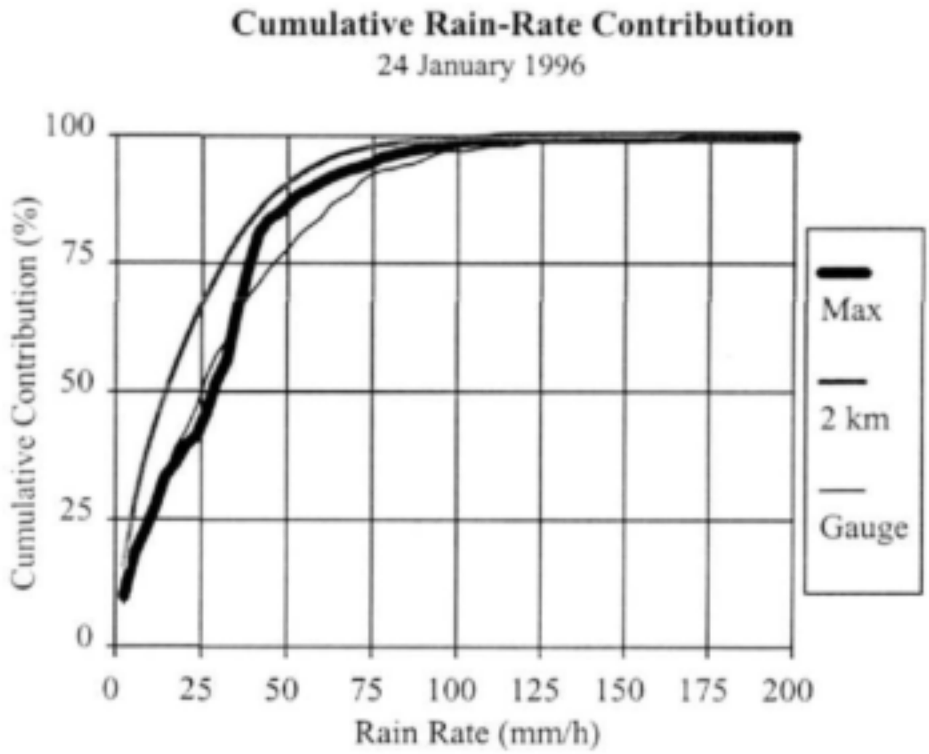


Figure 21. Cumulative contributions of rain rate distributions to the total rainfall for 24 January 1996 as measured by the Liebenbergsvlei rain gauges and the radar.

Based on this case study for a flood producing rain event it was decided to use the TITAN rainfall accumulation algorithms, unmodified, for the immediate future.

3.2.5 *Adjusting the Marshall-Palmer relationship*

In the previous analysis the radar-to-gauge ratio of 0.79 was obtained by using the Marshall-Palmer Z-R relationship $Z = 200R^{1.6}$. When using the Marshall-Palmer relationship for convective rainfall events, the lower rain rates are typically over-estimated and the higher rain rates under-estimated, when compared to the rain gauge derived rain rates. The ideal would be to determine a new Z-R relationship where the rain rate distribution of the rain gauges is used to adjust the radar-derived rain rate distribution, thus improving the radar rainfall estimate.

Log-log regression equations were determined between the rain gauge rain rate frequency distribution and the corresponding rain rates. The same approach was followed for the radar-derived rain rate frequency distributions as obtained when applying the Marshall-Palmer equation. Figure 22a and b show the scatter plots and the regression lines for the two data sets. The idea is to modify the radar-derived distribution (through the Z-R relationship) to correspond to that of the gauges.

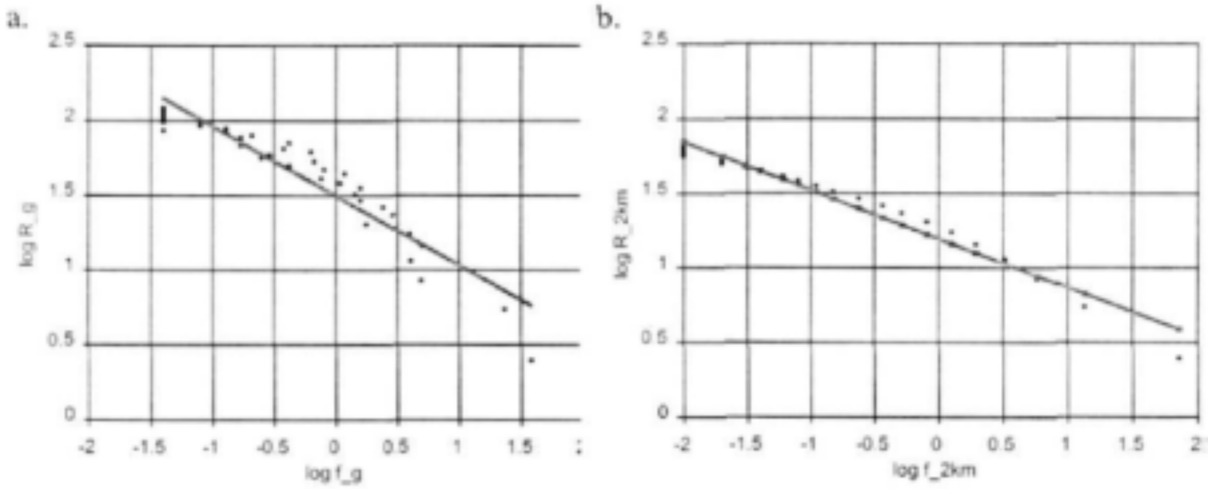


Figure 22. Scatter plot of the log (rain rate frequencies) and log (rain rates) for (a). the rain gauges and (b). the 2 km CAPPIs for 24 January 1996.

The difference between the offset and slope of the gauge derived and Marshall-Palmer radar derived regression lines provides a straight line ($\log R\_g - \log R\_rad = a \log R\_g + b$) which can then be rewritten as a Z-R relationship of the following form :

$$R = \left(\frac{Z}{200 \cdot 10^{-1.6b}}\right)^{\frac{1}{1.6(1-a)}}$$

The adjusted Z-R relationships for 24 January 1996 are therefore $R = (Z / 237)^{(1/1.48)}$ for the 2 km CAPPI data and $R = (Z / 206)^{(1/1.5)}$ when using the maximum reflectivity in the vertical at each point for rainfall estimation. Applying these relationships to the data results in a change in the rain rate frequency distributions as seen in Figure 23a and b.

a. b.

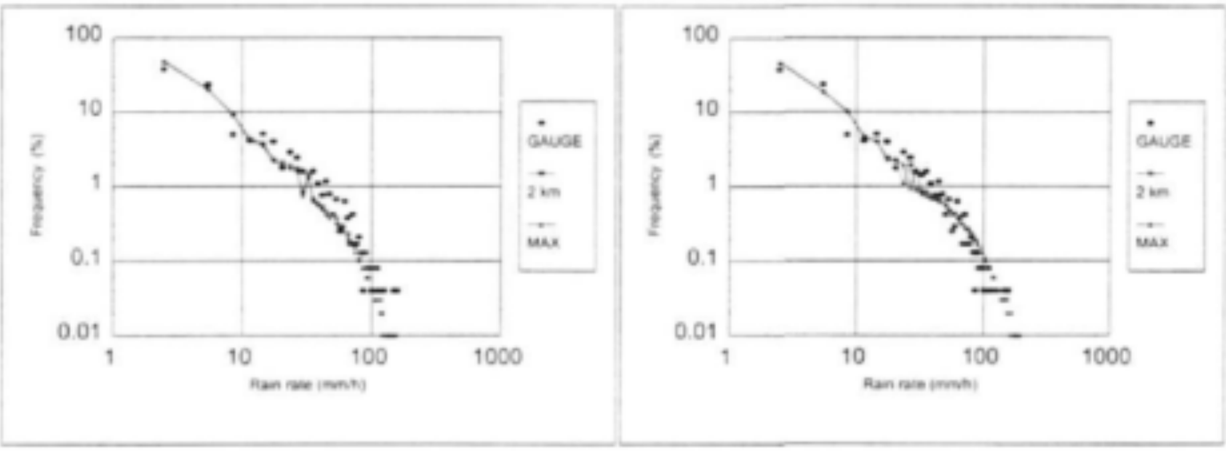


Figure 23. The rain rate frequency distributions obtained using (a). the Marshall-Palmer Z-R relationship and (b). the adjusted Z-R relationship.

When these adjusted relationships are applied to the data the radar-to-gauge ratio changes from 0.79 to 1.02 and 1.05 for the 2 km and composite reflectivity fields respectively.

3.2.6 Bright band amelioration

When radar is used to obtain an area rainfall estimate, the presence of the bright band is often a distinct feature of the vertical reflectivity profile (VRP), resulting in a set pattern in the vertical structure of the precipitation echo as well as a typical response of an over-estimation in the rainfall estimate. The accuracy of radar-rainfall estimates can be improved by using the three-dimensionality and especially the vertical characteristics of the radar echo. Mittermaier (1999), as part of her MScEng studies at the University of Natal developed a method to deal with this problem. The three-dimensional Cartesian data (CAPPIs) with a 1 km^3 resolution were analysed using the covariance biplot based on singular value decomposition (SVD) and an objective classification algorithm - CONSTRAT - combined with contoured-frequency-by-altitude-diagrams (CFAD) were developed. Multiple linear regression models were obtained for the precipitation groups which the biplot and CONSTRAT identified. The shape of the VRP was established at ranges less than 40 km to the radar where data are available at 1 km AGL.

Under predominantly stratiform conditions the biplot distinguishes between different precipitation groups based on height, a purely mathematical-statistical classification. A censoring method, simulating the availability of data with range, showed that as many as 3 levels (1 to 3 km AGL) can be removed before the characteristics of the groups are deformed significantly. All the regression models provided good estimates of the reflectivity at the 1 km level, improving the radar-rainfall estimates when compared to the conventional 2 km CAPPI radar-derived rainfall, especially for ranges less than 40 km. The extrapolation of VRP groups to longer ranges (< 70 km) showed an improvement in the estimate. The regression models showed that the quality of the spatial field could also be improved by removing substantial parts of the "annular" bright band feature in radar rainfall estimates.

Observed reflectivity values at 1 and 2 km as well as predicted reflectivity values at the 1 km level were converted to rain rates using the Marshall-Palmer Z-R relationship $Z = 200\,R^{1.6}$, and integrated in space and time over the period 18:33 to 20:09 on 29 October 1996. Figure 24 shows the time history of accumulation for the time window. The predicted-to-observed-at-1 km ratio for the area rainfall was 0.95, whereas the ratio for the observed values at 2 km was 0.51. This result shows the success of estimating 1 km values using data from higher levels. In this manner the over-estimation resulting from using 2 km CAPPIs could be reduced by a factor of two.

When compared to the rainfall as measured by the 10 TBRs in the Liebenbergsvlei catchment falling within the delimited study area, the radar-to-gauge ratio improves from 2.40 (using the usual 2 km CAPPIs for rainfall accumulation) to 1.20 for the time window.

Radar, by nature of the underlying microphysics, has the tendency of over-estimating stratiform rainfall. For this reason it is important to typify radar echoes according to whether they are stratiform or convective. To improve the radar-rainfall estimate, a convective-stratiform classification algorithm has been devised which utilizes the three-dimensional structure of the radar echo. A stack of CAPPIs (Constant Plan Position Indicators) are analysed and a classification made on a pixel-by-pixel basis. The algorithm identifies upright intense reflectivity cores of considerable vertical extent (purely convective regions) and thereafter tests for both vertical and horizontal reflectivity gradients to determine whether a given vertical profile is intermediate or stratiform.

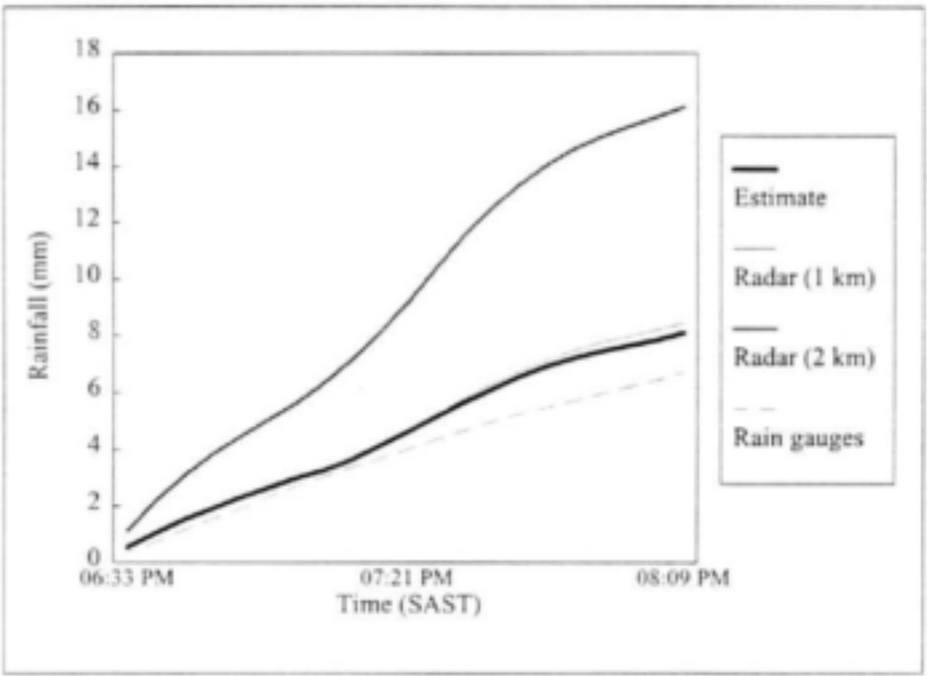


Figure 24. Observed radar and rain gauge accumulated rainfall for the time window 18:33 to 20:09 for 29 October 1996.

Contoured-Frequency-by-Altitude-Diagrams (CFADs) have been used to typify the differences in radar characteristics between stratiform and convective radar echoes using the frequency distributions of the reflectivity values (Yuter and Houze, 1995). By creating a CFAD, properties of a three-dimensional data volume, such as a stack of CAPPIs, can be summarized and displayed in two-dimensions. The CFAD is constructed with height on the y-axis and reflectivity on the x-axis. Contours describing the frequency of occurrence are then plotted in this domain. The CFAD can be used to measure the success of the classification scheme in distinguishing the two groups.

Being able to objectively classify radar echoes as convective or stratiform has important implications for radar rainfall measurement. A real-time classification scheme will prevent the superfluous computations of a bright band correction algorithm. The correct identification also has an impact on storm tracking software. Large 30 dBZ areas associated with a widespread general rain event cannot be called storms but are currently being tracked as such.

On 30 October 1996 a squall line with a marked Line Echo Wave Pattern (LEWP) and bow echo affected the north-eastern Free State resulting in wind damage and extensive rain. The squall line had a typical sharp convective boundary followed by an extensive trailing stratiform region with embedded convection. S-band data, from the Water Research Commission's MRL5 radar, for the period between 16:03 and 19:02 were used in evaluating the algorithm's ability in distinguishing between convective and stratiform areas. CFAD plots for the area show a progression from predominantly convective to predominantly stratiform. Figures 25 and 26 show the classification and CFADs for the different groups for 16:37.

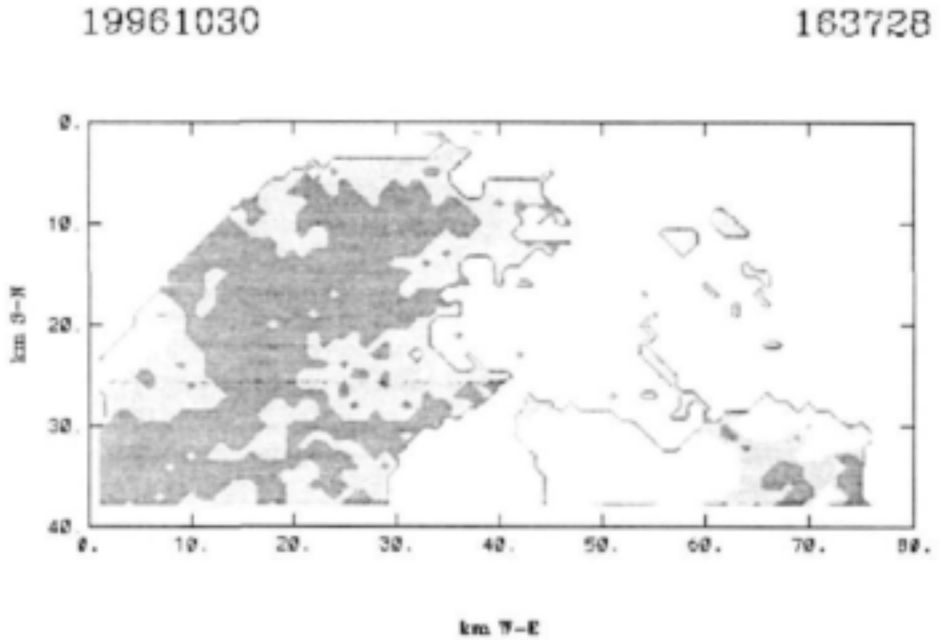


Figure 25. Classification of radar echoes. Dark shading indicates stratiform regions with the lightest shading purely convective. Intermediate shading shows the radar echo in a transitional stage.

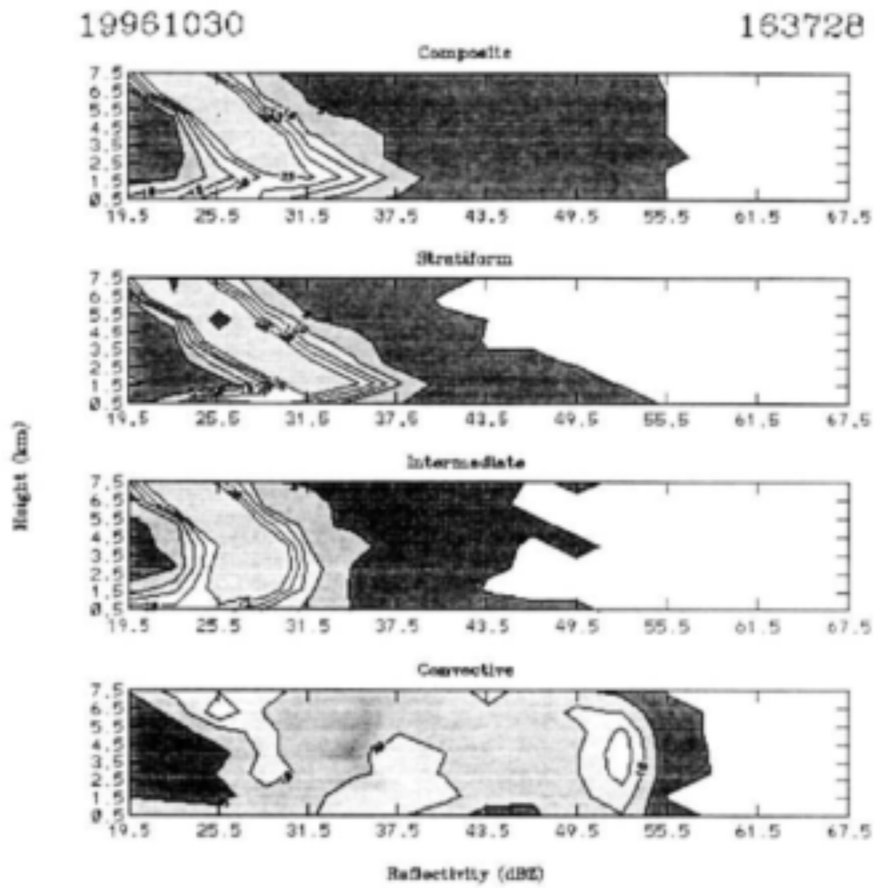


Figure 26. CFAD for the CONSTRAT groups and the composite. Contours represent the % occurrence of a radar reflectivity.

3.2.7 Using the Area Time Integral for rainfall estimates

Area-time integrals (ATI) can be used to estimate rainfall by utilizing the strong correlation between the area covered by a storm (its wetted area ratio), its duration and the rain volume. The ATI technique can be used to estimate the total rainfall over the lifetime of a convective storm (moving targets) or from snap shot observations over a fixed area. The technique is based on the existence of a well defined probability density function (PDF) of rain rate. The PDF can be approximated by looking at all the rain rates above a preset threshold over a large area ($10^4 km^2$) (Eulerian frame) or a sequence of rain rates over a storms lifetime (Lagrangian frame). A log-linear regression of the rain volume and the ATI results in a predictive equation of the form $V = K\ (ATI)^b$.

Research on using the ATI technique over a fixed frame (catchment area) to estimate daily rain volumes is being conducted. The ATI technique has been evaluated for three different situations, ground clutter or very little rain, a convective case and a stratiform case. The ATI's operational capabilities in validating the existing Z-R rain volume estimates using November 1998 data was determined for the three different situations. A rain rate threshold of 5 $mm.h^{-1}$ was used. The corresponding regression parameters obtained from the data set are $b=0.94$; $K=27.19$ and a logarithmic error of estimate *0.0151*. Figure 27 shows the performance of the ATI technique for the convective case using regression parameters of the whole data set and for the specific case. The better performance of the regression parameters obtained from the specific case shows that the optimized PDF will give better estimations. The ATI gives very good correlations with the trained parameter, in this case the radar estimated rain volume (RERV) using the Z-R relationship. This means that biases in one method, like the Z-R relationship, and certain situations, like the presence of hail, can be overcome by using the ATI method.

