Deployment, re-engineering and risk analysis of a C-band weather radar to build local capacity in South Africa

RG du Preez
22135928

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Supervisor	Prof JEW Holm
Co-Supervisor	Prof SJ Piketh
Co-Supervisor	Dr RP Burger

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DEDICATION

Soli Deo Gloria

“To God alone the glory”

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ABSTRACT

Deployment, re-engineering and risk analysis of a C-band weather radar to build local capacity in South Africa

A weather radar is an unparalleled tool, providing high spatio-temporal data over large areas to study storms and precipitation. The national weather radar network of South Africa is a world-class asset with enormous potential to provide real-time, high resolution data for various departments and research facilities. Unfortunately, due to budget cuts, the loss of skilled experts, and limited resources the South African Weather Services (SAWS) has been plagued by technical problems, struggling to maintain the entire system. The SAWS had also decommissioned most of their old C-band radars because of continued technical problems and interference from wireless LAN networks.

This research project focusses on bringing awareness and building much needed capacity in the weather radar environment using the Design Science Research framework. The North-West University acquired an outdated weather radar system in 2013 with the intent to upgrade the outdated radar to a state-of-the-art research grade radar because the hardware and software of a radar system have changed over the past few decades. Old radars can be re-engineered to provide state-of-the-art data by replacing key components with modern equivalents

The radar system was deployed on a site and operated for 9 months, after which it underwent partial re-engineering to improve the radar's capabilities and reduce many of its known risks. From the data collected, scans were compared between the radar and the SAWS flagship radar, Irene, showing a strong similarity and therefore validating the quality and accuracy of the radar.

All over the world similar weather radars are being abandoned, decommissioned and sold as spare parts, as were done in South Africa. One of the key aims of this project was to develop a methodology to extend the life of these old radars. This would make it possible for the SAWS to redeploy up to 6 radars in strategic locations to improve the resilience of the current network as well as to expand the coverage area. The process followed in this study can be used to re-deploy, re-engineer and conduct a risks analysis on similar weather radar systems throughout the world.

Keywords: Weather radar, radar deployment, radar re-engineering, risk analysis, design science research, TR-1061 solid state transmitter, WRC74C.

LIST OF ABBREVIATIONS

AZ	Azimuth
C	Consequence
CSIR	Council for Scientific and Industrial Research
DQE	Data Quality Estimation
DSR	Design Science Research
EEC	Enterprise Electronic Corporation
EL	Elevation
ETA	Event Tree Analysis
FMEA	Failure Modes and Effects Analysis
FTA	Fault Tree Analysis
FU	Functional Unit
GIS	Geographical Information System
HV	High Voltage
LNA	Low Noise Amplifier
NWU	North-West University
MDS	Minimum Detectable Signal
P	Probability
PPI	Plan Position Indicator
PRF	Pulse Repetition Frequency
UPS	Uninterrupted Power Supply
PRA	Probability Risk Assessment
RDAS	Radar Data Acquisition System
RHI	Range Height Indicator
RR	Risk Rating
S	Severity
SAWS	South African Weather Service
WSR	Weather Surveillance Radar
WRC	Water Research Commission

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CHAPTER 1: INTRODUCTION

This chapter provides an introduction to the research project, analysis from existing research at the time, the research approach followed in this research, and a research project overview.

1.1 INTRODUCTION

Weather radar is an unparalleled tool to study storms and precipitation. It provides high volumes of spatio-temporal data over large areas. The three-dimensional structure of thunderstorms can be sampled at spatial scales from hundreds of metres and temporal scales of a few minutes. The data can be used to inform decision support systems of all kinds, as well as generate a wide variety of derived geospatial products.

South Africa has been at the forefront of radar use since the early 1970s. In 2009 the national weather radar network part of the South African Weather Service (SAWS) upgraded its radar network with state-of-the-art Gematronik radars from Germany. This came at a cost of roughly R 240 Million. The national weather radar network is a world-class asset with enormous potential to provide real-time, high resolution data for various departments and research facilities. It can be used in the commercial sector, assist in an early warning system, help manage water resources, initiate research projects and much more. Recently, the SAWS had severe budget cuts, loss of skilled experts and limited resources. Therefore SAWS has been plagued by technical problems, struggling to maintain the entire system.

In 2014 the North-West University (NWU) acquired a 1974 EEC C-band weather surveillance radar (WSR) from the United States of America with the help of the Water Resource Commission (WRC). The purpose of the radar is to be used for research studies but also to provide meteorological data to the local community. With this project and future ones the NWU aims to build capacity in meteorological research and engineering.

1.2 PROBLEM ANALYSIS

1.2.1 Weather radars in South Africa

South Africa has a rich weather radar history, starting in the early 1970s (Carte, 1979). The Council for Scientific and Industrial Research (CSIR) operated an S-band radar with a 1.1 degree beam width and the radar was located 20km north of central Johannesburg. It was mainly used to study hail on the South African Highveld (Carte and Held, 1978, Mader, 1979). By the late 1980s, the focus of the CSIR was reshaped and the radar was decommissioned. The SAWS started acquiring C-band radars from Enterprise Electronic Corporation (EEC), mostly WSR-74C and WSR-88C models, for major weather stations across the country. The WRC also funded two radars in the 1980s, a C-band EEC and an S-band Russian-built MRL5. The WRC radars were transferred to SAWS and along with their own fleet modified radars. These modifications comprised custom-built signal processing (Terblanche et al., 1994, Terblanche, 1996) and the radars were later connected to yield a national radar network of 10 C-band and 1 S-band running on the Titan software platform (Dixon and Wiener, 1993, Terblanche et al., 2001). In the mid-2000s, funding was secured to acquire two METEOR 60DX mobile X-band dual polarized and 10 METEOR 600S S-band, one of which is dual polarized radars from Gematronik (now Selex ES) installed at Bethlehem. Although the S-band radars are more expensive and have a higher maintenance cost, they were bought because of observed attenuation by the C-band radars in typical Highveld storms, as well as increasing interference from local area network communication on the same frequency.

Currently, the national weather radar network managed by the SAWS consists of 14 operational radars and two mobile X-band radars that have been purchased but not yet deployed. The network covers most of South Africa, especially the highly populated areas and areas with the highest annual rainfall. Figure 1 and table 1 show the position, coverage range and key parameters of the 14 operational weather radars.

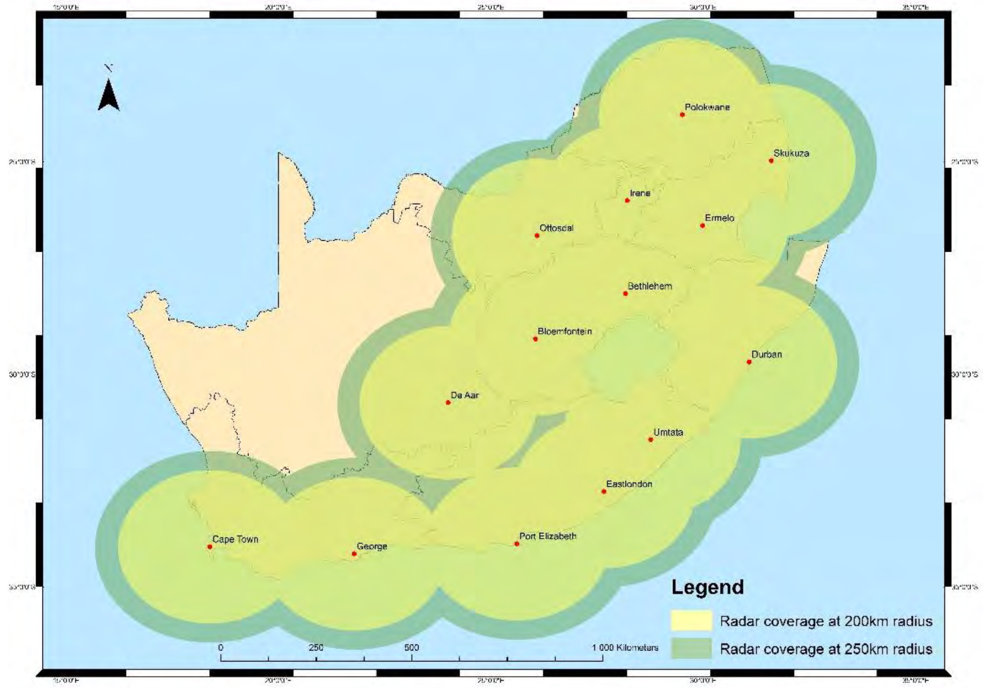


Figure 1: The position and coverage range of the national weather radar network managed by the SAWS (Piketh et al., 2015). The light green area shows the radar coverage at 200 km radius and the darker green at 250 km radius.

Table 1: Key parameters of the national weather radar network in South Africa. The height (m) is given above sea-level, beam refers to the beam width (degrees) of the antenna and the band refers to the frequency band operated in (Piketh et al., 2015).

Radar	Descriptor	Latitude	Longitude	Height	Beam	Band
Cape Town	FACTC	-34.05406	18.38532	905	1	C
Port Elizabeth	FAPEC	-33.98466	25.61075	75	1	C
East London	FAELS	-32.75567	27.66160	603	1	S
Durban	FADNS	-29.70723	31.08155	137	1	S
Umtata	FAUTS	-31.53714	28.76446	857	1	S
De Aar	FADYC	-30.66476	23.99267	1284	1.5	C
Bethlehem	FABLS	-29.16627	26.05105	1556	1	S
Bloemfontein	FABMS	-28.09837	28.16324	1722	1	S
Ermelo	FAEOS	-26.49803	29.98406	1773	1	S
Ottosdal	FAOTS	-26.73519	26.08766	1514	1	S
Irene	FAIRS	-25.91193	28.21072	1532	1	S
Skukuza	FASZS	-24.97395	31.60064	299	2	S
Polokwane	FAPPS	-23.89357	29.50569	1396	1	S
George	FAGGS	-34.21950	21.78265	236	1	S

Unfortunately, in recent years the national radar network has been plagued by technical problems. A drastic shift towards commercial operation and reduced funding has severely limited capacity and resources dedicated to the national weather radar network. The SAWS is governed by the South African Weather Service Act, Act No. 8 of 2001 (ANON_C, 2001). Within this Act, the Minister of Environmental Affairs is authorized to add additional regulations regarding the commercial and cost-recovery activities of the SAWS. Faced with decreasing government subsidy, the SAWS has to continuously expand its activities to cover its cost. Although the government has invested a substantial amount of money (±240 Million Rand) in the current infrastructure, the network is still underfunded and understaffed. Consequently, the national weather radar network is nowhere near to using its full potential. In addition to the reduced funds the SAWS has lost many skilled scientists, technicians, engineers and data analysts. Commercial interests dictate maximum coverage areas, whereas researchers are rather interested in high quality, high resolution data, therefore a much smaller coverage area.

The result of this is that the data quality from most of the radars is not suitable for research or rainfall estimation purposes. Many of the radars suffer from technical problems and limited spare parts to the extent that only about 54% of the data collected over a 12 month period is available. From the data available even less data is of high enough quality to be used for rainfall estimation or research purposes. Figure 2 shows the data availability of the 14 weather radars for a 12-month period. From the statistics it is clear that the radars situated in or close to a big city (eg. Johannesburg and Cape Town) are better maintained than those located near smaller towns (eg. Ermelo and George) (Piketh et al., 2015).

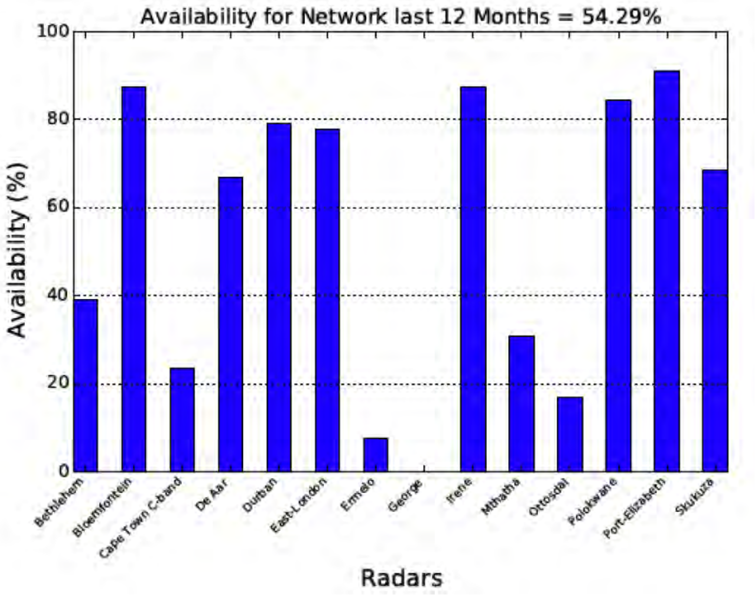


Figure 2: Data availability of the national weather radar network over a period of 12 months (Piketh et al., 2015).

1.2.2 Project problem statement

The national weather radar network has recently upgraded its network with 11 new S-band and two mobile X-band weather radars. Three older (WSR-88C) C-band radars are still in use while another six (WSR-74C and WSR-88C) decommissioned C-band radars are in storage at the SAWS. As the radars get older, they require more frequent maintenance and spare parts. But as the technology progresses, the components used in these radars are becoming obsolete, difficult to source and very expensive. An example of this is the thyratron tube used to pulse the magnetron which generates the radio signal. The thyratron has an expected operating lifespan of between one and three years. This component is rarely used in today's technology and therefore very difficult to obtain at a reasonable price.

In 2014 the NWU acquired an old WSR-74C weather radar form Cotulla, Texas, where it had operated for the last ±30 years. The radar serves as a research platform so local capacity can be expanded, research encouraged, and to facilitate education of engineers and scientists in South Africa. This project holds additional relevance for water research in South Africa as it aims to provide real-time research grade data to the scientific community.

In order for this outdated weather radar to be fully used as a valuable research tool, it will undergo a series of upgrades through a re-engineering process. However, due to a limited budget, time, knowledge and resources available at the time when this research started, this research project focused on smaller sections of the radar. The aim is to provide a framework for other research facilities to enable them to acquire and upgrade their own radars, while knowing the risks involved in re-engineering, commissioning, and operating an upgraded radar. The process of re-engineering a radar can also be used by the SAWS to upgrade and redeploy the nine old C-band (three still in service and six decommissioned) weather radars if needed.

1.3 RESEARCH APPROACH

1.3.1 Design science research

This project is based on the design science research (DSR) framework. DSR is a paradigm to create and evaluate artefacts intended to solve a specific or identified organizational problem. DSR does not only focus on the artefact alone but also on the process followed to solve the problem while contributing to research, evaluating different designs and communicating the results to the correct audience (Göbel and Cronholm, 2012, Peffers et al., 2007, Hevner, 2007). The artefact can range from a physical product to a theoretical model, method or process (Göbel and Cronholm, 2012). DSR is a unique research design methodology for the very reason that it delivers both a theoretical and real-world result (Hevner, 2007). Figure 3 represents a conceptual framework to better understand the DSR cycle paradigm.

The DSR framework consists of three main elements namely; an environment, design science research (method) and a knowledge base. The environment defines the area of interest, problem, system, task and possible opportunities. The DSR centre body consists of two phases, namely development and evaluation. Development (the top section) is the design and construction of the artefact and evaluation (bottom section) is the process of comparing the artefact with design requirements. The third body is the knowledge base that comprises a vast network of different scientific theories and engineering paradigms used in the development/build phase (Hevner, 2007, Göbel and Cronholm, 2012, Hevner and Chatterjee, 2010). In addition to the scientific theories and engineering paradigms the knowledge base also contains two other knowledge types namely; experience & expertise, and meta-artefacts (Hevner and Chatterjee, 2010). These main elements are interconnected with three cycles namely; the relevance cycle, design cycle and the rigor cycle (Hevner, 2007, Hevner and Chatterjee, 2010). Each of these cycles will further be described as they form an essential part of the DSR methodology.

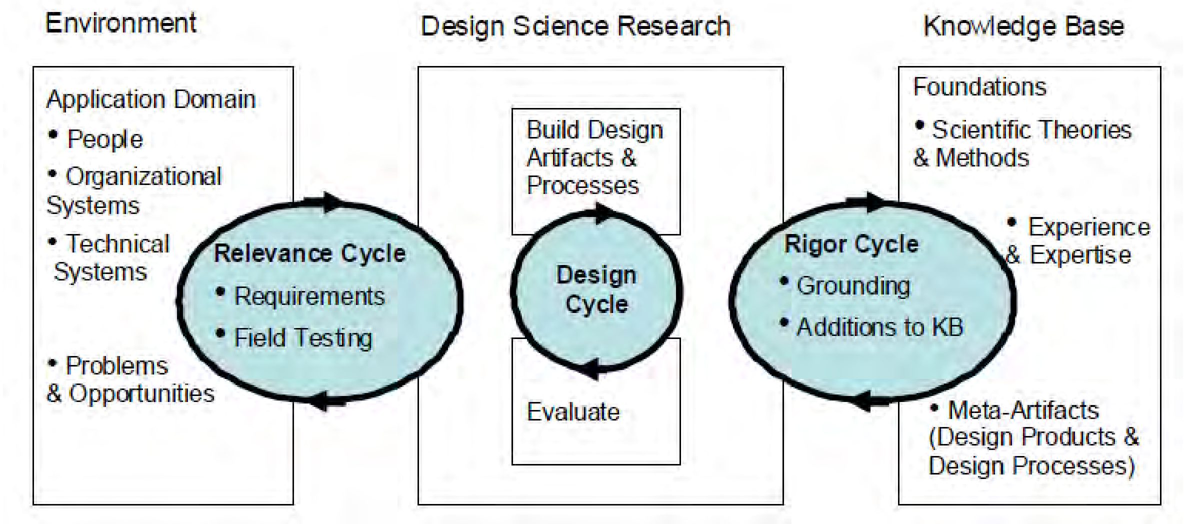


Figure 3: Design science research cycle paradigm (Hevner and Chatterjee, 2010)

A good DSR process will often begin with identifying opportunities and problems in an actual case study. Therefore, the relevance cycle is the important link between the environment and DSR body that initiates the design phase. It provides the requirements as an input to the process as well as defining the evaluation criteria of the research results. In short, the relevance cycle strives to improve the environment domain and also to evaluate the improvement afterwards (Hevner and Chatterjee, 2010).

The rigour cycle provides a link between the already available knowledge base and the research project, ensuring innovation. The knowledge base will keep expanding as a result of the design research of each project. These additional theories and models include all new artefacts, experiences gained throughout the design , and the testing of the artefact in the environment body (Hevner and Chatterjee, 2010, Hevner, 2007).

The design cycle is the heart of any DSR project and constantly rotates between the construction of an artefact and providing feedback from the evaluation for readjustment. The cycle between building an artefact and its evaluation will iterate until requirements are met. As mentioned, the design cycle is the core of the DSR methodology but its success strongly depends on both the relevance and rigour cycles. During the design cycle it is important to keep a balance between the construction and evaluation of the new artefact (Hevner, 2007, Hevner and Chatterjee, 2010).

The ultimate deliverable for a DSR project is the contribution to the scientific knowledge base. There are four possible knowledge contribution types in DSR namely; adaptation, routine design, invention and improvement. Figure 4 shows a matrix of the knowledge contribution framework for DSR.

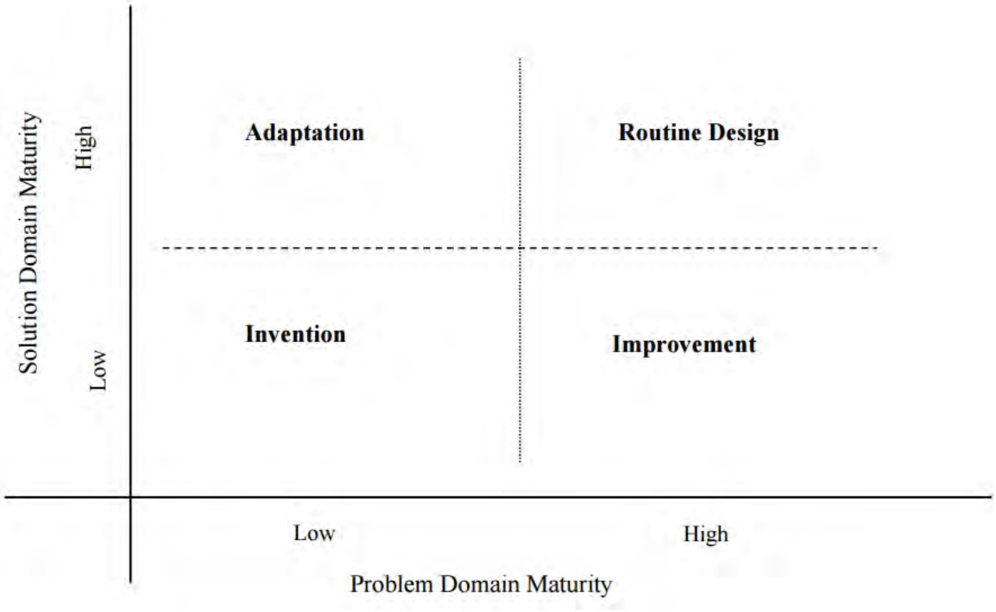


Figure 4: DSR knowledge contribution framework (Vaishnavi and Kuechler, 2004)

In this framework, invention refers to developing a new solution to a new or already existing problem. Improvement is the enhancement of knowledge or solution for a known problem. Adaptation is the innovative revision of knowledge or solution to a known problem. Routine design applies known knowledge or a solution to an already existing problem (Vaishnavi and Kuechler, 2004). Routine design is seldom considered as a DSR research contribution.

1.3.2 Inputs, constraints, resources and output

To further explain the research approach as well as define the research environment, a process modelling block (IDEF0) is used. The IDEF0 process block is designed to formally specify and communicate all the important aspects that influence engineering projects (Kim et al., 2003) as the project's inputs, constraints, resources and outputs. This method allows the researcher to identify all factors that influence a research project, including contributing and constraining factors, while still in the project's initial planning phase. Figure 5 shows the IDEF0 process block compiled for this research project:

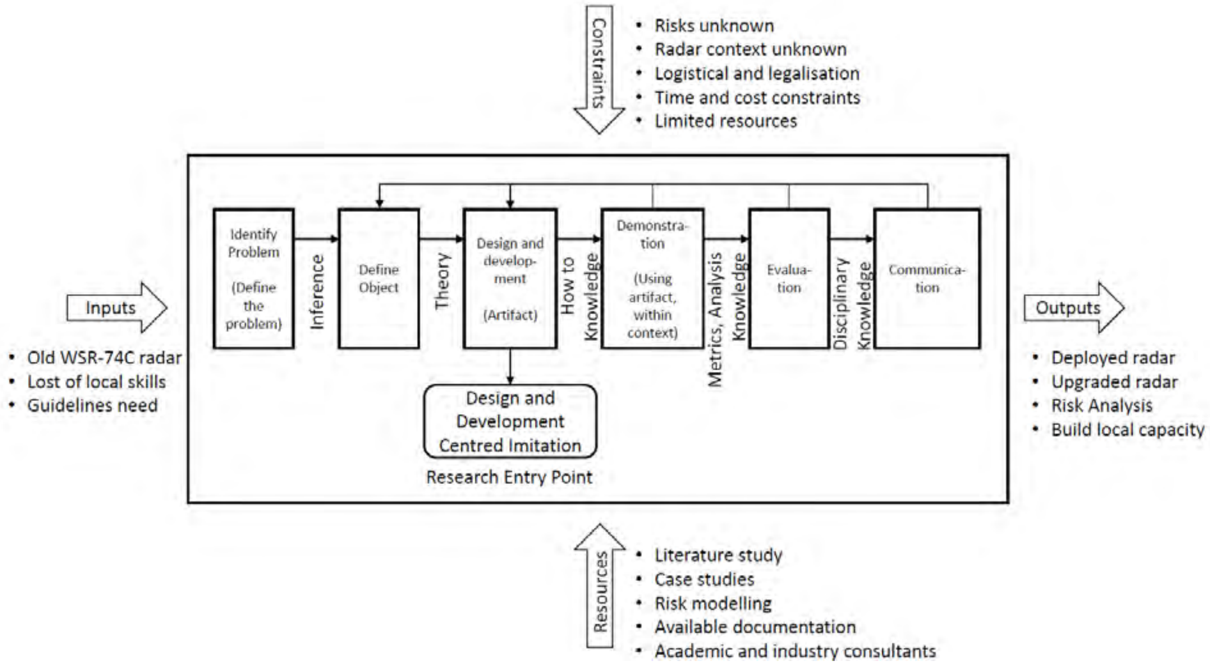


Figure 5: IDEF0 illustration of the research approach followed in this research. (modified from (Peffers et al., 2007))

1.3.2.1 Inputs

The main input to this research project process is a real-world problem, namely the need for re-engineering of an outdated radar station. The radar needs to be deployed and re-engineered, in conjunction with a risk analysis (and consequent management of risk) on the project. An additional input is the need for a guiding methodology to enable the research team to repeat this process in future projects on radar weather stations.

1.3.2.2 Constraints

There are certain constraints that can potentially hamper any research project's progress. It is therefore important that these constraints be known at the onset of research so that preventative action can be taken in advance. The expected constraints for this research project were identified as:

- Initially, the research project's technical and project risks were unknown – only an outdated radar system existed;
- Limited resources and documentation were available on the WSR74C radar system;
- Logistical requirements were not entirely clear at the onset of the project, including site location and related constraints;
- A list of legal and related requirements were not defined, which required investigation;
- Re-engineering and upgrading procedures were not defined and required research;
- Available time, budget and human resources were identified as constraints;
- External factors, such as the weather, played a significant role.

1.3.2.3 Resources

There is an abundance of literature available on the *general* radar environment, re-engineering procedures and risk analysis techniques individually; however, very little of the re-engineering process and risk analysis literature is based on weather radars *specifically*. This project also required specific resources, such as product manuals and procedures, which were not easily acquired. This is partially due to the age of some equipment used since the documentation was never fully digitized when this system was first developed in the early 1970s. The following list of resources was utilized for this project, not limited to the following:

- A comprehensive literature base on general aspects relating to radar systems;
- Available documentation, albeit limited, on the particular radar itself;
- Academic and industry consultants were available for consultation;
- Relevant case studies on re-engineering were available in literature;

- Documented local laws and regulations could be found.

1.3.2.4 Outputs

The output of this research project included both physical and theoretical artefacts. The physical artefact included the deployed and upgraded radar through a re-engineering process. The re-engineering process had to be documented, which added to the theoretical meta-artefacts. A risk analysis report (included in this thesis) was compiled on the overall project, radar system and re-engineering process to highlight possible risks that could be avoided, also included as meta-artefacts. These outputs in the model contributed to building much-needed local capacity in South Africa in the weather radar environment.

1.3.3 Research contribution

It is known that challenges often exist with radar systems, for example the installation process, maintenance, cost and human resources. If well-maintained, weather radars can operate for decades but as the technology progresses, older systems become obsolete. Finding spare parts and maintaining the system become daunting and costly tasks. As the radars age, they are sold for a fraction of the price of a new radar system. This gives smaller companies and research facilities the opportunity to purchase these inexpensive outdated radars. Radar systems are divided into functional blocks as described in the literature to follow in Chapter 2. This allows the engineer to re-engineer only the necessary sections of the radar, thus only upgrading the outdated or obsolete parts rather than the entire system. Although the methodology for deploying an old weather radar and upgrading it through a re-engineering process have been done on multiple occasions, very little literature is available, if any.