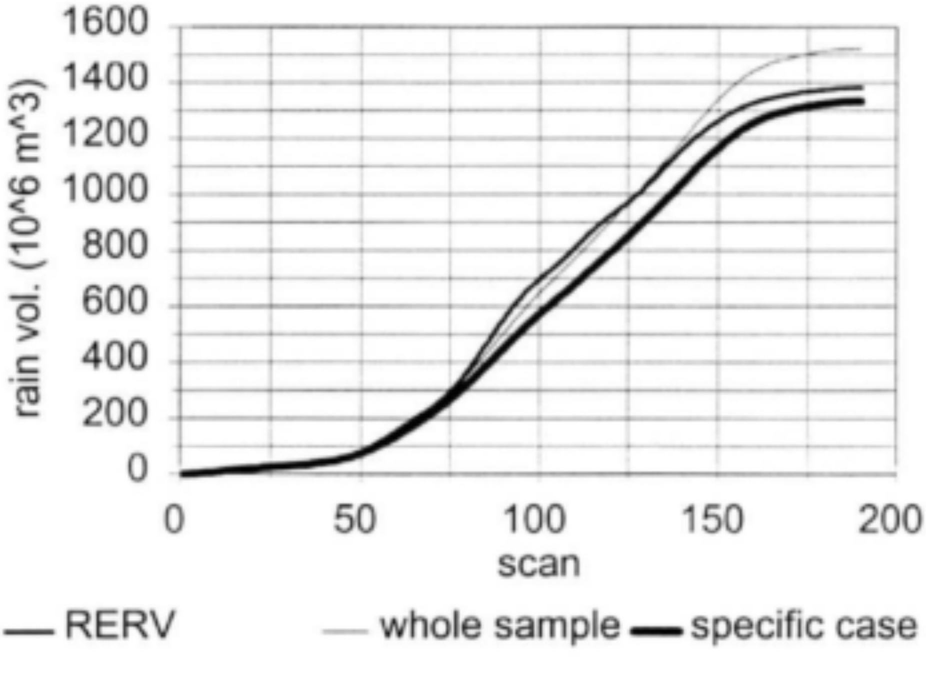


Figure 27. Rain volume for a convective event using Z-R (RERV) and the ATI with regression parameters obtained from the whole data set and from the specific case.

The case studies support the theory that the ATI under convective situations is much better correlated with observed rainfall than under stratiform conditions. There is however proof that the ATI can be used to obtain reasonable estimates of stratiform rainfall. An error of 9.9% and 30% was made in estimating the convective and the stratiform case. Noise has a negative influence in the training of the ATI. Once the ATI relation has been established, noise does not have a large effect on the daily estimates. The ATI technique shows great possibilities to produce daily rainfall estimates over a fixed area such as a catchment area. However more research is needed to investigate methods to optimize the PDF, how the ATI compares with rain gauge data, and how the ATI performs in hail storms, before it can be used operationally.

The successful use of the ATI is related to the strong link between the Wetted Area Ratio (WAR) and the Image Mean Flux (IMF) as shown by Pegram and Clothier (1999). This should be exploited, even though it applies to instantaneous radar fields (CAPPIs); the link with daily data is a bit more difficult.

3.2.8 *Hail Kinetic Energy (HKE) and Storm Structure Severity(SSS) method usage in precipitation measurement*

Convective storms are responsible for a large portion of the annual precipitation over the Vaal River basin. Since these storms often reach altitudes exceeding 10 km, they do contain a significant amount of ice and/or hail. When strong updrafts exists within these storms, supercooled droplets as well as graupel particles act as hail embryos as they are transported to freezing altitudes. The hailstones cascade down to cloud base and start to melt. Often they are coated with a small layer of water, which results in increased reflectivity being observed. It is generally believed that radar volume samples with radar reflectivity exceeding 45 dBZ can contain hail. Under these conditions, hail contaminated precipitation measurement with convective storms can occur. The more radar reflectivity exceeds 45 dBZ, the greater the possibility of hail being present in the sampling volume. With the current TITAN precipitation software, a radar reflectivity threshold of 55 dBZ is used to separate hail from water droplets. The following questions now arise from the above regarding heavy precipitation measurement:

- How much hail contamination occurs below the 55 dBZ threshold?
- How much precipitation is discarded above 55 dBZ due to this threshold?
- How can tropical, non-hail convective storms be separated from hail producing storms?

These questions were addressed by Pieter Visser as part of his MSc studies at the University of Pretoria (Visser, 1999). Firstly, investigations were done into the possibility of detecting hail in convective storms, by means of hail kinetic energy (HKE) and radar reflectivity comparisons. Secondly, an algorithm underlying the Storm Structure Severity (SSS) method, has been devised to summarize the properties within the vertical profile of convective storms. SSS is used to identify hail producing convective storms, in contrast to more tropically forced convective development.

- *Hail kinetic energy and crop damage reports*

It was shown by Schmid et al.(1992) that a conventional hail-measuring network could be replaced by a S-band radar to derive HKE and that it could be used for verification of hail prediction models. Although hail research has been done in South Africa before, the use of HKE has not been attempted. Crop damage reports of Sentraoes were used to verify the ability of HKE to detect hail on the ground. Three cases, on 16 October 1995, 28 November 1995 and 22 December 1995, representing the most severe hail damage events of the 1995 summer season, were investigated. Three different thresholds were used for deriving the Total Hail Kinetic Energy (THKE), which is a time integrated HKE entity. The first was a threshold with a scaling factor which commence at 45 dBZ until 50 dBZ. The second and third thresholds were taken at 50 and 55 dBZ, respectively. To ensure the calculation of HKE to a range of 150 km the 6 km reflectivity field was used.

Using the threshold with a scaling factor, 85 of the 92 farms of the 28 November 1995 case which reported hail were located within the THKE field generated. Figure 28 shows the THKE field generated using this method as well as the locations of reported crop damage for 28 November 1995. Most of the farms which reported crop damage are located within close proximity of the storm's footprint. Furthermore, 72% of the farms reporting damage had THKE exceeding

100 J.s^{-1}. When a time series above the farms was analysed, some farms had a radar reflectivity exceeding 45 dBZ for close to 3 h, while maximum radar reflectivity only exceeded 55 dBZ at short intervals. The THKE was thus generated not from the severity of the storms alone, but due to the persistence of reflectivity exceeding 45 dBZ. This occurred due to continuous redevelopment of convective storms on the rear flank of the storm complexes. This led to the continuous favourable conditions for persistent hail. The reflectivity values also indicate that the hail was most likely smaller than 15 mm in diameter. Hail of this size can still cause extensive damage to wheat. One hail damage report, in the Kroonstad district, represents an anomaly. On closer inspection it was found that the radar did not detect any significant convective development over this farm on this day.

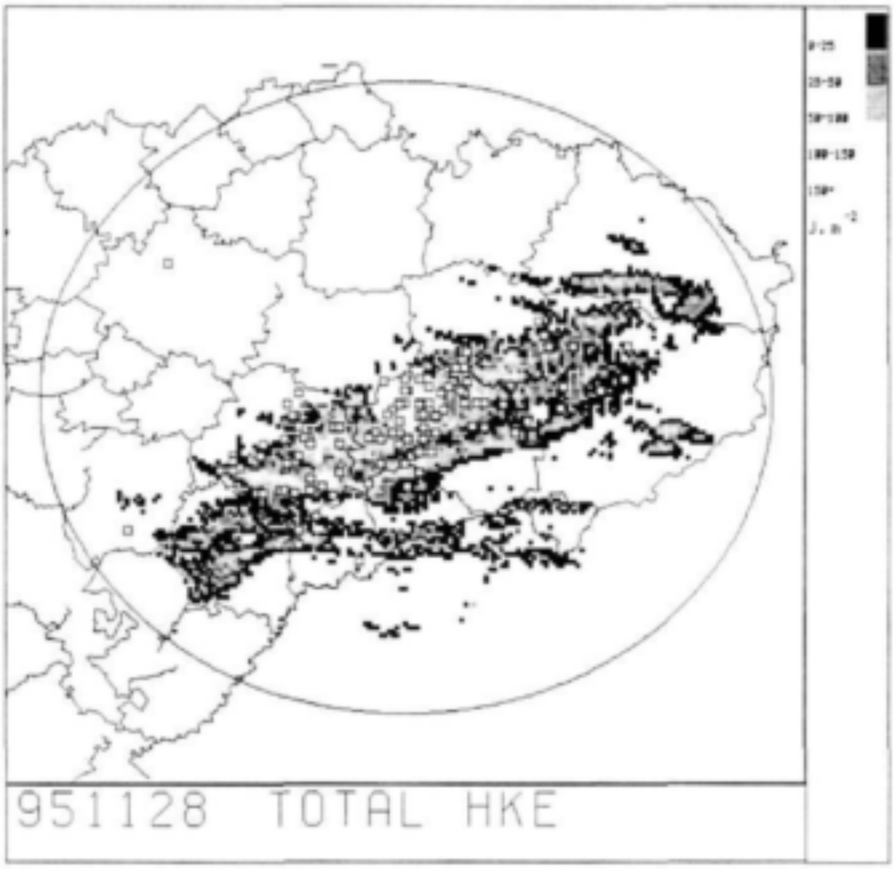


Figure 28. The total hail kinetic energy field for 28 November 1995 derived from using a threshold with a scaling factor. The location of farms with crop damage are indicates by the white squares.

Similar analyses were done using the 50 dbZ and 55 dBZ thresholds. In Figure 29 the distributions of THKE on 28 November 1995 at the farms with crop damage using the 3 radar reflectivity thresholds are shown. When the radar reflectivity threshold was increased to 50 dBZ, 17 of the 92 farm locations did not correlate with the THKE field. 45% of the locations had THKE exceeding 100 J.s^{-1}. With a threshold of 55 dBZ, the detection rate fell dramatically to only 25% of the cases. Clearly, the usage of 55 dBZ as a threshold would be too strict a criterion in this case.

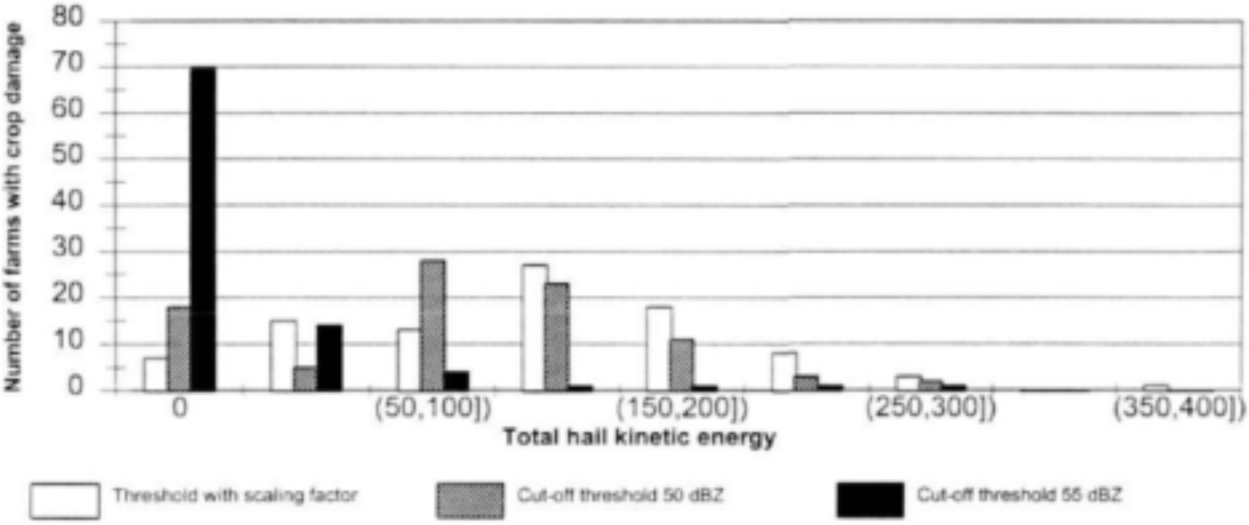


Figure 29. The distributions of THKE on 28 November 1995 at the farms with crop damage with the 3 radar reflectivity thresholds used.

Using the threshold with a scaling factor, 58 of the 62 farms which reported hail were located within the THKE field generated for 22 December 1995. Figure 30 shows the THKE field with the locations of the crop damage reports for 22 December 1995. 62% of the locations had THKE exceeding 100 $J.s^{-1}$. The convective storms of this day, were less organized compared to the 28 November 1995 case and storms were located over the farms for less than an hour. Figure 31 shows the distributions of THKE for 22 December 1995 at the farms with crop damage with the three radar reflectivity thresholds used. When the threshold was increased to 50 dBZ, 10 farms did not correspond with the THKE field and 42% had THKE exceeding 100 $J.s^{-1}$. With the threshold increased to 55 dBZ, 60% of the farms with crop damage were missed by the THKE field.

The threshold with a scaling factor seems to be the most reliable measure of detecting hail locations which correspond with "ground truth" hail reports. Therefore rather than a fixed threshold, a threshold with a scaling factor should be used to calculate HKE. This study suggests that radar reflectivity values below 55 dBZ contains enough hail to cause damage on the ground and therefore also contaminate precipitation measurement. To lower this threshold will risk ignoring all large rain rates contributions. The problem to be solved, is how to handle the transition spectrum between 45 and 55 dBZ to estimate short duration heavy precipitation.

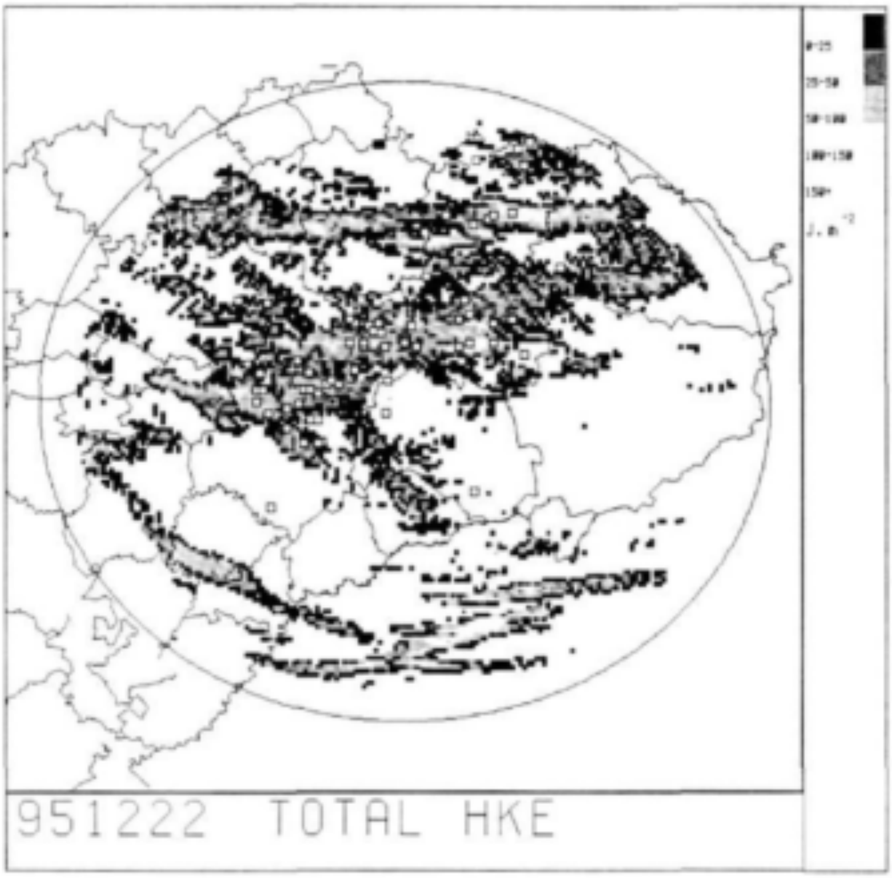


Figure 30. The total hail kinetic energy field for 22 December 1995, derived from a reflectivity threshold with a scaling factor. The location of the farms with crop damage indicated by the white squares.

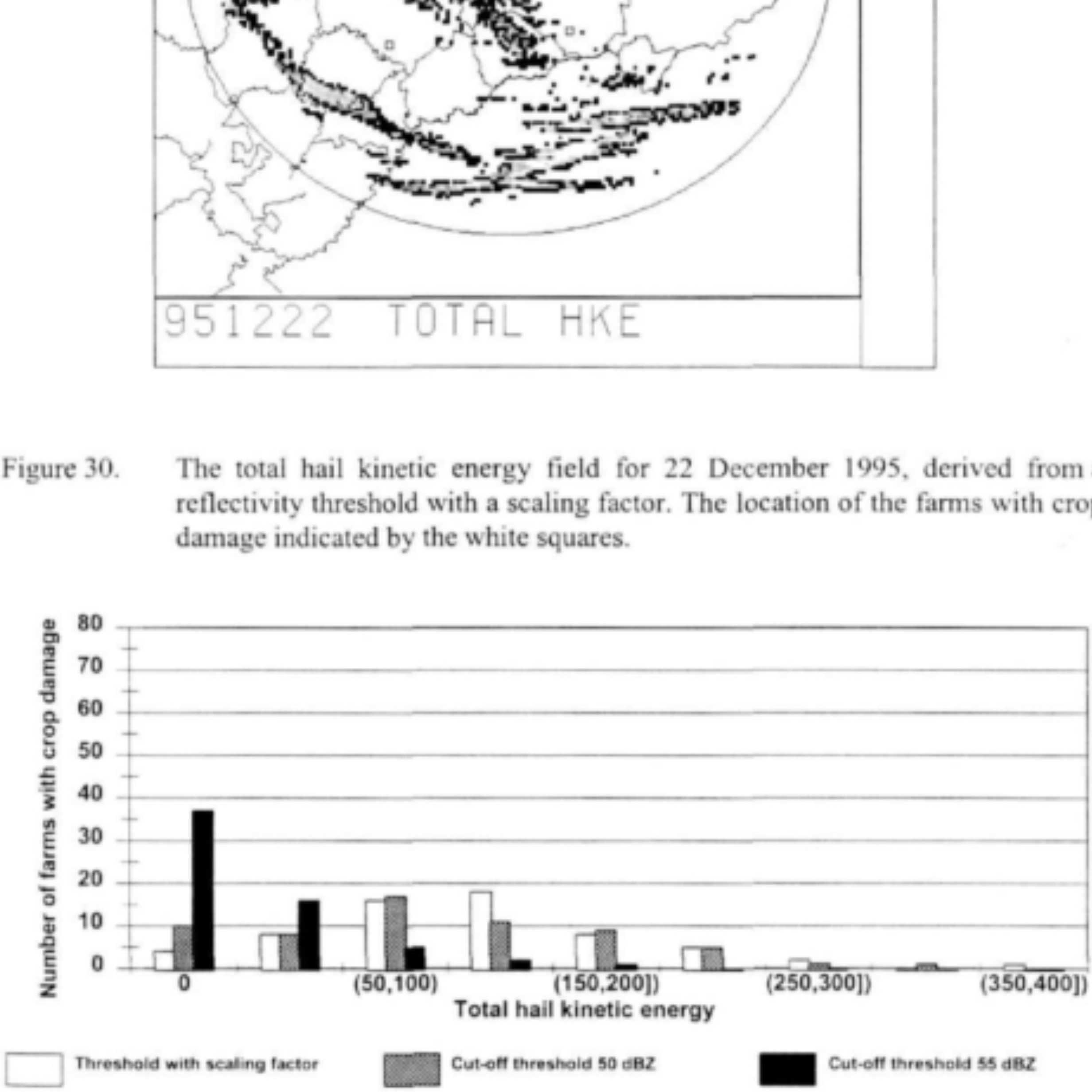


Figure 31. The distributions of THKE on 22 December 1995 at the farms with crop damage with the 3 radar reflectivity thresholds used.

- *The Storm Structure Severity method*

Convective storms consist of various cells in different stages of development. The structure of a vertical column within a convective storm can be obtained by obtaining a vertical distribution of the liquid water content and the average height ($\overline{H}$) of this distribution. When most of the liquid water is located above 8 km above sea level, one can infer that this region of the storm is developing, because strong updrafts must exist to produce this vertical liquid water distribution. Similarly, if most the liquid water is concentrated below 6.5 km above sea level, this region of a storm can either have downdrafts or this is a tropical convective storm with coalescence the major droplet formation mechanism. To obtain a stricter definition of the vertical structure of a column, the height of the maximum reflectivity in the column and the standard deviation (σ) of the inferred liquid water distribution around this level is included. With this, the following structural definition of a convective column, defined as either BASE, VOLUME or TOP is obtained as shown in Table 2. By using the maximum reflectivity a severity index, namely, (WEAK, MODERATE and SEVERE) is attach to each column as shown in Table 3.

Table 2. Structural classification method of convective cells

$\overline{H}$ (km)	σ (km)	Height of maximum radar reflectivity (km)	Structure
< 6.5	< 2.0	Not Applicable	BASE (B)
	≥ 2.0	2-5	BASE (B)
	≥ 2.0	≥ 6	VOLUME (V)
6.5 - 8	< 2.0	Not Applicable	VOLUME (V)
	≥ 2.0	2-5	BASE (B)
	≥ 2.0	6	VOLUME (V)
> 8	< 2.0	Not Applicable	TOP (T)
	≥ 2.0	2-6	VOLUME (V)
	≥ 2.0	≥ 7	TOP (T)

Table 3. Intensity classification of convective cell

Radar reflectivity Indices	**Intensity Classification**
30 - 40 dBZ	WEAK(W)
45 - 55 dBZ	MODERATE(M)
55+ dBZ	SEVERE(S)

When the structural and intensity classification are combined, this leads to a Storm-Structure-Severity classification for each column as shown in Table 4.

Table 4. Classification method of convective cells

	Weak	**Moderate**	**Severe**
Base	Weak Base (WB)	Moderate Base (MB)	Severe Base (SB)
Volume	Weak Volume (WV)	Moderate Volume (MV)	Severe Volume (SV)
Top	Weak Top (WT)	Moderate Top (MT)	Severe Top (ST)

An SSS field can be generated for a volume scanned radar field. An example of such a field is shown in Figure 32 of the Harrismith tornado event on 15 November 1998. The location of developing and decaying columns within the storm are observed.

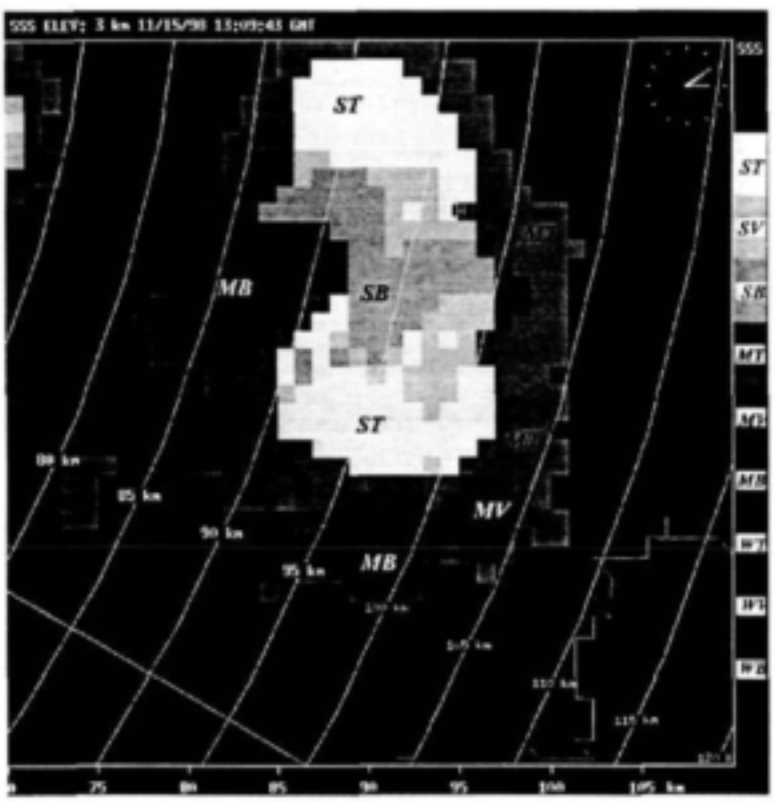


Figure 32. The SSS-field at 13:09 GMT on 15 November 1998 just before the spawning of a tornado.

This SSS-field can be used to identify hail producing storms more easily and assist in adjusting the precipitation fields generated by these convective storms to compensate for high reflectivity due to the presence of hail. The work, making use of HKE and SSS-field to address the higher rain rate estimations will continue.

- *The use of the SSS-method for improved hail fall estimation*

A method, consisting of six steps has been developed using only volume scanned radar reflectivity data to improve hail estimation. Information required for this scheme includes storm tracking information, a field generated by the SSS method and a THKE algorithm.

STEP 1: The storm tracking information from the TITAN (Dixon and Wiener, 1993) storm identification and tracking display system is used. Parameter files used within TITAN are set to perform identification and tracking only on storms with composite maximum reflectivity exceeding 44 dBZ and storm volume exceeding 80 km^3. This reflectivity threshold prevents the storm polygon from being too large for example during general rain conditions. It also restricts the tracking time of storms, since only well structured storms will continue to exceed the set parameters. TITAN does provide for complex tracks where families of merged and split storms are all assigned to similar complex track numbers, while individual storms of the larger family have their own simple track number. Every time a storm merge or split occurs, a new simple track number is tagged to the storm. The simple track numbers are used to keep track of the development history of a storm. For each volume scan the reflectivity centroid of each tracked storm is used as a position for the storm. A circular area, the size of the storm area, is placed in a storm mask field linked to that storm with a special identifier. The storm mask field is the output of the first step. The domain of this field is exactly similar to that of the initial radar field.

STEP 2: The second component of the hail estimation method makes use of the storm-structure-severity(SSS) method. The SSS-method identifies the convective cells where most of the liquid water in the vertical column is concentrated above 8.0 km above sea level. A convective cell is defined as a vertical column, 1 by 1 km pixel area, extending from the lowest CAPPI at 2 km to 18 km above sea level. The SSS method also attaches a reflectivity intensity classification to each convective cell. The SSS method is limited to 100 km range with the scanning strategy used for the MRL-5 radar. From the SSS-method the following SSS-classifications are tagged for exhibiting characteristics for generating hail:

SEVERE TOP(ST) - Convective cells with peak reflectivity exceeding 55 dBZ and in which most of the liquid water in the column is above 8 km above sea level.
SEVERE VOLUME(SV) - Convective cells with peak reflectivity exceeding 55 dBZ and in which most of the liquid water is between 6.5 and 8 km above sea level.
MODERATE TOP(MT) - Convective cells with peak reflectivity between 45 and 55 dBZ and in which most of the liquid water in the column exceeds 8 km above sea level.

This allows the identification of convective cells with strong vertical development or a reflectivity overhang and is used here as a signature for hail formation. Each convective cell with the above mentioned SSS classification as well as the nine surrounding pixels are tagged as having the characteristics for hail generation and placed in a SSS tagged field. In this manner heavy precipitating tropical storms, with the maximum reflectivity below 6.5 km above sea level are excluded.

STEP 3: The SSS tagged field generated in step 2 is then combined with the storm masked field generated in step 1 to produce a final mask to be used in the estimation of HKE for a volume scan. All tagged pixels from the SSS tagged field are automatically transferred to the final mask. If more than thirteen SSS tagged pixels fall within the circular mask of a tracked storm, that storm circular area is included in the final mask field. This requirement was necessary because of spurious occurrences of single, mostly MODERATE TOP's pixels in storm areas, which led to the whole storm being tagged as hail producing. By increasing the occurrence of SSS tagged pixels in a storm to more than thirteen, this problem was solved in the two cases examined.

STEP 4: All the tracked storms, which were tagged by the SSS mask field are assumed to have the capability to produce hail on the ground for the next 30 minutes, despite the fact that they might not exhibit any ST, SV or MT convective cells in their consecutive volume scans. It is thus assumed that storms with the identified SSS structures at a specific volume scan time can still generate hail on the ground 30 minutes after their initial detection. The storm areas of these storms, if they still exist, are automatically included into the future final masks at the positions of the storm centroid at that specific volume scan.

STEP 5: The final mask and HKE field generated using 5 km above sea level reflectivity or approximately 3.3 km above ground in the case of the MRL-5 radar, are overlayed. The HKE is only estimated at the pixel where the final SSS mask is flagged. A weighting factor in the estimation of the HKE (Waldvogel et al., 1978) is used.

STEP 6: The HKE fields produced for every volume scan are accumulated for a 24 hour period to generate the total hail kinetic energy (THKE) field.

- *Results for 28 November 1995*

The farm locations that reported crop damage on this day are indicated by asterisk symbols on Figures 33 and 34. Figure 33 shows the THKE field generated by only using the reflectivity values from the 5 km above sea level CAPPI in the conventional manner. In this case a hail threshold with a weighting factor between 45 and 55 dBZ was used. This produced a widespread distribution of estimated total hail kinetic energy.

Figure 33 differs from Figure 28 because of the use of the 5 km CAPPI here, compared to the 6km CAPPI in Figure 28.

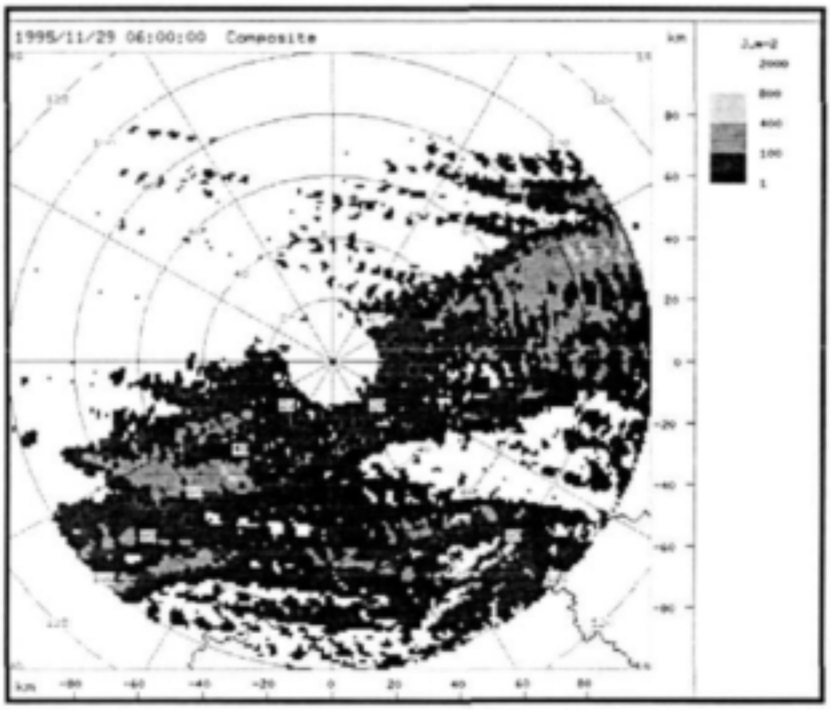


Figure 33. The THKE field generated for 28 November 1995 using the 5 km above sea level CAPPI radar reflectivity field and a threshold with a weight factor between 45 and 55 dBZ. The * indicate the location of farms that reported crop damage.

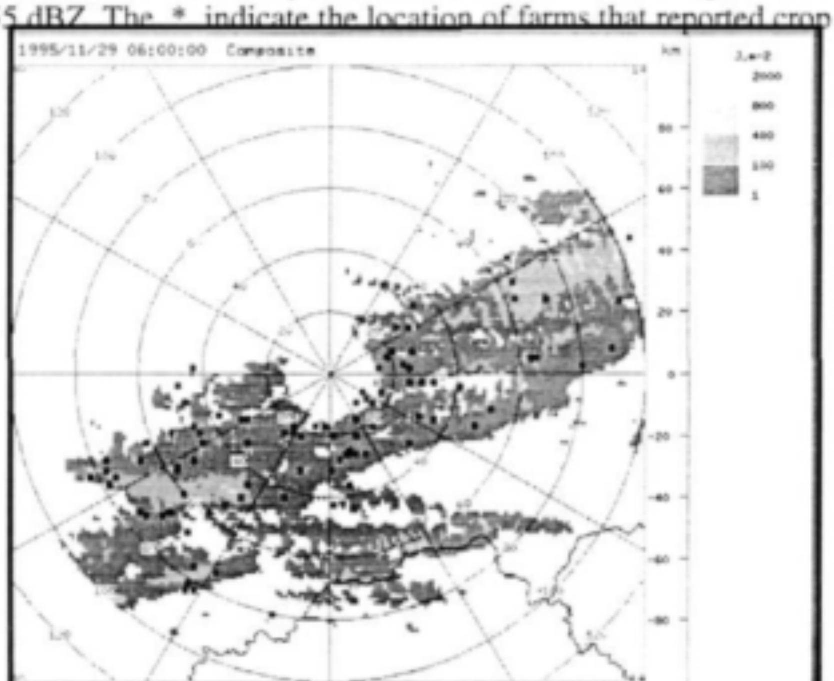


Figure 34. The THKE field generated for 28 November 1995 using the SSS-field to filter storms with no hail. The * indicates the location of farms which reported crop damage.

Visser (2000) found that for this specific case, the thresholds of 50 dBZ and 55 DBZ for HKE calculations were too strict and did not represent the hail field better than the weighting factors between 45 and 55 dBZ used here. The major trajectory southwest to northeast of the hail producing storm complex can be observed by the distribution of the crop damage locations. Figure 34 shows the result of the THKE field after the SSS filter was applied, using the same 5 km above sea level reflectivity CAPPI and the 45 to 55 dBZ weighting factor threshold. The narrowing of the hail field is significant and the farms with crop damage are well within the THKE field. Comparing the crop damage location as well as the difference between Figure 33 and 34, it can be seen that storms not producing hail had trajectories from the northwest to southeast, while those producing hail had trajectories from southwest to northeast. This seems to be a common feature in South Africa.

- *Results of 24 January 1996*

Heavy precipitation during the night resulted in widespread flooding in the eastern Free State on 24 January 1996. In the Liebenbergvlei River which flows in a northerly direction, a peak stream flow of 700 cubic meter per second was recorded, compared to the normal flow of less than 20. No hail damage reports were received for this day. Figure 35 shows the estimated THKE field using a weighting factor between 45 and 55 dBZ. The estimation of hail is widespread and according to the absence of hail reports this is a complete overestimation of hail.

Figure 36 shows the influence of using the SSS method to filter out the convective storms without overhangs and reflectivity exceeding 45 dBZ above 6.5 km above sea level from the calculation of the THKE field. The only storms that generated ST, MT or SV classifications were as shown in Figure 36. These storms occurred during the late afternoon 17:00 South African Standard Time (SAST), while the heavy precipitation which caused the flooding occurred at around22:00 SAST.

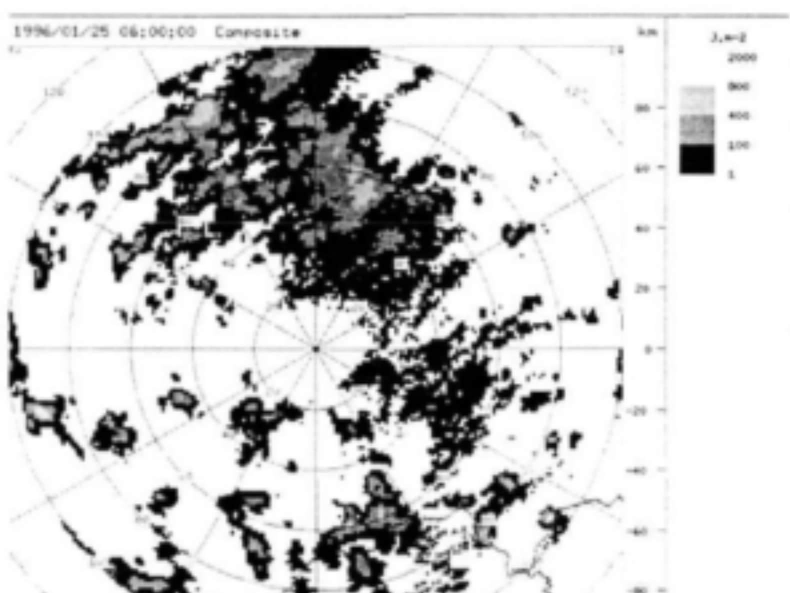


Figure 35. The THKE field generated for 24 January 1996 using the 5 km above sea level CAPPI radar reflectivity field

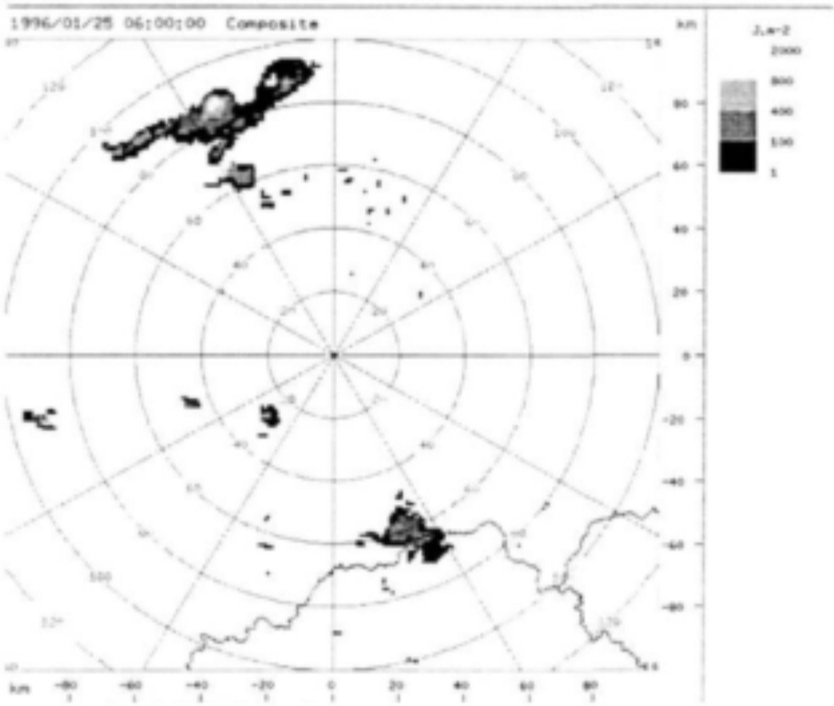


Figure 36. The THKE field generated for 24 January 1996 using the SSS-field to filter storms with no hail.

- *Summarizing the HKE / SSS approach*

Using the THKE obtained from a CAPPI level only 3 km above ground results in large over estimations of hail when a reflectivity hail threshold is used. Higher CAPPI levels can be used, but may not be representative of hail on the ground. The SSS method uses the vertical profile of liquid water content in a column. By including information from the SSS field into the THKE estimation, storms with no hail but heavy precipitation, such as tropical convective storms are identified and not included in the THKE estimation. This proved to be very successful in the case of 24 January 1996 which had very heavy precipitation amounts and no confirmed hail. Furthermore, on days with widespread hail such as 28 November 1995, the inferred hail field was modified less drastically by the SSS field, with the resultant field corresponding well with the observed field.

This method will be improved further, by using the actual 44 dBZ tracked storm polygon and not a circular area centred on the storm centroid. More verification of hail fall estimation on other days will further provide insight on the improvement of the hail field. The case studies presented here are positive signs that the method does significantly improve hail measurement by conventional weather radar.

3.2.9 An independent study on radar rainfall estimation by the MRL-5 radar

In the study by Van Heerden and Steyn (1999) on weather radar measurement of rainfall, the authors compared the MRL-5 S-band rainfall estimates with measurements obtained with a dense raingauge network operated between Bethlehem and Warden. They carried out several case studies of rain events that ranged from time scales of hours to seasons and found many examples where the radar estimates where within ± 10 % of the gauge measurements. There were some cases where the deviation was much larger. They concluded that the Marshall-Palmer Z-R relationship did remarkably well in the area for the various time scales investigated.

Studies of this type are of central importance as they provide independent verification of data quality and reliability.

4 RAINGAUGE MEASUREMENTS

4.1 TIPPING BUCKET RAINGAUGES

The SAWB possesses approximately 90 tipping bucket raingauges (TBRs) which were acquired during the late 1970's and the early 1980's. The two models, OTA and Weathertronics, of TBRs have the same characteristics. They have a resolution of 0.2 mm (minimum required by the WMO for scientific research) and a funnel diameter of 200 mm. These gauges are calibrated by the SAWB using either a static or dynamic calibration method. Data loggers developed in-house are being used. The memory of the data logger can accommodate 2550 tip events which is equivalent to 510 mm of rainfall using a 0.2 mm resolution TBR. During September 1993 the Liebenbergsvlei River raingauge network of 43 tipping bucket raingauges was established and in September 1994 expanded to 45 raingauges (Mather et al, 1997). A network of 26 tipping bucket raingauges was established during the winter of 1994 in the Vaalbankspruit catchment. The gauges were placed on a 5 km grid covering a catchment area in which stream flow was monitored by the Department of Water Affairs and Forestry (DWAF) using a network of stream gauging weirs. However, this network was terminated at the end of the 1998/99 season due to the lack of personnel and useful projects for which the data would be required.

4.1.1 The Liebenbergsvlei catchment raingauge network

This network has a spatial resolution of 10 km and has an areal extent of 4650 km^2. It is characterized by rolling countryside sloping gradually towards the north and bordered by the Rooiberge in the south, on average about 1600 metres above sea level. The network covers the Liebenbergsvlei River catchment that fulfills an important link in the Lesotho Highlands Project. The network area is further subdivided into 6 sub-catchments based on existing stream gauging weirs. Although the initial purpose of the network was to verify possible cloud seeding effect during the National Precipitation Research Programme (Mather et al, 1997), the emphasis has shifted towards complementing radar rainfall estimates and radar research.

The Liebenbergsvlei River raingauge network has been operational for more than 7 years. Although excellent data have been obtained during the long years of service, a point was reached where degradation of the network had occurred. To restore the network to its initial high standard, the following problems needed to be rectified:

- Many of the farms had been vacated since the initial installment and gauges are left unprotected.
- The visual appearance of most gauges was poor due to 6 years of exposure to the elements.
- Uncertainty in the measurements, since the gauges were last calibrated before they were installed.
- Sealed lead acid batteries with a lifetime of approximately 5 years are used, and most needed replacement.
- The data logger design is based on old technology and an upgrade could lead to better measurements.
- The software to process the data was in need of modernization.

The process of restoring the Liebenbergvlei network started during the winter of 1999. Thirty old batteries were replaced with new ones. A status inventory was drawn up for the network and damaged or degraded housings were re-painted. The TBRs that need to be moved to more secure sites are being moved as they are serviced and repaired.

The data processing software for TBR data processing has been significantly modified. This now allows for easy handling of requests for data as well as information on the quality and availability of the data.