In addition to the actual *re-engineering of a weather radar*, this research project *developed and documented a methodology* followed to deploy and re-engineer a weather radar. A further fundamental contribution includes the *risk analyses* of the radar system, which showed how risk was managed. The risk analysis serves as (i) a *management tool for prioritisation of effort and budget* and (ii) *validation methodology* to show that the research effort actually resulted in an improvement of the outdated system, and where these improvements were made. This research provides a risk analysis conducted on this radar system and concludes with a set of guidelines obtained from the literature study and personal experience for future projects of a similar nature.

To show how the project contributed to the research knowledge body, the DSR framework matrix from figure 4 was used to indicate the knowledge contribution.

1.3.4 NWU project objectives

The NWU acts as a stakeholder of this project whose objectives had to be met in parallel with the research effort. This research project redeployed the NWU weather radar to gather data as quickly as possible after its acquisition. The motive for first deploying and operating the radar was to gather data during the initial phase. The data generated by this original radar will then be compared to the data generated by the re-engineered radar. The radar operated for a number of months while the re-engineering process was being planned, acquiring necessary funds and procuring radar system components.

The second objective was to re-engineer and upgrade the radar as best as possible. The NWU would like to eventually upgrade the radar system to be equivalent to that of the USA's research grade radar at the National Centre for Atmospheric Research (NCAR). This means upgrading the radar to dual-polarization with Doppler Effect taken into account. Once the radar has been fully upgraded, it will be one of the best weather radars in Africa.

A risk analysis was conducted on the radar system before and after modifications. The documented analysis can be used as a motivation for upgrading a radar system in the future. A risk analysis was conducted on the entire project including the installation process, utilities, operating and maintaining the radar. This study provides valuable data and insights for future projects with the same objectives as this project.

As is known, the South African weather radar network has been struggling to maintain its 240 million rand network due to a lack of financial support and the loss of technical skills. This research helps to build much-needed capacity in South Africa towards installing, upgrading and maintaining outdated weather radars currently not used to their full potential.

1.4 RESEARCH PROJECT SUMMARY AND CONCLUSION

An introduction and problem analysis were provided in this chapter, followed by guidelines of Design Science Research (DSR). These guidelines were followed throughout the project and in particular in the radar re-engineering process in Chapter 3 and evaluation in Chapter 4. In addition, this chapter described the DSR environment and problem to be addressed in this research project.

Chapter 2 contains a literature study with an overview of the radar's operational design, installation requirements and radar-siting procedures. Background information is provided on how radar technology has progressed over the years and how it relates to the NWU's radar. Furthermore, Chapter 2 provides a discussion of risk analysis techniques and available tools. This chapter provides an overview of existing knowledge in the knowledge body of the DSR.

Chapter 3 contains the methodology used to install, re-engineer and conduct a risk analysis on the weather radar. The physical artefact and theoretical artefact is discussed in Chapter 3. The methodology can be used as a guideline by other radar enthusiasts to install and re-engineer an old weather radar.

The radar and project evaluation are presented in Chapter 4, followed by a conclusion and recommendations in Chapter 5. Finally, this thesis contains a bibliography and concludes with relative documents in the appendix.

To finalize this chapter, it is necessary to provide a clear problem analysis in the form of a matrix. The research methodology that is followed effectively translates project objectives, resources, and limitations into research challenges. Table 2 shows the research challenges and the information sources that contributed to the identification and definition of research challenges. The information sources together with the research need (as defined by the NWU) and its derived challenges thus validate the research problem.

Table 2: Research problem validation

Research Challenge / **Information Sources**	Radar environment and context are unknown	Radar installation and operation procedures not documented	Re-engineering of the radar system	Lack of previous risk analysis on a radar system	Risk analysis is mainly compiled from observations	Limited expert advice and knowledge
SAWS information	X	X				X
Radar documentation	X	X				X
Observations and previous case studies	X	X	X	X	X	X
Literature resources available	X	X	X	X	X	X

CHAPTER 2: LITERATURE STUDY

This chapter provides an in-depth explanation on the operation of a weather radar, its operational design and how radar technology has progressed over the past decades. This chapter also provides a guideline to select the best siting procedures and requirements for a radar system. It further explains the process of conducting a risk analysis. The reason for documenting basic radar functionality, steps to select a radar site, and other fundamentals, is based on the need to establish a research baseline for future use by the NWU.

2.1 WEATHER RADAR SYSTEM

2.1.1 Radar background

A radar is a complex electrical, electronic, mechanical and information system used to detect and track specific objects over a considerable distance. The word radar is an acronym used for **Ra**dio **D**etection **a**nd **R**anging first used by the U.S Navy in 1940 (Toomay and Hannen, 2004). The discovery of radar followed shortly after radio was established as a communication method. In 1934 Professor Albert Hoyt T. and Leo C. Young observed an aircraft interrupting their communication signal and proposed to use short pulses of radio energy to detect objects. Over subsequent years countries all around the world shared information on the development of radars. However, radar made its first major appearance in the Second World War where it was used to detect and track enemy movement. During the war scientists observed interferences on the monitor and processed it as noise. It later became known that the interference was caused by weather-related phenomena such as precipitation. After the war many of the surplus radars were purchased and modified by scientists to observe weather, hence the beginning of weather radars (Rinehart, 1997).

In modern times, a weather radar has become an unparalleled tool, providing real-time, high spatio-temporal data over large areas. The data is used to observe, detect and identify meteorological targets ranging from very small particles such as mist to large hail storms. Weather radars are not limited to meteorological targets and occasionally detect non-meteorological targets such as birds, bats, insects, veld fires and even sand storms (Büyükbas et al., 2006). Using modulation software the data collected from the radar can be used to derive multiple products every few minutes. The products derived will further be described in section 2.1.4.

2.1.2 Radar operation

The basic concept of a radar is relatively simplistic but the practical design and implementation are not. A radar operates on the principle of sending electromagnetic (EM) pulses towards a region of interest. Maxwell's equations describe the physics of these pulses – these fundamentals will not be repeated in this thesis as it is well-documented in literature (Richards et al., 2010). When the EM pulses encounter an obstacle, such as rain drops, the waves are reflected and scattered in all directions. The majority of energy will continue onwards, but a fraction returns to the radar, known as a radar echo. This effect is illustrated in figure 6. Due to the nature of the pulse and echoes received from backscatter, the radar can derive information about the target. This method of observation is not new to the animal kingdom where bats use ultrasonic pulses (120 kHz) to locate and avoid objects during flight (Büyükbas et al., 2006).

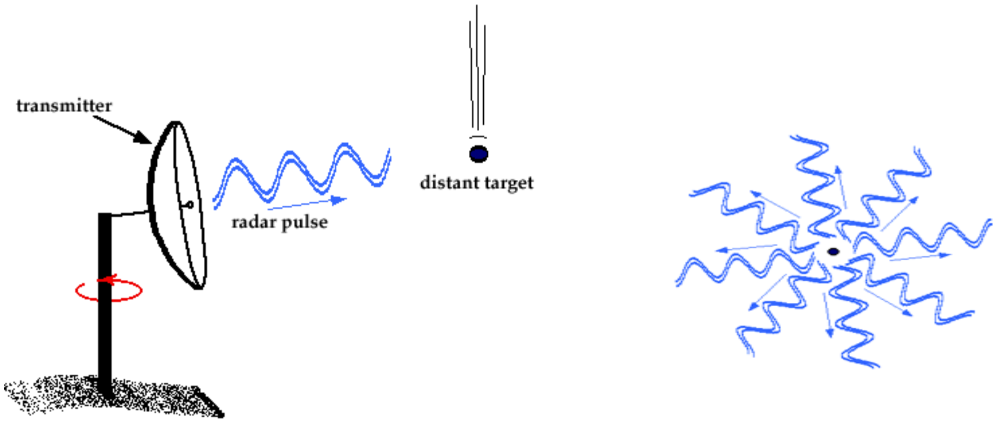


Figure 6: Principle of pulsed radar (ANON_F, 2016)

Radar systems have evolved significantly since the start of radar in the early 1940s, yet the fundamental operating principle has stayed the same. Although the detailed design of any specific radar system will be different, the basic design must include a transmitter, receiver, antenna, modulator, display, duplexer and master clock (Rinehart, 1997). Figure 7 shows an example of a block diagram representing the basic components of a radar system. This is not a standard diagram for all radar systems and is a simplified example. Each sub-system will further be elaborated upon so as to obtain a comprehensive understanding of a radar system’s operation.

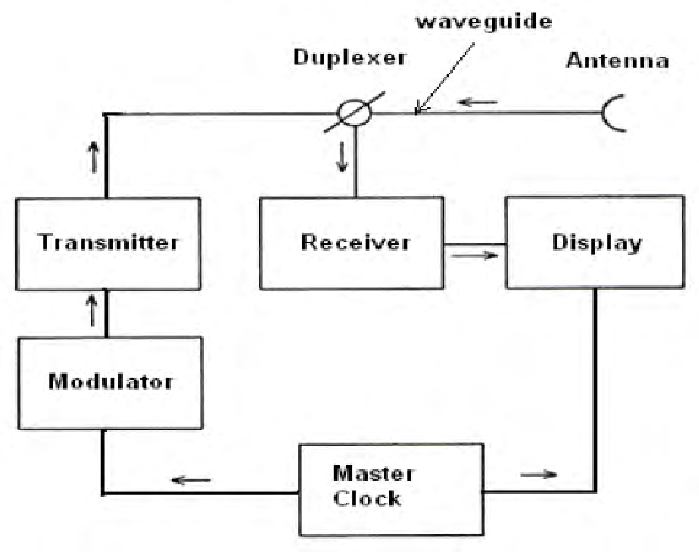


Figure 7: Basic weather radar functional block diagram (Büyükbas et al., 2006).

2.1.2.1 Transmitter

The transmitter generates high power EM pulses used to illuminate a specific target. There are different kinds of transmitters available varying in size, power output and frequency of operation. Radar characteristics depend on the application and type of target being observed. A typical transmitter consists of an oscillator or power amplifier, modulator and a power supply. Certain transmitters can generate pulses in excess of one gigawatt. The most common transmitters used for meteorological purpose are the magnetron tube, the klystron and the solid-state transmitter. For this study only the magnetron tube will be discussed.

Magnetrons were the first really high-powered EM transmitters invented before the Second World War. It has a strong permanent magnet field across the waveguide cavity. When a high voltage pulse ($27\ kV$) is applied to the terminals, the electric field creates EM pulses perpendicular to the magnetic field in the direction of the waveguide. The frequency is determined by the transmitter’s mechanical characteristics such as the number of cavities and the sizes of the cavities. Most magnetrons have a cavity adjustment knob which changes the cavity size within, making it possible to adjust the frequency by a few megahertz. Since the magnetron is self-oscillating it is a non-coherent transmitter meaning that there is not a constant phase between the first and second pulse (Richards et al., 2010). Magnetrons are light, high-powered and cost-effective transmitters extensively used by commercial airline weather monitors, military applications, collision avoidance radars, ground based weather radars and even certain low cost medical equipment.

Due to the magnetron's mechanical design, it has several undesired characteristics such as fixed frequency, arching, missing pulses, as well as frequency pushing and pulling (Richards et al., 2010). Figure 8 shows an example of a magnetron commonly used by a weather radar.

Figure 8: Example of a magnetron transmitter for a C-band weather radar (ANON_B, 1998)

2.1.2.2 Receiver

The transmitter sends out high-powered, short duration EM pulses for a short duration and waits a few milliseconds before sending out another pulse. In between each pulse the receiver listens for echoes reflected back from a target. EM pulses travel at the speed of light ($3\times10^{8} m/s$) covering approximately $300\,km$ per millisecond. Most receivers have a low-noise amplifier (LNA), placed directly after the duplexer, followed by a band-pass filter. The LNA is the first stage of amplification, boosting the weak received signal. The band-pass filter minimizes the receiver's noise figure and attenuates signals outside the passband. Weather radars operate at very high frequencies, usually above a signal processor's capability.

Therefore the signal is down-converted to a lower intermediate frequency using a mixer and local oscillator as a frequency reference. The receiver has multiple amplification and filter stages. The signal power reflected back from meteorological targets can range between $-110\,dBm$ to $0\,dB$ power. The receiver scales would normally be split into two parts; a linear scale for the weaker signals and a second logarithmic scale for the higher powered signals (Richards et al., 2010, Büyükbas et al., 2006). Receivers are therefore used as a first line of data processing, filtering out all the unwanted signals, amplifying the weak signals and only passing the correct signals to be further processed for data products.

2.1.2.3 Antenna

The antenna is the transducer between the radar system's RF section and the outside world. It is used to convert pulses of energy from the transmitter into EM waves in the atmosphere and to receive echoes reflected back. The pulses are sent from the transmitter through waveguides to the antenna. The feed horn is used to direct pulses of EM energy towards the parabolic antenna, which reflects it in a symmetrical cross section beam towards an area of interest. The antenna is fixed to a pedestal that rotates both in the azimuth (AZ) and elevation (EL) axes (Büyükbas et al., 2006). Figure 9 illustrates the effect of the feed horn and antenna.

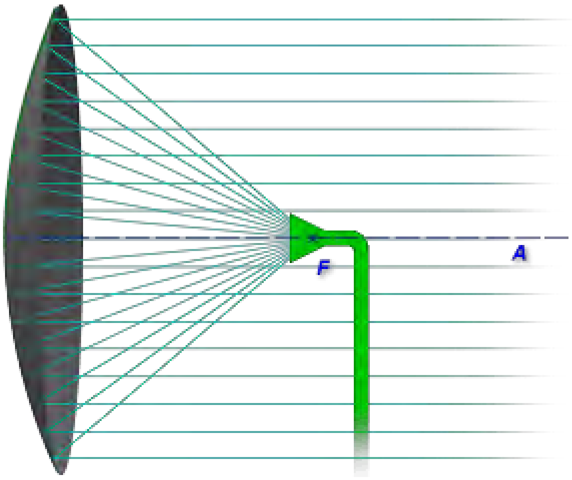


Figure 9: Principle of parabolic reflector antenna (Wolff, 1998)

The size of the antenna is determined by the frequency of the transmitter as well as the required gain (the size is limited by practical considerations such as available space and weight, as well as cost). For each frequency band there are different antenna sizes available. A larger antenna in the same frequency band will have a smaller focus beam width and therefore a better angular resolution (due to higher gain). However, a bigger antenna does increase the initial and maintenance cost of the radar (Büyükbas et al., 2006).

Ground-based weather radars are exposed to harsh weather conditions such as strong winds, hail, rain and sunlight. To protect the antenna from the elements, it can be housed in an enclosure known as a “radome” (portmanteau of radar and dome). The radome is a waterproof enclosure made from a non-metal based material such as fibre glass. However, the radome can possibly reflect or reshape small EM pulses, making it important for the radome to be well designed and characterized (Büyükbas et al., 2006).

2.1.2.4 Master clock

The master clock is used to synchronise all the subsections. Since the EM pulses are transmitted and received through the same antenna, it is crucial that the timing of each pulse is correct otherwise data can be lost. The receiver also uses the time from the transmitted pulse to the received echo to determine the distance of the target. In modern radar systems a high-accuracy GPS system with a high accuracy is used for synchronisation. An additional benefit of using a GPS system is it ensures that multiple radar systems within a single network are all synchronised (Büyükbas et al., 2006).

2.1.2.5 Duplexer

The duplexer, also known as a transmit-receive switch, is a device used to separate the transmitted signal from the received signal. Since a weather radar uses a single antenna to transmit and receive pulses, it is important that these paths be isolated from one another. The transmitter can generate pulses up to $1\,MW$ while the receiver can measure as low as $1\,nW$. If the duplexer fails to switch, it will damage the LNA or the entire receiver subsystem. It is therefore important that the correct duplexer is used or it could result in data loss, component damage, or introduction of unwanted noise in the received signal (Richards et al., 2010).

2.1.2.6 Display or signal processor

Once the receiver has amplified and down-converted the echoed signal, the signal processor performs analogue-to-digital conversion and applies filters or corrections to the data where needed. These filters include correction for attenuation (atmosphere, radome, and waveguide) and signal rejection from ground clutter. Desired signals are passed based on the distance to the target. After the signal has been corrected, data processing is applied to compute a set of products such as the reflectivity, mean velocity, distance, spectrum width, target recognition and automatic tracking, etc. The data is displayed in various formats, such as plan position indicator (PPI), constant altitude plan position indicator (CAPPI), range height, or amplitude range. The common method used for weather surveillance is the PPI display as shown in figure 10. A PPI is a map as a representation of the area around the radar, providing the target in a polar-coordinate (range and angles) layout.

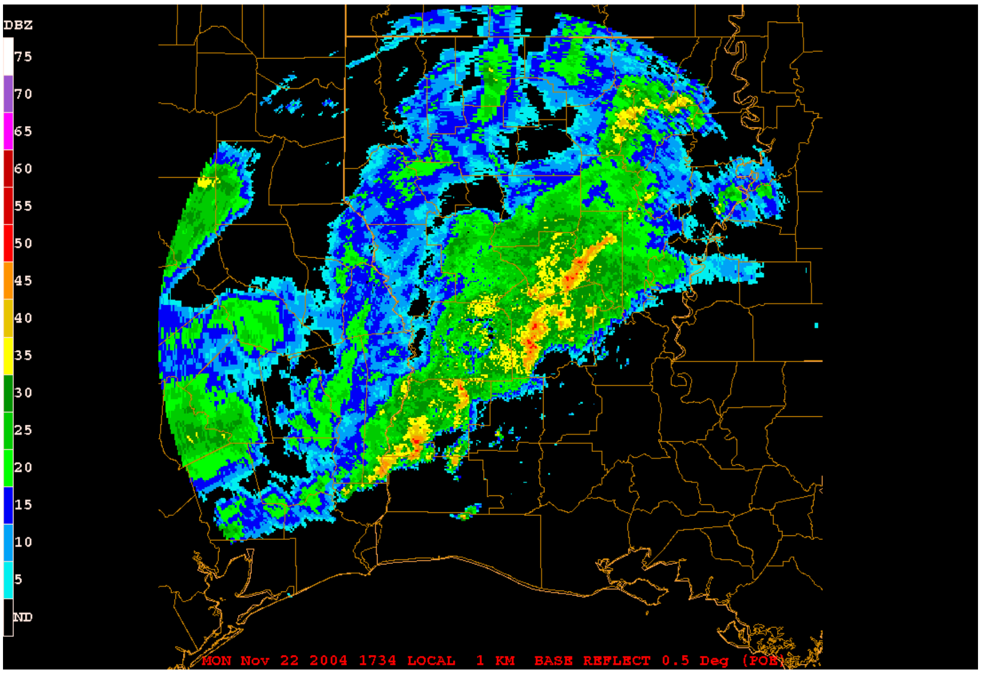


Figure 10: Example of a PPI display showing the base reflectivity of a storm in North America (ANON_F, 2016)

2.1.3 Types of weather radars

There are various types of weather radars available and they are classified in terms of their transmitter, receiver, operating frequency, type of transmitted pulse, and type of polarization. The main difference between radar types is its operating frequency band (S-, C- or X-band). Two other frequency bands, L- and K-band, can also be used for special purpose radars but are rarely used (Buyukbas, 2009). The choice of the operational frequency band is determined by a combination of factors such as the target, the radar application, engineering requirements, maximum range, antenna size and overall cost (Baldini et al., 2012). A higher frequency has a shorter wavelength and will therefore have a higher attenuation factor. This means that pulses transmitted in regions with heavy rain, hail or snow will likely be completely attenuated. This will hinder signal propagation and might result in unreliable or missing data. Attenuation in terms of a weather radar is the loss of pulse energy due to the scattering and absorption of energy as it hits particles in the atmosphere (Büyükbas et al., 2006). A weather radar is allocated to a frequency band but operates on a specific frequency within that band. This is to ensure that all weather radars comply with rules and regulations of a country's licensing sector. Each frequency band will briefly be described and summarized.

An L-band (1-2 GHz) radar operates on a very low frequency resulting in a long wavelength (15-30 cm) and is therefore not easily affected by attenuation, commonly used for clear air turbulence (CAT) studies. An S-band (2-4 GHz) radar operates on a higher frequency (2.9 GHz) than the L-band. The frequency is still relatively low, therefore not easily attenuated, making this radar ideal for long-range observations. However, due to the long wavelength the radar requires a much stronger transmitter and large antenna, adding to the procurement and maintenance cost. The S-band is mainly used to detect and track severe storms over large areas such as tornados, hail storms and hurricanes. The C-band (4-8 cm) radar operates on a frequency of 5.6 GHz making the radar more sensitive to attenuation. The C-band radar is used for shorter distance observation, requires a smaller antenna and less power, making it ideal for a mobile unit. This radar was the preferred radar for many years until recent wireless communication started to operate on the same frequency band as the radar. Wireless communication has a wide bandwidth causing major loss of data.

The X-band (8-12 GHz) radar has a high frequency of 9.3 GHz making the radar very sensitive to small particles. Due to the high attenuation the radar has a very short operating range. These radars are mainly used for scientific studies on cloud development, to observe light precipitation, as terminal Doppler weather radars at airports (Buyukbas, 2009, Baldini et al., 2012, Büyükbas et al., 2006). Table 3 shows a summary of the three main frequency bands for a weather radar.

Table 3: Radar frequency band summary (Büyükbas et al., 2006)

	S-Band Radar	**C-Band Radar**	**X-Band Radar**
Frequency	2-4 GHz (2,9 GHz)	4-8 GHz (5,6 GHz)	8-12 GHz (9,3 GHz)
Wavelength	15-7,5 cm (10,3 cm)	7,5-3,8 cm (5,3 cm)	3,8-2,5 cm (3,2 cm)
Typical Range	300-500 km	120-240 km	50-100 km
Peak Power	500 MW - 1 kW	250 - 500 kW	50-200 kW
Measuring Sensitivity	Rain, snow, hail	Rain, snow, hail, drizzle	Rain, snow, hail, light drizzle
Attenuation	Less than C- or X-band	Less than X-band but more than S-band	Much more than compared to S- or C-band
Antenna Size	7,5 m	4,2 m	2,5 m
Cost	1,5 times C-band 2 times X-band	0,7 times S-band 1,3 times X-band	0,5 times S-band 0,8 times C-band

2.1.4 Derived weather radar products

Weather radars provide multiple sets of data from a single scan which are converted into accurate and meaningful data. To better understand the operation of a radar and how the data is processed, important parameters are briefly described. The basic radar parameters are:

- Maximum unambiguous range (Rmax);
- Reflectivity (Z);
- Rainfall rate (R);
- Velocity (V);
- Spectrum width (W); and
- Differential reflectivity (ZDR).

2.1.4.1 Maximum unambiguous range

The maximum unambiguous range refers to the longest distance that a transmitted pulse can travel and return before the next pulse is transmitted. The returned pulse must still provide sufficient energy to generate accurate and reliable data. The $Rmax$ of any radar pulse is calculated using the equation below where c is the speed of light at $3x10^8 m/s$ and *PRF* the pulse repetition frequency.

$$Rmax = c/(2xPRF) \tag{2.1.1}$$

The PRF is the number of pulses sent from the radar in one second. A higher PRF means more data scans, giving a higher accuracy but limited operating range. If the PRF is too fast, a pulse might return to the radar after the next pulse has already been sent, resulting in false data. The effect is known as range ambiguity and it is difficult for a radar's signal processor to distinguish between the two pulses (Büyükbas et al., 2006, Richards et al., 2010).

2.1.4.2 Reflectivity

Reflectivity is the measurement of how much power was scattered back from a target. The amount of reflected power is directly related to the sum of cross sections (D) of particles to the sixth power per volume scan as shown in the following equation:

$$z = \sum_{VOL} D^6 \tag{2.1.2}$$

The reflectivity value can give false measurements because it cannot determine the size of the particles measured but gives an estimation of the total volume of the scan. A single $1/4$ inch rain drop reflects the same amount of signal as 64, $1/8$ inch rain drops and yet the $1/8$ inch rain drop has 729 times more liquid (Büyükbas et al., 2006). Evidently reflectivity has a wide range of values ranging from 0.001 (fog) to $40{,}000{,}000\ mm^6/m^3$ (heavy hail). To simplify these values reflectivity is expressed on a logarithmic scale known as dBZ (Büyükbas et al., 2006, Rinehart, 1997).

$$dBZ = 10 \log z \tag{2.1.3}$$

Table 4 shows the correlation between the linear reflectivity, its logarithmic, dBZ (decibel relative to Z) value, and description of expected weather conditions.

Table 4: Reflectivity of different weather conditions (Büyükbas et al., 2006)

Linear Value $z(mm^6/m^3)$	**Logarithm value $\log_{10}z$**	**Decibels dBZ**	**Weather Condition**
1000000	6	60	Extremely heavy rain, hail storms
100000	5	50	Heavy rains, thunderstorms, possible hail
10000	4	40	Moderate rain, showers
1000	3	30	Light rain
100	2	20	Very light rain, drizzle
10	1	10	Mostly non-precipitation clouds
1	0	0	Insignificant

2.1.4.3 Rainfall rate

Rain is characterised by its fall rate to earth known as “rain rate” and measured in millimetres per hour (mm/h). Rain rate was one of the earliest quantitative precipitation estimation methods used by weather radar and has stayed the same over the years. As mentioned, weather radars are not able to directly measure precipitation but the reflectivity caused by the rain reflecting the radar signal. To convert radar reflectivity measured aloft to the rain rate at ground level is a complex procedure. However an empirical model known as the Z-R relationship can be used to estimate the rain rate (Büyükbas et al., 2006).

$$Z = A.R^b \tag{2.1.4}$$

The Z is the reflectivity measured in dBZ representing a value of the rain rate R at ground level. Both A and b are variables determined by the assumed raindrop distribution model. The relation between reflectivity and rain rate was first described by Marshall and Palmer in 1948 (Marshall et al., 1947). These days numerous models for measurement of drop size distribution have been established focussing on different rain types as stratiform, orographic, thunderstorm, convective rain and snow (Handbook, 2005, Büyükbas et al., 2006, Blake, 1969).

2.1.4.4 Velocity (V)

Most modern radars are equipped with Doppler capability and are thus known as Doppler radars. Doppler radar works on the principle of the Doppler effect, where, as the target moves towards or away from the radar, it changes the frequency of the reflected pulse relative to the transmitted pulse. The radar measures the frequency transmitted and that of the echo returned. The phase difference between the two signals is converted into a radial velocity (Büyükbas et al., 2006, Leeson and Johnson, 1966). This radial velocity measures and predicts the movement of rainfall activity and is useful to end users.

2.1.5 Radar calibration techniques

2.1.5.1 Transmitter calibration

Routine maintenance, inspection and calibration are essential to ensure accurate quantitative precipitation estimation (Thorndahl and Rasmussen, 2012). Calibrating a radar consists of three aspects, namely calibrating the transmitter, receiver, and antenna. The maximum range of a radar is determined by the peak output power of the transmitter (Richards et al., 2010). As the output power decreases, so will the received echo signal decrease in amplitude, therefore under-estimating rainfall reflectivity. During the calibration, the following parameters must be measured for any fluctuations: pulse width (PW), pulse repetition frequency (PRF), duty cycle (DC), peak power, and voltage standing wave ratio (VSWR) (Büyükbas et al., 2006).

For the sake of completeness, each calibration process is explained briefly as documented in the original calibration manual EEC (1975) (as presented on the following pages).

1) Pulse width

The pulse width is the duration of the EM pulse measured from its start to its finish in seconds.

i. Position the antenna away from any constant echoes and switch the antenna control to “OPERATE”;
ii. Connect the 20 dB attenuator to the forward port on the bi-directional coupler at the transmitter followed by a crystal detector;
iii. Using a BNC “T” connector, the one end is connected to the crystal detector, the other end to a 50 Ω termination load and the middle to an oscilloscope port. The trigger from the transmitter can also be used to externally trigger the oscilloscope;
iv. Start transmitting and the adjust oscilloscope until a clear pulse can be seen;
v. The pulse width is measured at 70% of the pulse amplitude, also known as the -3 DB value.

2) Pulse repetition frequency (PRF)

The PRF is the number of pulses sent from the radar in one second.

i. Readjust the oscilloscope to see at least two pulses;
ii. Measure the time from the start of one pulse to the next, also known as the pulse repetition time (PRT);

The PRF is calculated using the following equation:

$$\mathrm{PRF} = \frac{1}{\mathrm{PRT}} \quad (2.1.5)$$

3) Duty cycle (DC)

The (DC) in dB is determined using the following equation:

$$\mathrm{DC} = 10\log\left(\frac{1}{\mathrm{PW} \times \mathrm{PRF}}\right) \quad (2.1.6)$$

4) Peak power

The peak power measurement is important to ensure the operational status of the transmitter and accurate data analysis.

i. Connect a 20 dB attenuator to the forward port on the bi-directional coupler at the transmitter;
ii. Connect the power meter to the attenuator, start transmitting and record the measurement.

The peak power is calculated using the following equations:

$$\begin{aligned}\text{Peak Power} = \ & \text{Attenuator} \\ & + \text{Duty Cycle} \\ & + \text{Coupler Attenuation} \\ & + \text{Power measurement}\end{aligned}$$

6) Voltage standing wave ratio (VSWR)

As energy propagates through a transmission line, a small amount of the energy is reflected back to the transmitter known as voltage standing wave ratio. The VSWR can give an indication of a defective wave guide, the condition of the antenna or any impedance mismatch between the transmitter/ receiver and the antenna. VSWR is expressed as a ratio between the transmitted and reflected power. A VSWR of 1:1 indicates that no power is reflected back to the transmitter, an ideal situation but rarely ever obtained. For an accurate VSWR reading the measurement should be taken at the point of interest for example the antenna. Most radars will have two bi-directional couplers positioned at the transmitter and the second one at the antenna.

The VSWR is calculated as follows:

i. Position the antenna away from any constant echoes;
ii. Connect the power meter through a 20 dB attenuator to the reverse power port on the bi-directional coupler and start transmitting at full power;
iii. Record the power measurement and switch transmitting off;
iv. Reposition the 20 dB attenuator and power meter to the forward power port on the bi-directional coupler and start transmitting at full power;
v. Record the power measurement and switch the transmitter off.

The total forward power is calculated by adding the dB value of the attenuator, bi-directional coupler attenuation, and the measurement on the power meter. The reverse power is calculated in the same manner. A realistic VSWR is 1:1.1 or a return loss of between 26 and 40 dB. Return loss is the difference between the forward and reverse power.

The following equation can be used to calculate the VSWR (EEC, 1975).

$$\mathrm{VSWR} = \left[1+10^{(-\mathrm{Return\ loss}/20)} \big/ 1-10^{(-\mathrm{Return\ loss}/20)}\right] \text{ (Pozar, 2009) (2.1.7)}$$

2.1.5.2 Receiver calibration

The radar receives signals over a wide range from -110 dBm (Büyükbas et al., 2006). With such a wide range the receiver makes use of a logarithmic scale to better represent the data. The logarithmic data is used to establish a correlation between the received signal strength in dB and rainfall rate, also known as a Z-R relationship (Rinehart, 1997). The Z-R relationship is used to present 0.004 to 150 mm/h rainfall rate generally divided into 14 levels (Teschl et al., 2007). The receiver uses a response curve to translate the received signal strength from the receiver to a DBZ value used in the Z-R relationship. The primary focus of the calibration is to ensure that the response curve is accurate. To calibrate the receiver, it is important to know the minimum detectable signal (MDS) (Büyükbas et al., 2006). The MDS is the smallest signal or reflectivity that the receiver can receive to distinguish between data and noise. The following process is determined to measure the MDS (EEC, 1975):

i. Always ensure the antenna control is set to “SAFE” before starting with any receiver calibrations;
ii. Ensure the radar is switched to local control and AFC/MFC to MFC;
iii. Connect the oscilloscope to the video output of the radar and the trigger to both the oscilloscope and modulator for sync;
iv. Set signal generator to external trigger mode. Always decrease the signal generator output power before connecting or removing the cable;
v. Connect the signal generator to the forward port on the bi-directional coupler;

vi. The modulator is connected to the signal generator external trigger and setup as follows: external sync, delay with approximately 400 µs and pulse width of 100 µs;
vii. Increase the signal generator output power until a clear pulse can be seen on the oscilloscope;
viii. Use the MFC adjustable frequency knob to peak the pulse in amplitude;
ix. Decrease the signal generator output power until only 50 % of the pulse amplitude is above the noise level. Record the signal output power for further calculations.

To calibrate the response curve, repeat setup steps from i to viii. The response curve consists of different signal power increments representing a certain dBZ value. The increments are determined by the type of receiver software used. The following steps are followed to complete the receiver calibration (EEC, 1975):

i. Set the signal generator power to the first increment according to the software;
ii. Use the MFC adjustable frequency knob to peak the pulse measured on the oscilloscope;
iii. Record the measurement with the receiver software;
iv. Repeat xi and xii for every increment required.

Since no radar system is identical to another, a radar constant is calculated representing that specific radar. The radar constant is determined using the equation below:

$$c = \frac{1024\ \ln(2)\ \lambda^2}{\pi^3\ p_t\ g^2\ \theta\ \phi\ h\ |K|^2} \qquad (2.1.8)$$

Where λ is the wavelength (meter), p_t is the peak power of the transmitter (watt), g is the antenna gain (dB), θ is the horizontal beam width (degrees) and $\emptyset$ the vertical (degrees), h is the radar's pulse length (meter) and K is the dielectric constant taken as 0.93 for radars of this type.

2.1.5.3 Antenna calibration

The third calibration is the antenna's alignment to true north. If the azimuth alignment is out by only one degree, a cloud that is 150km away would be detected off centre by a distance of 2.6 km. There are two techniques used to check the radar's alignment, viz. a fixed echo or tracking the sun. The first technique uses an obstacle that generates a constant echo such as a building, mountain, tower, or metal-coated sphere balloon. These echoes have a specific elevation and azimuth. To test the radar's alignment, the antenna is directed to generate a known echo. If the radar receives an echo, the antenna is still aligned (ANON_D, 2014). The second technique and more commonly used is to mathematically determine the sun's position relevant to the radar. The receiver is capable of picking up the sun's radiation if the antenna is pointing directly at the sun. This phenomenon is also known as a solar spike and occurs during early morning or late afternoon. Modern software packages include sun-tracking calibration tools. It's a quick and effective method to check or recalibrate the antenna's position (ANON_D, 2014, Huuskonen and Holleman, 2007).

The EEC C-band pedestal has both an electronic switch and mechanical stopper preventing the antenna from moving out of bounds. The pedestal has two switches, an inner switch (3S2A) used for the lower limit and the outer switch (3S2B) for the upper limit. Each switch consists of two adjustment screws "A" and "B". The installation of the limit switches on a WASR74C radar is as follows (EEC, 1975):

i. Always ensure the antenna control is set to "SAFE" before entering the radome area;
ii. Remove the elevation cover and manually lower the antenna to the minimum elevation required;
iii. Connect a multimeter testing for continuity on the inner switch between the normally open (N.O.) and common terminals;
iv. Loosen the clamp screw "A" on the lower switch, turn the adjustment screw fully clockwise and fasten the screw again;
v. Repeat step iv for "B" but only turn the adjustment screw until the connection between the N.O. and common terminals is a closed connection and fasten the screw;

vi. Manually raise the antenna to the upper elevation and connect the multimeter between the N.O. and common terminal of the outer switch;

vii. Loosen the clamp screw “B” on the outer switch, turn the adjustment screw fully counter-clockwise and fasten the screw again;

viii. Repeat step vii for “A” but only turn the adjustment screw until the connection between the N.O. and common terminals is a closed connection and tighten the screw;

ix. Manually lower and raise the antenna to check the limit switch through measuring the connection between the N.O. and common terminals on each switch. Replace the elevation cover and switch antenna control back to “OPERATE”.

The limiting switches should always be set to a broader span than specified in the scan strategy to prevent the antenna from stopping prematurely. It is suggested to set the lower limit to -1 ° and the upper to 60 ° just before the mechanical stop (EEC, 1975). The mechanical stopper is only used as a last resort since the forceful stop can damage internal components such as the motors or gearbox.

2.2 SITE SELECTION

The site selection process consists of two criteria: strategic and logistic. The strategic criterion is determined by the purpose of the radar and the type of target observed while logistics focus on what is required to make the project feasible (Domenikiotis et al., 2010, Dalezios et al., 1990).

2.2.1 Strategic criteria

The primary objective of most weather radars is to aid a weather network with real-time, high-resolution rainfall estimates over a large area (NOAA, 2010). However, due to the characteristics of EM pulses, weather radars can only see a target as long as it has clear line-of-sight. This poses a series of problems since radars generally operate in complex orographic areas surrounded by mountains or buildings causing partial or full beam blockage (Shipley et al., 2006). When the EM wave is partially blocked some of the energy travels reflected back to the radar while the rest travels on until it reaches another target. Figure 11 shows an example of a partial beam blockage to the left with a thunderstorm behind the obstruction. Because the radar has received both an early echo and that of the storm it creates false data as shown to the right. There are some algorithms available to correct a portion of the data if the data processing algorithm recognises the error.

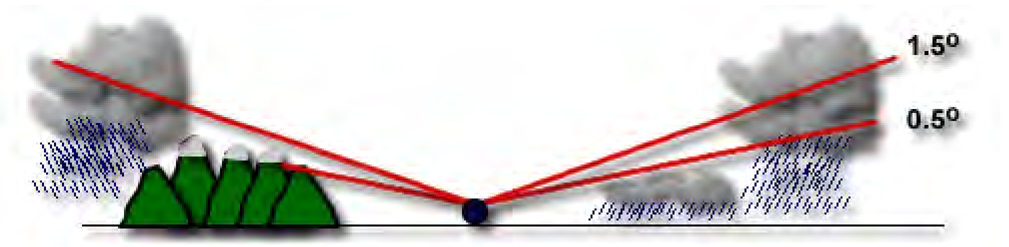


Figure 11: Partial beam blockage and its effect (ANON_I, 2012).

However, if the EM pulses are fully blocked the radar will not be able to see any target behind the obstruction.

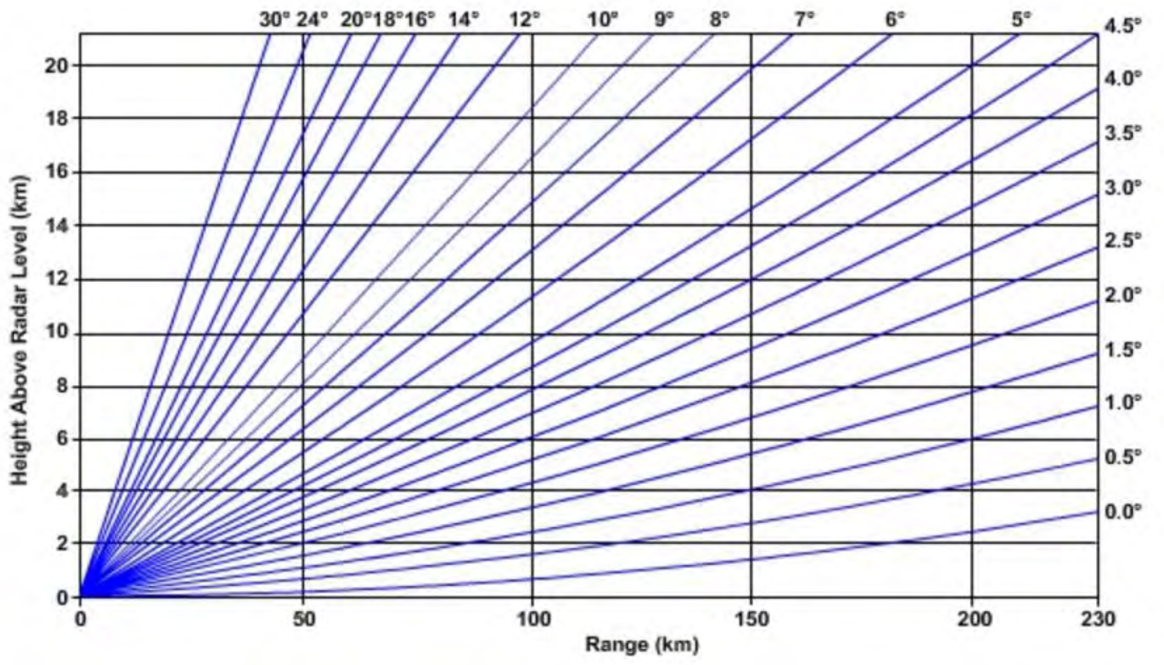


Figure 12: Height above the ground of radar samples as a function of range (ANON_H, 2012).

One method to minimize the beam blockage is to raise the elevation level of the scan but it is not advised to do so. A higher scan elevation will result in the loss of data (Dalezios et al., 1990). This is due to the fact that EM pulses do not follow the earth's curvature but propagate almost in a straight line, therefore increasing in altitude with distance. Figure 12 (on the previous page) shows an example of a C-band weather radar scan strategy and how the pulses increase in elevation (km) over a certain distance (km).

There are cases where the radar is deliberately placed in a non-ideal location knowing that there would be problems with beam blockage and ground clutter. An example is if the radar's purpose is more research related so as to study hail storms, cloud seeding, ground clutter or high flash flood regions. It is likely that the radar will be situated in a non-ideal location where these phenomena occur more frequently (Domenikiotis et al., 2010). As a research radar, part of the Bethlehem Precipitation Research Project is used to monitor cloud-seeding effects (Terblanche et al., 1994). The Bethlehem region is not an ideal site for weather radars because of the Drakensberg mountain range toward Lesotho with a maximum altitude of 3000m above sea level. It was known that there will be problems with beam blockage and ground clutter, yet Bethlehem was chosen because of its advantages to the case study (Terblanche et al., 1994). All of this needs to be taken into account when considering a possible site location for a radar system.

2.2.2 Logistic criteria

Site selection is largely dependent on the meteorological purpose of the radar, but equally important are the logistic criteria including the infrastructure, power supply, security, access, communication link and licencing conditions (NOAA, 2010). The infrastructure consists of two structures: a building for the radar system and a platform to elevate the antenna above the building. The radar building houses the radar's transmitter/receiver, antenna control unit, signal processing, calibration equipment and computers. A good ventilation unit is compulsory as the transmitter generates substantial heat. The second infrastructure is the antenna platform usually elevated above the transmitter/receiver unit. It is preferred that the platform be elevated above buildings or trees in close proximity to minimize ground clutter. A radar will ideally be located on the crest of a peak exposed to severe weather conditions. These conditions can include heavy rain, hail, wind and constant sun. Radars are designed to operate for years on end therefore they require a solid and stable platform. Lower scan elevation will produce a higher resolution but increases the chance of ground clutter (Büyükbas et al., 2006). A method to overcome this problem is to raise the antenna's height. Though it will decrease beam blockage and clutter, a higher tower will increase the lobbing effect therefore requiring a much stronger structure (Domenikiotis et al., 2010). It becomes a trade-off between higher resolution, constant clutter and infrastructure cost.

The site preparation and radar installation are expensive and time-consuming processes. It is imperative that the correct site be chosen before proceeding with the installation. Once possible locations have been identified, an assessment of the data quality estimation or radar quality index can be determined through software models (Büyükbas et al., 2006). These models use local topography data to determine the lowest useable elevation scan for a certain range (Dombai, 2010). There are multiple software packages already available such as ArcView, ArcGIS, FTAY and RMDS (Baltas and Mimikou, 2002, Shipley et al., 2006). Most of these models are based on the Geographic Information System (GIS) database.

After a potential location has been identified, it is important to ensure that all the required utilities also meet set demands before continuing with the installation. Radars require a constant and stable power supply with at least 20A at 220V or 4.4 kVA available (Domenikiotis et al., 2010). The receiver makes use of sensitive components and any fluctuation in the power might alter the data or damage sensitive components. It is recommended to use an inline filter system such an uninterruptable power supply (UPS) with a backup generator supporting the UPS in case of a power outage. Once the UPS shuts down most radars will not automatically restart. The backup generator must not be used in the same building as the radar unit unless completely isolated from gases and vibrations. Security is always a concern, not only to keep the equipment safe but to protect individuals from climbing on top of the antenna platform, especially while the radar is transmitting. Modern weather radars can transmit in excess of 1 MW pulses which can cause negative effects if a human is exposed to it for long periods of time (Michaelson, 1974).

Most radars are located on a peak in an open field which makes it susceptible to lightning strikes. Lightning is one of the most destructive events for electrical equipment. A radar makes use of very sensitive components and a voltage spike can cause major damage. It is therefore important to have a solid grounding network providing a low impedance ground path. The grounding is typically made of a copper conductor network beneath the ground to provide a maximum resistance of one ohm. Any metal equipment must be earthed to the same ground and connected through a level 1 and 3 surge protection device (SPD) to the lightning ground (Kasemir, 1960).

It is well known that C-band weather radars are prone to microwave interference from modern communication systems. There is a real concern as the need for wireless internet operating at 5 GHz keeps increasing. Regulations prohibit Radio Local Area Networks from operating on the same frequency as weather radars but it is difficult to implement such a rule. Modern communication systems consist of dynamic frequency selection which allows the software to only use frequency bands that are not used. Unfortunately most users are unfamiliar with this function and its interference with weather radars (Joe et al., 2005, Büyükbas et al., 2006). Being aware of this problem, precautions can be taken to determine whether a site is electromagnetically compatible before proceeding with the installation.

Radars require routine inspection, maintenance and refuelling of the generator, therefore it is necessary that the site can be accessed using a vehicle, preferable a small truck. A communication link with the site is necessary so that the radar can be controlled and data collected remotely.

2.3 RISK MANAGEMENT

There are always risks involved in a project no matter the size or scale of the project. The question is whether these risks are being addressed or simply ignored. In recent years the industry has shifted to a better understanding of all the risks involved before blindly proceeding. It is strongly motivated that risk management provides a tool for balancing the struggles with exploring new opportunities on the one side and avoiding losses, damage or disasters on the other side (Aven, 2011). There are different forms of risk management available, yet all of them strive to reach the same conclusion namely that a risk management process should provide information on the risks involved, their likelihood to occur, the consequence if it does occur and how these risks can be reduced. According to the International Organization for

Standardization (ISO 31000:2009) the definition for risk is “the effect of uncertainty on objects” (Purdy, 2010). Risk management is therefore the systematic process of identifying, analysing and minimizing the risk of a certain item (or system) or a project. Various methodologies are available to conduct a risk assessment, each adapted to suit the specific type of project. Figure 13 shows an example of a risk assessment methodology (Smith, 2011). Risk management describes the procedures, structures and methodology followed while a risk analysis (a subsection of risk management) describes the systematic approach of identifying all possible risks and evaluating them accordingly.

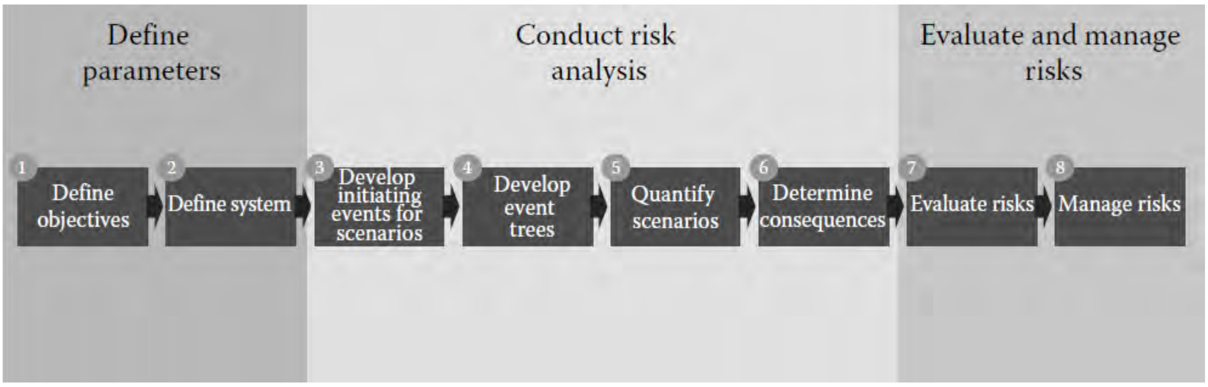


Figure 13: Example of a risk assessment layout (Smith, 2011)

The initial phase of the risk management process is to define the parameters of the project as the objectives and focus area. The second phase is conducting the risk analysis by identifying and quantifying the probability and consequence of the risks. The last phase is evaluating the known risks and managing them accordingly. The second phase of the risk management process will further be elaborated upon.

A common risk analysis method used is probabilistic risk assessment (PRA). PRA is a systematic and comprehensive methodology to identify risk, determine the likelihood that a risk might occur, and the consequences if the risk materialises. PRA combines various tools and techniques to build an integral risk model. An example of these tools and techniques is a cause-and-effect diagram, fault tree analysis (FTA), event tree analysis (ETA), and failure modes and effects analysis (FMEA) (Ostrom and Wilhelmsen, 2012, Smith, 2011, Stamatelatos et al., 2011).

The cause-and-effect diagram, also known as the fishbone diagram, is a unique method used to illustrate how various project factors are linked with one another. This diagram helps to identify possible problems or risks on a higher design level, keeping the diagram focused on the basic interfaces commonly overlooked. To start a cause-and-effect diagram, decide on the effect being examined. The effect can vary from project management to a specific objective or technical performance. Identify the main causes that contribute to the risk of the effect. Examples of possible causes on a cause-and-effect diagram are: methods, material, people, politics, procedures, people, and the environment. Beneath each cause possible factors that might contribute to that cause are listed. Figure 14 (on the following page) shows an example of a cause-and-effect analysis.

Both ETA and FTA are complementary to one another and often used together. FTA focuses on events that might lead to an unwanted event, while ETA focuses on stopping an already existing event before escalating further. When the two techniques are used together it is referred to as the bow-tie analysis.

FTA is a top-down method starting from the top with an event or failure then branching down listing all the events in the system that must follow in order for the top-event to occur. This top-down method forces the user to conduct a systematic process of listing sequential and parallel events. These events can occur in isolation or as a combination of events. Logic gates and Boolean symbols are used to show how the events are interconnected and in what manner. If the probability of each occurring event is known the overall probability of the top event failing can be calculated as explained in Smith (2011). It is important to note that not all the system events are listed but only the ones that can cause the top-event to fail (Smith, 2011, Ostrom and Wilhelmsen, 2012). Figure 15 (on the following page) shows an example of an FTA analysis.

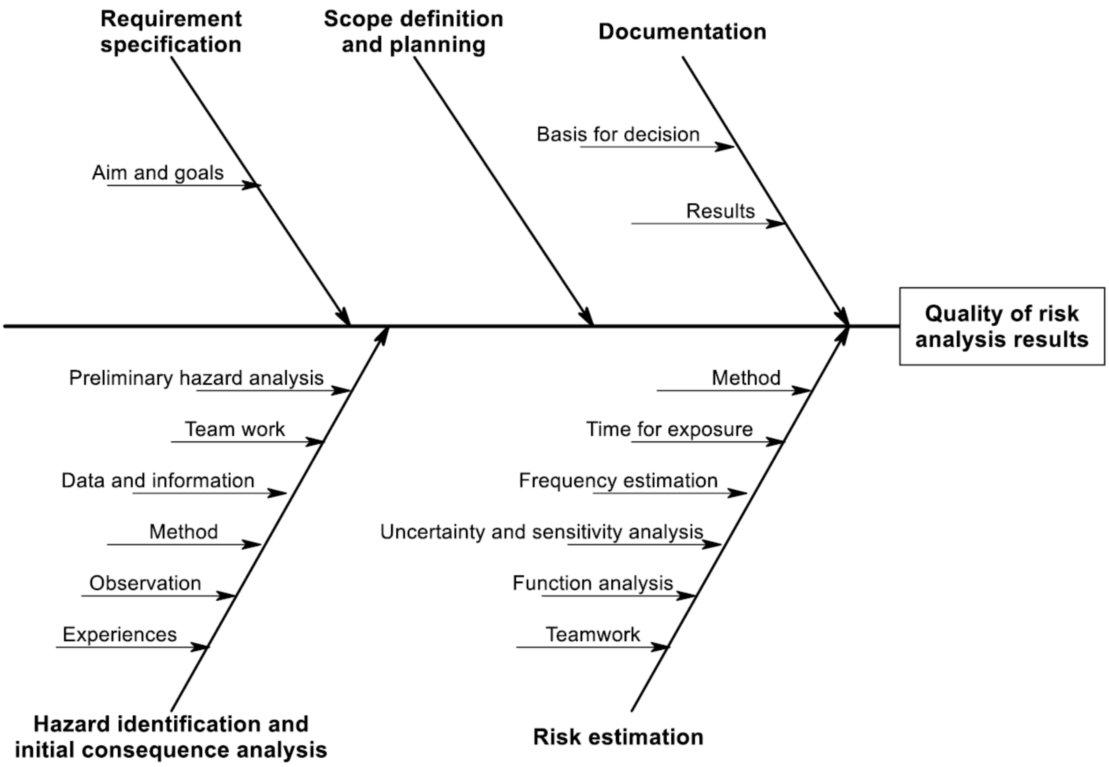


Figure 14: Example of a cause-and-effect diagram (Backlund and Hannu, 2002)

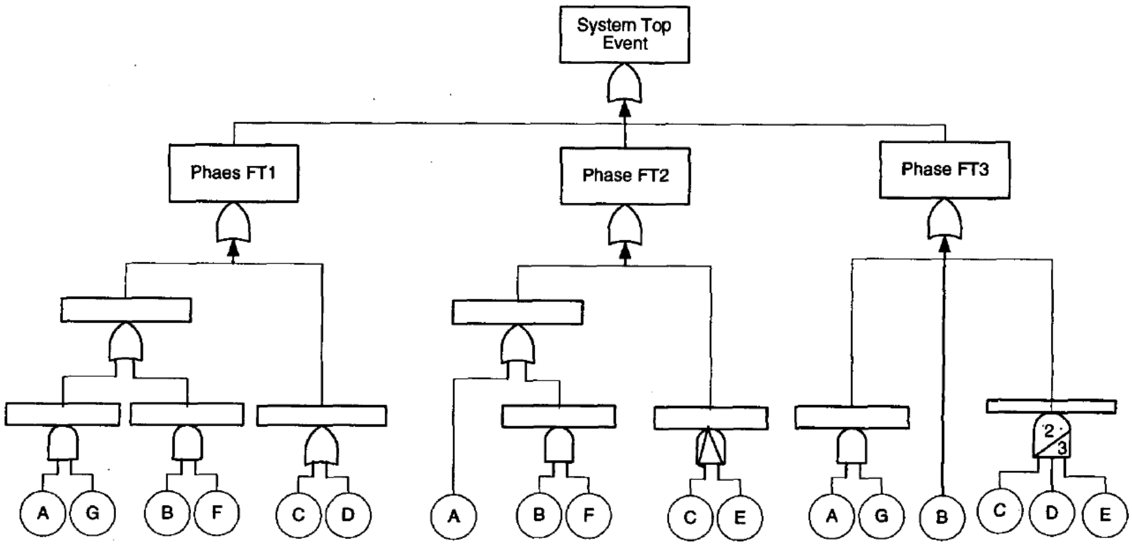


Figure 15: Example of a phased-mission system fault tree analysis (Meshkat et al., 2003).