4.1.2 The Ermelo raingauge network

The raingauge network installed in the district of Morgenzon, consisted of 16 raingauges. The raingauges collected data for two and a half years and were finally removed in April 1999. The distance to this network, contributed to several discontinuities in the data set, since 4 of the gauges were vandalized or completely removed. Nevertheless, all the available raingauge data have been processed and can still be considered for specific studies. VIPOS has also led the project team to conclude that one such a network is probably good enough for detailed studies, especially if the data within areas of overlap between radars are used optimally for evaluations.

4.2 DAILY RAINGAUGE DATA

4.2.1 Daily and other reporting raingauges in the Vaal Dam catchment

One of the first tasks after the inception of VIPOS was to perform an assessment of the hydrometeorological infrastructure currently operational within the Vaal Dam catchment boundaries. Several government departments, other institutions as well as private individuals measure rainfall for their own purposes without it being reported at a centralized point from where it can be disseminated to interested parties. The purpose of this inventory was two-fold:

- To assess the rainfall measurement infrastructure in the Vaal Dam catchment for the purpose of possible integration with radar rainfall estimates.

- To create awareness of the possible benefits to institutions of cooperating in order to expand the overall rainfall measurement network and to minimize duplication.

Three institutions were identified as being major role players with regards to rainfall measurement in this region, namely:

- Department of Water Affairs & Forestry (DWAF)

- The Climate Section of the South African Weather Bureau (SAWB)

- Agricultural Research Council (ARC)

Each was approached and requested to supply a list of rain gauges operated by them within the boundaries of the Vaal Dam catchment. These lists were then combined into one database representing all ground based rainfall measurement infrastructure within the Vaal Dam catchment. This information is given in Appendix A.

Certain problems encountered by DWAF with their tipping bucket raingauges in the Vaal Dam catchment also received attention. Two of these gauges have been tested and recommendations made on possible modifications to improve their reliability.

From the start of VIPOS, the main stumbling blocks to incorporate surface rainfall measurements appeared to be the following:

- The availability of data from the institutions and lack of mechanisms for data transfer to a central location.
- Time required to access the data.
- Different formats in which data is archived at each institution
- The problems that accumulated rainfall amounts (especially after weekends and holidays) and other discrepancies in the daily rainfall records can cause.

4.2.2 Real-time raingauge data acquisition

A raingauge acquiring data at a single point is the long-standing standard means of measuring precipitation. Data from reporting raingauges are important inputs for validating and integrating radar and satellite derived precipitation fields. One aim of VIPOS was to include daily reporting raingauge information into an integrated system. As a start, data from synoptic reports at 06:00 UT and available daily reporting raingauge data are being ingested into a file on a daily basis. This file is made available at 12:00 SAST. Software has been developed to transfer this file into the MDV format and to generate a daily display of rainfall from the gauges over an area for which a remotely sensed estimated 24 hr accumulated rainfall field is also being obtained.

Although systems are in place, accessibility of daily reporting raingauge data remains a problem. The Climate section of the Weather Bureau has undertaken drastic revision of its data base setup to address the Y2K problem and problems arising from the resignations of several key personnel. This led to the termination of some systems and the rapid creation of an interim new data handling system. The restructuring of the Climate section lead to a long period of uncertainty regarding the data format and systems which will provide daily reporting rain gauge data to this project. A manual system of getting the data from the database, which started in November 1999, ended on 31 December. A suitable new system was only in place in September 2000 for sending daily raingauge data to METSYS in Bethlehem. This system, however, still demands human intervention. This can lead to an unreliable flow of data and, obviously, an automated system is needed.

Data input still needs to be expanded to include other sources of daily reporting rain gauge data, such as those from the Department of Water Affairs and ARC and others. The Climate section is currently engaged in negotiations with these organisations.

5. INTEGRATION OF PRECIPITATION ESTIMATIONS

5.1 A NEW APPROACH TO RADAR-RAINGAUGE INTEGRATION

Both radar and rain gauges are prone to errors in estimating rainfall. The standard raingauge is especially prone to wind errors (Huff, 1971) and also to many human errors. Hail can also constitute a large problem. Using radar, the most important initial consideration is the calibration and the applicability of the Z-R relationship (the relationship used to convert radar reflectivity Z to rain rate R) used. Other aspects such as attenuation, range effects, anomalous propagation and ground returns, the presence of hail or the bright band can also introduce errors to the rainfall estimate. Whilst attenuation and range effects result in a decrease in the returned signal from a target, anomalous propagation and ground returns will cause rain to be estimated where there is none. Hail or the bright band will result in an over-estimation in the rainfall total. The size of hailstones violates the basic assumption that the target diameter must be small compared to the wavelength. The detection of the bright band is linked to the melting layer, where graupel melts and is transformed into relatively large water covered particles. As the reflectivity of water is three times that of ice the returned signal from these relatively large ice particles, covered by a thin water layer, is enhanced.

5.1.1 Data

S-band data collected using the Water Research Commission's (MRL-5 dual-wavelength) radar were used for this study, concentrating on the significant rainfall events between November 1995 and October 1996. These data were processed from spherical to Cartesian co-ordinates using a method devised by Mittermaier and Terblanche(1997), producing a stack of eighteen 200 by 200 km planes at 1 km^2 horizontal and 1 km vertical resolution (referenced to mean sea level), at about 5 minute intervals. Daily rainfall fields were computed using the maximum reflectivity detected in the vertical column (the so-called composite reflectivity) Z and the Marshall-Palmer Z-R relationship (Marshall and Palmer, 1948) $Z = 200\ R^{1.6}$, where R is the rain rate in mm.h^{-1}. Although a maximum range of 75 km for radar rainfall estimation is suggested for shallow stratiform rain (Collier, 1986a; Collier, 1986b; Collier and Knowles, 1986), the range for convective rain, which has a much larger vertical extent, can be increased substantially. This is accomplished by using the composite reflectivity. Data from the 45 METSYS tipping bucket rain gauges in the Liebenbergsvlei catchment were used as the calibrating gauges (Mather et al.,1997). The Liebenbergsvlei catchment is a 4650 km^2 sub-catchment of the Vaal river system in the northeastern Free State.

5.1.2 The technique

The technique suggested for combining the point measurements of rainfall by raingauge and spatial fields of radar estimated rainfall is based on the following algorithm.

The effect that a rain gauge k has on a given radar pixel i is dependent on the Euclidean distance d_{ik} between the rain gauge and each radar pixel in the field (Barnes, 1964; Brandes, 1975). A weight w_{ik} of a given rain gauge's influence on the radar grid is then calculated using a double exponential decay function (eq. (1)) (similar to a Gaussian distribution) and a smoothing factor S, which is determined from the rain gauge density, as follows:

$$w_{ik} = \exp\left(- d_{ik}^{\ 2} / S \right) \qquad i = 1, \ldots, N \tag{1}$$

For the Liebenbergsvlei catchment the rain gauges are 10 km apart, providing a rain gauge density of 1 gauge per 100 km^2.

The nine-pixel daily radar-rainfall average R_k centred on the pixel in which the rain gauge is located is then calculated and the radar-gauge-ratio RGR_k is determined using eq. (2)

$$RGR_k = R_k / G_k \tag{2}$$

where G_k is the daily rain gauge rainfall total.

The wetted-area ratio (WAR) is calculated using eq. (3) :

$$WAR = (N - N_0) / N \tag{3}$$

where N represents the number of pixels in the Liebenbergsvlei catchment and N_0 the number of "dry" pixels; in this case a threshold of 2.5 mm was used to distinguish between a "wet" and "dry" pixel.

The WAR is an indicator of how much of a given area, such as the Liebenbergsvlei River catchment, experienced rainfall exceeding a specific threshold, during a day. Its magnitude is an indicator of rainfall type, in the broadest sense. When the WAR is small only isolated rainfall was experienced. The larger the WAR becomes, the more general the rainfall that occurred. Note, however, that the WAR alone cannot describe the degree of uniformity or homogeneity of the rainfall field. Days with scattered thundershowers and widespread general rain may produce the same WAR but the underlying rain rate distributions are very different. Nonetheless, the WAR is a valuable parameter when determining the influence that raingauge totals should have in the verification and/or modification of a spatially determined radar rainfall field. The reasoning for this is as follows: on days when the WAR is small, the rain gauges may be missing rainfall that is falling between them. Under these conditions the radar is likely to provide a more complete representation of rainfall distribution and the modification of the radar rainfall field using the rain gauge data should be limited. On the other hand when the WAR is large, the rain gauges should be representative of the rainfall and therefore the radar-gauge ratios should be near unity after correction. To achieve this, a linear scaling function F (eq. (4)) was devised so that when WAR is zero the radar rainfall field would not be adjusted at all. On the other hand when WAR is unity, the radar rainfall field is forced to coincide with the gauge measured rainfall at the rain gauge locations.

$$F_k = 1 + WAR * \left(\frac{1}{RGR_k} - 1 \right) \tag{4}$$

A modified rainfall field $R_f(i)$ is then determined using

$$R_f(i) = R_o(i) \frac{\left(\sum_{k=1}^{Ng} w_{ik} * F_k \right)}{\left(\sum_{k=1}^{Ng} w_{ik} \right)} \tag{5}$$

where $R_0(i)$ is the original radar rainfall field, i a specific radar rainfall pixel, and k a given rain gauge in the range of gauges between 1 and Ng.

This algorithm is a departure from the method suggested by Barnes and modified by Brandes. It has the appeal that it explicitly weights the contribution of the gauges in modifying the radar estimated rainfall field based on the WAR, which is a meteorological rather than a mathematical surface fitting technique.

5.1.3 Results

The abovementioned methodology was applied to radar and gauge data for the well-documented rainfall events of the 1995/96 rainfall season (Mittermaier and Terblanche, 1997; Mather et al., 1997; Terblanche, 1996). These are mostly cases in which the WAR was large, with the algorithm thus allowing the raingauge measurements to have a significant effect on the radar estimated rainfall fields. A few cases with small WAR values were also included just to show how they are handled by the algorithm. However, it should be kept in mind that gauges will not sample the rainfall well under these conditions and that the ratios between radar and gauge are not significant. The results for all the cases are summarized whereafter some of the individual cases are dealt with in more detail. Table 5 summarizes all the days that were studied. The columns showing the "ratio at gauges before/after" shows the radar-raingauge ratios at the raingauge sites in contrast to the other ratios (in brackets) that are determined for the whole catchment area. During the period between 42 and 45 of the total 45 rain gauges were in working order.

Table 5. Summary of all the rainfall events studied between November 1995 and October 1996 using all the available Liebenbergsvlei raingauges. The radar-raingauge ratios for the whole catchment area are given in brackets.

Rainfall Measured at 08:00 on	Rain Gauge	Composite radar	WAR	Adjusted	Ratio at gauges before	Ratio At gauges after	# gauges used
950314	2.1	8.4 (3.84)	0.70	7.5 (3.57)	2.26	1.94	45
951129	12.4	25.8 (2.19)	0.95	13.1 (1.06)	2.23	1.27	42
960125	62.0	63.2 (1.02)	0.95	63.8 (1.03)	1.18	1.11	44
960210	1.2	4.3 (3.52)	0.34	4.0 (3.33)	1.27	1.24	44
960211	25.1	18.6 (0.74)	0.95	23.6 (0.94)	0.96	1.05	44
960212	36.2	31.3 (0.86)	0.95	34.0 (0.94)	1.11	1.08	44
960213	0.02	0.53 (26.5)	0.09	0.53 (26.5)	1.00	1.02	44
960214	33.2	34.6 (1.04)	0.95	33.5 (0.97)	1.13	1.07	43
960215	5.2	2.2 (0.42)	0.92	5.0 (0.96)	0.55	1.11	43
960216	11.7	6.3 (0.54)	0.94	11.7 (1.00)	0.62	1.11	43
961030	24.9	42.0 (1.68)	0.98	25.8 (1.04)	1.76	1.09	45
961031	27.8	36.0 (1.29)	0.98	28.1 (1.01)	1.33	1.06	45
Total	241.24	273.23 (1.13)	-	250.63 (1.04)	-	-	-

Results for the linear regression of the unadjusted and adjusted radar estimated rainfall against the raingauge measurements are listed in Table 6 and visually depicted in Figure 37. The correlation coefficient r was computed between the rain gauge totals and the unadjusted and adjusted series. The standard error of the estimates (i.e. the unadjusted and adjusted series) are also listed. The adjusted rainfall totals match the rain gauge totals very closely ($r = 0.99$). More significantly, the standard error of the daily catchment rainfall has been reduced by a factor of 4 by calibrating the radar rainfall field using the Liebenbergsvlei gauges.

Table 6. Summary statistics for the cases examined.

Field	Ratio	Correlation coefficient r	Standard Error (SE)
Unadjusted	1.13	0.92	7.82 mm
Adjusted	1.04	0.99	1.97 mm

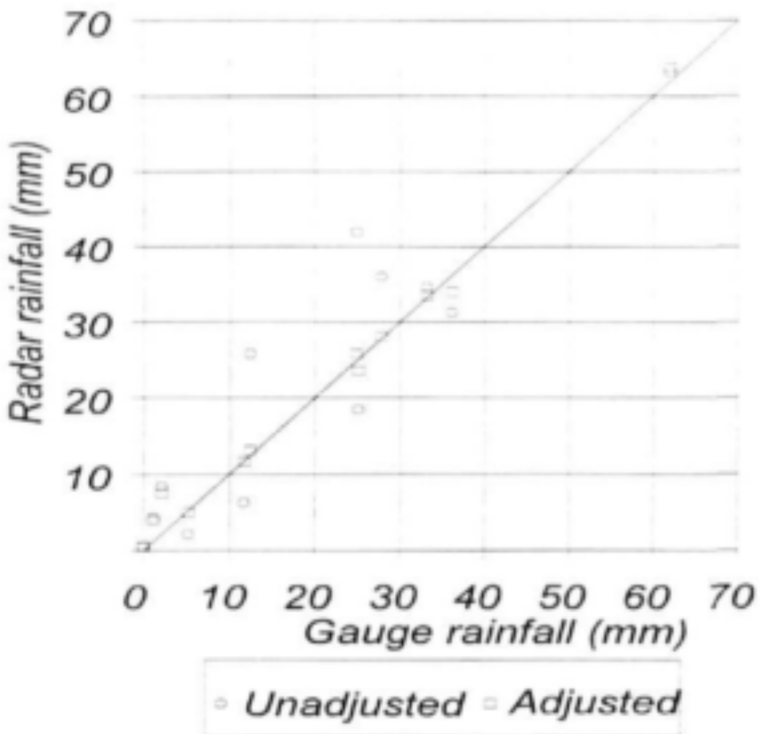


Figure 37. Scatter diagram of daily radar and raingauge estimated rainfall for the Liebenbergsvlei catchment before and after applying the integration technique.

Five of the Liebenbergsvlei raingauges were selected to simulate the typical density of the standard daily reporting gages in order to determine the effect of fewer gauge measurements on the algorithm. In Figure 38a the positions of the all 45 gauges in the Liebenbergsvlei catchment are shown and in Figure 38b the 5 gauges that were selected to simulate the density of the standard daily reporting gauges are indicated.

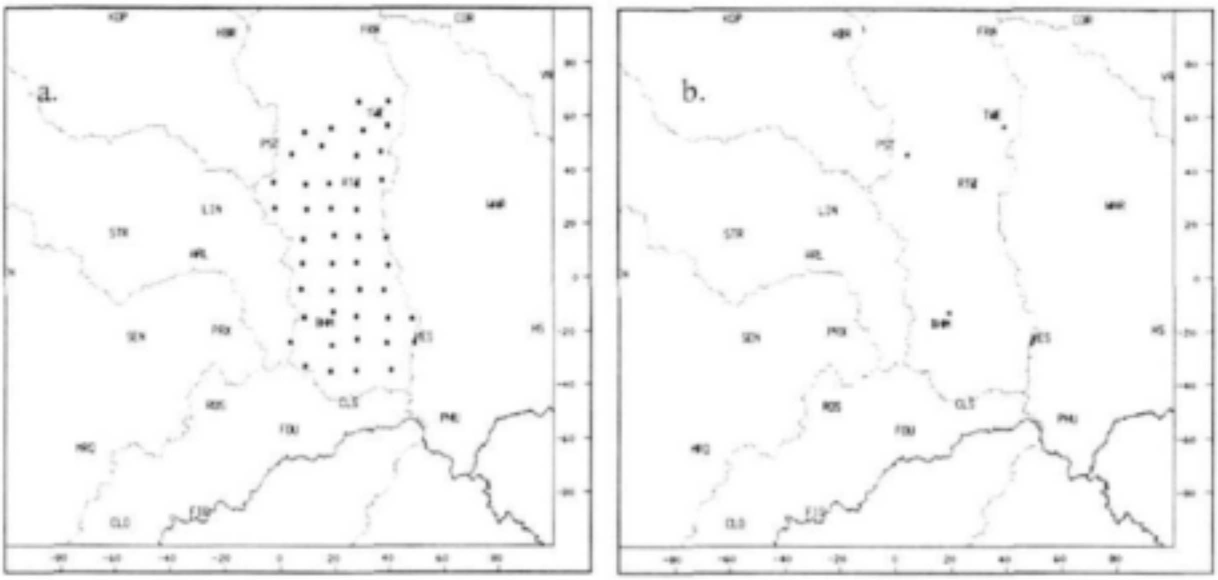


Figure 38. a. The 45 gauges in the Liebenbergsvlei catchment and, b. the 5 gauges selected to simulate the density of the standard daily reporting stations.

- *14 March 1995*

On this day isolated thundershowers occurred over the catchment. The radar rainfall field (Figure 39a) clearly shows that the rain fell predominantly between the rain gauges. The adjusted field, using all the gauges is shown in Figure 39b and that using the 5 gauges in Figure 39c. The algorithm resulted in the field being only slightly modified for both cases. This case was analysed by Mather et al. (1997), Terblanche (1996) and Terblanche et al. (2000). Terblanche et al. (2000) show that the underestimation of the WAR by the gauges explained the difference in the catchment rainfall.

- *29 November 1995*

Hail damage in excess of R 5.6 million was reported as a result of the storms that passed through the eastern Free State districts, R 3.2 million in the Bethlehem district alone (Mather et al., 1997). The presence of hail contaminated the radar–rainfall field as seen in Figure 40a resulting in an over-estimation. Applying the algorithm, using all the gauges brought about a significant improvement in the catchment rainfall total as is evident from Table 5 and Figure 40b. However, using only the selected 5 gauges (Figure 40c) resulted in an erroneous local maximum to the east-northeast of the radar.

- *25 January 1996*

One of the gauges in the Liebenbergsvlei catchment recorded 177.6 mm in less than 12 hours (Mather et al., 1997). This severe local flooding event washed away one of the stream-gauging weirs in the Liebenbergsvlei catchment. It provides an example of radar's superior spatial sampling capabilities – even when large areas are experiencing rainfall, i.e. when the WAR is large. The underlying rainfall formation process was convective and therefore large spatial variations can be expected. The integration with all the rain gauge data causes a slight spatial adjustment rather than a quantitative adjustment, as seen in Figures 41a and b. Using only the 5 selected gauges also produced reasonable results as depicted in Figure 41c.

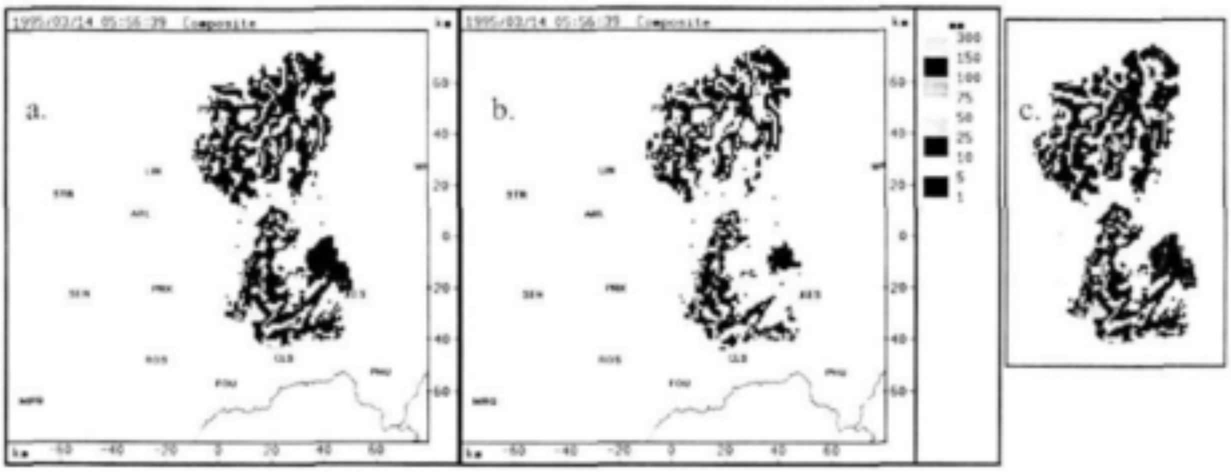


Figure 39. Radar rainfall field for period ending at 08:00 on 14 March 1995: (a). Unadjusted, (b). adjusted with all Liebenbergsvlei raingauge values and, (c). adjusted with 5 raingauges.