ETA is very similar to an FTA but with a bottom-up approach to identify and evaluate possible events at a lower level rather than the top-level. This approach has only two possible outcomes, failure or success (Ostrom and Wilhelmsen, 2012). The analysis starts by defining an initial event on the left followed by a second event. Each event is presented as a path with two possible outcomes, success or failure. The process continues until a consequence has been reached. One benefit of an ETA above the FTA is that it evaluates what is required to succeed while still considering what the consequences are. As with the FTA, each path can be given a probability of occurring, therefore estimating the total probability of an event failing. Figure 16 shows an example of an ETA for a fire in a building. If all the events were a success, the end result is minimum damage but if one or more of the events would have failed the end result would be moderate to severe.

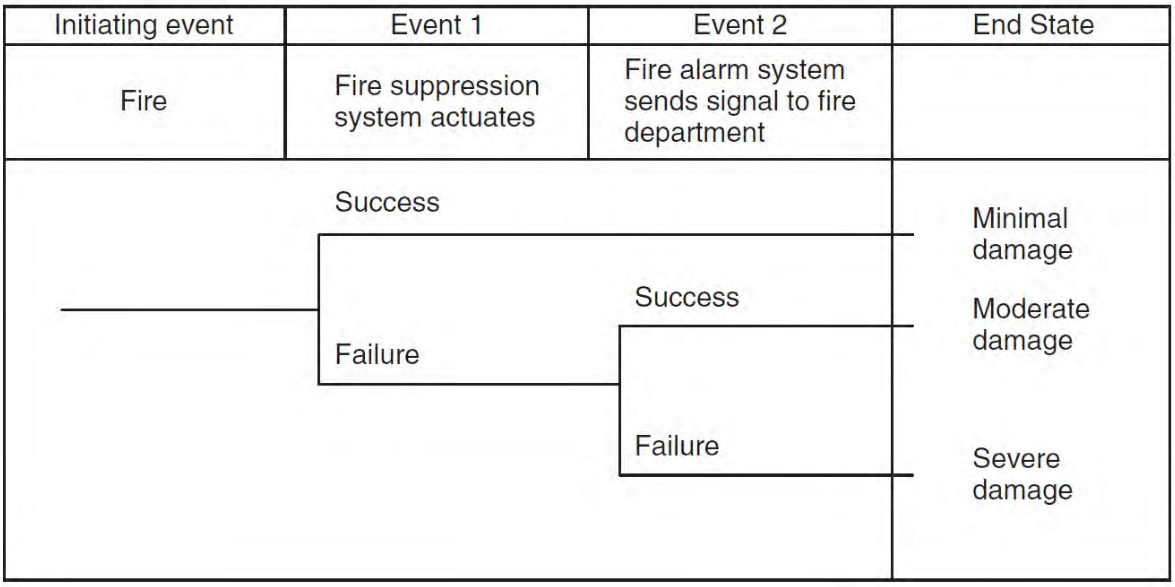


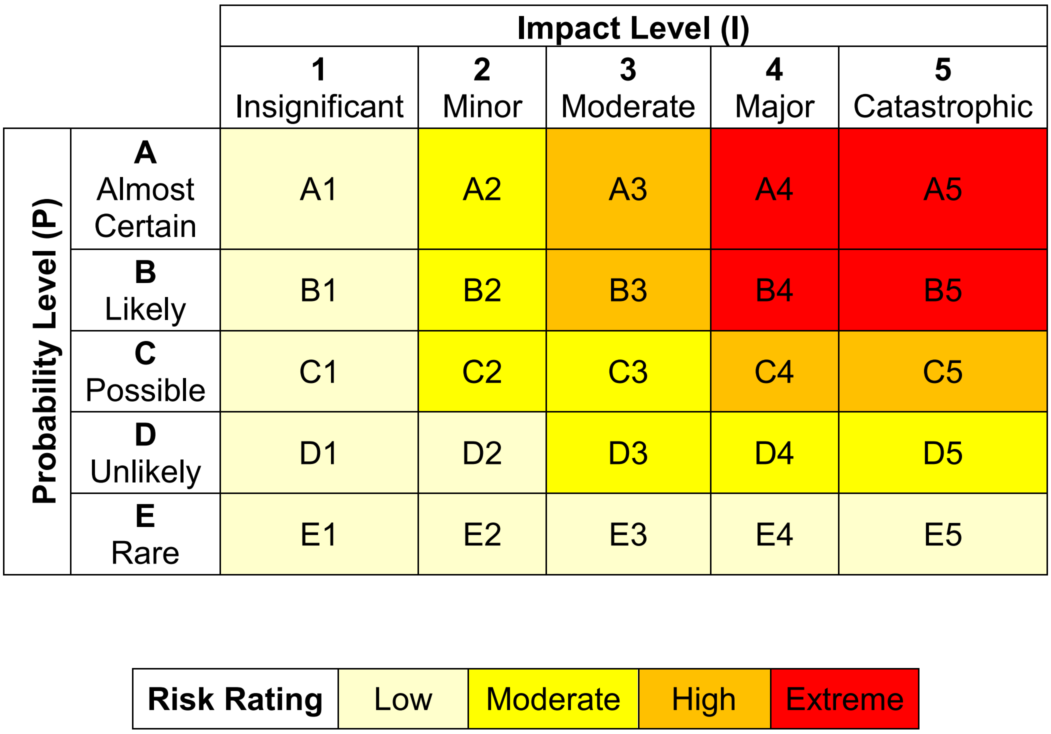
Figure 16: Example of an ETA for a fire within a building (Ostrom and Wilhelmsen, 2012)

FMEA is a bottom-up indicative method to evaluate an individual component or section of a project, identify possible failures and their effects on the system. This method is also used to prioritise events from high to low depending on its rating (Blanchard and Fabrycky, 2014). FMEA is presented in a worksheet consisting of a table listing all the potential failure modes, effects and risk given a risk rating RR (Kmenta and Ishii, 2001). The RR is calculated by determining the probability PR, consequence CS and in some cases the severity SE of an event (Duncan, 1996). Probability is the likelihood that the event will occur or component will fail, consequence is the effect that a failure would have on the system and the severity describes the impact of a failure (Carbone and Tippett, 2004). The RR is calculated using the following equation:

$$RR = PR \times CS \times SE \tag{2.3.1}$$

Probability is generally presented as a value or percentage specifying the likelihood a failure can occur. Most modern components or products undergo rigorous testing to determine their reliability or probability to fail (Blanchard and Fabrycky, 2014). In some cases, especially with older components, its probability of failure is unknown. For these cases a probability scale is used to assign a rating to the component. A scale can be created for any unknown variables. An example of a probability scale is shown in table 5.

Table 5: Semi-quantitative risk matrix example (Woffenden et al., 2008).



		Impact Level (I)				
		1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
Probability Level (P)	**A** Almost Certain	A1	A2	A3	A4	A5
	B Likely	B1	B2	B3	B4	B5
	C Possible	C1	C2	C3	C4	C5
	D Unlikely	D1	D2	D3	D4	D5
	E Rare	E1	E2	E3	E4	E5

Risk Rating	Low	Moderate	High	Extreme

2.4 WEATHER RADAR TECHNOLOGY PROGRESSION

The radar engineers could never have anticipated that their invention would also completely change the meteorological world. Since the radars were modified to observe weather-related targets, a focus was placed on the development and improvement of weather radar technology. For the first few decades following the initial weather radar designs the focus was on improving the entire radar system including triggering the magnetron, rotating the antenna and displaying the data on a computer screen. During these years weather radars were only capable of observing single reflectivity, showing the extent of precipitation and occasional hail storms (Zrnic, 1996). The second significant breakthrough in radar technology came with the development of the Doppler radar, especially the WSR-88D radar released in 1988. This radar was commonly referred to as the second-generation meteorological radar and replaced many of its predecessors (Handbook, 2005). In recent years weather radars have undergone a third upgrade implementing dual-polarization technology. Dual-polarization allows the radar to scan in both horizontal and vertical axes which provides many additional benefits to the meteorological world. It is worth mentioning this new technology but will not form part of this study. Figure 17 shows a graph of how radar technology has progressed over the last 60 years.

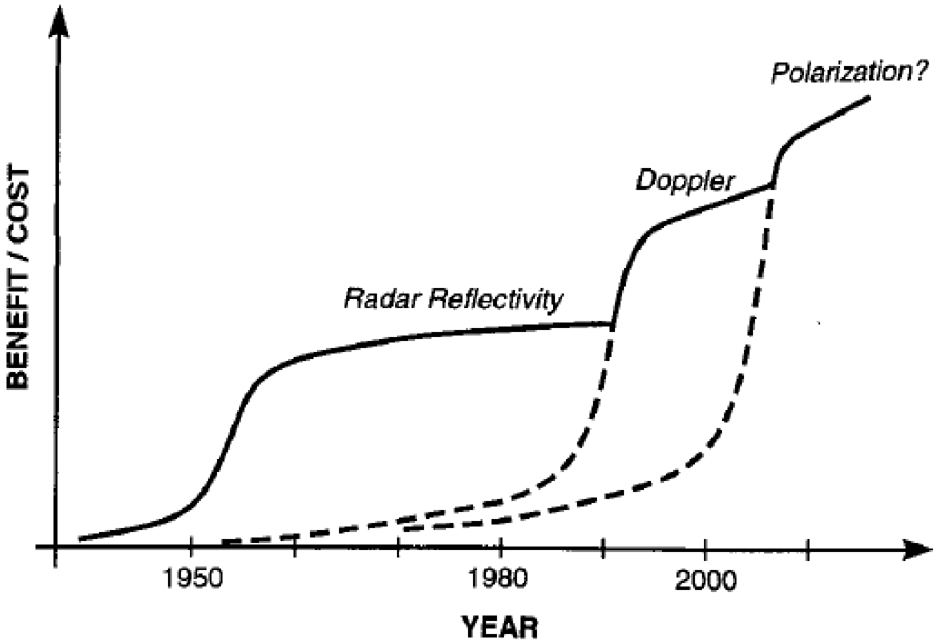


Figure 17: Radar technology progression over 60 years

2.5 MORE ON THE DOPPLER EFFECT

Many of the previous generation (single reflectivity) weather radars have been re-engineered and upgraded from a single reflectivity radar to accommodate the Doppler Effect. This process consists of modifying or replacing the receiver unit. The receiver unit measures the phase difference between two signals and processes the data to determine the target’s travelling speed. Some minor modifications are also required to sample the initial pulse from the transmitter (including a T-coupler and attenuators in the RF line). Doppler radars have certain limitations in the velocities and ranges that they can measure. As mentioned earlier in the literature study, the radar’s unambiguous range is determined by its sample rate or the PRF. The Doppler Effect is also influenced by the radar’s sample rate. A higher PRF will result in a lower unambiguous range and a lower PRF will give a longer listening time therefore a longer range. However, with the Doppler Effect there is an inverse relationship between the range and velocity. A lower PRF will have a higher range, while low velocity range and a higher PRF will result in a smaller operating range, but higher velocity range. This phenomenon is also known as the Doppler dilemma (Büyükbas et al., 2006). Therefore, in addition to modifying the radar’s receiver it is important that the transmitter’s PRF is adjustable. Most radar of the WSR-88 range and on can change its PRF; the transmitters on previous models are generally fixed at $3\ \mu s$.

2.6 RE-ENGINEERING PROCESS

The combination of ever changing technology, old-fashioned habits and techniques, a new life-cycle environment, reformed regulations (Prasad, 1997) and politics have increased the complexity of product development. However, as the complexity of development increases, the marketing time-frame decreases. A simple illustration of this phenomenon is the continuous progress of the central processing unit (CPU) found in computers (Prasad, 1997). The CPU these days found in smart phones cannot be compared to the CPU in a desktop computer of 10 years ago. There is a real concern to companies introducing new technologies that after a few years their product would become unattractive to the market. However, it is not good for a company’s business solutions to keep introducing new products every few years. The entire process of designing, building, testing and improving a new product is an expensive and time-consuming process (Prasad, 1997). Figure 18 shows an example of the life-cycle and demand for a new product introduced by a company. Every product starts with an initial concept or idea followed by the prototype. After the prototype has been finalised the product advances to the final development and production phase. These four initial phases described are the most expensive and risky stages of any product's life-cycle. During these phases no income is collected and it can stay that way for months on end. After the product has been launched the maintenance phases start and the product demand improves. This is the ideal phase to stay in because it generates income. As the product gets older its maintenance increases, adding to the income of the company because more spare parts are required. This effect is commonly referred to as the bathtub curve (Klutke et al., 2003). Still, every product has an expected life-time ending in two possible ways, either the product is decommissioned called the end of life cycle (EOL) or the product can be re-engineered to prolong its service.

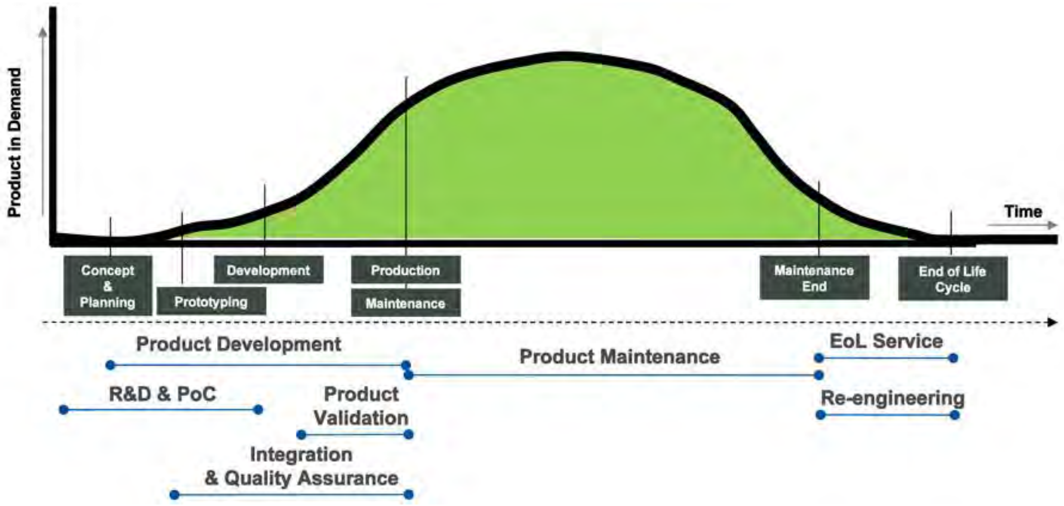


Figure 18: General representation of a new product introduced life-cycle (ANON_J, 2015)

Re-engineering, also referred to renovation or reclamation, is the process of evaluating and altering a system to be reconstituted and implemented again (Chikofsky and Cross, 1990). This allows the product to extend its EOL. The re-engineering process is not only limited to a physical design or product, in recent years it has played a big role in the improvement and restructuring of businesses. This process is referred to as business process re-engineering. From this point on wards both the re-engineering of a process or project will simply be referred to as a product. Hammer and Champy (Hammer and Champy, 1993) described a methodology framework to re-engineer a product consists of four sequential phases (Hammer and Champy, 1993):

- Identify the product to be re-engineered.
- Understand the operating environment.
- Improve or redesign the product.
- Implement the new product or artefact.

This first phase aims to establish a set of boundaries within the product space to be addressed. Hammer and Champy (Hammer and Champy, 1993) suggest using three criteria to help identify the area of focus namely: importance, feasibility and dysfunction. The importance focus describes how significant the process or product is to the overall success of the project, feasibility describes the probability that the process can be re-engineered, and dysfunction looks at which process or product is the deepest in trouble (ANON_E, 1999, Hammer and Champy, 1993). After the boundaries have been set, the environment should thoroughly be understood before proceeding with any redesigns. If the same company that originally designed the product does the re-engineering process, the risk would be low. However, if a product is being re-engineered by a different company, it is likely that they will not have the original designs or schematics, or any institutional knowledge unless the individuals who had worked on the product are available for consultation. This is especially the case with older equipment. Rarely, the designs of older products were well documented or kept throughout the years. If the original documentation is available, there is always the possibility that modifications might have been made to the product without updating the documentation. Therefore, it is important to fully understand the product environment. As the product goes through its life-cycle the technology used during the initial design might be outdated or even obsolete. These sections or components would be high on the re-engineering priority list because if such a component would fail it will extend the product’s mean time between failures (Blanchard and Fabrycky, 2014). The re-engineering can be as simple as replacing a section of the original product with newer technology but in most cases modifications will have to be made to certain parts of the system if not entirely.

2.7 CONCLUSION

The literature study presented in this chapter covers the literature focus areas relevant to the research challenges defined in Chapter 1. The literature in this chapter consists of available information on weather radars, the site-selection process, as well as risk assessment- and re-engineering methodologies. In summary, Table 6 on the following page shows the literature focus areas in rows with the research challenges and proposed solutions in columns. The table further indicates which literature focus areas validate research challenges and which focus areas contribute to the research solution by means of indication arrows as shown by the legend.

Table 6: Literature study focus areas that validate research challenges

Research Challenges **Literature Focus Area**	Radar environment and context are unknown	Radar installation and operation procedures	Re-engineering of the radar system	Lack of previous risk analysis on a radar system	Risk analysis is mainly compiled from observations	Limited expert advice and knowledge
Weather radar background	↓	↑	↑	↑		↓
Weather radar operations	↑↓	↑	↑↓	↑	↑	↑↓
Radar logistical and legislative procedures	↓	↑↓		↑	↑	↑↓
Risk management framework		↑		↑↓	↑↓	↓
Existing risk assessment tools and techniques				↓	↓	↓
Re-engineering framework and techniques			↑↓	↑		↑↓
Literature Focus Area **Research Solutions**	Familiarize and understand the radar environment	Follow available procedures and acquire additional advice from experts	Follow an integrated systems approach	Follow a proactive risk management approach	Make use of validated, available risk tools and techniques	Create a base of knowledge and skills

Legend: - ↑ Literature focus area validates research challenges

- ↓ Literature focus area contributes to research solutions

CHAPTER 3: METHODOLOGY AND SOLUTIONS

This chapter provides the methodology followed to deploy, re-engineer and conduct the risk analysis on the weather radar. The research is presented in this way for ease of reading. The methodology includes the process followed to first identify site criteria for selecting the correct site. After the site had been selected, the radar was deployed, calibrated and operated for a period of time to collect data. This chapter also contains the re-engineering process that was followed to upgrade the transmitter subsection of the radar and elaborates on challenges experienced during the upgrade process, how the radar and its components were tested and corrected, followed by a new calibration. Lastly the chapter provides a documented risk analysis on the radar project, the radar system and the re-engineered sections.

3.1 RADAR DEPLOYMENT

The NWU acquired a weather radar from the USA in 2014 to be deployed in South Africa as a research grade radar. The radar is a WSR74-C model designed and manufactured by Enterprise Electronic Corporation. The radar has been modified from its original design, upgraded, the original PPI display was removed, a remote access unit was installed, as well as an RDAS2k signal processing and antenna control unit (Terblanche et al., 1994).

3.1.1 Site selection and radar deployment

As described in the literature chapter 2.1.1, the site selection process involves two main criteria, strategic and logistic. The strategic processes describe the purpose of the radar and how it will be applied. In this case study the radar’s objectives were predefined and were used to form the strategic criteria. The objectives as described in the introduction chapter are summarised below:

- The radar will be used as a research tool to provide high-resolution, spatio-temporal data to research projects;
- The radar should provide real-time meteorological data to both the commercial and the local community;
- To build local capacity towards weather radars in South Africa.

In addition to these objectives, the following criteria were supported by the NWU research department who was the sole project sponsor for this project:

- The radar should cover a portion of the highest populated region in South Africa;
- The entire Mooi River rain gauge network forming part of the NWU network must be covered;
- The radar coverage must overlap with at least 1 other weather radar from the national weather radar network;
- The highest data quality possible within limited budget should be provided;
- The radar must be situated in close proximity to the NWU.

A second set of criteria was used to further describe the radar's logistic requirements. These criteria were important to minimize unexpected costs, damage or failures causing data loss. The criteria for the requirements are as follows:

- Fairly easy access to the site;
- Protection (security) of all equipment;
- Communication system to the NWU computer server;
- Constant, reliable and stable power supply;
- Temperature controlled environment for the radar electronic equipment;
- Adequate protection from external elements.

Considering the broad range of objectives, requirements and endless possible sites, it was necessary to first define a focus area to start the site selection process. Once the focus area had been selected, possible sites within that area could be identified and compared. Looking at the project's objectives, three requirements could primarily be used to define a focus area:

- The site should be in close proximity to the NWU;
- The radar scans should overlap with the NWU's rain gauge network;
- The radar should cover the highest populated regions in Gauteng.

The NWU is based in Potchefstroom to the south-west of Gauteng. The maximum distance between the radar and the NWU could not be more than 50km. This area can roughly be demarcated by the towns surrounding Potchefstroom namely Klerksdorp, Ventersdorp, Carletonville and Parys. The second requirement to further define the area was the NWU's rain gauge network. The network forms part of another research project consisting of 21 rain gauges in the Mooi River catchment area. This is not the official name of the catchment area as it actually forms part of a group of four quaternary catchments. The catchment area is situated on the Highveld of South Africa between 25° and 26°S Latitude and 25° and 27°E Longitude (Piketh *et al*., 2015). Figure 19 shows the layout and location of the rain gauges to the north-northeast of Potchefstroom.

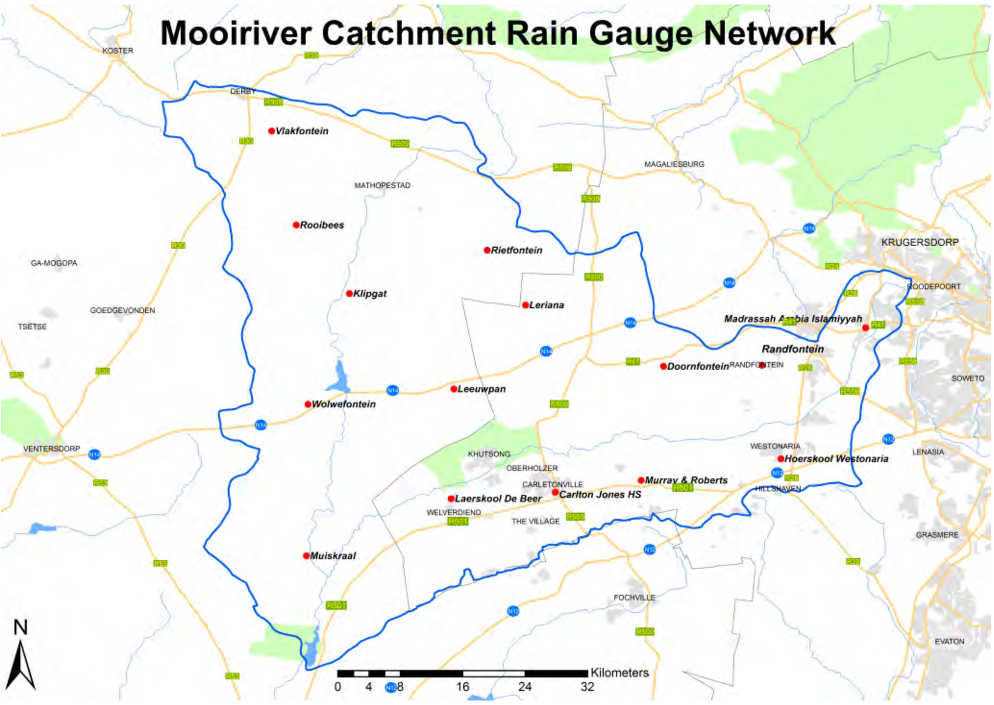


Figure 19: The layout and location of the NWU rain gauge network (Piketh et al., 2015). Potchefstroom is not indicated on this map

The third requirement was that the radar should cover the high-density areas of the population in the Gauteng area, stretching from Vereeniging to Pretoria. The furthest area of interest away from Potchefstroom is north-east Pretoria, which is approximately 170 km away. Because the radar has a scan radius of 200 km it limits the area southeast of Potchefstroom to only 30 km.

Using information including local topography maps, data quality estimation software, site inspections and correspondence with several of the land owners, the area was narrowed down to four possible sites. The first candidate site that was identified is on the NWU's premises but elevated on a 30 m tower to overlook the surrounding buildings. The second candidate site was on a small hill just outside Potchefstroom, locally known as Feather Hill. The third candidate site was on a wildlife estate part of the ALS group roughly 10 km north-east of Potchefstroom and the last candidate site was at Ganskop about 20 km north-east of Potchefstroom.

The data quality estimation (DQE) analysis was done using a software model developed by the NWU. The software uses local topography data from a GIS database and determines the minimum scan elevation required to clear all the natural blockages. Figure 20 shows the DQE of each of the four sites (A: NWU, B: Feather Hill, C: Wildlife Estate and D: Ganskop). The DQE is represented in a graph format showing the selected site in the centre (red dot) and the minimum elevation required to clear the obstacle is illustrated with lines drawn around the centre. The software starts with a low elevation scan and determines all the possible blockages at that elevation. After completing a 360° scan, it scans again with a higher elevation degree. This process is iterated up to the highest elevation scan as defined in the software. The minimum elevation required to clear all the blockages are shown using a CAPPI format.

From the four DQE scans, it is clear that site A (NWU) has the highest expected beam blockages, almost completely surrounding the site with a minimum elevation of between 4–4,75 km above sea level. This will cause major loss in data that is not acceptable. The beam blockage of site B (Feather Hill) is similar to that of site A (NWU), but less blocking is encountered to the south-west, but with less to the south-west. Site C (Lekwena) has no beam blockages to the west and few to the south-east, therefore site C is a better option than site A or site B. The ideal site would be D (Ganskop) because it barely has any beam blockage making it the ideal site for any weather radar.

To determine the most suitable site, the four sites were compared with one another. Each site was evaluated against the site criteria as described above using evaluation Table 7. If one of the criteria is not met or unavailable the site received a 0 score, disqualifying the site from the list. Each topic was also given a factor value between 1 and 10 to show the importance of each criterion.