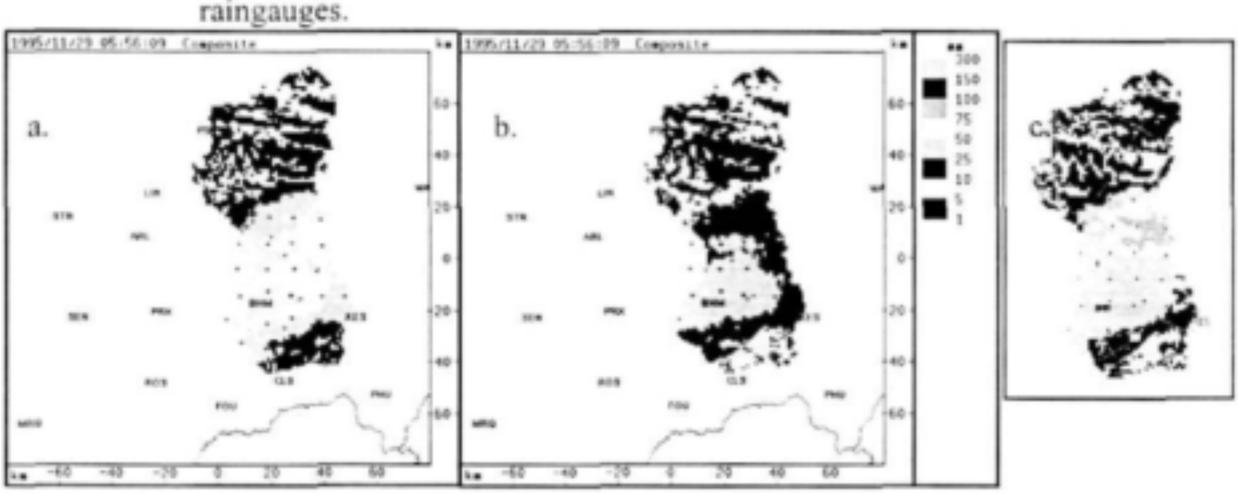


Figure 40. Radar rainfall field for period ending at 08:00 on 29 November 1995: (a). Unadjusted, (b). adjusted with all Liebenbergsvlei raingauge values and, (c). adjusted with 5 raingauges.

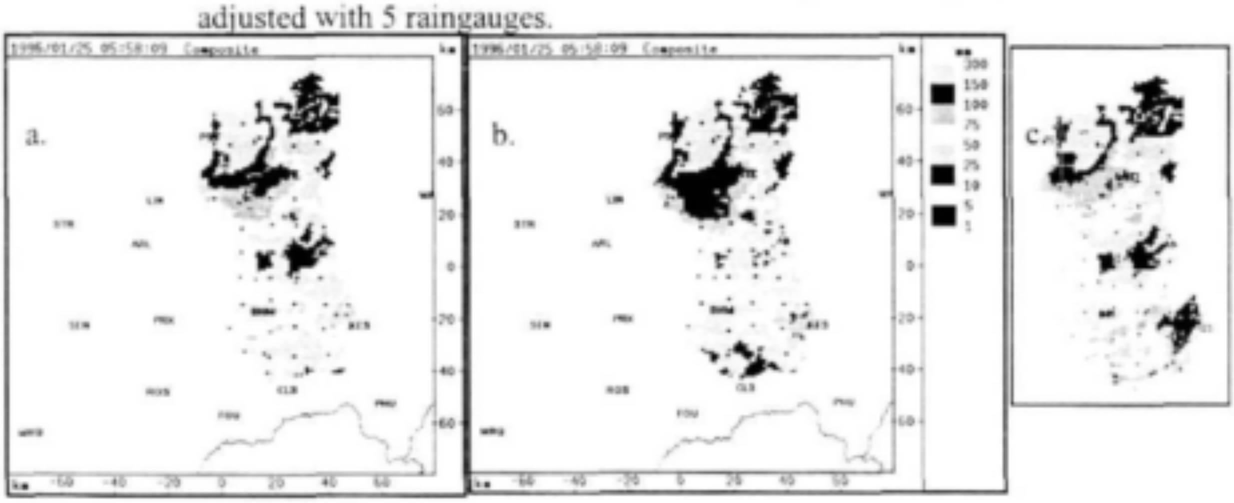


Figure 41. Radar rainfall field for period ending at 08:00 on 25 January 1996: (a). Unadjusted, (b).adjusted with all Liebenbergsvlei raingauge values and, (c). adjusted with 5 raingauges.

From the above it is quite clear that the more gauges used the better the results will be. Furthermore, the method could also hold promise for a less dense network of gauges but it is preferable to first deal with the problems radar has with rainfall estimation(attenuation, range effects, anomalous propagation, ground returns and the presence of hail or the bright band). This method is thus more suited to compensate for a systematic bias in radar estimated rainfall field.

5.1.4 A randomly selected case study using SAWB daily reporting gauges

In the 24-hours before 06:00 Z on 16 January 2000 (a Saturday morning) fairly widespread rain fell over the Vaal Dam catchment. In Figure 42 the mask used for determining the WAR is shown. This mask was chosen to only include areas within 100 km range from the radars at Ermelo and Witbanksfontein to ensure that in the WAR was calculated in those areas where the two radars had a good view of the (shallow) precipitating systems.

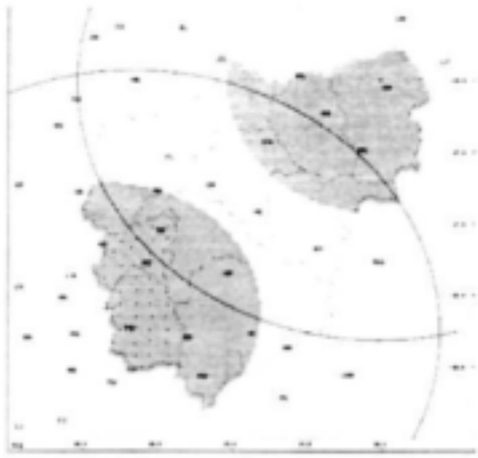


Figure 42. The mask used to determine the WAR for 16 January 2000 case.

Figure 43a shows the 24-hour radar estimated rainfall field and Figure 43b the same field but after applying the integration algorithm using the raingauge information from all 45 raingauges in the Liebenbergsvlei network and the three other daily reporting SAWB gauges from which data were received on that day. This is probably a worse-case scenario in terms of the number of daily reporting raingauge values received. It indicates what can happen and how the resulting changes to the radar estimated rainfall field can present a distorted picture. Obviously the more than 300 mm shown in isolated areas in Figure 43b is wrong. The small changes made by the algorithm suggest that the original radar estimated rainfall field was actually quite good over the Liebenbergsvlei network and that the non-integrated field is probably closer to the true rainfall field. This example shows how important raingauge information is and typifies the problems that occur over weekends, when rainfall collected by raingauges is sometimes allowed to accumulate before measurement.

Rainfall on this day was produced by fairly shallow stratiform precipitating systems, also showing that under these conditions radar rainfall estimation is not good beyond about 75 km range. An additional radar system between the MRL-5 and Ermelo would go a long way towards improving radar rainfall estimates over the Vaal Dam catchment under such conditions.

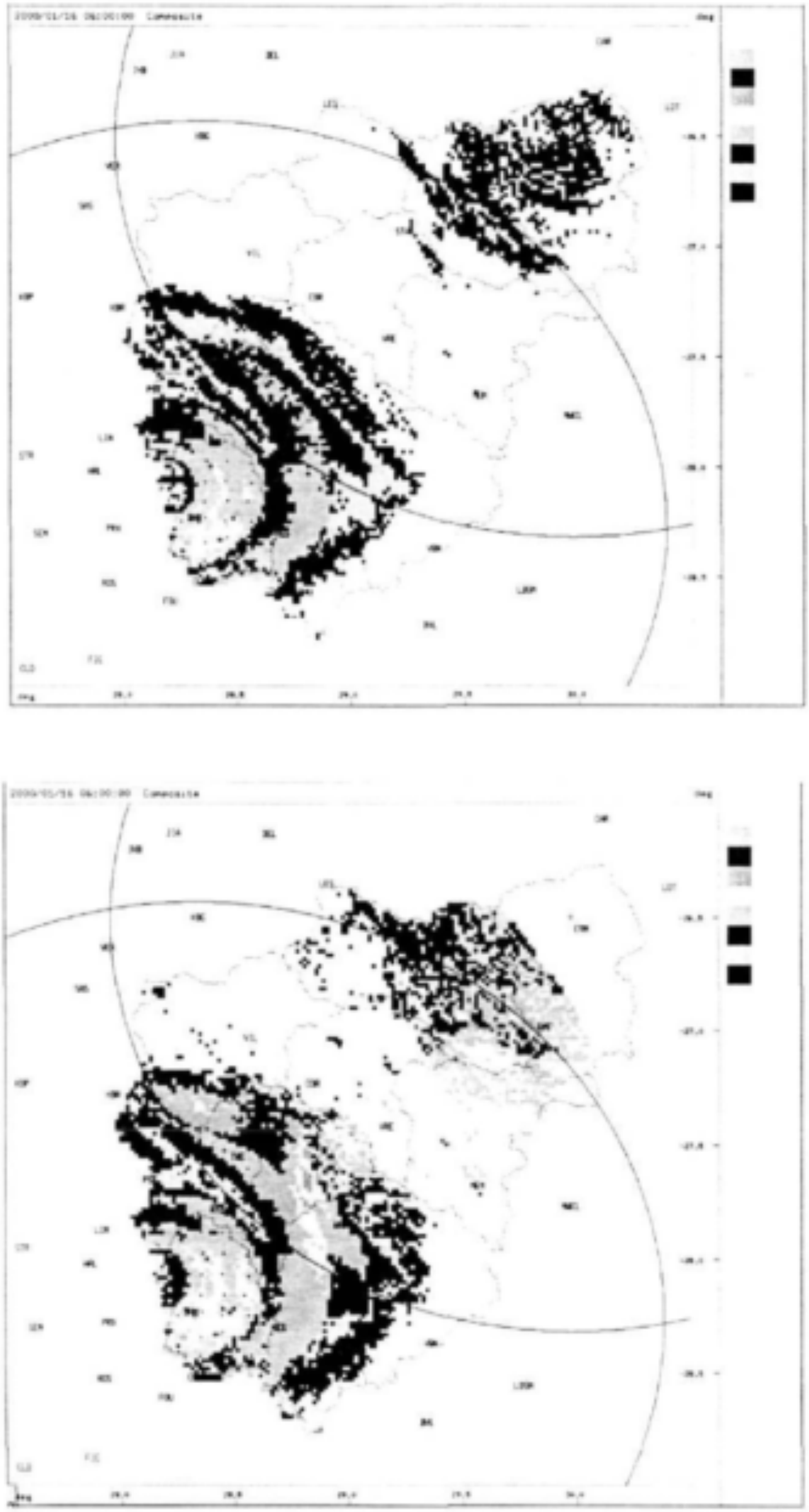


Figure 43. (a). The radar estimated 24-hour rainfall field for 08:00Z on 16 January 2000 and, (b). the field after adjustment with the available raingauge data.

5.2 REPRESENTIVITY OF RAINGAUGE MEASUREMENTS UNDER CONVECTIVE CONDITIONS

There are currently approximately 300 regularly, daily reporting SAWB daily raingauges in South Africa. Given the areal extent of the country (~1.2 million km^2) this implies that there is a rain gauge for every 4000 km^2. This figure is very similar to a situation of having, on average, one daily reporting rain gauge in the size of the Liebenbergsvlei catchment used in this study. Consider a rainfall scenario dominated by isolated thundershowers over the catchment such as 14 March 1995. Figure 44 depicts the frequency distribution of derived rainfall for all the pixels in the Liebenbergsvlei for this day, expressed as a probability P (R = r). Keeping in mind that rainfall can be adequately approximated as a lognormal distribution, if a rain gauge were randomly placed within the catchment, the probability that it would have sampled rain (irrespective of intensity) in excess of 2.5 mm is 0.7 based on the WAR. From Figure 44 a cumulative probability function can be determined which evaluates the likelihood that the rainfall was less than or equal to a given value, i.e. P (R <= r). Using the rainfall distribution for the day and given the average unadjusted estimated catchment rainfall of 8.4 mm, the probability that the rain gauge would have measured less than the this value would be 0.74, as can be inferred from Figure 45. The probability that it would measure less than half (< 4 mm) the radar estimated rainfall would be 0.57 and there is a 0.52 probability that it would record less than a quarter of the radar estimated rainfall. Based on these calculations it can be concluded that for such a rainfall pattern a single rain gauge in such an area will not provide a true reflection of the rainfall that occurred. The likelihood that the rain gauge will frequently underestimate the area rainfall is therefore great. Occasionally it may grossly overestimate the area rainfall (the probability of overestimation is 0.26).

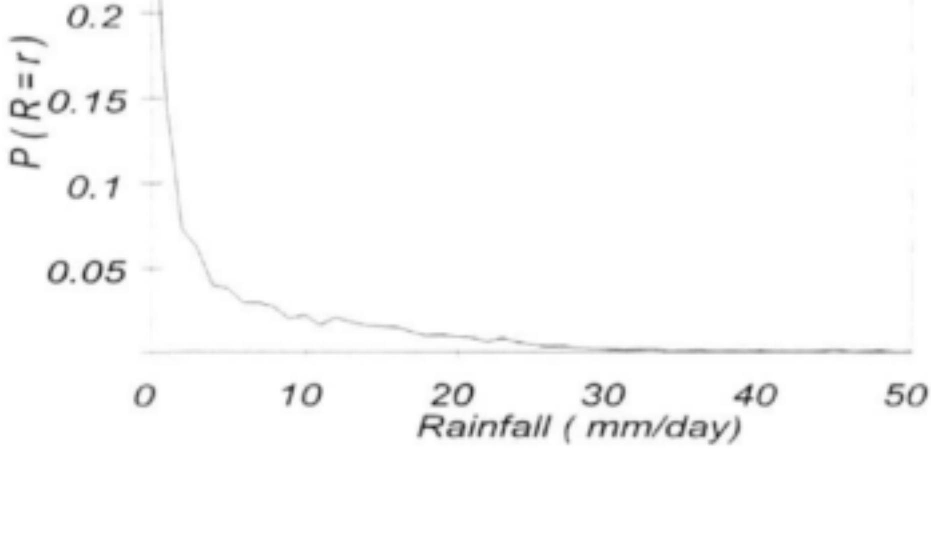


Figure 44. Frequency distribution expressed as a probability of occurrence, of the daily rainfall estimates for all the radar pixels in the Liebenbergsvlei catchment for 14

March 1995. Distribution is truncated at 50 mm.h^{-1} for the figure.

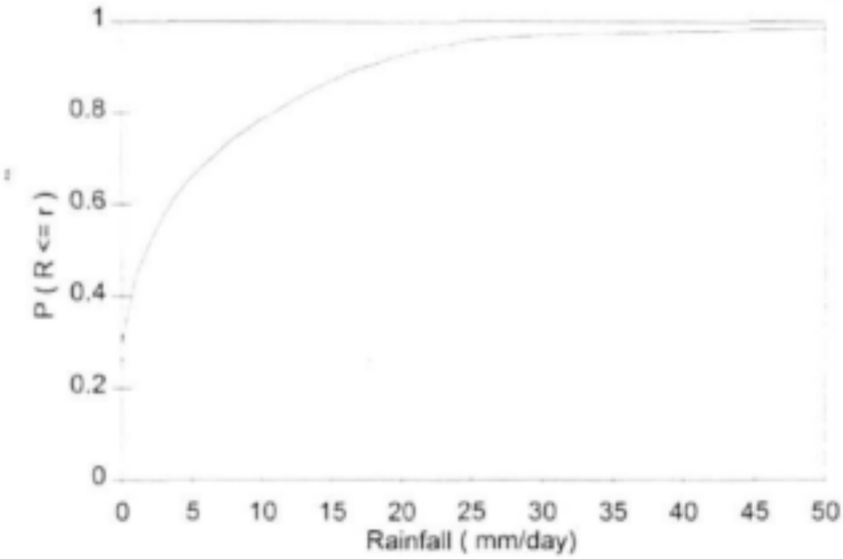


Figure 45. The cumulative probability function for 14 March 1995 where P (R < = r) represents the likelihood that the rainfall is less than r.

5.3 SUMMARIZING PROGRESS AND DECISIONS RELATED TO RADAR-RAINGAUGE INTEGRATION

The new algorithm outlined in Section 5.1.2 that facilitates the integration of radar estimated rainfall and daily rain gauge totals, improved the spatial rainfall estimates for the described dense network scenario provided by the instrumented Liebenbergsvlei catchment. The results of the study reported on in the previous sections represent ideal conditions, i.e. a regularly spaced network of rain gauges at ranges within 50 km from the radar. Within this framework real improvements can be made to quantitative catchment rainfall estimates even if the radar-rainfall field was contaminated by the occurrence of hail or a bright band. It is however strongly advisable to eliminate these sources of contamination before any integration of radar-rainfall and rain gauge data are attempted when the spacing of gauges is sparse, irregular and far from the radar site. Future work will focus on the integration of radar-rainfall fields with the sparse data density that is available on a day-to-day basis. The spacing of radars in South Africa is not ideal for rainfall estimation over the entire country and therefore satellite estimates of rainfall will need to be incorporated to provide complete coverage. In the light of above it was decided to address the operational integration process as a part of the new Spatial Interpolation and Mapping of Rainfall (SIMAR) programme where satellite information will play an important role. During the year of overlap between VIPOS and SIMAR good progress has been made with the integration and data preparation process.

In the meantime products are available on the web where the user can access both radar estimated rainfall fields and figures for the various sub-catchments of the Vaal Dam catchment, as well as the data from the daily reporting stations available through the Climate section of the Weather Bureau. An example of the products is shown in the next section. A further example, for a day when the MRL-5 radar had calibration problems early in the 2000/2001 summer season, is presented and discussed in Appendix D.

5.4 DISSEMINATING DATA

5.4.1 Products available on the Internet

Under the option "rainfall" and "Vaal Dam catchment and subcatchment maps", the following products are available on the internet at ***http://metsys.weathersa.co.za*** :

- Previous day's 24-hour rainfall map - updated at 06:00 GMT:

This provides a radar estimated rainfall field with the Vaal Dam catchment and subcatchments as background. The average subcatchment rainfall figures are shown at the top of the figure and plotted in each of the subcatchments. An example of this product is shown in Figure 46 a.

- Table of previous day's accumulated rainfall over subcatchments of the Vaal Dam - updated at 06:00 GMT:

Half-hourly accumulations of average subcatchment rainfall figures for each of the subcatchments are provided in spreadsheet format. An example of this product is shown in Table 7.

- Previous day's 24-hour sub-catchment totals and raingauge measurements - updated at 09:30 GMT:

A map of daily reported rainfall figures plotted on a map with the Vaal Dam catchment and subcatchments as background is presented. Also shown are the radar estimated average subcatchment rainfall figures. In Figure 46 b an example of this product is given.

- Present day's rainfall map - updated every 30 minutes from 06:30 GMT:

This shows the present day's accumulated radar-estimated rainfield, commencing 06:00 GMT. As in the first map but for the present day.

- Previous hour's rainfall map - updated at 10 minute intervals:

This shows the accumulated rain for the past hour, with updates at 10-minute intervals.

- Download archives:

GIF images of 24-hour radar-estimated rainfall fields of the Vaal Dam catchment.

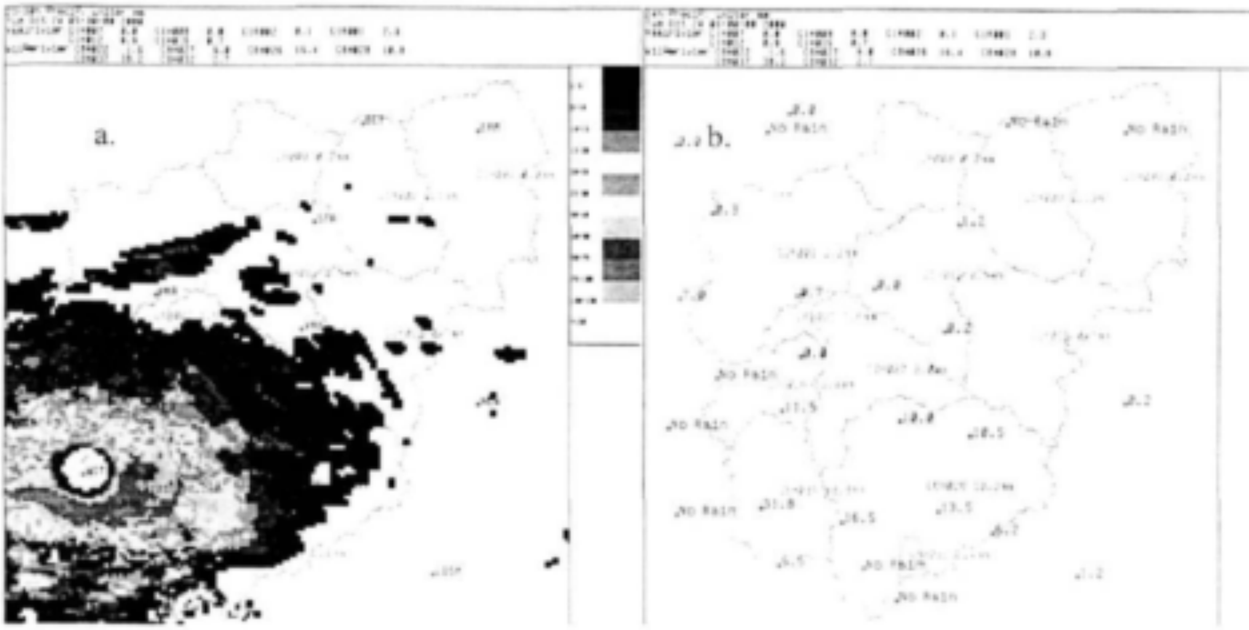


Figure 46. Example of the information made available on the web: (a). The previous day's 24-hour radar estimated rainfall field over the Vaal Dam catchment (the first option) and (b). The radar estimated sub-catchment rainfall and 24 hour rainfall figures from daily reporting gauges (the third option).