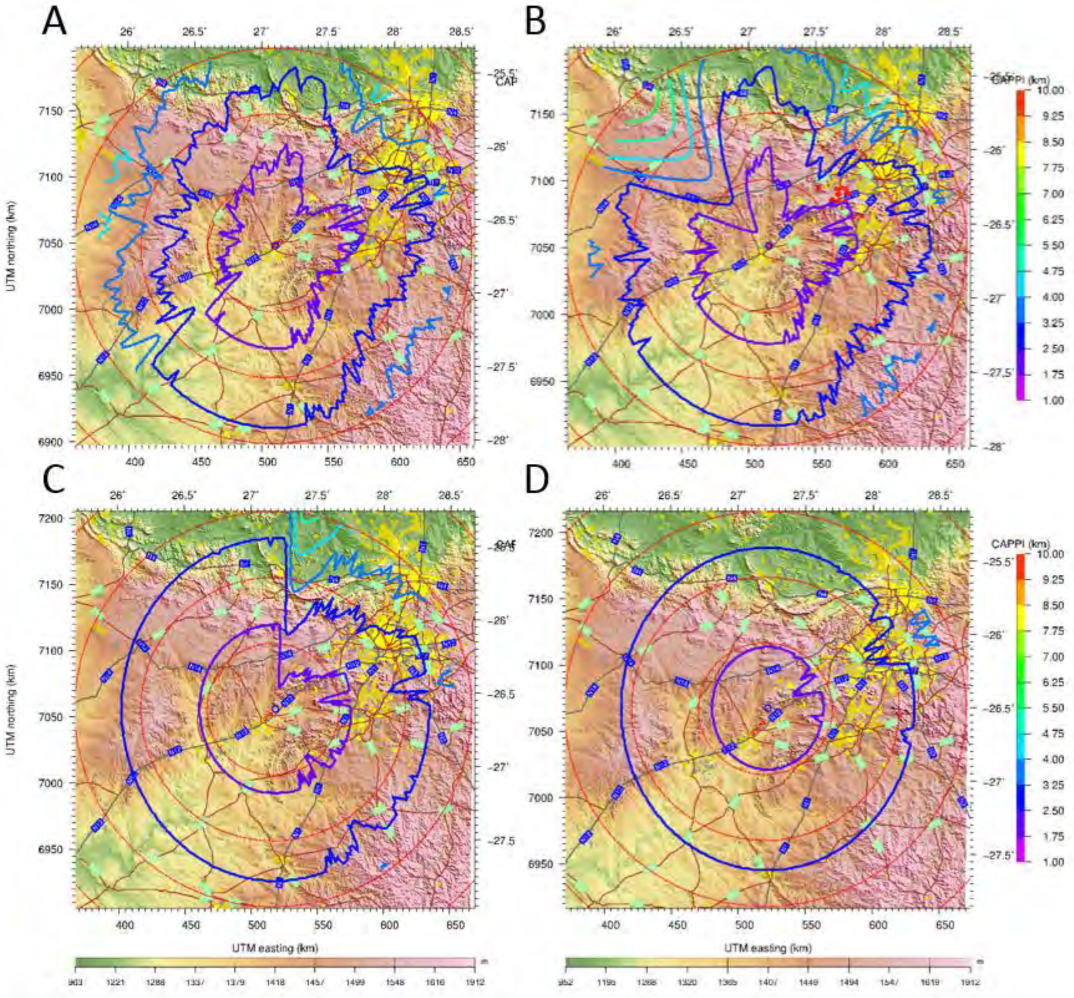


Figure 20: DQE of the four possible radar sites, A: NWU, B: Feather hill, C: Wildlife estate and D: Ganskop

Table 7: Site evaluation scoring.

Scoring Table	
0	Not available or suitable
1	Available but not suitable
2	Suitable but not optimal
3	Optimal

The evaluation consisted of 9 criteria as explained in the site criteria. Each criterion and its implications will be described briefly. The first criterion requires the radar to cover the populated areas around Gauteng. Criterion 2 requires the radar to cover the NWU's rain gauge network as indicated in Figure 19. This is important because it can be used to determine the difference between radar's estimated rainfall and the ground truth measured by the rain gauges. The third criterion requires the radar to cover at least one other radar forming part of the national weather radar network. One radar is the minimum requirement but more would be preferred. The overlap between these two groups of radars should be at least 30% to be deemed as valid. It is important to ensure that the site selected will be able to yield high quality data. Various factors can influence the data quality of which one is the beam blockage. As described in the literature chapter, beam blockage prevents the radar from detecting behind an obstruction, causing loss of or incorrect data. A DQE assessment was conducted for each of the four sites. Criterion 5 requires that the radar site be located in close proximity to the NWU. As stipulated in the site requirements. Requirements: The site should be within 50 km of the NWU Potchefstroom Campus. Topics 6, 7 and 8 of the criteria are necessities for the radar to function and be maintained. Because the NWU is a research facility and will not profit from commercial use, it is preferred not to have any additional cost other than an energy consumption cost. It is important to rather spend most available money on maintenance or upgrades than on a monthly operating expense.

Not all of the 9 criteria were equally important for site selection. As an example, it is more important to have a stable power supply and communication link than to have easy access to the site. To factor in the importance of each criterion, a scaling factor between one and ten was allocated. The scaling factor is multiplied by the score obtained from Table 7. The full score of each criterion was calculated by summing all individual scores. The highest score available was calculated by multiplying the highest evaluation score by the number of criteria and the scaling factor of 10, giving 270. The fit for purpose figure of each site is the percentage of the criterion's total score out of 270. Table 8 shows the site evaluation and each site's fit for purpose score.

Table 8: Site evaluation table

Topic	Criteria	Factor	NWU	Feather Hill	Lekwena Wildlife Estate	Ganskop
1	Coverage of populated areas	6/10	2	2	2	3
2	Coverage of the NWU's rain gauge network	8/10	3	3	3	3
3	Overlap with the national weather radar network	6/10	3	3	3	2
4	Data quality estimation graph	10/10	0	0	2	3
5	Within close proximity to the NWU	5/10	3	3	3	1
6	Easy access to the site	6/10	3	2	2	1
7	Constant power supply	10/10	3	2	2	2
8	Communication link to the NWU	10/10	3	3	2	2
9	Site annual cost	6/10	3	1	2	2
Total out of a possible 270			165	137	153	152
Fit for purpose %			**61**	**51**	**57**	**56**

Performance: According to the site evaluation matrix, the NWU received the highest performance score of the four possible sites with a fit for purpose of 61%. It is on the NWU's premises, all the required utilities are available and there are no communication or safety concerns.

Hurdles: There are disqualifying factors (hurdles based on a GO / NO-GO principle) that were considered in addition to performance criteria alone, taken into consideration as follows: According to the DQE, the NWU will have the highest beam blockage, producing the lowest data quality of the four possible sites. Also, the site is located within a few hundred metres of high residential hostels adding to a health risk. It was therefore decided to disqualify the NWU site from the list.

Lekwena Wildlife Estate passed the hurdles and received the second highest fit for purpose performance score. The site is owned by a private construction company, the ALS Group. The site is on the crest of a hill to the north-east of the premises, approximately 1512 m above sea level. According to SAWS three radars of the national weather radar network (Irene, Ottosdal and Bethlehem) are in close proximity to the site at Lekwena. Figure 21 shows the Lekwena-NWU’s position relative to the other three. The radar site would also provide full coverage of the Mooi River rain gauge network and the land owner offered to provide the site free of charge.

The third site is located just outside of Potchefstroom and would have been ideal because it is close to the NWU, has easy access to a stable power supply and communication link. However the DQE estimated major beam blockages up to 4km and the land owner required a monthly payment. Therefore, the site received a fit for purpose of only 51%. The fourth site is located on a hill close to Johannesburg. The site had an excellent DQE with the least amount of beam blockages. However it is quite a distance from the NWU and does not have easy access to all the utilities such as a stable power supply. Therefore the site received a fit for purpose of 56%.

The site with the highest fit for purpose is on the Lekwena Wildlife Estate. It was therefore decided to situate the radar on a hill on the estate. The owner had the following requirements:

- Because the site is on a wildlife estate the radar must be concealed as far as possible for aesthetic purposes;
- Any damage to the environment during the installation process must be rehabilitated;
- Data collected must be free and available online for the residents to access.

The radar must be named after the company, therefore it is referred to from here onwards as the Lekwena–NWU weather radar.

3.1.2.1 Infrastructure

The infrastructure consists of two sections - the main building and an elevated platform for the antenna. The main building is used to contain the radar units, computers, documentation, spare parts and calibration equipment. For practical purposes and to save time and money, a 6.05 m (L) x 2.44 m (W) x 2.59 m (H) container was used for the main building. The container is well insulated and includes a 1200 BTU air-conditioning unit. The advantages of using a pre-manufactured container are that it lowers the installation cost significantly and provides a well-insulated and airtight construction.

The site was prepared and a 5 m x 9 m concrete slab with reinforced steel mesh was poured to use as a foundation for the container and antenna platform. The concrete slap is rectangular for to accommodate a backup generator at the back.

Because the site is on the crest of a hill it will not benefit from using a 30 m tower to elevate the platform. Instead the 4 m x 4 m platform should be built directly over the container standing on four steel I-beams. The platform was elevated to 4 m above the ground, giving a 1.4 m clearance between the container and antenna platform. The 4 m elevation serves two purposes: it allows the user to access from the bottom through a hatch and it raises the antenna above the surrounding tree line, minimizing surrounding ground clutter. The platform was made wider than required to accommodate a bigger radome and antenna in the future. Figure 21 shows a CAD drawing of the infrastructure design as given to the building contractors as guideline.

Figure 21: CAD drawing of the infrastructure design to contain the radar and antenna.

3.1.2.2 Power connection

A weather radar requires a constant and stable power supply to ensure good quality data. The site selected for the radar is on the crest of a hill with the nearest power supply at the base of the hill, approximately 700 m away. Alternatively, solar panels and a battery bank could be used to power the radar. As mentioned in chapter 2.2.2 the minimum power required is at least 4.4 kVA (Domenikiotis et al., 2010). Table 9 below shows an estimation of the power consumption for the radar station. The power consumption rates were calculated using available datasheets of the components used.

Table 9: Power consumption summary

Equipment	Power Consumption Estimation [VA]
Weather Radar	1300
Air Conditioning	2000
Computer	400
Lights	200
Auxiliaries	300
TOTAL	**4.20 kVA**

According to the table, the radar station should use approximately 4.2 kVA of power when all the components are switched on. The power consumption will fluctuate because the air conditioner will switch on and off to regulate the temperature in the container. It was recommended to increase the available power to at least 10 kVA (if possible) to compensate for future increases in power consumption. Two methods to provide power at the site were explored, as discussed below.

3.1.2.3 Solar power and backup batteries

Solar panels are a good alternative source of power where a public electricity utility (ESKOM in South Africa) is not easily accessible. An example of a primary power supply is the power company in South Africa, ESKOM. The main concern with using solar panels for this project is cloudy days where minimal sunlight is available. During these times the radar is most needed. The sizing and installation of the electricity supply system will be outsourced to a private company. For the solar panel solution the site will be supplied with 4.4 kVA as recommended (Domenikiotis et al., 2010). If the site is upgraded or requires more power later on, the solar system can be upgraded easily. Therefore the minimum requirements on the solar system were defined as follows:

- The batteries must be able to supply 4.4 kVA for 24 hours;
- The solar panels must provide enough power to power the radar and to charge the batteries during the day;
- The inverter should be able to support the high starting current drawn by the air conditioner;
- The batteries should have a lifetime of at least 5 years;
- The system should accommodate a generator to replace the solar panels when needed after 24 hours of overcast weather.

The requirements were put out on tender to three companies for sizing and quotations. Table 10 shows a summary of three quotations received from companies. In order to protect the identity of the companies, they are only referred to as company 1 to 3.

Table 10: Solar panel quotation summary and comparison

Company	1	2	3
Number of solar panels	84	124	48
Solar array size	21 kW	29,76 kW	14,4 kW
Number of Batteries	96 @2V	48 @ 4V	36 @ 2V
Battery size	159,36 kA/h	144 kA/h	59,76 kA/h
MPPT size	Not specified	5 kW	6 kW
DC-to-AC inverter size	8 kW	5 kW	5 kW
Total Cost	R 1 150 964,70	R 982 610,00	R 577 558,04

The quotations from company 1 and 2 complied with the requirements as provided. Quotation 3 did not have adequate capacity to power the radar for 24 hours and to charge the batteries during the day. The prices for quotation 1 and 2 were, however, very high and not a viable option. In addition to the price, quotation 2 required 124 solar panels each roughly 1.6 m X 1 m in size. The area needed for the solar panels is much more than what is available at the site. Considering the cost and space required to contain the batteries and solar panels, solar power was not considered a viable solution as a power supply in this case.

3.1.2.4 Power supply from ESKOM

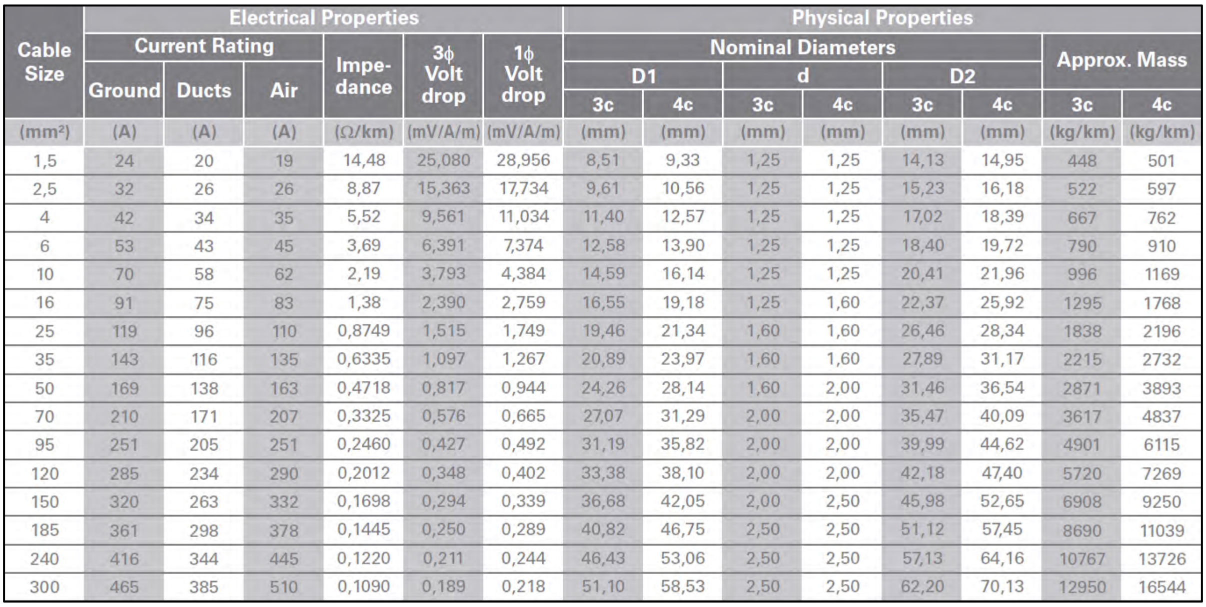
ESKOM has a distribution board at the base of the hill next to the road with three phase $(380\,V)$ power available. The concern was getting a cable from the distribution board to the radar. An overhead power cable would not be accepted by the land owner, leaving only an armoured ground cable. Fortunately, the radar could be positioned close to a water container of which the pipes run downhill to the nearest road as showed in Figure 22. The radar and water container are not shown in the figure. The water pipes were buried at a depth of 1 m. Therefore the same path could be used as far as possible for power cables. The distance between the radar site and power supply is approximately 700 m. According to regulations by SANS 10142-1 (ANON_G, 2013) the maximum voltage drop over the length of the cable under load conditions must be less than 5% (Cables, 2008). As mentioned in section 2.2.2 the minimum power required is $4.2\,kVA$, but if possible could be increased the $10\,kVA$. It will be very difficult and expensive to upgrade to power supply once the cable has been buried under the ground. Therefore the load for the cable sizing was decided to be $10\,kVA$. The thickness of the cable is determined by the current of the load. The current is determined using the following equation:

$$I = \frac{Load(kW) \times 1000}{\sqrt{3} \times V} \quad (3.1.1)$$

The voltage drop over a cable can be determined using two methods:

a) Multiply the current of the load with the impedance of the cable length. The voltage drop percentage is calculated by reference to the phase to earth voltage;
b) Multiply the current of the load and the length of the cable with the voltage drop per amp per meter as shown in the table 11 (Cables, 2008).

Table 11: Electrical and physical properties of 3 and 4 core PVC insulated, SWA Armoured 600V/1000V cables manufactured to SANS 1507-3 standard (Cables, 2008).



Cable Size	Electrical Properties						Physical Properties							
	Current Rating			Impe-dance	3ϕ Volt drop	1ϕ Volt drop	Nominal Diameters						Approx. Mass	
	Ground	Ducts	Air				D1		d		D2			
							3c	4c	3c	4c	3c	4c	3c	4c
(mm^2)	(A)	(A)	(A)	(Ω/km)	(mV/A/m)	(mV/A/m)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(kg/km)	(kg/km)
1,5	24	20	19	14,48	25,080	28,956	8,51	9,33	1,25	1,25	14,13	14,95	448	501
2,5	32	26	26	8,87	15,363	17,734	9,61	10,56	1,25	1,25	15,23	16,18	522	597
4	42	34	35	5,52	9,561	11,034	11,40	12,57	1,25	1,25	17,02	18,39	667	762
6	53	43	45	3,69	6,391	7,374	12,58	13,90	1,25	1,25	18,40	19,72	790	910
10	70	58	62	2,19	3,793	4,384	14,59	16,14	1,25	1,25	20,41	21,96	996	1169
16	91	75	83	1,38	2,390	2,759	16,55	19,18	1,25	1,60	22,37	25,92	1295	1768
25	119	96	110	0,8749	1,515	1,749	19,46	21,34	1,60	1,60	26,46	28,34	1838	2196
35	143	116	135	0,6335	1,097	1,267	20,89	23,97	1,60	1,60	27,89	31,17	2215	2732
50	169	138	163	0,4718	0,817	0,944	24,26	28,14	1,60	2,00	31,46	36,54	2871	3893
70	210	171	207	0,3325	0,576	0,665	27,07	31,29	2,00	2,00	35,47	40,09	3617	4837
95	251	205	251	0,2460	0,427	0,492	31,19	35,82	2,00	2,00	39,99	44,62	4901	6115
120	285	234	290	0,2012	0,348	0,402	33,38	38,10	2,00	2,00	42,18	47,40	5720	7269
150	320	263	332	0,1698	0,294	0,339	36,68	42,05	2,00	2,50	45,98	52,65	6908	9250
185	361	298	378	0,1445	0,250	0,289	40,82	46,75	2,50	2,50	51,12	57,45	8690	11039
240	416	344	445	0,1220	0,211	0,244	46,43	53,06	2,50	2,50	57,13	64,16	10767	13726
300	465	385	510	0,1090	0,189	0,218	51,10	58,53	2,50	2,50	62,20	70,13	12950	16544

For load at $10\ kVA$ and $380\ V$ (three-phase) the current is calculated to be $15.2\ A$ per phase. Using the three-phase voltage drop values from table 11 the voltage drop and percentage can be calculated for each cable. Table 12 shows the voltage and percentage drop for each cable between 1.5 mm^2 and 70 mm^2.

Table 12: Voltage drop per phase for a 10 kVA load, 380 V over 700 m.

Cable area [mm2]	3Φ Voltage drop [mV/A/m]	Voltage drop per phase	%
1,5	25,08000	266,74	**70,2**
2,5	15,36300	163,39	**43,0**
4	9,56100	101,68	**26,8**
6	6,39100	67,97	**17,9**
10	3,79300	40,34	**10,6**
16	2,39000	25,42	**6,7**
25	1,51500	16,11	**4,2**
35	1,09700	11,67	**3,1**
50	0,81700	8,69	**2,3**
70	0,57600	6,13	**1,6**

According to table 12, the smallest cable required to power the radar site with 10 kVA is a 25 mm² cable, giving a voltage drop of 4.24%. As the size of the cable increases so does the price. The estimated prices provided for cable sizes 6, 10, 16 and 25 mm² by a local company in Potchefstroom are shown in table 13 below.

Table 13: Cable cost p/m for 6, 10, 16 and 25 mm²

Cable area [mm2]	Price p/m incl VAT	Price for 700 m
6	R 51,87	R 36 309,00
10	R 68.32	R 47 824,14
16	R 104.54	R 73 176,60
25	R 112.24	R 78 571,08

The voltage drop on a cable is determined by the length of the cable and current under load condition (Cables, 2008). Increasing the voltage with a transformer will decrease the current and so also the voltage drop, allowing a smaller, less expensive cable to be used (Guru and Hiziroglu, 2001). This was achieved by using two $10\,kVA$ transformers to step-up the three phase voltage from $380\,V$ to $1000\,V$ at the source and back down to $380\,V$ at the load. At $1000\,V$ the current was calculated to be $5.77\,A$ per phase. This meant that a 4 mm^2 cable would be adequate and would comply with the cable regulations. However, it was requested by the North-West University to install a bigger cable to accommodate any other projects that might be placed on the same hill, therefore a 10 mm² cable was installed. This cable would be able to support a load of up to $33\,kVA$.

A 23 kVA 3 phase generator was installed to provide backup power in case of a power outage. The generator is connected via an automatic transfer switch. When there is a power outage the generator automatically starts and supplies power to the radar system.

Inside the container there are two UPS modules to support the radar and computer. The UPS used for the radar is a 5 kVA on-line UPS that supports the transmitter and receiver units, as well as the antenna unit. The UPS acts as a power supply filter for the radar, which is important because the radar's electronic components are sensitive to power spikes or dips. As the air conditioning unit switches on and off, the voltage fluctuates briefly. These under- and overvoltages are filtered out by the in-line filter of the UPS. The computer and communication system are connected to the second 3 kVA UPS.

Figure 22: Path for the power cable down the hill towards the power supply on the right side

3.1.2.5 Ground earthing

To ensure good earth grounding, a 70 mm^2 copper wire was buried 500 mm deep around the site with 8 earth spikes at selected positions. On the southwest side a 10 m trench was dug downhill with another 2 earth spikes connected to the grid. This method increases the capability to conduct voltage spikes away from the container. Every metal object such as the container, pedestal frame, lightning rod on the radome and both radar units (transmitter/receiver and antenna unit) is connected to a common ground.

3.1.3 Lekwena-NWU weather radar design and specifications

It is important to define the radar in terms of its design and specifications for future reference. Also, this generic definition (block diagram) allows for risk analysis as all elements are identifiable.

For this study, the radar is divided into five basic functional units, namely the transmitter, receiver, antenna, signal processor and computer software. Figure 23 shows how the five elements are interconnected - each element is given a unique functional unit (FU) number.

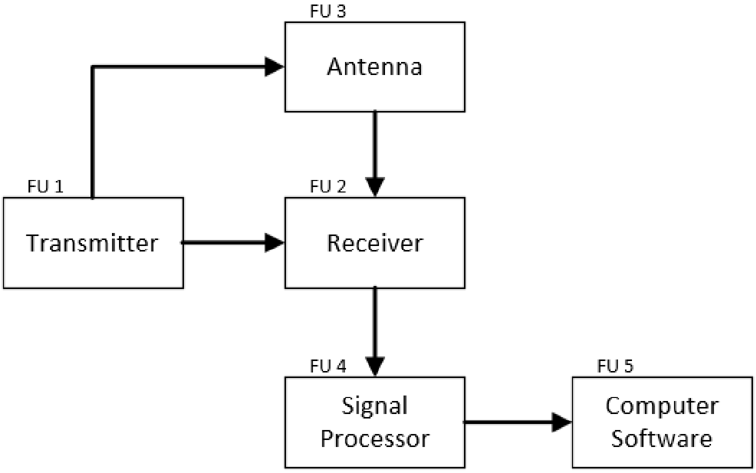


Figure 23: Weather radar basic functional unit layout

In short, the transmitter (FU1) generates a high power EM pulse and sends the pulse from the magnetron through the wave guides to the antenna unit. The magnetron is triggered by a master clock which also synchronises the entire system. The receiver (FU2) receives any echoes reflected back from a target. The echoes range from nanowatts to milliwatts depending on the size, type and distance of the target (Büyükbas et al., 2006). The receiver amplifies the received analogue signal and converts it to baseband where it is processed by a signal processor. The signal processor (FU4) RDAS2000, also known as RDAS2k, is a multipurpose radar data acquisition system (RDAS) (Terblanche et al., 2001, Terblanche et al., 1994, Terblanche, 1996). The RDAS2k converts the analogue signal from the receiver to a digital signal for processing by the computer software (FU5). In addition, the RDAS2k remote unit can be used to switch the transmitter on or off, to start or stop the transmitter radiation, to control the pedestal's elevation and azimuth, to show the status of the radar, and to provide additional programmable input/output functions for sensors.

The antenna unit (FU3) controls the movement of the pedestal and accurately controls its position relative to true north. The pedestal is an aluminium stand containing motors and gears to orient the antenna in the right direction. On the one end the antenna is connected to a feed horn that converts the guided EM waves into free space EM waves and on the other end it acts as a counter-weight. The entire antenna is covered by a radome to protect it from adverse weather conditions. Table 14 gives a summary of the radar's specifications.

Table 14: NWU Lekwena specification sheet

Radar Transmitter & Receiver	**Specification**
Frequency band	C-Band
Magnetron frequency	5620 MHz
Output power [dB]	81 dBm
Output power [W]	150 kW
Duty cycle	30,03 dB
Pulse width	3,75 us
Pulse repetition frequency	266.67
Pulse repetition time	3,75 ms
Minimum detectable signal	-108,8 dBm
Maximum range	±150 km
Dielectric constant	0,93
Voltage standing wave ratio	1:1,049
Antenna	**Specification**
Antenna diameter	2,4 m
Antenna gain	40 dB
Beam width horizontal	1,65°
Beam width vertical	1,65°
Height from ground	4,6 m
Height above sea level	1516,6 m
Rotation speed	30° per second
Upper EL limit	35°
Lower EL limit	1,8°
Time per volume scan	3 min 23 sec
Software	**Specification**
Signal processor	RDAS2k
Processing software	TITAN
Remote communication access	2,4 GHz point-to-point connection

3.1.4 Radar calibration

The importance of keeping a radar system well calibrated cannot be overstated. A radar cannot directly measure precipitation but rather the reflectivity caused by precipitation. To measure precipitation, a conversion is applied between calibrated returned power and rainfall rate. Because of this conversion, a small error in the reflectivity will result in a large rainfall rate error, showing the importance of calibration. Various calibration methods are available, ranging from straightforward to highly complex mathematical equations. It is also important to use a standardised calibration method as used by other radar stations that form part of the network. For this study, the same method as used by the SAWS will be applied to ensure uniformity in order for the radars to be compared later on. In order to calibrate a weather radar, three individual subsections need to be calibrated, namely the transmitter, receiver and antenna subsections. For this study, only basic calibration procedures will be discussed as calibration of each subsection on its own is a specialised task.

3.1.4.1 Transmitter calibration

Generally with the transmitter calibration, all parameters are measured and recorded for later use. The parameters are only adjusted when required or if parameters deviated from a previous calibration. During the calibration, the following parameters are measured: the transmitter frequency, peak output power, pulse width (PW), pulse repetition frequency (PRF), duty cycle (DC), and voltage standing wave ratio (VSWR). To calibrate the transmitter, the procedures are followed as described in the literature section 2.1.5.1.

3.1.4.2 Receiver calibration

The receiver is divided into two sections; viz. the analogue and digital systems. The purpose of the first (analogue) system is to process and convert received analogue data into a format usable by the signal processor. The receiver makes use of filters, amplifiers, mixers, discriminator, local oscillators and a line driver. Each component has its own calibration procedure (which did not form part of this project’s scope due to its specialist nature). The second (digital) section is to convert the already processed data (video signal) from analogue to digital. This is done by the RDAS2k signal processor developed specifically for ground-based weather radars by a company called Electronic Systems Development. RDAS2k is capable of measuring up to 3 channels of 14 bit log-video signals and controlling and monitoring user defined parameters on the radar and antenna servo system. This receiver has been designed to work with TITAN software running on a Linux operating system.

Before the calibration can start, it is important to measure the receiver sensitivity or minimum detectable signal (MDS). This is achieved as described in the literature section 2.1.5.2. The receiver software is setup according to the RDAS2k installation manual. To calibrate the receiver's response curve, the software generates a table of reference values ordered from low to high. The transmitter is disabled and a calibrated signal generator is used to induce a signal directly into the receiver according to the table. The output power of the signal generator is then adjusted to the reference value in the table. The receiver will detect the signal and sample the count for that specific setting. This process is repeated for all values in the table to create a response curve.