Table 7. Half-hourly accumulated radar estimated rainfall for the various sub-catchments of the Vaal Dam (the second option).

	C1H007	C1H008	C1R002	C1R001	C1H012	C1H015	C8H022	C8H027	C8H026	C8H028	C8H037	C8H032
20001023063000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
20001023070000	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.2	0.1	0.1	0.0
20001023073000	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.4	0.2	0.1	0.0
20001023080000	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.4	0.2	0.2	0.0
20001023083000	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.4	0.3	0.2	0.0
20001023090000	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.4	0.4	0.4	0.0
20001023093000	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.4	0.5	0.6	0.0
20001023100000	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.4	0.6	1.1	0.0
20001023103000	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.4	0.7	1.4	0.0
20001023110000	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.4	0.8	1.6	0.0
20001023113000	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.4	1.0	1.9	0.0
20001023120000	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.4	1.2	2.1	0.0
20001023123000	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.4	1.3	2.2	0.1
20001023130000	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.4	1.4	2.3	0.1
20001023133000	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.1	0.4	1.5	2.4	0.1
20001023140000	0.0	0.0	0.0	0.7	0.0	0.1	0.0	0.1	0.4	1.6	2.5	0.1
20001023143000	0.0	0.0	0.0	1.1	0.0	0.1	0.0	0.1	0.4	1.6	2.6	0.1
20001023150000	0.0	0.0	0.0	1.2	0.1	0.1	0.0	0.1	0.4	1.6	2.8	0.1
20001023153000	0.0	0.0	0.0	1.2	0.1	0.1	0.0	0.1	0.4	1.7	2.9	0.1
20001023160000	0.0	0.0	0.0	1.2	0.1	0.1	0.0	0.2	0.4	1.7	3.0	0.1
20001023163000	0.0	0.0	0.0	1.3	0.1	0.1	0.0	0.2	0.4	1.7	3.9	0.1
20001023170000	0.0	0.0	0.1	1.2	0.1	0.1	0.0	0.2	0.4	1.8	5.4	0.1
20001023173000	0.0	0.0	0.1	1.2	0.1	0.1	0.0	0.2	0.4	2.0	5.9	0.1
20001023180000	0.0	0.0	0.1	1.3	0.1	0.1	0.0	0.2	0.4	2.2	7.0	0.4
20001023183000	0.0	0.0	0.1	1.3	0.1	0.1	0.0	0.2	0.4	2.3	10.2	0.4
20001023190000	0.0	0.0	0.1	1.3	0.1	0.1	0.0	0.2	0.6	2.9	13.6	0.7
20001023193000	0.0	0.0	0.1	1.2	0.1	0.1	0.0	0.8	3.1	3.8	15.9	1.3
20001023200000	0.0	0.0	0.1	1.4	0.1	0.1	0.0	1.9	8.3	5.2	19.6	1.3
20001023203000	0.0	0.0	0.1	1.9	0.1	0.1	0.7	4.4	12.5	6.8	26.4	2.3
20001023210000	0.0	0.0	0.1	2.1	0.2	0.3	1.3	7.3	15.3	8.3	33.2	2.3
20001023213000	0.0	0.0	0.1	2.2	0.8	0.6	1.4	8.8	16.2	9.6	35.7	2.7
20001023220000	0.0	0.0	0.1	2.2	0.9	0.7	1.6	9.0	16.3	10.1	35.9	2.7
20001023223000	0.0	0.0	0.1	2.2	0.9	0.7	1.6	9.0	16.3	10.2	36.3	2.7
20001023230000	0.0	0.0	0.1	2.2	0.9	0.7	1.6	9.0	16.4	10.2	36.6	2.7
20001023233000	0.0	0.0	0.1	2.2	0.9	0.7	1.6	9.0	16.4	10.3	36.7	2.7
20001024000000	0.0	0.0	0.1	2.2	0.9	0.7	1.6	9.0	16.4	10.3	36.8	2.7
20001024003000	0.0	0.0	0.1	2.3	0.9	0.7	1.6	9.0	16.4	10.4	37.0	2.7
20001024010000	0.0	0.0	0.1	2.3	0.9	0.7	1.6	9.0	16.4	10.4	37.1	2.7
20001024013000	0.0	0.0	0.1	2.3	0.9	0.7	1.6	9.0	16.5	10.5	37.3	2.7
20001024020000	0.0	0.0	0.1	2.3	0.9	0.7	1.6	9.0	16.5	10.6	37.4	2.7
20001024023000	0.0	0.0	0.1	2.3	0.9	0.7	1.6	9.0	16.4	10.6	37.5	2.7
20001024030000	0.0	0.0	0.1	2.3	0.9	0.7	1.6	9.0	16.4	10.6	37.6	2.7
20001024033000	0.0	0.0	0.1	2.3	0.9	0.7	1.6	9.0	16.4	10.7	37.7	2.7
20001024040000	0.0	0.0	0.1	2.3	0.9	0.7	1.6	9.0	16.4	10.7	37.9	2.7
20001024043000	0.0	0.0	0.1	2.3	0.9	0.7	1.6	9.0	16.4	10.7	38.0	2.7
20001024050000	0.0	0.0	0.1	2.3	0.9	0.7	1.6	9.0	16.4	10.7	38.0	2.7
20001024053000	0.0	0.0	0.1	2.3	0.9	0.7	1.6	9.0	16.4	10.8	38.2	2.7
20001024060000	0.0	0.0	0.1	2.3	0.9	0.7	1.6	9.0	16.4	10.8	38.3	2.7

5.4.2 Data archiving

Through the Internet (http://metsys.weathersa.co.za) a user can obtain archived GIF images for the 24-hour radar estimated rainfall fields over the Vaal Dam catchment. These images include the subcatchment rainfall figures for the same 24-hour period and are similar to the example shown in Figure 46 a. The basic reflectivity data, as collected through the network in real time, the merged fields and products derived from these data are archived in Bethlehem in the standard MDV format. This information can be obtained by contacting the METSYS offices in Bethlehem directly through the address provided on the webpage. All reasonable requests will be dealt with and especially so if they are in support of research and training.

In the long term it is the intention that some of the basic information will be made available through the Climate Section of the Weather Bureau but the detail of this arrangement still needs to be negotiated.

6. CONCLUSIONS AND THE WAY FORWARD

Taking the original VIPOS aims one by one, the following progress has been made:

- Further exploiting the capabilities of the MRL-5 dual-wavelength (S-and X-band) radar and related infrastructure at Bethlehem for refinement of the radar-based techniques for areal rainfall measurement.

The combination of the MRL-5 radar and the Liebenbergsvlei network of raingauges continued to play a central role in investigations dealing with those issues that have a detrimental effect on radar rainfall estimation. These include a method of using composite reflectivity (the maximum reflectivity in the vertical column at each point) for rainfall estimation which extends the range of useful data under especially convective conditions. Although this method can also introduce problems, its goes a long way in compensating for the less than ideal spacing of the weather radars in the South African network. A mathematical procedure has also been developed to adapt the Z-R relationship using the information from the gauge network and the customary Marshall-Palmer based radar rainfall estimates. Furthermore, a method was also developed to extract hail information from volume-scan radar data with the dual advantage of identifying hail storms from radar information but also in the context of VIPOS to discriminate between storms with the same reflectivity values that produce hail and those that don't in order to make more objective corrections to the radar estimated rainfall fields. A member of the VIPOS team received an MSc degree at the University of Pretoria for the work on using radar for the identification of hail. The "bright band" also received attention during VIPOS with another project team member receiving an MScEng degree at the University of Natal for a method developed to deal with this issue. Although no new progress was made with more sophisticated ground clutter suppression methods, a standard "clutter map" method for the partial removal of ground clutter has been introduced at all the radars in the network. Ground clutter and anomalous propagation are problems on the MRL-5 radar due to its fairly wide beam width, its location and purely due to the fact the ground clutter to weather ratio is higher at S-band than at shorter wavelengths.

- Transferring refined radar-rainfall measurement technology to other (C-band) radar installations potentially contributing to overall coverage of the Vaal Dam catchment, testing the technology and making necessary adaptations.

More progress in this regard has been made than initially anticipated with the development of the MDV-based radar networking system and with all its components (RDAS, CAPPI generation software, TITAN) being introduced on all 11 operational weather radars in South Africa. During 1998 and 1999 restructuring of the components within the Weather Bureau that deal with radar resulted in increased responsibilities for the project team. The networking system was also designed to support the many other uses of radar information which include rainfall enhancement experiments, short term weather warnings and forecasts as well as the needs of the aviation industry. Although these developments had some negative impacts on the scientific depth of progress made, they augurs well for the future. The National Radar Network and its applications can now be dealt with in a more holistic fashion. Operating such a network is placing quite a strain on the personnel, many of whom are still technically relatively inexperienced and busy with on-the-job training. Inter-calibration problems with the radars emerged as one of the major problems to deal with. This is not unique to South Africa, as this issue is still central to many arguments related to the USA's primary radar network (NEXRAD). The project team attempted to address this problem and learn more about it by conducting a number of unique case studies on the statistics of radar data in the overlap areas and even including data from the TRMM satellite's Precipitation Radar (which was also converted to the MDV format). Some of these discrepancies are still not understood fully but will remain high on the list of priorities. Discussions are underway with Dr Mike Dixon at NCAR to develop software that will form an integral part of the MDV networking system and that will produce the intercomparison statistics in real time for the whole network. Of great concern, especially during the 2000/2001 financial year, was the severely limited budget available for the network as a whole. The available funds available at the SAWB represent less than 10% of the budget that was estimated as necessary to operate this country-wide network in a professional and sustainable manner. This issue needs high level and urgent attention.

- Locating and calibrating other potential useful rainfall-measuring devices in the Vaal Dam catchment and linking them, together with the radar installations, into a fully integrated precipitation observing system, specifically for hydrological applications.

A thorough inventory of the conventional rainfall measurement systems in the Vaal Dam catchment was compiled as part of VIPOS. It was, however, realised during VIPOS that the daily reporting raingauge information in South Africa represents a major problem as ownership is scattered amongst a number of institutions and formats, etc., differ. The SIMAR (Spatial Interpolation and MApping of Rainfall) umbrella programme, which aims to produce an country-wide, integrated, daily rainfall map based on satellite, radar and raingauge information and which overlaps with, and builds on VIPOS, is absolutely dependent on this information. The project team came to the conclusion that this issue should be addressed at a national level and those sections within the Weather Bureau ultimately responsible should be assisted and motivated to take up this challenge. In this regard the VIPOS project team initiated discussions with, and between the various owners of this information. Although the whole issue has not been resolved, a communications system to deal with this data has been developed and is in use. At this stage the system sends the (~300) daily reporting raingauge data available at the Weather Bureau's Climate section to Bethlehem each morning. As more information becomes available at the Climate section it will simply be added. Software has also been developed to convert the data to the MDV format which will facilitate merging and comparison with radar and satellite estimated rainfall fields. Towards the end of VIPOS the project team also undertook to test, repair and calibrate the DWAF tipping bucket raingauges in the Vaal Dam catchment.

Although satellite rainfall estimation did not form a part of VIPOS, it was recognised early on that this type of input will be crucial in improving rainfall estimation. Apart from the progress made by one of the project team members on satellite rainfall estimation, for which he is also still enrolled at the University of Natal despite leaving the Weather Bureau, a real-time system was introduced during 2000 to transmit the satellite information from the receiving equipment in Pretoria to Bethlehem. This information is converted to the MDV format to ensure data compatibility.

The components for a fully integrated precipitation observing system, on a national scale, are now in place with many of the underlying studies completed. A fully operational system is not in place at the end of VIPOS and in this respect this ambitious aim was not reached. It is however believed that the SIMAR programme will deal with this complex issue in a more holistic manner and significant progress has been made in the theoretical design and developments needed for the integration process.

- Developing appropriate software and communications systems needed to underpin the precipitation observing system and ensure operational reliability within the water resources management context.

Cooperation between the project team and Dr Mike Dixon from NCAR during VIPOS has led to the state-of-the-art MDV-based radar networking system. This system is a unique combination of South African developed hardware and software, data merging software developed by Dr Dixon and the TITAN system. During the course of VIPOS, this system was gradually extended from those radars that contribute to the Vaal Dam catchment to eventually include all 11 radars in the network. In some respects this system is the most sophisticated in use in the world, especially as three dimensional data are available for merging in Bethlehem. During the project period the Weather Bureau's Frame Relay Network also came on line and after several upgrades is proving to be a viable means of radar data communication.

- Design a spatial database in which data from the observing system, appropriately processed, can be stored and from which it can be withdrawn in near-real time for hydrological and modelling purposes.

The underlying MDV data format of the networking system also forms the basis of the TITAN-based data archiving system were data are stored in directories divided according to type and date. As TITAN was originally conceived as a research tool, a thorough job was done in ensuring that archived data is dealt with in a manner needed to underpin research needs and therefore the access to historic data is straightforward. All radar, satellite and raingauge data and derived products are stored in the archiving systems which allow the same analysis and display systems to be used.

- Ensuring the long-term sustainability of the observing system through the training and transfer of scientific and technical expertise.

The restructuring of the Weather Bureau's radar components which culminated in the METSYS section in 1999 has been the major development on this front. It has now become possible to have constructive feedback between scientists and technical staff. At the same time 13 data technologist posts were created in METSYS and these posts were filled with a representative cross section of the population. Significant progress has, therefore, been made during the past year in attracting and training a new generation of technicians in weather radar.

From the above it is clear that most of the aims were satisfied and in some cases more achieved than originally envisaged. However, in terms of aim two, which deals with the fully integrated working system the team fell short but we are full of confidence that this will be dealt with as part of SIMAR which will encompass the whole country and in which the Vaal Dam catchment will remain of central importance.

The overall, long term funding of the National Radar Network needs urgent attention. There is a real danger that the expertise and achievements to date can be lost, as has happened in the past, if this issue is not addressed. There are critical areas that are still not sufficiently covered by radar in South Africa and this needs urgent attention. As discussed in this report, even the coverage over the Vaal Dam catchment can benefit from a additional radar system in the Standerton area to ensure that the 100 km range of useful precipitation estimates are not exceeded.

In this study it also became clear that the quality and reliability of data received from the daily reporting raingauges are of central importance. There are threats to this dwindling infrastructure and a concerted effort is needed to ensure that this valuable asset is not allowed to deteriorate further.

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The work reported in this progress report is the result of a team effort and close cooperation between scientists, technicians and information technology staff of the Weather Bureau, and contracted parties. Professor Geoff Pegram, from the University of Natal has played a constructive role in this project through his involvement with the studies of several team members as well as in his assistance in the development of the radar-raingauge integration technique. The authors are particularly grateful to the technical and IT staff of the METSYS section of the Weather Bureau (including the contracted parties) who have been under tremendous pressure in the last few years with all the changes in the radar network and its utilization.

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The research team is also grateful for contributions made by the steering committee consisting of:

Dr G.C. Green (Chairperson)
Mr H. Maaren
Mr E. Poolman
Mr S. van Biljon
Prof G.G.S. Pegram
Mr S.D. Lynch
Prof J. van Heerden
Dr R.S. Mckenzie
Mr K. Monnik
Mr W.J. van den Berg
Ms B. van Wyk
Mr M. Summerton
Prof S. Walker
Mr S.D. de Kock

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APPENDIX A.

RAINGAUGE INFRASTRUCTURE IN THE Vaal Dam CATCHMENT

Town/Farm	LAT	LONG	Institution	Contact	Address	Code
Oorsprong-Oos	2708	2757	ARC-ISCW			
Schoongezicht	2724	2802	ARC-ISCW			
Turffontein	2716	2822	ARC-ISCW			
Catharinasvlei	2712	2835	ARC-ISCW			
Vrede-TNK	2725	2910	ARC-ISCW			
Paardekopplaas	2711	2938	ARC-ISCW			
Rietpoort	2707	2951	ARC-ISCW			
Vaaldam-Pol	2653	2807	ARC-ISCW			
Oranjeville -Skl	2659	2813	ARC-ISCW			
Schikfontein	2636	2814	ARC-ISCW			
Middelpan	2658	2823	ARC-ISCW			
Balfour-Mag	2639	2835	ARC-ISCW			
Rietbult	2637	2836	ARC-ISCW			
Greylingstad-SAR	2645	2845	ARC-ISCW			
Sandbaken	2645	2900	ARC-ISCW			
Standerton	2656	2914	ARC-ISCW			
Amersfoort-SAp	2700	2952	ARC-ISCW			
Goedehoop	2643	2959	ARC-ISCW			
De Emigratie	2646	3007	ARC-ISCW			
Blaawkop	2631	3016	ARC-ISCW			
Sheepmoor-SAP	2643	3018	ARC-ISCW			
Doornkuil	2627	2754	ARC-ISCW			
Heidelberg	2630	2821	ARC-ISCW			
Tweefontein	2624	2946	ARC-ISCW			
Douglas dam	2628	2956	ARC-ISCW			
Welgelegen	2620	3006	ARC-ISCW			
Villiers Ko-op	2702	2837	ARC-ISCW			
Ermelo: Nooitgedacht	2631	2957	ARC-ISCW			
Goedgevonden	2700	2909	ARC-ISCW			
Tevrede	2718	2844	ARC-ISCW			
Koppie Alleen	2711	2902	ARC-ISCW			
Erfenis	2734	2817	ARC-ISCW			
Reitz	2748	2826	ARC-ISCW			
Tweeling- SAP	2733	2831	ARC-ISCW			
Woudzicht	2734	2852	ARC-ISCW			

Warden-Mag	2751	2858	ARC-ISCW			
Buckland Downs	2758	2908	ARC-ISCW			
Rocco	2744	2910	ARC-ISCW			
Verkykerskop - SAP	2755	2917	ARC-ISCW			
Tygerfontein	2735	2927	ARC-ISCW			
Vrede-TNK	2725	2910	ARC-ISCW			
Reitz Ko-op	2748	2826	ARC-ISCW			
AWS	2757	2814	ARC-ISCW			
AWS	2756	2817	ARC-ISCW			
AWS	2740	2831	ARC-ISCW			
AWS	2749	2834	ARC-ISCW			
AWS	2759	2835	ARC-ISCW			
AWS	2746	2841	ARC-ISCW			
AWS	2733	2847	ARC-ISCW			
AWS	2743	2900	ARC-ISCW			
AWS	2755	2905	ARC-ISCW			
AWS	2739	2920	ARC-ISCW			
AWS	2727	2828	ARC-ISCW			
AWS	2730	2858	ARC-ISCW			
Arras	2735	2810	ARC-ISCW			
Biesiesfontein	2741	2812	ARC-ISCW			
Reitz-Riga	2739	2819	ARC-ISCW			
Tertius	2752	2827	ARC-ISCW			
Venus	2755	2926	ARC-ISCW			
Rosetta	2746	2820	ARC-ISCW			
Witsieshoek	2832	2848	ARC-ISCW			
Vaalbank	2801	2810	ARC-ISCW			
Marjiesvlei	2805	2816	ARC-ISCW			
Nil Desperandum	2818	2828	ARC-ISCW			
Bethlehem -Loch Lomond	2810	2818	ARC-ISCW			
AWS	2839	2818	ARC-ISCW			
AWS	2834	2819	ARC-ISCW			
AWS	2831	2832	ARC-ISCW			
AWS	2807	2812	ARC-ISCW			
AWS	2825	2813	ARC-ISCW			
AWS	2812	2814	ARC-ISCW			
AWS	2817	2816	ARC-ISCW			
AWS	2820	2820	ARC-ISCW			
AWS	2803	2829	ARC-ISCW			
AWS	2808	2830	ARC-ISCW			

AWS	2806	2833	ARC-ISCW			
AWS	2819	2837	ARC-ISCW			
AWS	2815	2846	ARC-ISCW			
AWS	2808	2914	ARC-ISCW			
Harrismith-Blokhuis	2819	1907	ARC-ISCW			
Petra	2820	2819	ARC-ISCW			
Leliefontein	2804	2930	ARC-ISCW			
Rosetta	2747	2820	Weather Bureau	Mr. R.J. Becker	P.O.Box 567 Reitz	9810
Cado	2747	2816	Weather Bureau	Mr.Cerneels Claassen	P.O.Box 93 Reitz	9810
Biesiesfontein	2741	2813	Weather Bureau	Mr. G.H.Joubert	Biesiesfontein Petrus Steyn	9640
Torpedo	2746	2833	Weather Bureau	Mr. Janie Room	P.O.Box 115 Reitz	9810
Reitz Dorpsplaas	2747	2827	Weather Bureau	Mr.C.D.Potgieter	P.O.Box 26 Reitz	9810
Bulthoek	2752	2816	Weather Bureau	Mrs. C.J.Jordaan	P.O.Box 126 Reitz	9810
Magdalena	2752	2809	Weather Bureau	Mr. D.R de Wet	P.O.Box 203 Lindley	9630
Kameelpoort	2752	2821	Weather Bureau	Mr. J. de Beer	P.O.Box 802 Reitz	9810
Tertuis	2752	2827	Weather Bureau	Mr. J.J. Oosthuizen	P.O.Box 543 Reitz	9810
Moedersdeel	2758	2834	Weather Bureau	Mr. Tokkie Visser	P.O.Box 144 Reitz	9810
Homestead	2731	2828	Weather Bureau	Mr. Nick van Zyl	P.O.Box 185 Tweeling	9820
Taragona	2735	2834	Weather Bureau	Mr. J.H.Muller	Taragona Tweeling	9820
Annies Rust	2731	2834	Weather Bureau	Mr. H.Muller	P.O.Box 427 Frankfort	9830
Highlands	2824	2816	Weather Bureau	Mr. John Boshoff	P.O.Box 309 Bethlehem	9700
Albrecht	2747	2808	Weather Bureau	Mr. C.A.Beukes	P.O.Box 160 Petrus Steyn	9640
Tevrede	2736	2828	Weather Bureau	Mr. Gerhard Human	Elizabetth Grove 353 Pretoria	81
Nooitgedacht	2741	2827	Weather Bureau	Mr. C.J.Muller	P.O.Box 394 Reitz	9810
Kafferskraal	2741	2821	Weather Bureau	Mr. H.Read	P.O.Box 587 Reitz	9810
Mowbray	2741	2833	Weather Bureau	Mr. Paul Carshagen	P.O.Box 531 Reitz	9810
Kliprand	2736	2821	Weather Bureau	Mr. Jan Meyer	P.O.Box 140 Petrys Steyn	9640
Katbosch	2737	2815	Weather Bureau	Mr. M.S.Fletcher	Katbosch Petrus Steyn	9640
Strydfontein	2758	2828	Weather Bureau	Mr. P.J.F de Villiers	P.O.Box 521 Reitz	9810
Kransfontein	2819	2840	Weather Bureau	Mrs. Susan Kruik	19 Waterbokstreet Bethlehem	9700
Cathara	2819	2834	Weather Bureau	Mr. Danie Beneke	P.O.Box 34 Kestell	9860
Exelsior No3 Plot	2814	2815	Weather Bureau	Mr. P.G. Steyn	P.O.Box 178 Bethlehem	9700
Susanna	2814	2827	Weather Bureau	Mr. M.E.Prinsloo	P.O.Box 1616 Bethlehem	9700
Bethlehem Water Works	2813	2822	Weather Bureau			
Nil Desperandum	2818	2827	Weather Bureau	Mr. Johan Beneke	P.O.Box 486 Bethlehem	9700
Friedrich's Ruhe	2825	2827	Weather Bureau	Mr. J.B.Palm	P.O.Box 453, Bethlehem	9700
Kruisvallei	2825	2821	Weather Bureau	Kwe Kwe Naude	P.O.Box	
Lisbon	2825	2835	Weather Bureau	Mr. Kobus Van Lars	P.O.Box 311 Kestell	9860
Houtkop	2820	2821	Weather Bureau	Mr. P.S.Naude	P.O.Box 343 Bethlehem	9700
Serami	2819	2815	Weather Bureau	Mr. Andries Coetzee	P.O.Box 786 Bethlehem	9700
Strydfontein	2814	2834	Weather Bureau	Johnny Kirchner	Strydfontein Kransfontein	9706
Sophia	2803	2827	Weather Bureau	Mr.Nico Pieterse	P.O.Box 1133 Bethlehem	9700
Cronjesfontein	2803	2822	Weather Bureau	Mr. H.P.Venter	Nelsrus Danielsrus	9705
Oskraal	2804	2834	Weather Bureau	Mrs. E.M. Naude	P.O.Box 30 Kransfontein	9706
Tweepan	2758	2822	Weather Bureau	Mr. Johan de Jager	P.O.Box 112 Reitz	9810

Erfenis	2758	2815	Weather Bureau	Mr. W.J. van der Spuy	P.O.Box 1541 Bethlehem	9700
Brakpan	2803	2815	Weather Bureau	Mr. A.H.T de Klerk (Manie)	P.O.Box 536 Bethlehem	9700
Paulus	2808	2815	Weather Bureau	Mr. O.F.Lategan	P.O.Box 139 Bethlehem	9700
Groenkop	2814	2840	Weather Bureau	Mr. Freddie Marais	P.O.Box174 Kestell	9860
Fraaiuitzicht	2809	2822	Weather Bureau	Mr. Hendrik Knoetze	P.O.Box 821 Bethlehem	9700
Tiger River	2809	2834	Weather Bureau	Mr. I.M.Van Niekerk	P.O.Box 20 Kransfontein	9706
Bethel	2808	2828	Weather Bureau	Mr. Kobus Van Zyl (Jnr)	P.O.Box 1706 Bethlehem	9700
Welverdiend	2803	2838	Weather Bureau	Mr. D. van Niekerk	P.O.Box 1 Kransfontein	9706
Vocata	2802	2843	Weather Bureau	Mr. P. Kleynsmidt	P.O.Box 806 Reitz	9810
Aurora	2801	2846	Weather Bureau	Mr. J. Noome	Auroma Kransfontein	9706
Uitlanderskraal	2807	2841	Weather Bureau	Mr. P.Steyn	P.O.Box	
Middelpunt	2805	2848	Weather Bureau	Mr. D. van Eeden	P.O.Box 240 Kestell	9860
Uitzicht	2812	2846	Weather Bureau	Mr. Pieter Room	P.O.Box 77 Kestell	
Petra II	2815	2842	Weather Bureau	Mr. S. van Vuuren	P.O.Box 170 Kestell	9860
Mooiplaas	2802	2847	Weather Bureau	Mr. Posthumus	P.O.Box	
St Julian	2808	2842	Weather Bureau	Mr. P.Ras	P.O.Box 1531 Bethlehem	9700
Georgina	2808	2844	Weather Bureau	Mr. F. van Niekerk	P.O.Box 173 Kestell	9860
Allemanspruit	2805	2843	Weather Bureau	Mr. F.B Jooste	P.O.Box 173 Kestell	9860
Fanie	2804	2845	Weather Bureau	Mr.L. van Vuuren	38 Loeriestreet Heilbron	9650
Somerset	2806	2846	Weather Bureau	Mr. C.F Crous	P.O.Box 163 Kestell	9860
Jolly Kop	2807	2837	Weather Bureau	Mr. J.D.Heyns	Jolly Kop Kransfontein	9706
Slangfontein	2804	2839	Weather Bureau	Mr. F.Fourie	P.O.Box 10 Kransfontein	9706
Joeys Home	2803	2841	Weather Bureau	Mr. F. Van Reenen	P.O.Box 55 Kransfontein	9706
Somerby	2809	2850	Weather Bureau	Mr. K.Beukes	P.O.Box 529 Harrismith	9800
Max	2801	2840	Weather Bureau	Mr. D. van Niekerk	P.O.Box 1 Kransfontein	9706
Vaalpan	2800	2842	Weather Bureau	Mr. W.J.Oosthuizen	Vaalpan Kransfontein	9706
Werda	2757	2843	Weather Bureau	Mr. F. Potgieter	P.O.Box 22 Warden	9890
Skietkoppies	2809	2847	Weather Bureau	Mr. G. Swart	P.O.Box 32 Kestell	9860
Mooimeisiesrus	2812	2839	Weather Bureau	Mr. H. Wales	P.O.Box 35 Kestell	9860
Sunnyside	2808	2849	Weather Bureau	Mr. Tinie Orsmond	P.O.Box 88 Bethlehem	9700
Waterloo	2811	2843	Weather Bureau	Mr. J.J van Zyl	P.O.Box 1706 Bethlehem	9700
Maizelands	2815	2845	Weather Bureau	Mr. P.J. Heyns	P.O.Box 166 Kestell	9860
Goedgedacht	2809	2829	Weather Bureau	Mr. W.A. de Klerk	P.O.Box 1387 Bethlehem	9700
Jim Fouche Resort	2700	2822	Agriculture	Officer in Charge	P.O.Box 114, Frankfort	9830
Rocco	2744	2910	Agriculture	Mr. A. Strazacker	P.O.Box 066, Vrede	2455
Rietspruit	2724	2837	Agriculture	Mr. A..Krogman	P.O.Box 295, Frankfort	9830
Dundas			Agriculture	Mr. H. Burger	P.O.Box 494, Frankfort	9830
Harrismith	2817	2908	Agriculture	Officer in Charge	P.O.Box 391, Harrismith	9880
Vrisgewaagd	2752	2812	Agriculture	Mr. P.Marx	P.O.Box 402, Frankfort	9830
Tygerpoort	2737	2905	Agriculture	Mr. D.G.Cillie	P.O.Box 338, Vrede	2455
Erfdeel	2838	2829	Agriculture	Mr. J.L.B.Muller	P.O.Box 207. Vrede	2455
Waaihoek	2723	2827	Agriculture	Mr. G.Muller	P.O.Box 426, Frankfort	9830
Elma	2745	2835	Agriculture	W.C.B. Le Roux	P.O.Box 161, Reitz	9810
Oosthuizenshoek	2755	2825	Agriculture	Mr. J.J. Oosthuizen	P.O.Box 222, Reitz	9810
Sterkfonteindam	2904	2825	Agriculture	Officer in Charge	P.O.Box 24, Harrismith	9880
Emden	2750	2840	Agriculture	Mr. S. Muller	P.O.Box 364, Reitz	9810
Eeram	2808	2902	Agriculture	Officer in Charge	Private Bag X809	9980

Reitz dorp	2745	2825	Agriculture	Town Clerk	P.O.Box 15 , Reitz	9810
Langspruit	2745	2820	Agriculture	Mr. J.B.R Jacobs	P.O.Box 611, Reitz	9810
Leliefontein	2804	2930	Agriculture	Mr. T.C. Brunsdon	P.O.Box 65 , Harrismith	9880
The Dam	2806	2907	Agriculture	Mr. M.F.Bester	P.O.Box 505 , Harrismith	9880
Venus	2755	2926	Agriculture	Mr. J.F.Steyn	P.O.Box 679 , Harrismith	9880
Buckland Downs	2758	2908	Agriculture	H.R.Meiring	P.O.Box 84, Harrismith	9880
Waterfall	2818	2925	Agriculture	Mr. R.F.Dillion	P.O.Box 171 , Harrismith	9880
Berlin	2751	2934	Agriculture	Mr. C. Vicory	P.O.Box 591, Harrismith	9880
Uilhoek	2808	2914	Agriculture	Mr. R.D. Sharatt	P.O.Box 634, Harrismith	9880
Harrismith Prison	2817	2908	Agriculture	Officer in Charge	Private Bag X977 , Harrismith	9880
Vorentoe	2809	2850	Agriculture	Mr. P.J.Du Preez	P.O.Box 664, Harrismith	9880
Killiecrankie	2826	2909	Agriculture	Mr. J.J.Strachen	P.O.Box 161, Harrismith	9880
Petra	2820	2819	Agriculture	Mr. G.B. Steyl	P.O.Box 168, Bethlehem	9700
Waterbron	2757	2814	Agriculture	Mr. M.P.Van Der Spuy	P.O.Box 509 , Bethlehem	9700
Meme	2812	2814	Agriculture	Sensako	P.O.Box 556, Bethlehem	9700
Loskop	2818	2810	Agriculture	Mr. F.P.Cillie	P.O.Box 539 ,Bethlehem	9701
Record	2814	2802	Agriculture	Mr. W. Watson	Record	9800
Randrivier	2713	2822	Agriculture	Mr. H. Van Rensburg	P.O.Box 424, Frankfort	9830
Cilliersrust	2727	2818	Agriculture	Mr. P.J. Theron	P.O.Box 479 , Frankfort	9830
Erfhoek	2720	2845	Agriculture	Mr. P.R. Botha	P.O.Box 442 , Frankfort	9830
Glen Alphen	2707	2831	Agriculture	Mr. P.J.Schort	P.O.Box 279 , Frankfort	9830
Mara	2725	2831	Agriculture	Mr. H.Muller	P.O.Box 386 , Frankfort	9830
Langspruit	2719	2923	Agriculture	Mr. A.C.Scholtz	P.O.Box 40, Vrede	2455
Rome	2726	2920	Agriculture	Mr.J.J.F.Prinsloo	P.O.Box 217, Vrede	2455
Meadowberk	2722	2909	Agriculture	Mr. N.J.Van Der Nest	P.O.Box 392, Vrede	2455
Glen Alpen	2708	2833	Agriculture	Mr. P.Schabort	P.O.Box 635, Frankfort	9830
Tygerfontein	2735	2927	Agriculture	Mr. J.G.Wessels	P.O.Box 33 , Vrede	2455
Draaihoogte	2739	2920	Agriculture	Mr. P.R.Botha	P.O.Box 346, Vrede	2455
Koppie Alleen	2711	2902	Agriculture	Mr. J.D.Claasen	P.O.Box 556, Vrede	2455
Rietfontein	2719	2927	Agriculture	Mr. J.F. Van Der Merwe	P.O.Box 380, Vrede	2455
Philliesdeel	2715	2911	Agriculture	Mr. A.I.Bester	P.O.Box 269 , Vrede	2455
Hartlam	2745	2836	Agriculture	Mr. M.J.Claassen	P.O.Box 197, Reitz	9810
Kameelpoort	2747	2821	Agriculture	Mr. H.J. Barnard	P.O.Box 150, Reitz	9810
Sorgvliet	2733	2919	Agriculture	Mr. J.A.Dreyer	P.O.Box 424, Vrede	2455
Vishoek	2741	2823	Agriculture	Mr. P.Eksteen	P.O.Box 108, Reitz	9810
Vadersgift	2711	2858	Agriculture	Mr. R.Cockroft	P.O.Box 212. Vrede	2455
Baltimore			Agriculture	Mr. H.Lourens	P.O.Box 487, Vrede	2455
Gewin	2755	2842	Agriculture	Mr. N.Steyn	P.O.Box 416, Reitz	9810
Estancia	2624	2952	OTK			
Grootvlei	2647	2831	OTK			
Harvard	2702	2914	OTK			
Bloekomspruit	2644	2821	OTK			
Balfour	2639	2834	OTK			
Davel	2627	2940	OTK			
Morgenzon	2644	2943	OTK			
Overvaal	2642	3008	OTK			
Platrand	2707	2932	OTK			

Holmdene	2651	2904	OTK			
Leeuspruit	2652	2832	OTK			
Maizefield	2639	2933	OTK			
Leandra			Water Affairs	AO.Naude	P.O.Box 18, Leslie	2265
Morgenzon	2644	2937	Water Affairs	AO. Schoeman	P.O.Box 30, Morgenzon	2315
Harrismith			Water Affairs	SAP	P.O.Box 169, Harrismith	9880
Charl Cilliers	2640	2911	Water Affairs	SAP	P.O.Box 119, Charl Cilliers	2301
Greylingstad	2645	2846	Water Affairs	SAP	P.O.Box 19, Greylingstad	2415
Val	2647	2856	Water Affairs	Mrs. Oosthuizen	P.O.Box 1, Val	2425
Villiers	2702	2836	Water Affairs	SAP	P.O.Box 32, Villiers	9840
Petrus Steyn	2739	2808	Water Affairs	SAP	P.O.Box 1, Petrus Steyn	9640
Oranjeville	2700	2813	Water Affairs	Mrs. Steyn	P.O.Box 6, Oranjeville	1995
Perdekop	2710	2938	Water Affairs	SAP	P.O.Box 83, Perdekop	2465
Vaal-Langverwyl	2351	2920	Water Affairs			
Vaal-Bloukop	2654	2943	Water Affairs			
Vaal-Elandsl	2652	2853	Water Affairs			
Vaal-Gladderif	2700	2846	Water Affairs			
Klip-Delangesdrif	2710	2914	Water Affairs			
Vaal-Langverwyl	2655	2917	Water Affairs			
Vaal-Vaaldam	2653	2807	Water Affairs			
Vaal-Grootdraaidam	2655	2918	Water Affairs			
Vaaldam-Confluence			Water Affairs			
Vaaldam-Wilgerpoort			Water Affairs			
			Water Affairs			
			Water Affairs			
			Water Affairs			
Liebenbergsvlei-Roode	2741	2823	Water Affairs			
Wilge-Kimberley	2718	2829	Water Affairs			
Liebenbergsvlei-Frederik	2726	2832	Water Affairs			
Wilge-Ballingtomp	2718	2835	Water Affairs			
Wilge-Bavaria	2749	2847	Water Affairs			
As-Tunnel	2826	2824	Water Affairs			
Soetevelde Farms Vetapn	2802	2834	Weather Bureau	Officer in Charge		
Oskraal	2806	2833	Weather Bureau	Mr. van der Merwe		
Visgat	2802	2831	Weather Bureau	Mr. Strauss		
Sterkfonteindam	2824	2858	Weather Bureau	Officer in Charge		
Kestell	2819	2842	Weather Bureau	Officer in Charge		
Strydfontein	2814	2834	Weather Bureau	Mr. Kirchner		
Mooifontein	2803	2829	Weather Bureau	Mr. Fourie		
Groenvlei	2820	2820	Weather Bureau	Mr. van Doornick		
Petra	2820	2819	Weather Bureau	Mr. Steyl		
Highlands	2824	2816	Weather Bureau	Mr. Boshoff		

Nil Desperandum	2818	2828	Weather Bureau	Mr. Beneke		
Stephanium	2824	2823	Weather Bureau	Mr. Van Doornick		
Trentham	2807	2821	Weather Bureau	Mr. Bredenkamp	P.O.Box 429, Bethlehem	9701
Doornkloof	2744	2743	Weather Bureau	Mr. Theron		
Edenville	2733	2741	Weather Bureau	Officer in Charge		
Steynsrus	2757	2734	Weather Bureau	Officer in Charge		
Eikehoff	2736	2753	Weather Bureau	Mr. Botha		
Rivierplaas	2735	2752	Weather Bureau	Mr. Wessels		
Van Tondersrus	2756	2748	Weather Bureau	Mr. Potgiter		
Mooibult	2736	2732	Weather Bureau	Mr. Keeve		
Swartkoppie	2754	2715	Weather Bureau	Mr. Kleynhans		
Henneman	2758	2702	Weather Bureau	Officer in Charge		
Uithoek	2808	2914	Weather Bureau	Mr. Sharrat		
Taaibos	2759	2728	Weather Bureau	Mr. Engelbrecht		
De Kamp	2742	2720	Weather Bureau	Mr. Santoro		
Zuurkloof	2751	2716	Weather Bureau	Mr. Griesel		
Leslie	2622	2856	Weather Bureau			
Kestell	2819	2842	Weather Bureau	Mrs. Human	P.O.Box 14, Kestell	9860
Grootvlei			Weather Bureau	Mrs. Lategan	P.O.Box 12, Grootvlei	2420
Standerton	2656	2914	Weather Bureau			
Reitz	2748	2826	Weather Bureau	Miss. Horn	P.O.Box 39, Reitz	9810
Memel	2741	2934	Weather Bureau	Mrs. Prinsloo	P.O.Box 6, Memel	2970
Frankfort	2716	2830	Weather Bureau	Mrs. De Lange	P.O.Box 39, Frankfort	9830
Bethlehem Weather Office	2815	2820	Weather Bureau	Officer in Charge	Private Bag X15, Bethlehem	9700
Bethal	2627	2929	Weather Bureau			
Amersfoort	2701	2952	Weather Bureau	SAP	P.O.Box 2, Amersfoort	2490
Ermelo	2631	2958	Weather Bureau	Officer in Charge	P.O.Box 1466, Ermelo	2350
Deneysville	2653	2807	Weather Bureau			
Cornelia	2714	2851	Weather Bureau	Mr. Kruger	P.O.Box 13, Cornelia	9850
Meriba	2807	2812	Weather Bureau	Mr. Fourie		
Le Long	2801	2805	Weather Bureau	Mr. Louw		
Record	2814	2802	Weather Bureau	Mr. Watson		
Susannasvlei	2817	2816	Weather Bureau	Mr. van Niekerk		
Sensako Marne	2812	2814	Weather Bureau	Officer in Charge		
Libanon	2825	2813	Weather Bureau	Mr. van der Merwe		
Witsieshoek	2832	2848	Weather Bureau	Officer in Charge	Private Bag X 18, Puthaditjhaba	9866
Van Reenen	2822	2923	Weather Bureau			
Tweeling	2733	2831	Weather Bureau	Officer in Charge	P.O.Box 2, Tweeling	9820
Tsiame	2817	2900	Weather Bureau			
Warden	2757	2903	Weather Bureau			
Vrede	2725	2910	Weather Bureau			
Verkykerskop	2755	2917	Weather Bureau	Officer in Charge	P.O.Box 12, Verkykerskop	9882
Heilbron	2717	2758	Weather Bureau	Officer in Charge		
Oorsprong Oos	2708	2757	Weather Bureau	Mr. Leonard		
Doorndraai	2716	2736	Weather Bureau	Mr. Steyn		
Witklip	2719	2810	Weather Bureau	Mr. Naude		
Schoongezicht	2724	2802	Weather Bureau	Mr. Room		

Driefontein	2726	2759	Weather Bureau	Mr. Room		
Koppies I.R.R. Lourensia	2714	2734	Weather Bureau	Officer in Charge		
Welvaart	2723	2713	Weather Bureau	Mr. Leonard		
Tygerfontein	2735	2927	Weather Bureau	Mr. Wessels		
Venus	2755	2926	Weather Bureau	Mr. Steyn		
Morgenrood	2721	2733	Weather Bureau	Mr. Le Roux		
Dunkeld	2718	2727	Weather Bureau	Mr. Barraclough		
Heuningspruit	2727	2725	Weather Bureau	Officer in Charge		
Robertsdrift	2701	2901	Weather Bureau	Mr. Hapkin		
Eureka	2730	2858	Weather Bureau	Mr. Malan		
Cornelia	2714	2851	Weather Bureau	Officer in Charge		
Varkenspruit	2706	2930	Weather Bureau	Mr. Heydenrich		
Rietfontein	2719	2927	Weather Bureau	Mr. Van Der Merwe		
Vrede	2725	2910	Weather Bureau	Officer in Charge		
Dewetshoop	2709	2846	Weather Bureau	Mr. De Wet		
Mara	2724	2831	Weather Bureau	Mr. Muller		
Glen Alpen	2707	2831	Weather Bureau	Mr. Schabort		
Turffontein	2716	2822	Weather Bureau	Mr. Cronje		
Tevrede	2718	2844	Weather Bureau	Mr. Crous		
Villiers	2702	2836	Weather Bureau	Officer in Charge		
Catharinasvlei	2712	2835	Weather Bureau	Mr. De Jager		
Poortjie	2733	2821	Weather Bureau	Mr. De Jager		
Riga	2739	2819	Weather Bureau	Mr. Cilliers		
Erfenis	2734	2817	Weather Bureau	Mr. Cilliers		
Oosthuishoek	2754	2826	Weather Bureau	Mr. Oosthuizen		
Reitz	2748	2826	Weather Bureau	Officer in Charge		
Jacobsdal	2736	2823	Weather Bureau	Mr. Cronje		
Slaapplaas	2746	2809	Weather Bureau	Mr. Beukes		
Lindley	2753	2755	Weather Bureau	Officer in Charge		
Oatlands	2745	2755	Weather Bureau	Mr. Van Vuuren		
Uitzicht	2739	2754	Weather Bureau	Mr. Muller		
Newton Grange	2753	2805	Weather Bureau	Mr. Walker		
Rafidum	2752	2805	Weather Bureau	Mr. Pienaar		
Erfdeel	2757	2755	Weather Bureau	Mr. Van Tonder		
Hopedale	2755	2905	Weather Bureau	Mr. Olivier		
Warden	2751	2858	Weather Bureau	Officer in Charge		
Woudzicht	2734	2852	Weather Bureau	Mr. Kohler		
Draaihoogte	2739	2920	Weather Bureau	Mr. Botha		
Verkykerskop	2755	2917	Weather Bureau	Officer in Charge		
Rocco	2744	2910	Weather Bureau	Mr. Straszaker		
Wildealskraal	2733	2847	Weather Bureau	Mr. Mouton		
Taragona	2735	2833	Weather Bureau	Mr. Muller		
Tweeling	2733	2831	Weather Bureau	Officer in Charge		
Tertius	2752	2827	Weather Bureau	Mr.		
Elma	2746	2841	Weather Bureau	Mr. Le Roux		
Sarie	2739	2836	Weather Bureau	Mr. Rautenbach		
Rietfontein	2749	2834	Weather Bureau	Mr. Steyn		

APPENDIX B.