3.1.4.3 Antenna calibration

The third calibration requirement is the antenna's alignment to true North. If the azimuth alignment is out by only 1 degree, a cloud that is 150 km away will be detected off centre by a distance of 2.6 km. There are two techniques used to check the radar's alignment, viz. a fixed echo or tracking the sun. The first technique is used with a known constant echo from a building, mountain, tower or metal-coated sphere balloon. These echoes have a specific elevation and azimuth. To test the radar's alignment, the antenna is directed towards a known obstacle. If the radar receives an echo, the antenna is still aligned (ANON_D, 2014). The second technique and one that is more commonly used is to mathematically determine the sun's position relative to the radar. The receiver is capable of picking up the sun's radiation if the antenna is pointing directly at the sun. This phenomenon is also known as a solar spike and occurs during early morning or late afternoon. Modern software packages include sun tracking calibration tools. It's a quick and effective method to check or recalibrate the antenna's position (ANON_D, 2014, Huuskonen and Holleman, 2007).

3.2 RE-ENGINEERING OF THE NWU-LEKWENA WEATHER RADAR

All products have specific types of life-cycles. Figure 18 explains a typical life-cycle process of a product with the concept and planning phase as the start, and the end of life (EOL) as an end. When a project reaches its EOL phase, it can either be decommissioned or re-engineered. Re-engineering is the process of evaluating and altering a system or subsystem to reconstitute and implement it in a new, improved form (Chikofsky and Cross, 1990). In short, re-engineering a product improves the original design for a specific environment and extends its life cycle.

The Lekwena-NWU radar operated for ±30 years in the USA before it was relocated to Lekwena Wildlife Estate. The NWU deliberately chose an older but cheaper radar system with the intent to re-engineer and upgrade the radar. The reason for this choice was twofold; it lowers the initial project cost and helps to build much needed capacity in South Africa. Currently the SAWS has three commissioned WSR 88C model and six, four WSR-74C model and two WSR-88C model decommissioned weather radars in the same condition as the Lekwena-NWU radar. These decommissioned radars were replaced with newer models when the network was upgraded.

The reader is reminded that this research project must provide a method to re-engineer these old radars, either to be redeployed or sold. This case is not only limited to South Africa but applies to all weather radars of the same model around the world.

According to Hammer and Champy (Hammer and Champy, 1993), there are four steps involved in re-engineering a product, namely identifying the product, understanding the operating environment, improving or re-designing the product and implementing the new design. These four steps will be implemented to re-engineer and upgrade the Lekwena-NWU radar.

3.2.1 Re-engineering

Hammer and Champy (Hammer and Champy, 1993) suggest using three criteria to identify the area of focus, namely (i) importance, (ii) feasibility and (iii) dysfunction.

The importance describes the significance of different sections found in the radar system, feasibility describes the probability that the section can be re-engineered, and dysfunction determines which process is the deepest in anguish (ANON_E, 1999, Hammer and Champy, 1993).

It is important to emphasise that the Lekwena-NWU radar was manufactured in 1974. Over the years the radar had been modified and certain improvements had been made such as upgrading the signal processor, computer software and the display screen. Figure 17 illustrates how radar technology in general has progressed from single reflectivity (1950's) to polarization (2000's) and now dual-polarization in the 2010s. When comparing the Lekwena-NWU radar's technology with the latest generation radars, it is clear that the radar is outdated by at least ±30 years.

To fully use this radar as a state-of-the-art, research grade weather radar, the complete radar had to be re-engineered. Unfortunately due to a limited budget, time and resources available the radar was re-engineered in three phases. The first phase was to re-engineer the transmitter, followed by re-engineering of the receiver and finally the antenna. The signal processor and computer software will all form part of the receiver re-engineering phase. Because the radar was upgraded in three stages, it was important to determine the correct re-engineering sequence.

At this point, it is important to reiterate the importance of a risk analysis (which will be discussed in later sections). The risk analysis' purpose was to identify and prioritize system and technical risk factors, as well as project risk factors. By doing a failure mode analysis (also discussed in a later section), it was possible to identify imminent points of failure and their corrective actions, which is analogous to conducting a technical risk analysis with mitigation. This resulted in the identification of the transmitter as a high-risk item, which was then prioritized for immediate action.

The transmitter replacement phase consisted of replacing the original transmitter with a solid-state version. The transmitter was not bound by the receiver interface – therefore the transmitter could be upgraded with limited effect on other units. The original transmitter still used technology developed in the early 1970s. Therefore, one of the major constraints was finding spare parts. As technology gets older, the components become more difficult to source and become more expensive each year. Therefore, when a component as small as a relay malfunctions, the radar will be out of service until the part is replaced or a modification is made. As shown in Table 14, the radar only generated 125 kW of power, roughly 50% of its rated full power. This was a real concern because it would decrease the effective range of the radar.

The receiver re-engineering phase addressed the receiver section only, where the existing receiver still used the original analogue components as manufactured in 1974. This unit had to be replaced with a new, modern digital receiver. To use this radar as a research grade radar it is important that the radar can also measure Doppler Effect and accommodate both single- and dual-polarization. With this upgrade the receiver, signal processor and computer software had to be replaced. The receiver upgrade would be the biggest and most expensive upgrade of the three.

Finally, the antenna re-engineering phase focused on the antenna sub-assembly, where the assembly consisted of an antenna control module, pedestal and parabolic dish. Replacing the parabolic dish with a bigger one would give a smaller focus beamwidth, therefore a higher resolution scan. The existing pedestal at the time could not accommodate a bigger antenna. This antenna system could thus only be used to measure single and not dual polarization. Replacing the antenna would be an important, but costly process.

The re-engineering sequence that was followed is summarised as follows. All three phases had to be completed to reach the desired goal of a research-grade radar system. Only one phase could be completed due to budget limitation. From the explanation above (supported by a risk analysis that will be presented in later sections) it is clear that the transmitter had first priority, followed by either the receiver or antenna. Upgrading either the receiver or antenna section would not have benefited the overall radar system if the magnetron could not generate its rated full power. In addition, the re-engineering phase was identified as the most affordable of the three, giving the NWU more time to acquire necessary funds.

During the radar's initial tests it was noted that the receiver's power supply providing $\pm 15\,V$ and $\pm 28\,V$ was underperforming. The power supply had to be replaced with newer and smaller power supplies although it did not form part the transmitter re-engineering phase.

3.2.2 Understanding the operating environment

Before the upgrade process could start, it was important to understand the operating environment. The operating environment includes the transmitter system itself and all of the components linked with it. Because the new transmitter had to be incorporated into the old system, it was important to understand what transmitter components were being used at the time and how a change would affect the other functional units. The transmitter system (FU1) is further divided into smaller functional units as shown in a block diagram format (Figure 24).

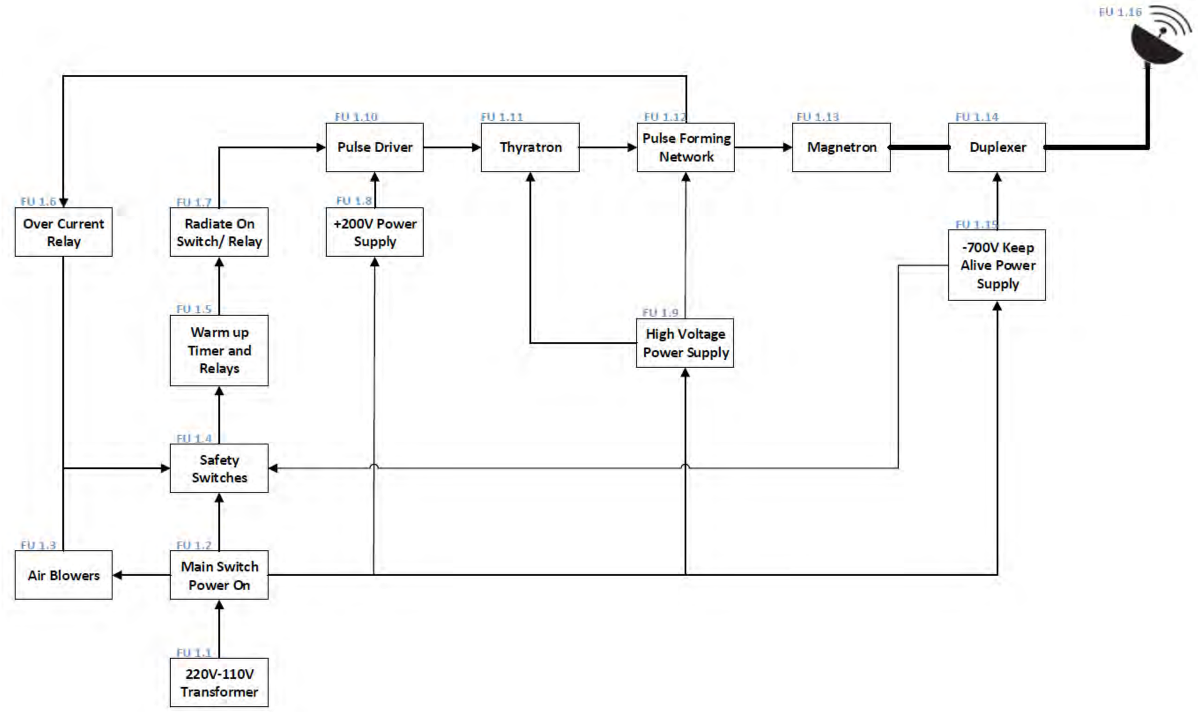


Figure 24: Weather radar functional unit layout before transmitter upgrade – current system

To keep the transmitter functional diagram as simple as possible, every enclosed unit is seen as a sub-functional unit. The sub-functional units are numbered with a primary index of 1, followed by a secondary index numbered from 1 to 17. The primary index number (1 in this case) shows that the new functional sub-unit is part of the transmitter functional unit as shown in figure 24.

Below, each functional sub-unit is described generically by how it is interconnected as well as its purpose (at the time when the transmitter was analyzed - that is, before any component was replaced.).

FU 1.1 220 – 110 V Transformer

Because the radar was originally used in the USA, it operated on $110\,V\,AC$. Since South Africa operates on $220\,V\,AC$, a $220\,V\ to\ 110\,V$, $5\,kVA$ step-down transformer was installed to compensate for the voltage difference. To convert the radar to a $220\,V$ system all the internal transformers would have had to be replaced. The transformer provides power to the entire radar system except the computer that already operates on $220\,V$.

FU 1.2 Main Switch

The main switch is a mechanical switch used to trigger the power supply relay. The relay is connected to the Transformer (FU 1.1) on the one end and to the live bar on the other. When the radar is switched on, a number of components are powered simultaneously, including the Air Blower (FU 1.3), keep-alive power supply, high voltage variac, as well as power to the +200 V power supply and the Safety Switches (FU 1.4).

FU 1.3 Air blower

As the magnetron radiates EM pulses, it heats up substantially. Within the transmitter unit there are two air blowers. One blower is located at the bottom of the transmitter unit used to cool the main cabin. A second blower (figure 27 D) is placed directly below the magnetron to cool the magnetron. This magnetron blower is very important because if the magnetron is not kept below a pre-set temperature, it can result in permanent damage to the magnetron.

FU 1.4 Safety switches

The transmitter is operated for long periods of time without any supervision, and thus it is important to use safety switches to protect both the radar system and operator. There are multiple safety switches in place to stop the magnetron from radiating. To protect the transmitter, three safety switches are used, namely a magnetron air blower pressure switch, over-current relay, and a keep-alive power supply. The over-current relay is used to trip the magnetron power supply whenever the maximum current drawn by the magnetron is exceeded. If the keep-alive power supply fails the magnetron must stop radiating or it could damage part of the receiver system.

FU 1.5 Warm-up timer and relays

When the radar is switched on, the magnetron requires a warm-up period before it can start radiating. The 5 to 10 minutes timer is engaged when the magnetron is switched on. As soon as the timer is ready it will activate a “ready” relay that enables the magnetron to start radiating. However, it was experienced that the timer did not always work and had to be switched on and off manually. This timer in particular added to the rationale why it was so important to upgrade the transmitter system.

FU 1.6 Overcurrent relay

The over-current relay is used to protect the magnetron, as mentioned earlier. The relay is triggered by a pulse from the pulse-forming network and opens up the safety switches, stopping the magnetron from radiating.

FU 1.7 Radiate on switch and relays

Once the timer has engaged, the magnetron can be switched on by the push of a button or remotely from the computer. When the button is pressed, it activates a relay that activates the pulse driver.

FU 1.8 +200 V power supply

The $+200\,V$ power supply (Figure 27H) is provided by a transformer and rectifier system to provide a high voltage of $+200\,V\,DC$ to the pulse driver.

FU 1.9 High-voltage power supply

The high voltage power supply is used to power the pulse-forming network. The voltage is controlled by a variac transformer system (Figure 27C). A switch is used to power an electric motor that adjusts the variac to supply the required voltage. The voltage is rectified and filtered before it is processed by the pulse forming network.

FU 1.10 Pulse driver

The pulse driver is pulsed by the modulation trigger. When the pulse driver is triggered, it activates a set of BJT transistors that switches $+200\,V\,DC$ from the power supply with the same pulse shape as the modulation pulse.

FU 1.11 Thyratron

A thyratron is a gas-filled tube used as an in-line modulator to switch the energy stored in the pulse-forming network (2002, 2002). The thyratron is triggered by the pulse driver and controls the discharge of the pulse energy to initiate the subsequent charging cycle.

FU 1.12 Pulse-forming network (PFN)

The PFN is an electrical circuit that accumulates electrical energy and releases it in a relatively square pulse when triggered by the thyratron. The energy is stored in a series of capacitors and inductors powered by the high voltage power supply. Due to the characteristics of the PFN, the stored voltage is roughly twice that of the power supply (2002, 2002). When the thyratron triggers the charged PFN, the stored energy is discharged through the primary side of the pulse transformer (Inc.). For this radar the PFN provides a voltage up to $27\,kV$ and the maximum power peaks at $250\,kW$.

FU 1.13 Magnetron

The magnetron (Figure 27 B) is a high-powered microwave oscillator used to generate EM pulses. The pulses are sent into the atmosphere using a series of waveguides and a feed horn. The thicker lines in Figure 24 indicate the waveguides used for the transmitter section. The magnetron is powered by high-powered pulses generated by the PFN. Figure 25 illustrates how the high voltage power supply (HV In), pulse driver (Trigger In), thyratron as the (trigger), pulse forming network, pulse transformer and magnetron all fit together to produce a high-powered EM wave. The thyratron, PFN and pulse transformer are all enclosed in an aluminium enclosure called the “Hot Box” shown in Figure 27 A.

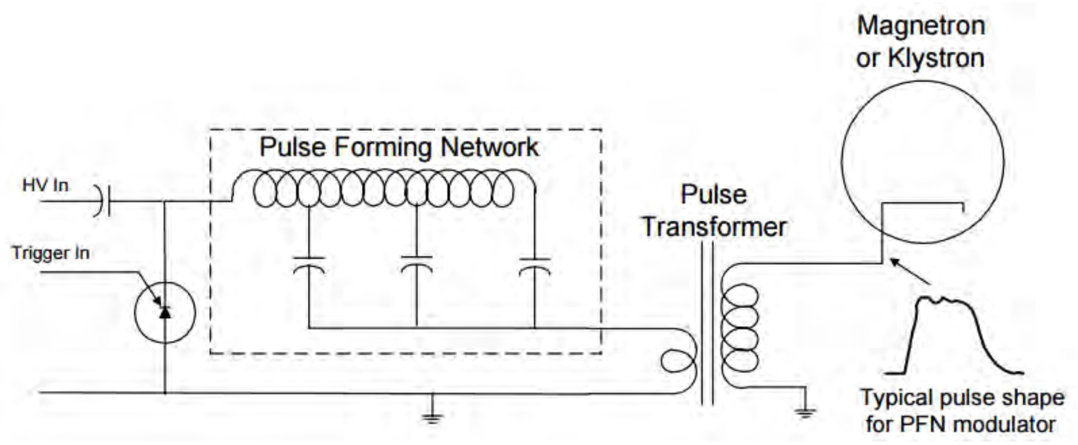


Figure 25: Weather radar pulse forming network with magnetron layout (ANON_A)

FU 1.14 Duplexer

The duplexer (Figure 27 E), also known as a transmit/receive switch, is used to protect the receiver from the high-powered EM pulses generated by the magnetron. Because the EM pulses exit and enter the radar system using the same antenna, it is necessary to switch between transmit and receive modes. When the magnetron is transmitting, it must prevent the RF and EM energy from entering the receiver and when the magnetron is off, the reflected waves must be allowed to enter the receiver. This duplexer is gas-filled and requires a high negative DC voltage to keep the gas particles ionized. This power supply is known as the keep-alive PSU (Büyükbas et al., 2006, Skolnik, 1990).

FU 1.15 -700 V keep-alive power supply

The keep-alive PSU provides a $-700\ V\ DC$ to the duplexer to keep the gas particles inside the unit ionized. If the keepalive should fail, the high-powered EM waves can damage the receiver unit. Therefore the keep alive PSU is connected to the safety relays to stop the magnetron from radiating in the PSU fails.

Figure 26 shows the radar unit electrical components and Figure 27 shows enlarged figures of the major components.

Figure 26: Internal weather radar components

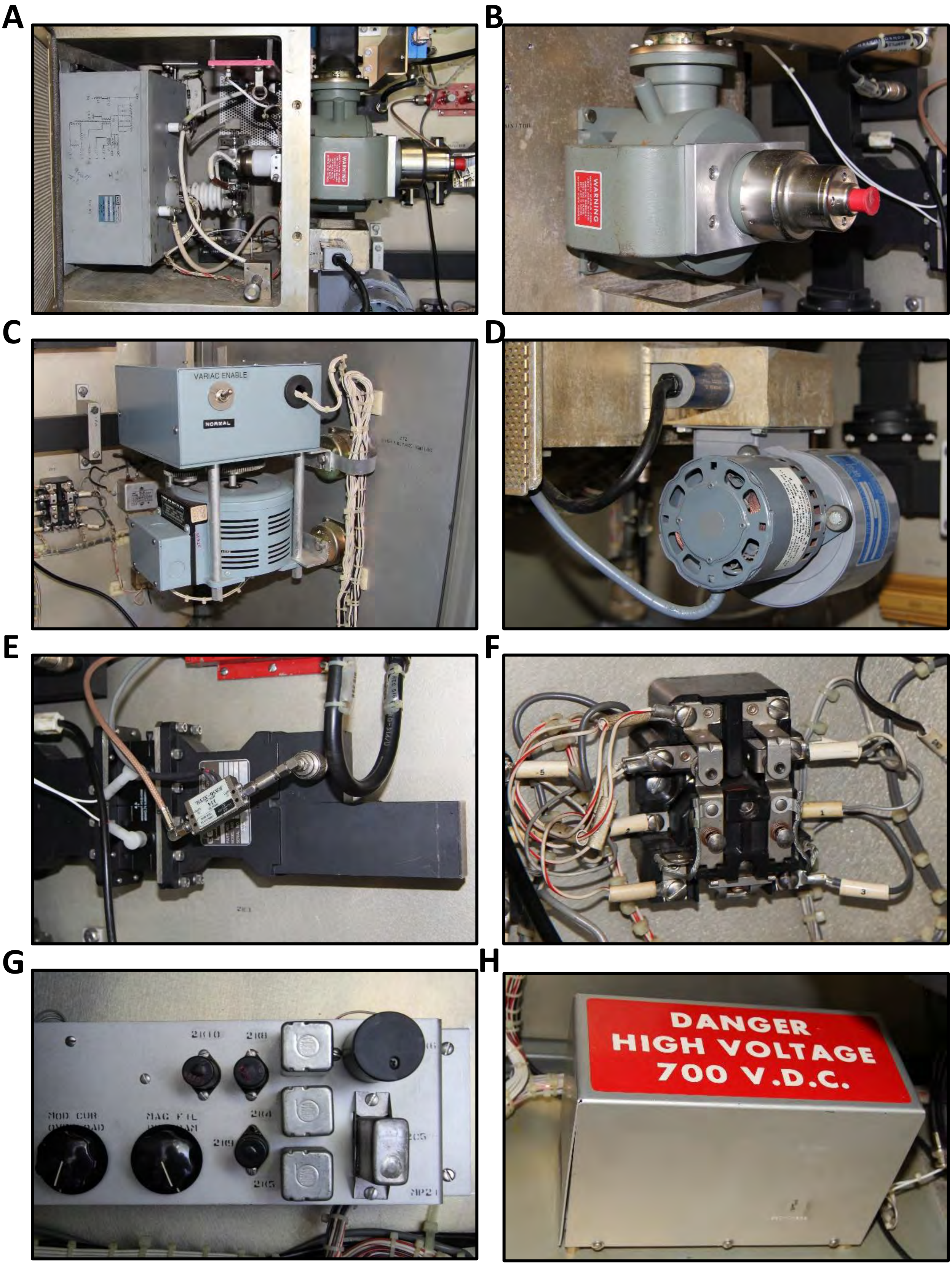


Figure 27: Transmitter components: A – hot box, B – magnetron, C – variac transformer, D – air blower, E – duplexer, F – relay, G – over current adjustment, safety relays and timer and H – +700 VDC power supply.

3.2.3 Re-engineering the transmitter system

The third phase of the re-engineering process was to improve or re-design the artefact. In this case, the transmitter unit had to be upgraded with newer and more reliable equipment. The purpose of this upgrade was to replace the original transmitter with a newer generation model. The criteria for the new transmitter are as follows:

- The transmitter must be compatible with the other radar sub-systems such as the magnetron, receiver, signal processor and antenna;
- The transmitter must be able to power the 250 kW magnetron with its frequency as specified in table 14;
- The magnetron's pulse width must be adjustable;
- Use solid-state transistors instead of conventional switching gear as a thyratron.

Very few companies supply transmitters that meet the required specifications. Some of the bigger companies such as Vaisala, Advanced Radar Corporation, and Selex Gematronik have their own transmitter systems. These systems can be used but with moderate to major modifications to the rest of the system. However, one company, Pulse System Inc., specifically designed a transmitter to replace the original EEC radar transmitters. The system is called the TR-1061 solid-state transmitter. Because the TR-1061 is based on the EEC radar, replacing the old transmitter would require minimum modifications to the rest of the radar system and complies with all requirements. It was therefore decided to install the TR-1061 transmitter system. According to the terms and conditions of Pulse System Inc., this document may not contain any circuit diagrams of the transmitter. Therefore, the transmitter setup and requirements will only be described briefly. The transmitter consists of three main sections; the main high voltage power supply, modulator and front control panel.

The power supply provides an adjustable DC voltage between $0\,V$ and $750\,V$ to the modulator. The power supply includes various safety procedures, switches and relays to protect both the transmitter and magnetron against misfiring, overcurrent and over duty cycling conditions. The PRF of the radar is introduced into the transmitter system through the power supply module. It is important to note that the PRF input is transistor-transistor logic (TTL) with a maximum of 5 V. The power supply modifies the PRF to the selected pulse width. The controls on the power supply are used to adjust the output levels and to reset any system faults. The front panel controls the pulse width adjustment, transmitter on/off and radiate on/off.

The modulator receives the input signal and provides a high-powered pulse of 26 to 28 kV to the magnetron. This causes the magnetron to oscillate at C-Band frequency with the pulse width as selected. The modulator is filled with oil for both insulating and cooling purposes. Figure 28 shows the TR-1061 solid-state transmitter/ modulator on the left and power supply to the right. The front panel comprises various switches, indicators and analogue monitors displaying the current status of the transmitter. The panel is only connected to the power supply.

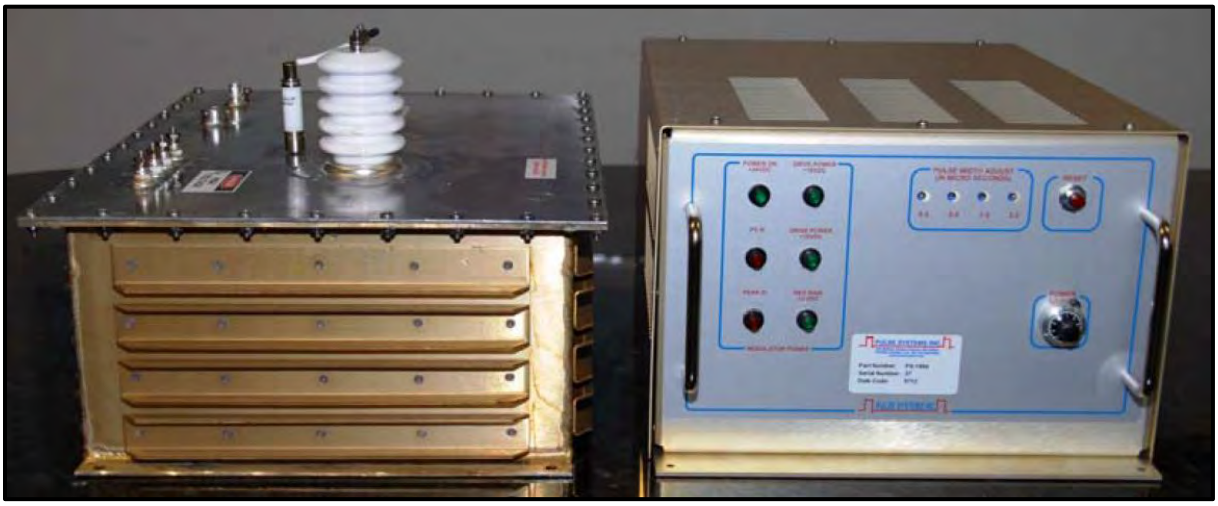


Figure 28: TR-1061 solid-state transmitter modulator on the left and the power supply on the right-hand side.

After the systems has been connected as shown, the following procedures should be followed to set up the transmitter parameters, as outlined below.

Transmitter setup:

1) Before applying power to the system, ensure that the high voltage potentiometer is turned counter clockwise to 0, ensuring that the magnetron will receive almost 0 V;

2) The power supply is turned on by the main switch located on the front panel;
3) The modulator will apply the required power to the magnetron’s filament;
4) A timer set to 5 minutes will ensure that the magnetron’s heater reaches its required temperature before proceeding. After 5 minutes a green LED will indicate that the transmitter is ready to radiate;
5) The magnetron is switched on by engaging the radiate switch located on the front panel.

When ready to radiate, the potentiometer can be turned up until the required output power has been reached. The pulse can be seen using a high voltage probe and oscilloscope. Table 15 shows a summary of the transmitter specifications.

3.2.4 Implementing the transmitter upgrade

The final phase in the re-engineering process was to implement the new artefact. For this study, it comprises replacing the original transmitter system with a newer generation model designed by Pulse System, Inc. The operating environment was described in Chapter 3.2.2 and the new transmitter system in Chapter 3.2.3. Table 16 shows a summary of the original transmitter components and which of them had to be removed, re-used or modified. The process followed to implement the new transmitter is described below.

3.2.4.1 Remove all the old transmitter components

Before the new transmitter could be installed, all the original transmitter components were removed. Even if the component would be re-used, it was temporarily removed and cleaned using the correct cleaning agent. It is important not to damage any of the components during the process because all of it will either be re-used, sold as spare parts, or displayed later on for training purposes. Because the receiver’s power supply was starting to present problems it had to be replaced with newer, smaller power supplies. Only the receiver unit, signal processor, duplexer, magnetron isolator, and waveguides were left in the casing. The removal process can be seen in Figure 33.