CONFERENCES, PUBLICATIONS AND DISSERTATIONS

Conference papers

Mittermaier, M.P., 1998: Radar-derived differences between convective and stratiform radar echoes : An objective means of classification. *14th Annual SASAS Conference*, 29-30 October 1998, Pretoria, South Africa.

Mittermaier, M.P., 1999: Using contoured-frequency-by-altitude diagrams to investigate the three-dimensional structure of hygroscopically seeded and natural storms.

Mittermaier, M.P. and G.G.S. Pegram, 1998: Characterizing the vertical reflectivity profile under predominantly stratiform conditions. *14th Annual SASAS Conference*, 29-30 October 1998, Pretoria, South Africa.

Mittermaier, M.P. and D.E. Terblanche, 2000: The integration of daily rain gauge and radar rainfall estimates for the Liebenbergsvlei catchment. *The Millennium Conference of SASAS*, 16-17 October 200, Pretoria, South Africa.

Pegram, G.G.S. and M.P. Mittermaier, 1998 : Estimating rainfall at low altitude, at distance from radar CAPPI data. 4th International Symposium on Hydrological Applications of weather radar, April, San Diego, CA.

Terblanche, D.E. and M.P. Mittermaier, 1999: Radar rainfall estimation: Recent progress in South Africa. Invited presentation at the French-South African workshop on water research issues. July, Pretoria, South Africa.

Terblanche, D.E., P.J.M. Visser, M.J. Dixon, M.P. Mittermaier, K.P.J. de Waal and J.F. Stuart, 1999: Recent progress with radar networking in South Africa. 29th Intl Conf on Radar Meteorology, AMS, 12-16 July, Montreal, Canada, 74-77.

Terblanche, D.E., N.J. Kroese, M.P. Mittermaier, P.J.M. Visser and K.P.J. de Waal, 2000: The South African weather radar network. *The Millennium Conference of SASAS*, 16-17 October 200, Pretoria, South Africa.

Visser, P.J.M, 1999: Analysis of severe storms in South Africa with the Storm-Structure-Severity Method. 29th Intl Conf on Radar Meteorology, AMS, 12-16 July, Montreal, Canada, 90-93.

Visser, P.J.M., 2000: The use of the SSS-method for improved hail fall estimation in South Africa, 20th Conf. On Severe Local Storms, Orlando, AMS, 534-537.

Publications

Mittermaier, M.P. and D.E. Terblanche, 2000: The integration of daily rain gauge and radar rainfall estimates for the Liebenbergsvlei catchment. Accepted for publication in *S A Journ. Sci.*

Terblanche, D.E., G.G.S. Pegram and M.P. Mittermaier, 2000: The development of weather radar as a research and operational tool for Hydrology in South Africa. Accepted for publication in the *J. Hydrol.*

Visser, P.J.M. and J. van Heerden, 1999: Comparisons of Hail Kinetic Energy derived from radar reflectivity with crop damage reports over the Eastern Free State. Accepted by Water SA, July 1999.

Visser, P.J.M., 2000: The Storm-Structure-Severity method for the identification of convective storm characteristics with conventional weather radar. Accepted for publication in Meteorol. Appl.

Honours, M.Sc. and Ph.D. Dissertations

Burger, R.P., 1998: Daily estimates over a fixed area utilizing the area-time integral. Honours project dissertation. Chair in Meteorology, University of Pretoria, Pretoria, South Africa, 30pp.

Mittermaier, M.P., 1999: Investigating the characteristics of the radar vertical reflectivity profile. *M.ScEng* dissertation. Dept of Civil Engineering, University of Natal, Durban, South Africa, 177pp.

Visser P.J.M., 1999: The use of volumetric scanned weather radar reflectivities for the identification of convective storm characteristics. *M.Sc* dissertation, Chair in Meteorology, University of Pretoria, Pretoria, South Africa, 175pp.

APPENDIX C.

EXECUTIVE SUMMARY OF THE RADAR WORKSHOP HELD ON 18 NOVEMBER 1998.

Introduction

With an average rainfall of less than 500 mm per annum Southern Africa is one of the regions identified by the World Meteorological Organization most likely to experience serious water shortages early in the 21st century. Due to the increased burden placed on water resources by an ever increasing population as well the increase in water usage by agricultural activities to satisfy the food requirements, some areas in our country already suffer from water shortages. Adding to this the climatological outlook that natural disasters in the form of floods and droughts are going to occur not only more frequently but with an increased intensity is going to burden decision makers and managers and force them to make use of all the technological aids and information in decision making processes. The demands of securing water resources and ample supply of food sources in future is what can spark regional conflicts. Rainfall being the primary source of water for all of industrial and socio-economic development is the main issue under scrutiny.

Radar technology and radar-derived products were introduced at this workshop as a remote sensing device capable of surveying large areas with unsurpassed spatial resolution and above that, real-time precipitation measurement capabilities. The objective of this workshop was to have managers of the water resources, agricultural and disaster management industry meet jointly with scientists to determine the most effective usage of this technology in each sector respectively. Furthermore the workshop aimed to bring under the attention of managers in these sectors the capabilities of radar and the progress made during recent years.

Workshop Activities and Recommendations

The workshop consisted of presentations of papers reviewing radar technology in South Africa and the advances made during recent years. Papers were also presented which were aimed at highlighting the application of radar technology to sector specific issues. The sectors being targeted here :

- Hydrology and Water Management
- Agriculture
- Disaster Management and Mitigation

Following these presentations and discussions, participants convened into three working groups, representing the above mentioned sectors, with the task of accomplishing the following:

1) To discuss and identify opportunities and problem areas which radar technology can address in each sector.

2) To identify the potential benefits of using radar technology in conjunction with or replacing current systems in use for precipitation monitoring.

3) To identify and put on the table their respective data requirements in order to address problem areas in each sector effectively.

4) To identify effective communication, and other linkages between each sector and the provider of radar data and products.

At the conclusion of the workshop each working group presented their recommendations. Summaries of these recommendations are as follows:

I - Hydrology and Water Management

The management of water within a catchment will under the new Water Law be the responsibility of the appropriate Catchment Management Authority (CMA). The improved monitoring of not only pollution and water quality but also the rainfall runoff processes within catchments will become all the more important in modern catchment management procedures. Incorporating high resolution rainfall measurements with appropriate catchment models for real-time flood forecasting poses an exiting challenge to hydrologists. This working group also identified the need for improved rainfall forecasts from the meteorological fraternity implying a multi-disciplinary approach to water and flood management.

Discussions in this working group also identified the need to liaise with the Disaster Management fraternity as the practice of flood plains encroachment by people is becoming more of a problem necessitating the need for flood forecasting, issuing of warnings and helping communities cope with the aftermath. The need to know the area of rain/no rain is of vital importance to the response time of catchments in flood forecasting- radar can measure this.

Key Recommendations - Hydrology and Water Management

- **To develop appropriate catchment models for real-time flood forecasting using high resolution radar rainfall fields as input.**
- **International cooperation with Lesotho regarding the monitoring of precipitation in that country to improve management of inflows to the Gariep and Van der Kloof dams for flood management and hydro-power generation.**
- **Defining flood prone areas and monitor the catchments of these areas with radar.**

II - Agriculture

The focal point in discussions on the application of radar technology in agriculture was the ability of radar to measure rainfall distribution (spatial variation) and rainfall amount to acceptable levels of accuracy. Supplement the above with the fact that radar data and products are available in real-time, adds a whole new perspective and possibilities for the utilization of this data. Applications utilizing these strengths were then identified where radar data can play a significant role in agricultural decision making processes.

Some agricultural systems require accurate measurement of precipitation eg. irrigation scheduling whereas others require more detailed information regarding the spatial distribution of rainfall eg. locust control.

Shortcomings related to sparse radar coverage over the Northern Province and Northern Cape was also expressed as an issue to address in future. Radar technology should be used in conjunction with other remote sensing systems eg. satellites as well as the current raingauge infrastructure. Emphasis should also be directed towards the collection, processing and archiving of all precipitation data including real-time data and appropriate quality control procedures should be devised.

Key Recommendations - Agriculture

- **The expansion of the current network to include areas where no coverage exists i.e. The deployment of additional radar systems.**
- **The upgrading of the remaining radars within the network to the level of Bethlehem and Ermelo**
- **To formalize linkages between agriculture and the Weather Bureau in order to make**

this data more accessible and part of daily usage in the agricultural sector.

III - Disaster Management and Mitigation.

Radar's capability as an early warning tool received much attention during the discussions in the working group for disaster management. The identification of the type of disaster where radar could play a role was narrowed down to the following:

1)Flood Warning - Flood management in large river systems
Flash Flooding (local, short lived) incidents

2)Short Term Weather Predictions - Warnings of localized but short lived severe weather phenomena

Deliberations also touched on the chain of communication when warnings are issued. Although this was not part of this workshop's terms of reference it certainly is an important issue.

Key Recommendations - Disaster Management and Mitigation

- **An "HOLISTIC" warning service must be provided i.e. it must be available not only to main metropolitan centres but also smaller communities.**

- **Central Government should take responsibility to maintain and upgrade the radar network.**

- **There is a need for partnerships between the Hydrology, Meteorology and Disaster Management fraternities to effectively address the management of natural disasters**

Workshop Conclusions

In concluding the workshop it has been affirmed that:

- Progress, over recent years, in adapting and refining weather-radar data technology for cost effective rainfall measurement has been exceptional.

- The near real-time access to radar rainfall data already available on the Internet is tangible proof that radar technology is already starting to satisfy long-felt data needs with regard to spatial and temporal distribution of intensity and quantity.

- Without the future availability of radar technology to supplement current data sources,

    - potentially valuable early warning capabilities could not be realised long-felt data requirements would not be met, the more so because of the shrinkage and increasing sparseness of conventional precipitation monitoring networks.
    - the capacity to satisfy monitoring requirements associated with new water and environmental legislation would probably not be available.
    - while potentially highly cost effective for the country as a whole, the development and maintenance of a national radar network which satisfies the needs of all sectors is too costly an undertaking for the Weather Bureau alone. Such a network should be regarded as a "National Facility" (asset), with co-ownership and co-responsibility for management and costs to be assumed by various users.

- A weather radar users interest group is needed to:
    - encourage the Weather Bureau in its endeavours to expand an effective weather radar service for South Africa.
    - advise the Weather Bureau on services required.
    - mobilise support (financial and otherwise) to ensure that the desirable level of service is achieved and maintained.

- Participants at the workshop should form the inaugural core of the radar users interest group.

APPENDIX D.

USING THE WEB SOFTWARE TO INVESTIGATE RAINFALL ESTIMATION DURING MRL-5 CALIBRATION PROBLEMS.

The radars in the network were switched on during September 2000 for a period of testing before the official summer season which start in October. During this period fairly widespread rain fell over the Vaal Dam catchment. DWAF provided the project team with data for the 24-hour period to 06:00 GMT on 20 September where the radar estimation was clearly off, resulting in gross underestimation of the rainfall. Using the software that was developed for the latest products on the web and using additional raingauge information obtained from the ARC, Figure D2 was produced.

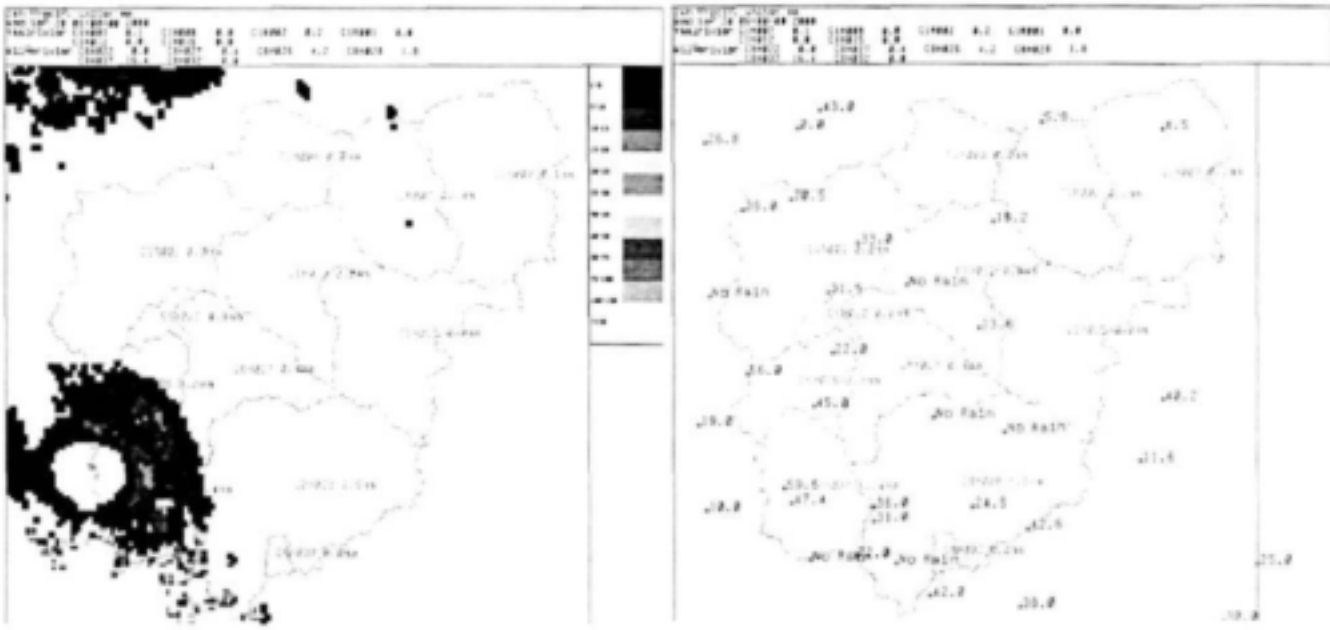
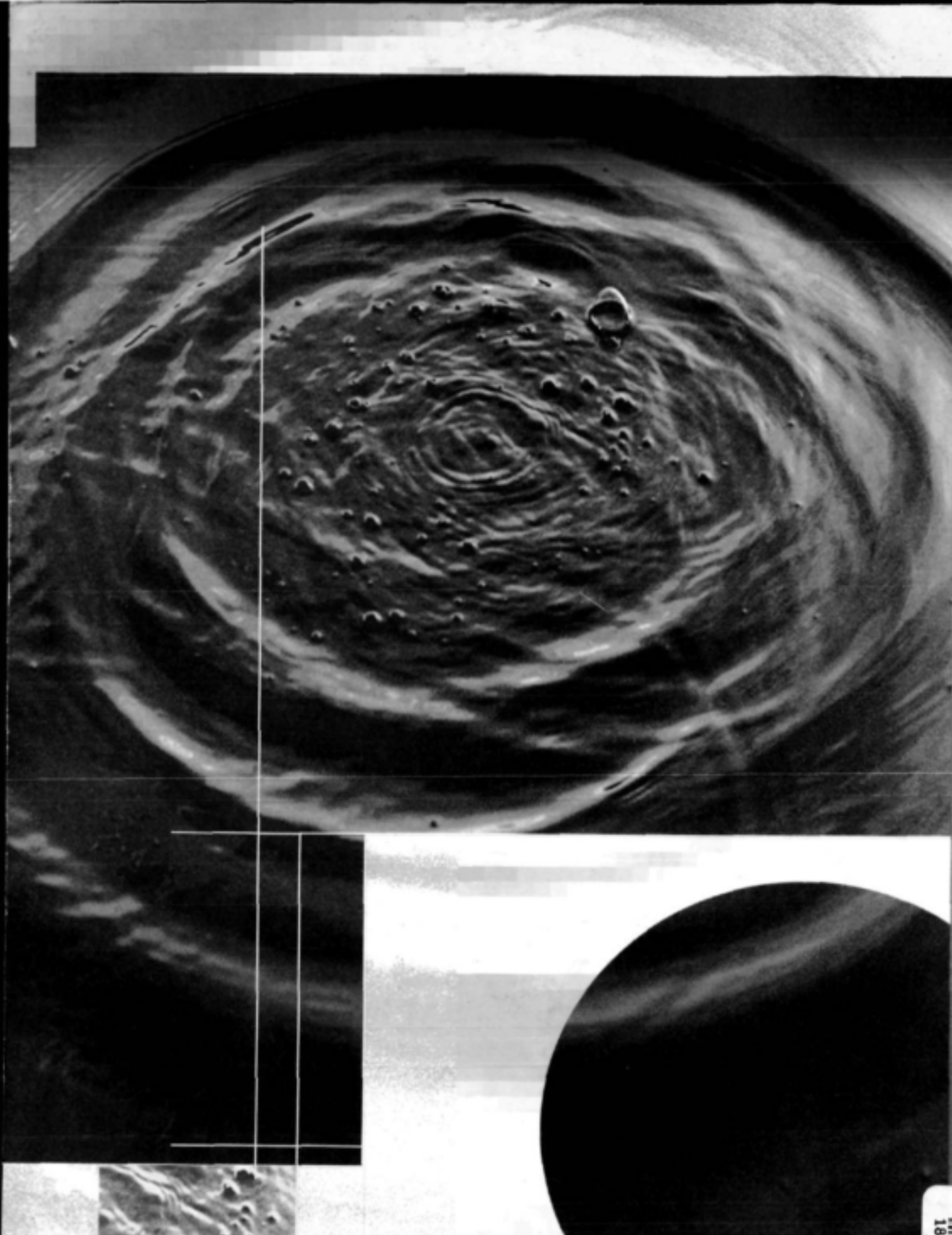


Figure D2. (a). The 24-hour radar estimated rainfall field over the Vaal Dam catchment for the 24-hour period to 06:00 on 20 September 2000 and (b). The radar estimated sub-catchment rainfall and 24 hour rainfall figures from daily reporting gauges for the same period.

This event was during a time that all the radar technicians were involved in the installation of the Pietersburg radar and the problem could only be resolved on 9 October 2000 when they returned to Bethlehem. It was found that the Automatic Frequency Control circuitry on the MRL-5 S-band receiver malfunctioned resulting in the receiver not being tuned to the frequency of the transmitted microwaves. This is an example of what happens when things go wrong and places even more urgency on the development of a system that will provide statistics on the radar data in the areas of overlap on a real-time basis.

Since this event the project team routinely provides notes on the web page on the status of the radar network and on any problems known.



Water Research Commission

PO Box 824, Pretoria, 0001, South Africa

Tel: +27 12 330 0340, Fax: +27 12 331 2565

Web: http://www:wrc.org.za