Table 15: TR-1061 Solid-state transmitter specifications

TR-1061 Solid-State Transmitter Specifications	
Transmitter Specifications	
Magnetron:	C-Band VMC-1891A
Frequency:	5210-5700 MHz
Duty:	0.001
Magnetron Input:	25 kV, 24 A
Peak Power:	250 kW
Pulse Widths (Measured at -3 dB of the RF pulse)	
A:	0.5 µsec
B:	0.8 µsec
C:	1.0 µsec
D:	2.0 µsec
Rise Time:	60 nsec
Fall Time:	150 nsec
Pulse Jitter:	5 nsec Max
Output Requirements	
Stability:	0.1 dB, pulse to pulse
Spectrum:	12 dB, down on sidebands
Modulator Output	
Output Voltage:	Adjustable between 0 to - 30 kV Pulse
Filament Voltage:	+9.5 V DC
Filament Current:	12 A DC
Input Trigger:	5.0 V Peak 2.0 µsec
Environmental Specifications	
Max Altitude:	10,000 feet
Ambient Temp:	-40 °C to +50 °C
Max Humidity:	95%
Cooling:	Internal, forced air

3.2.4.2 Modifications to the hotbox and front panel

After the transmitter components had been removed, two modifications on the radar casing were made. The casing housing the magnetron, also known as the “hotbox“, needed a 100 mm diameter hole at the bottom for the magnetron power cables. The original magnetron was connected to the power transformer within the hotbox but in this case the power supply is outside the hotbox. The edge of the hole was cut 60 mm from the front door and 50 mm from the magnetron's side as shown in Figure 29.

Table 16: Summary of the components to be removed, re-used or modified

Original Transmitter Analysis				
FU	***Component***	***Remove***	***Re-use***	***Modify***
1.1	220 - 110 V Transformer		***X***	
1.2	Main Power On Switch		***X***	
1.3	Air Blowers		***X***	
1.4	Safety Switches		***X***	***X***
1.5	Warm-up Timer and relays	***X***	***X***	
1.6	Over Current Relay	***X***		
1.7	Radiate on Switch/ Relay	***X***		
1.8	+200 V Power Supply	***X***		
1.9	High Voltage Power Supply	***X***		
1.10	Pulse Driver		***X***	***X***
1.11	Thyratron	***X***		
1.12	Pulse Forming Network	***X***		
1.13	Magnetron		***X***	
1.14	Duplexer		***X***	
1.15	-700V Keep Alive Power Supply		***X***	
1.16	Antenna unit		***X***	

Figure 29: Hole cut in the hotbox for the magnetron wires

The second modification was on the front panel on the door. The new control panel is smaller than the original panel and needed an extra aluminium or steel modification plate to compensate for the gap. The outside dimensions are shown in Figure 30, the CAD drawing. Figure 31 shows the end results of the modification plate installed on the front door.

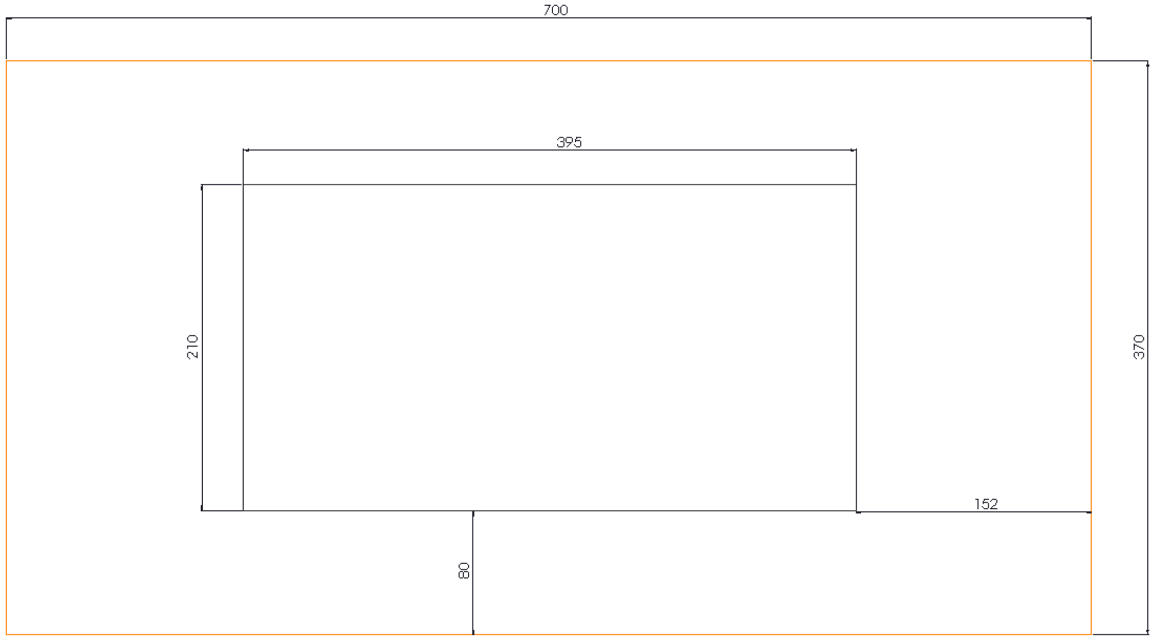


Figure 30: Front panel modification CAD.

Figure 31: The modification plate after installation.

3.2.4.3 Power-supply connection

As discussed, the radar power supply will be kept at 110 V internally, with external power at 220 V to suit South African conditions. The circuit diagram in Figure 32 shows how power is supplied to sub-units.

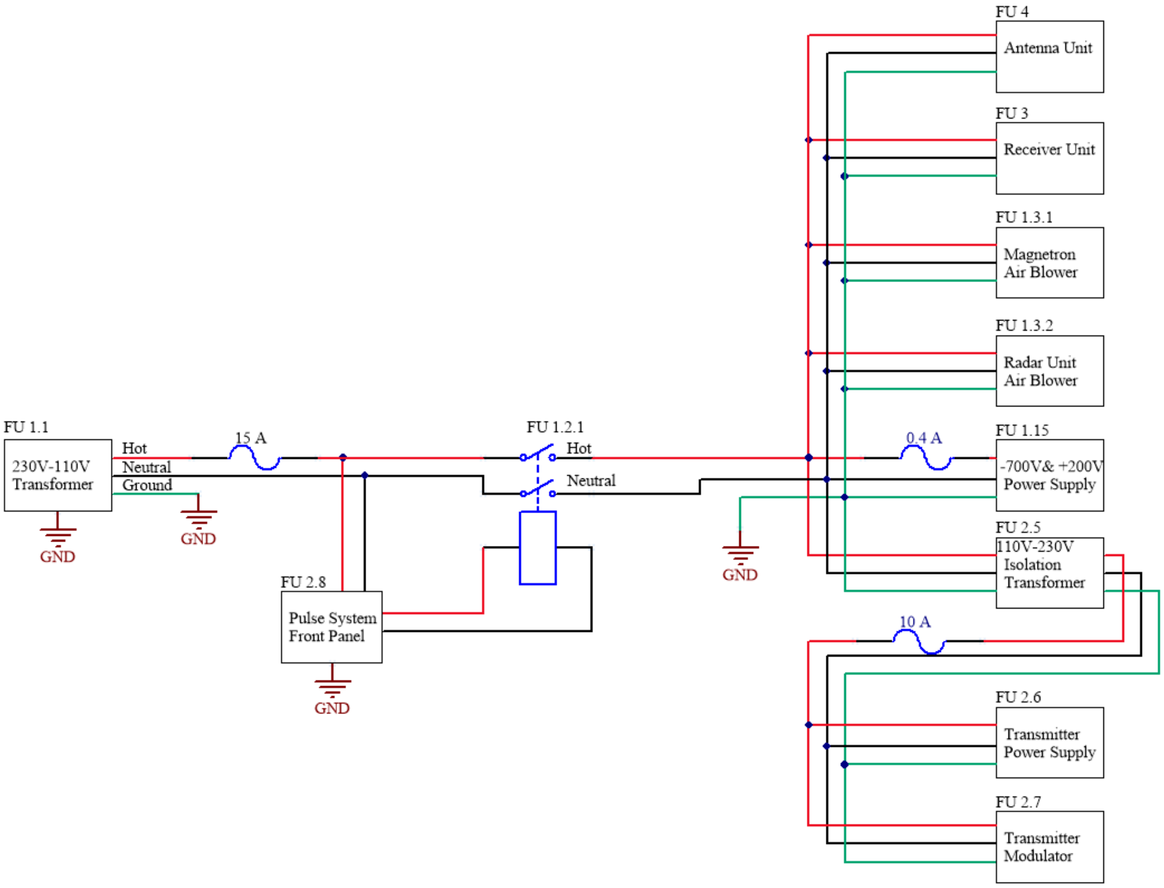


Figure 32: Modified power circuit diagram

The main transformer (FU 1.1) is a $220 - 110\,V$, $5\,kVA$ step-down transformer. The power to the radar is supplied from the transformer to socket 2J1 where port A is connected to live (Hot), B to neutral and C to ground. From the socket the hot wire is directly connected to a $15\,A$ slow-burn fuse. Following the fuse both the hot and neutral wires are connected to a double pole double throw (DPDT) relay. The relay is used as the main switch to power the radar system. The relay's coil is powered by a switch on the front panel (FU 2.8) connected directly to the main supply via the fuse. It is therefore important to note that the main switch will always be live. The following components are directly connected to the secondary side of the relay:

- Antenna unit (FU 4);
- Receiver unit (FU 3);
- Magnetron air blower (FU 1.3.1);
- Radar unit air blower (FU 1.3.2);

- $-700V$ & $+200\ V\ DC$ and power supply (FU 1.15);
- $110\ to\ 220\ V$ isolation transformer (FU 2.4).

The $110\ to\ 220\ V$ isolation transformer is a $3\ kVA$ step-up transformer supplied by Pulse Systems Inc. According to the company it is advised to power the transmitter system through an isolated power supply. An isolated transformer isolates the power supply from the load to provide additional protection. Both the transmitter power supply and transmitter modulator are connected to the power supply through a $10\ A$ fuse as shown in the circuit diagram. The transformer is installed in the bottom rear part of the unit.

3.2.4.4 Transmitter installation.

Since all the original transmitter components and the receiver's power supply had been removed, sufficient space was left available to install new components. The hotbox, holding the magnetron and air blower in position, was installed in its original position. The transmitter power supply (FU 2.6) was installed in the top left-hand corner where the receiver's power supply originally had been and the transmitter modulator (FU 2.7), being the heaviest, in the bottom left corner. It is important to have the modulator as close to the magnetron as possible to keep the connecting wires short. The front panel was mounted to the modification plate on the front door.

The newly cut hole in the hotbox, Figure 29, was used to run the wires from the magnetron to the modulator. The wires were kept separated from one another and the casing's sides. A block of polystyrene was placed inside the hole with the wires running through it. This provided both insulation and kept the wires in position as seen in Figure 34B. The hotbox had another hole cut out for a fan used to cool down the original pulse forming network, however it was not necessary for this upgrade. Because the fan was no longer required, the hole had to be covered with tin foil or mesh to minimize the RF leakage.

The receiver's new power supplies were installed below the transmitter power and above the hotbox as seen in Figure 34A. This allows for easy access to the connection bar connected to the receiver components.

Figure 33: Removing all the transmitter components before implementing the new transmitter.

3.2.4.5 Modification and protection circuits

The radar is synchronised with a pulse generator at 3,75 ms intervals, known as the pulse repetition frequency (PRF). Originally, the PRF generator was used to trigger the thyratron through a pulse driver that provided the required power. The same PRF generator and pulse driver were used to trigger the new transmitter, but the new transmitter requires a TTL input, therefore maximum 5 V pulses. The pulse driver's original circuit diagram is shown in Appendix A and consists of multiple individual transistors. The circuit diagram has eight output ports but only ports E2, E3 and E5 needed to be changed. These three ports all receive their power from a common line connected to the 15 V bus (port E7). The easiest method to change the output voltage from 15 to 5 V was to lower the supply voltage of the transistor. This was achieved by disconnecting the one wire supplying power to the bottom part of the circuit. The power was diverted to a 5 V regulator to enable TTL-level pulses.

To protect the receiver from high-powered pulses, a duplexer also known as a transmit/receive switch (Büyükbas et al., 2006) is used. The original duplexer is a gas-filled duplexer which requires a keep-alive DC voltage

The circuit shown in Figure 35 is a transistor switching circuit used to power the keep-alive safety relay, which in turn protects the transmitter. The -700V power source has a 90 kΩ, 10 W internal series resistor that connects to a 2.6 kΩ resistor between the output and ground to form a voltage divider with an output of -19.6 V. A 47 kΩ resistor in series will limit the base current of the BC 327 PNP transistor, acting as a switch to power the relay from an external power source through a 12 V voltage regulator. Any small 12V relay can be used as long as the required coil power is less than 0.45 W (Neamen, 2010).

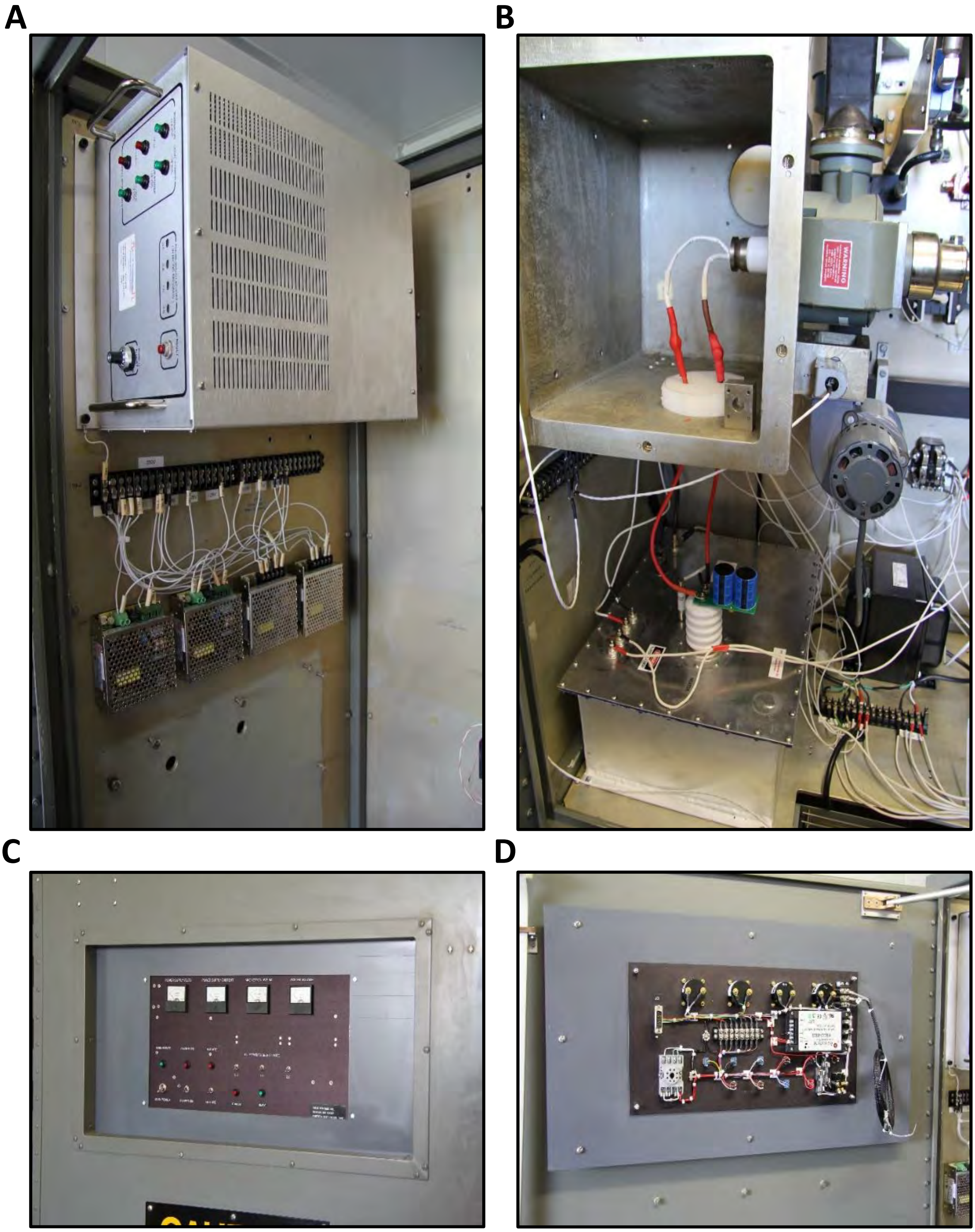


Figure 34: Transmitter components: A – transmitter and receiver power supplies, B – transmitter modulator and magnetron connection, C –control panel from front, D – front panel from back.

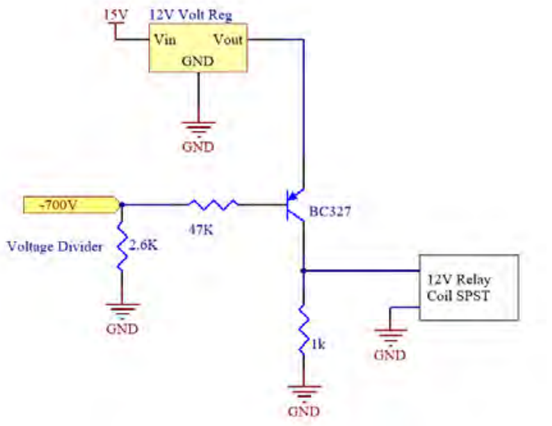


Figure 35: Protection circuit diagram ensuring the keep-alive is always operational.

The new transmitter consists of internal protection systems to protect both the transmitter and magnetron unit. Despite this, additional protection is required for external components as well as to protect the operator from accidental exposure to radiation. The additional protection safety switches include the following:

- Pressure switch at the magnetron blower;
- Safety switch on the antenna power supply FU 2 as shown in Figure 23;
- Keepalive voltage relay.

These additional switches were connected in series between the radiate switch and warm-up timer. The safety switch on the servo unit was connected through the 2J1 socket. According to the cable diagrams provided by EEC, port “u” and “v” on socket 2J1 were used. Figure 36 illustrates how the switches are connected.

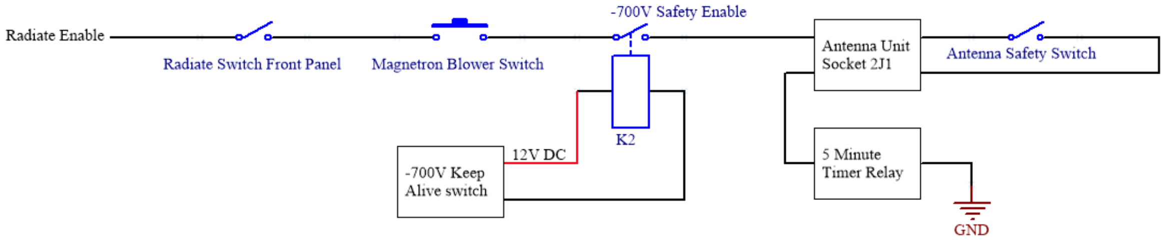


Figure 36: Radiate enable circuit diagram with the safety switches.

3.2.4.6 Replacing the receiver’s power supply.

During the transmitter upgrade, the receiver’s DC power supply was replaced with four new power supplies to provide: +15 V, -15 V, +28 V and -28 V, each at a rating of 35W. The power supply was replaced because it occupied space needed for the transmitter’s power supply and did not provide a stable voltage to the receiver unit. This upgrade did not form part of the transmitter re-engineering process, but it is important to comment on the benefits it provided to the receiver. With the new stable power supply it was noticed that the baseline of the receiver was considerably more stable than before. It was also noticed that the ground clutter surrounding the radar was less than before.

3.2.5 Radar functional block diagram

Some of the original components were re-used in the new system – it is important to understand where these components fit in. The original function block diagram, Figure 24, was adapted to show the re-engineered transmitter. The original block diagram was modified to incorporate the new transmitter with the original radar system elements as shown below in Figure 37. As with the original diagram, every functional unit (FU) is given a block and reference number. All the units re-used have the same number as before, while the new or modified units have a new reference number starting with two.

3.3 RISK ANALYSIS

There are always risks involved in any project, no matter the size or cost. Therefore, it is important to identify and manage these risks. Despite radar systems having been used for decades, there is still very little literature available on the risks associated with them. This study identified possible risks with the NWU-Lekwena radar system, managed them accordingly and helped address the literature gap on radar risks. Risks on this project were identified throughout by means of research, observations and experience from the case study.

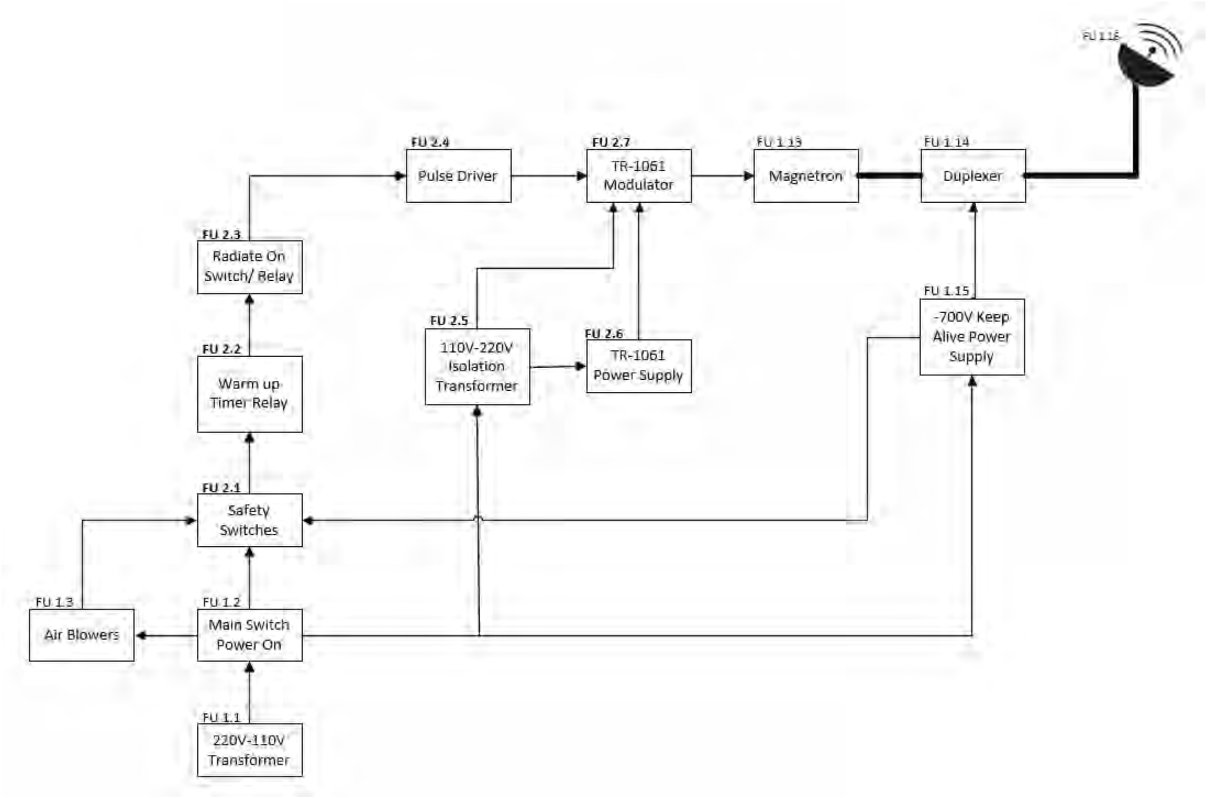


Figure 37: Weather radar functional unit layout after transmitter upgrade

The risk analysis conducted in this study was used to measure the improvement – that is, reduction in risk – due to the re-engineering intervention. A risk analysis was conducted before re-engineering to set a baseline risk, and afterwards to show the improvement achieved by re-engineering and planning.

For this case study, the risk assessment was divided into three sections (levels) namely operational, modular and component level. The operational analysis describes the project at a higher level with less detail. This includes all risks having an influence on the overall system such as politics, logistics, procedures, available resources, strategies, implementation, etc. The modular analysis focusses more on the radar subsystems, therefore a smaller focus with more detail. The operational risk analysis assists one to identify the risks of the system at modular level. The lowest level analysis focusses on the components of the subsystems in the radar system and is in more detail. The modular analysis again assists one to identify the risks on the component level. After both the operational and component analyses risks had been identified they were managed as best as possible and re-evaluated afterwards. Figure 38 shows a flow diagram of how the three analyses are constructed and how they fit together.

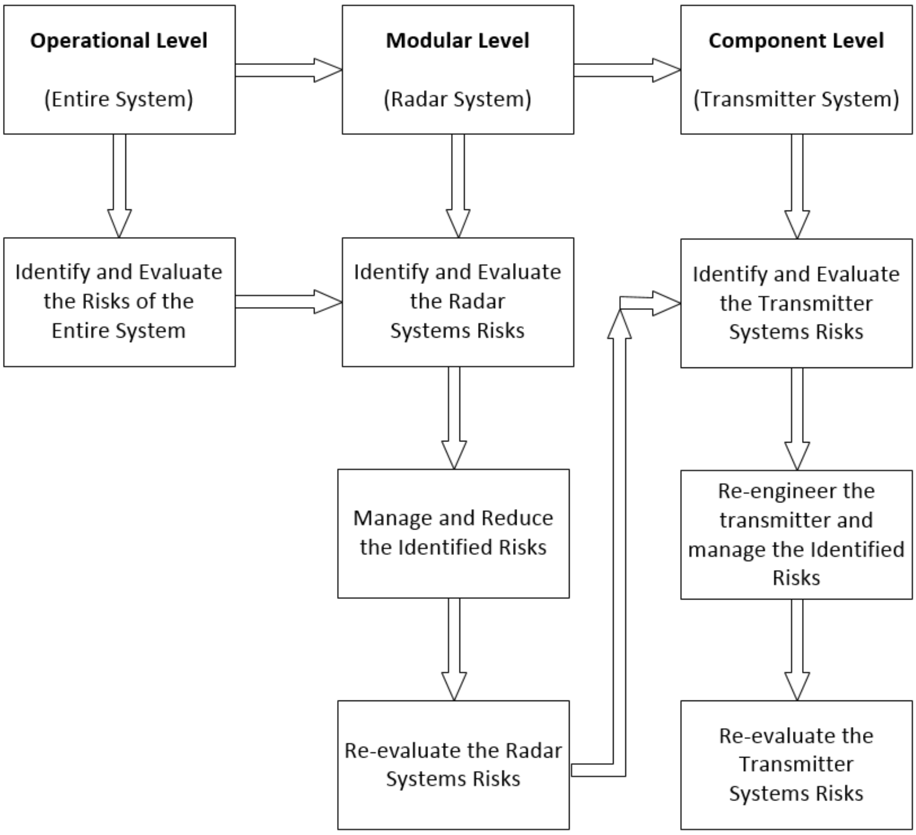


Figure 38: Operational, modular and component risk analysis layout.

Different methods and techniques are available to conduct a risk analysis, each with its own advantages and disadvantages. For this study a common method was used known as a probabilistic risk analysis (PRA). A PRA is a systematic and comprehensive methodology consisting of three phases - risk identification, analysis and evaluation (Smith, 2011). The PRA uses visualization techniques to help identify possible risks or events through visual diagrams such as cause-and-effect diagrams, fault tree analyses (FTA), event-tree analyses (ETA), and failure modes and effects analyses (FMEA). In the analysis phase, each risk is given a risk rating (RR) according to a rating matrix or table. After all the risks are given a RR they are ranked from high risk to low risk. The advantages of this method are it visually illustrates the risks, lists and prioritises them.

3.3.1 Operational risk analysis

The **first risk analysis**, done at operational risk level, was used to provide a broad view of the risks associated with the entire project. The operational analysis was further divided into two more sections, the radar installation (technical) and radar project risks. For both these analyses cause-and-effect diagrams are provided below to visually illustrate, identify and list the risks.

3.3.1.1 Radar installation risk analysis

Figure 39 shows the cause-and-effect diagram for the radar installation risks. The diagram was compiled after the radar had already been installed. The risks listed in the cause-and-effect diagram are actual risks that manifested during the project. Five main risk areas were identified, namely logistics, legalisation, procedures, resources and hazardous conditions. Each of these was further defined by risks at lower a level. For this assessment, only the main risk areas received a risk rating value after evaluating the risks at the lower level.

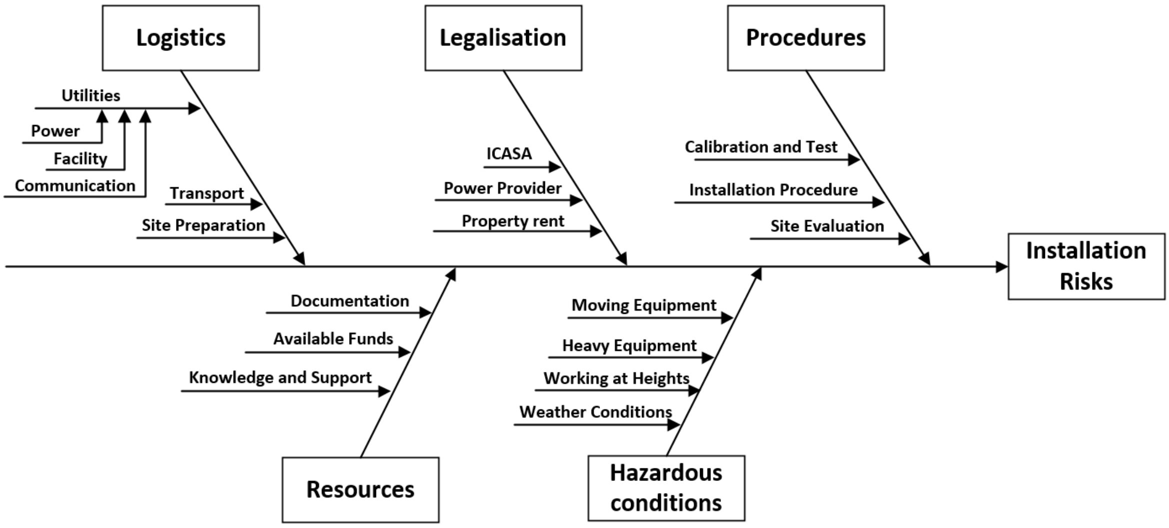


Figure 39: Radar Installation risk cause-and-effect diagram.

Logistics risks are all the risks related to the radar installation. This includes transport arrangements, basic utilities such as a stable power supply, communication links to the NWU and ensuring that the radar is housed in a building with adequate space, light, power plugs and air-conditioning. Because the radar was installed in a remote area, logistics proved to be a much higher risk than initially envisaged. The biggest risk was not being able to provide electric power to the site. The closest power supply was roughly 700 metres from the site. A 700 m long, 500 mm deep trench needed to be excavated up along the hill to the radar site, adding to the cost and risk of possible failure. The second concern was the communication link between the radar site and the NWU. The distance is approximately 15 km with no line of sight, requiring additional relay stations. The site preparation and steel platform were outsourced to a private contractor, adding to the cost but lowering the risk. The radar building is a pre-manufactured container with well-insulated walls, air-conditioning, proper lighting and enough space to accommodate the radar system, equipment, extra tables and cupboards. The overall risk for the logistics was evaluated and given a score of 16 out of 25 as shown in Table 17. The high risk is due to the power supply and communication network that posed multiple risks and concerns to the project.

Table 17: Installation logistic risk matrix.

		Consequence (C)				
		1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
Probability (P)	**5** Almost Certain	5	10	15	20	25
	4 Likely	4	8	12	**16**	20
	3 Possible	3	6	9	12	15
	2 Unlikely	2	4	6	8	10
	1 Rare	1	2	3	4	5

Legislative compliance was a challenging task due to politics and communication problems. This should have been much easier if the right procedures were followed and if the correct documentation were available. Because this type of application is not regularly applied for at the Independent Communications Authority of South Africa (ICASA), who is responsible for providing the licence, it took longer than expected. Applying for a power connection at ESKOM is fairly straight forward, given that the power connection required is available and already active. After evaluation the legislative risk was given a risk rating of 9 out of 25 as shown in Table 18.

Table 18: Installation legislative risk matrix.

		Consequence (C)				
		1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
Probability (P)	**5** Almost Certain	5	10	15	20	25
	4 Likely	4	8	12	16	20
	3 Possible	3	6	**9**	12	15
	2 Unlikely	2	4	6	8	10
	1 Rare	1	2	3	4	5

One of the higher risks for this project was the lack of available resources, as presented in Table 19. Because the radar was ±40 years old, much of the original documentation had been lost or never updated throughout the years. Fortunately for this project a few local experts, who have experience on similar radars, were available to assist where needed. Their knowledge greatly contributed to the successful installation and testing of the radar system. Without their contribution to the project the risk of successfully installing the radar would have been much higher. Another high risk identified was the lack of funds necessary to complete the project. Because this is a non-profit research project mainly sponsored by the NWU, the budget was very limited. Due to the budget constraints and resources available, the resources risk was given a high risk rating of 16 out of 25.

Most projects have some degree of hazardous conditions posing a risk of accidents or personal injuries (Table 20) – therefore an occupational health and safety risk. Due to the nature and design of this project, the highest risk was during the installation phase. An example of a high risk is the installation of the antenna unit on the elevated platform. The antenna pedestal and dish are heavy and needed to be lifted by a crane, followed by the radome panels. The radome panels are bulky, curved-shaped and fairly light, therefore a sudden gust of wind could damage then panels or even knock a person down from the platform Other risks were carrying or moving heavy equipment and working in non-ideal weather conditions. Since the radar was installed on the crest of a rocky hill, there is a risk of lightning strikes. The hazardous conditions to a person's life give it a high consequence but it was not likely to happen, therefore it was evaluated with a risk rating of 10 out of 25 as shown in table 20.

Table 19: Installation resources risk matrix.

		Consequence (C)				
		1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
Probability (P)	**5** Almost Certain	5	10	15	20	25
	4 Likely	4	8	12	**16**	20
	3 Possible	3	6	9	12	15
	2 Unlikely	2	4	6	8	10
	1 Rare	1	2	3	4	5

Table 20: Installation hazardous conditions risk matrix.

		Severity Level (S)				
		1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
Probability Level (P)	**5** Almost Certain	5	10	15	20	25
	4 Likely	4	8	12	16	20
	3 Possible	3	6	9	12	15
	2 Unlikely	2	4	6	8	**10**
	1 Rare	1	2	3	4	5

The last risk for radar installation involved processes that needed to be followed with the site evaluation, radar installation, calibration, and testing of the system afterwards. Site evaluation was probably one of the more important processes. Various sources in literature were available on requirements and processes to evaluate and select the best site. Therefore, even though the installation process was important, it had a lower risk because of available resources. The installation procedure was fairly straightforward and easy to complete even without an installation manual. The highest risk for this section was the calibration and testing procedures because of limited experience, knowledge and resources available. For this project, assistance was available in the form of local experts. Due to limited knowledge and resources available, the project received a risk rating of 12 out of 25 as shown in Table 21.

Table 21: Installation process risk matrix.

		Severity Level (S)				
		1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
Probability Level (P)	**5** Almost Certain	5	10	15	20	25
	4 Likely	4	8	**12**	16	20
	3 Possible	3	6	9	12	15
	2 Unlikely	2	4	6	8	10
	1 Rare	1	2	3	4	5

3.3.1.2 Radar project risk assessment

The second risk analysis is based on the overall project risks as listed in the cause-and-effect diagram (Figure 40). As with the first cause-and-effect diagram, this diagram was also compiled after the radar had already been installed. Therefore, the risks listed are actual risks that manifested during the project or were identified throughout the project. Five main risk areas were identified namely resources, environment, people, software and hardware. Each risk area is further defined by smaller risks and given an overall risk rating represented on an evaluation matrix.

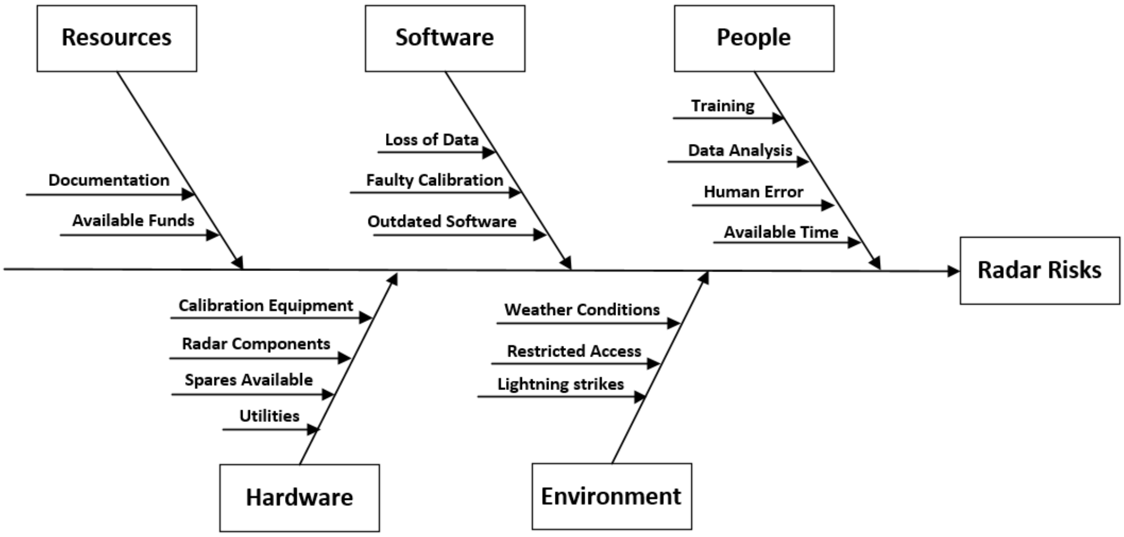


Figure 40: Radar maintenance risk cause-and-effect diagram.

Limited documentation was available on the installation of the radar system and its calibration procedures. After installation, additional documents are always required to maintain the system through its operational years, including start-up and shutdown procedures, maintenance modules, routine calibrations, and basic operations, design layout and circuit diagrams. Most of these documents were available but were out of date and in bad condition. However, some newer up to date documents were available such as the RDAS2K signal processor manual (Dixon and Wiener, 1993). Another resource risk is the funds available to maintain the radar. The initial installation cost is usually high, but substantial funds are required to keep the radar operational in the future. Looking at all the risks, the resources risk was given a 12 out of a possible 25 as shown in the Table 22.

One of the site-selection criteria is that the radar had to be sited on the crest of a hill overlooking the surrounding area. This makes the radar station susceptible to severe weather conditions such as heavy rain, wind and possible lightning strikes. The wind can also shake the antenna platform sideways, decreasing the accuracy of the data collected. If any small cracks or holes are exposed, water can seep through and damage the electrical components. In addition to the natural risks there is the risk of restricted access to the site. The weather radar is situated on a wild-life estate with access solely controlled by the landowner. The access to the site could be restricted or limited for any reason outside of operational control. After evaluating the environment risk, it received a risk rating of 8 out of 25 as shown in Table 23.

Table 22: Radar resources risk matrix evaluation.

		Consequence (C)				
		1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
Probability (P)	**5** Almost Certain	5	10	15	20	25
	4 Likely	4	8	12	16	20
	3 Possible	3	6	9	**12**	15
	2 Unlikely	2	4	6	8	10
	1 Rare	1	2	3	4	5

Table 23: Radar environmental risk matrix evaluation.

		Consequence (C)				
		1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
Probability (P)	**5** Almost Certain	5	10	15	20	25
	4 Likely	4	8	12	16	20
	3 Possible	3	6	9	12	15
	2 Unlikely	2	4	6	**8**	10
	1 Rare	1	2	3	4	5

One of the biggest risks for this project was the lack of knowledge and experience in radar systems. An example is the magnetron that generates a peak power output of up to $250\ kW$, and if correct attenuators are not used, it could damage the receiver or calibration equipment. Basic training was provided during this project but more knowledge and skills still need to be gained - for that reason this section received a risk rating of 16 out of 25 as shown in Table 24.

Table 24: Radar people risk matrix evaluation.

		Consequence (C)				
		1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
Probability (P)	**5** Almost Certain	5	10	15	20	25
	4 Likely	4	8	12	**16**	20
	3 Possible	3	6	9	12	15
	2 Unlikely	2	4	6	8	10
	1 Rare	1	2	3	4	5

The radar system comprises many components, from a small safety switch to amplifiers and magnetrons. The concern is that most of the hardware was as old as the radar itself - some of the components had already started to fail and when they do in the future, it will become an expensive and daunting task to source spare parts. This problem will only increase as the radar gets older. Recently, some of the wires had also started to get brittle which could cause a short circuit. The hardware is a real risk, and therefore was assigned a high risk rating of 20 as shown in Table 25.

The radar software had more up-to-date versions available compared to the radar hardware. The radar system has a state-of-the-art computer system with the latest version of TITAN and RdasControl. However, even with these latest versions, some connection failure could occur between the hardware and software resulting in a time-out and loss of data. This is more common during a power dip or spike, fortunately this is a rare event. For that reason the software received a risk rating of 4 out of 25 as shown in Table 26.

Table 25: Radar hardware risk matrix evaluation.

		Consequence (C)				
		1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
Probability (P)	**5** Almost Certain	5	10	15	**20**	25
	4 Likely	4	8	12	16	20
	3 Possible	3	6	9	12	15
	2 Unlikely	2	4	6	8	10
	1 Rare	1	2	3	4	5

Table 26: Radar resources risk matrix evaluation.

		Consequence (C)				
		1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
Probability (P)	**5** Almost Certain	5	10	15	20	25
	4 Likely	4	8	12	16	20
	3 Possible	3	6	9	12	15
	2 Unlikely	2	4	6	8	10
	1 Rare	1	2	3	**4**	5

3.3.2. Modular-level risk analysis

When managing known risks, it is always good practice to address risks with highest priority and work down to lower priorities. According to the operational analysis, the highest risk rating for this project was the hardware of the system. A **second risk analysis** was therefore conducted on hardware alone. This assessment was done at **modular level** instead of operational, meaning a more in-depth study than before. After all the risks had been identified and evaluated, they were managed accordingly to mitigate and reduce risk before a follow-up risk analysis was done afterwards for comparative purpose.

To identify, evaluate and prioritise each risk, a “failure modes and effects analysis” (FMEA) was used in both *before* and *after* analyses. FMEA is commonly used to identify and determine the reliability of a system by determining what the probability (P) is of a failure occurring and if such a failure occurs, what the consequence (C) of the failure could be. The probability and consequence values are determined by using a qualitative risk matrix as shown in Table 27. This qualitative method is commonly applied in risk analysis where the exact values are unknown, making it ideal for this application.

Table 27: Risk matrix – score allocation.

		Consequence (C)				
		1 Insignificant	**2** Minor	**3** Moderate	**4** Major	**5** Catastrophic
Probability (P)	**5** Almost Certain	5	10	15	20	25
	4 Likely	4	8	12	16	20
	3 Possible	3	6	9	12	15
	2 Unlikely	2	4	6	8	10
	1 Rare	1	2	3	4	5

The qualitative risk matrix shows the consequence in the top columns ranging from insignificant to catastrophic represented by a value from 1 to 5. The probability is shown in the rows on the left-hand side ranging from rare to almost certain represented by a value from 1 to 5. These values are multiplied to give a risk rating (RR). The risk matrix shown in Table 28 further evaluates the risk between low, moderate to high and extreme. Low risk is achieved by a risk rating between 1 and 5, moderate between 6 and 10, high between 12 and 15 and extreme between 16 and 25. Low to moderate risks are in most cases still acceptable. High to extreme risks are not acceptable and have the highest priority when mitigation planning and budget are considered.

Table 28: Modular risk analysis priority table.

Risk Rating	**Low**	**Moderate**	**High**	**Extreme**

The risks for this study are mainly identified from the hardware section in the cause-and-effect diagram (Figure 40).

Table 29: Modular FMEA table before the re-engineering process.

HW	**Potential failures**	**Possible causes**	**Consequence of failure**	**P**	**C**	**RR**
Utilities	Power failure	ESKOM power outage; Circuit breaker trips; Cable failure; Transformer failure	UPS carries load; Generator starts provide power	4	1	**4**
	Generator failure	Battery flat; Out of diesel; ATS failure	UPS carries load	3	1	**3**
	UPS failure	Switching failure; Converter failure; Battery failure	System failure	2	5	**10**
	Structure failure	Improper design; Weathering of construction materials	Structure damage; System damage	1	5	**5**
	Surge protection failure	Short circuit; Transformer inrush current; Lightning	System damage	3	5	**15**
Transmitter	Maximum output power failure	Modulator failure; Magnetron failure; Waveguide attenuation;	Minimize maximum scan radius; Heating of components; Inaccurate data	5	3	**15**
	Continuous radiate failure	Power failure; Modulator failure; Magnetron failure; Safety feature	Radar downtime; Loss of data; Component damage	3	3	**9**
	Magnetron power fluctuations	Unstable power supply; Modulator failure; Magnetron failure	Inaccurate data	2	4	**8**
	Arcing in waveguide	Damaged waveguide; Waveguide misalignment;	Loss of power; RF leakage	2	3	**6**

		Damaged O-ring				
	Insufficient cooling	Air blowers failure; High ambient temperature	Radar overheating; Magnetron damage; System failure	2	3	**6**
	Safety switches failure	Component failure; Connection failure	Magnetron damage; Receiver damage; System failure	2	4	**8**
	Calibration failure	Incorrect calibration; High component tolerances	Inaccurate data	2	4	**8**
	Maintenance failure	Lack of knowledge; No spare parts Obsolete components; Extensive cost	System failure; Considerable radar downtime	4	4	**16**
Receiver	High noise levels	Unstable power supply; High component tolerances; Thermal noise; Loose connections	Inaccurate data	3	3	**9**
	RF interference	External RF sources; Ground clutter; Waveguide reflected RF: Radome reflected RF	Loss of data; Inaccurate data	5	3	**15**
	Automatic Gain Control failure	Unstable power supply; Attenuation failure; False reflected power;	Inaccurate data	2	3	**6**
	Calibration failure	Incorrect calibration; High component tolerances	Inaccurate data	2	4	**8**
	Maintenance failure	Lack of knowledge; No spare parts Extensive cost	Loss of data; Inaccurate data; Radar downtime	3	4	**12**
Antenna	Radome Leakage	Defects in Radome; Improperly installed	Loss of data; High attenuation; Antenna damage	3	3	**9**
	Antenna mechanical failure	Warn out components;Motor misalignment; Reference signal failure	Antenna failure	2	4	**8**

	Alignment failure	Improper installation; Calibration failure; Reference signal failure	Inaccurate data	2	3	**6**
	Calibration Failure	Incorrect calibration; high attenuation; Reference signal failure	Inaccurate data	2	4	**8**
	Maintenance failure	Lack of knowledge; No spare parts Extensive cost	Loss of data; Radar downtime	3	3	**9**
Signal Processor	Analogue to digital failure	Rdas2k failure; Communication failure	Loss of data; Inaccurate data	2	4	**8**
	RDAS2k to TITAN communication failure	Communication failure; Calibration failure	Loss of data	1	4	**4**
Computer	Computer Failure	UPS failure; Network failure; Software Freezes	Loss of data	2	4	**8**
	Calibration Failure	Incorrect calibration; Reference signal failure	Inaccurate data	1	4	**4**
			Total Risk Rating			**227**

Most of the risks above can be managed by doing routine inspections and tests. This will lower the probability that the failure can occur but will not change the consequence. To limit the consequence, a specific element either needs to be repaired, modified or replaced entirely. Because the transmitter has undergone a re-engineering process, most of the old transmitter components have been replaced. The first FMEA analysis (above) is based on the radar as it was before the re-engineering process and the second FMEA (below) is based on the modified system. This is to illustrate the effect of re-engineering just the transmitter section of the entire system. Other components were also replaced such as the receiver power supply units and electrical cables. It was important to improve the stability of the receiver and lower the noise levels, hence it formed part of re-engineering and risk reduction. The original power supplies were bulky and occupied space required for the new transmitter power supply. After all the improvements had been made, a new FMEA analysis was conducted on the improved system to compare it with the original assessment. The new FMEA analysis is shown in Table 30 below. In addition to the original FMEA table, the new analysis has two additional columns namely risk mitigation and improvement (*Imp*). The risk mitigation column list all the actions that were taken to lower the risk rating of that specific risks and *Imp* shows by how many points the risk rating improved.

Three different types of actions were taken to lower the risks of the system. These actions are distinguished from one another through colour coding. The first action (green) is general routine and inspection, which lowered the risk rating with 1 point. The second action (blue) is a permanent modification to the system that can easily be implemented without requiring a re-engineering process. This action lowered the risk rating with 13 points. The third action (orange) is the re-engineering of the system. This action lowered the risk rating with 29 points.

Table 30: Modular FMEA table after the re-engineering process.

HW	Potential Failures	Risk Mitigation	Possible Causes	Consequence of Failure	P	C	RR	Imp
Utilities	Power failure	None	ESKOM power outage; Circuit breaker trips; Cable failure; Transformer failure	UPS carries load; Generator starts provide power	4	1	4	**0**
	Generator failure	Routine inspection and test	Battery flat; Out of diesel; ATS failure	UPS carries load	2	1	2	**1**
	UPS failure	None	Switching failure; Converter failure; Battery failure	System failure	2	5	10	**0**
	Structure failure	Routine inspection and test	Improper design; Weathering of construction materials	Structure damage; System damage	1	5	5	**0**
	Surge protection failure	Installation of class 2 and 3 surge protection; earthing all metal structures and equipment	Short circuit; Transformer inrush current; Lightning	System damage	2	4	8	**7**
Transmitter	Maximum output power failure	Re-engineering the transmitter; new modulator and power supply system	Modulator failure; Magnetron failure; Waveguide attenuation	Minimize maximum scan radius; Heating of components; Inaccurate data	3	3	9	**6**

	Continuous radiate failure	Re-engineering the transmitter; new modulator and power supply system	Power failure; Modulator failure; Magnetron failure; Safety feature	Radar downtime; Loss of data; Component damage	2	3	6	**3**
	Magnetron power fluctuations	Re-engineering the transmitter; new modulator and power supply system	Unstable power supply; Modulator failure; Magnetron failure	Inaccurate data	2	3	6	**2**
	Arcing in waveguide	Routine inspection and test	Damaged waveguide; Waveguide misalignment; Damaged O-ring	Loss of power; RF leakage	2	3	6	**0**
	Insufficient cooling	Additional safety switches	Air blowers failure; High ambient temperature	Radar overheating; Magnetron damage; System failure	2	2	4	**2**
	Safety switches failure	Replacing old switches	Component failure; Connection failure	Magnetron damage; Receiver damage; System failure	2	2	4	**4**
	Calibration failure	New modulator and power supply system	Incorrect calibration; High component tolerances	Inaccurate data	2	3	6	**2**
	Maintenance failure	Use of new components with longer life cycle; spare parts available	Lack of knowledge; No spare parts Obsolete components; Extensive cost	System failure; Considerable radar downtime	3	3	9	**7**
Receiver	High noise levels	New stable power supply	Unstable power supply; High component tolerances; Thermal noise; Loose connections	Inaccurate data	2	3	6	**3**
	RF interference	Radome repairs and non-metal based paint; Minimize RF noise by involving ICASA	External RF sources; Ground clutter; Waveguide reflected RF; Radome reflected RF	Loss of data; Inaccurate data	4	3	12	**3**
	Automatic Gain Control failure	New stable power supply	Unstable power supply; Attenuation failure; False reflected power;	Inaccurate data	2	3	6	**0**
	Calibration failure	None	Incorrect calibration; High component tolerances	Inaccurate data	2	4	8	**0**
	Maintenance failure	None	Lack of knowledge; No spare parts Extensive cost	Loss of data; Inaccurate data; Radar downtime	3	4	12	**0**

Antenna	Radome Leakage	Repair defects;	Defects in Radome; Improper installed	Loss of data; High attenuation; Antenna damage	2	3	6	**3**
	Antenna mechanical failure	None	Warn out components; Motor misalignment; Reference signal failure	Antenna failure	2	4	8	**0**
	Alignment failure	Routine inspection and test	Improper installation; Calibration failure; Reference signal failure	Inaccurate data	2	3	6	**0**
	Calibration Failure	Routine inspection and test	Incorrect calibration; high attenuation; Reference signal failure	Inaccurate data	2	4	8	**0**
	Maintenance failure	None	Lack of knowledge; No spare parts Extensive cost	Loss of data; Radar downtime	3	3	9	**0**
Signal Processor	Analogue to digital failure	None	Rdas2k failure; Communication failure	Loss of data; Inaccurate data	2	4	8	**0**
	RDAS2k to TITAN communication failure	None	Communication failure; Calibration failure	Loss of data	1	4	4	**0**
Computer	Computer Failure	None	UPS failure; Network failure; Software Freezes	Loss of data	2	4	8	**0**
	Calibration Failure	None	Incorrect calibration; Reference signal failure	Inaccurate data	1	4	4	**0**
				Total Risk Rating	**184**			**43**

3.3.3 Component risk analysis

The **third level analysis** is based on re-engineering of the transmitter. Through re-engineering of the transmitter, additional benefits were added to the entire system, such as the possibility to further upgrade the system to a Doppler radar or even dual-polarized system. With this intervention, the re-engineering process also had a positive effect on the reliability of the system. The purpose of this analysis is to evaluate the *re-engineering process of the transmitter only* and how it changed the risks associated with the transmitter before and after the modifications. This analysis is also known as a component level analysis and is another level lower than the modular level, focussing on the individual modules and components. In the future, when re-engineering the receiver and making improvements, a similar analysis can be done to show improvement (this is outside of the scope of this project).

The same methodology and techniques used in the modular risk analysis above will be applied in this analysis, with slight modifications. The modules and components that had to be evaluated had already been identified in the form of functional block diagrams. Figure 41 shows the functional diagram of the radar system before the re-engineering process and Figure 42 shows the functional diagram after re-engineering was done.

The risks are evaluated using a FMEA method as done in the previous analysis. The risks for this study are the probability that one of the transmitter components could fail, causing radar downtime. Each risk is evaluated against three scales, the probability (P) that the component can fail, the consequence (C) if a failure occurs and the severity (S) if that component would fail. The probability and consequence have both been used in the previous two risk analyses. The severity is an additional evaluation for this analysis as the focus of this research is on the transmitter alone, which deserves a more in-depth analysis. Severity looks at what the implications are if a component fails. If a switch fails, it can easily be sourced and replaced, therefore having a low severity. However if the transmitter modulator, power supply or magnetron fails, it would mean that the component needs to be sent back to the USA for repairs or, it must be replaced. If the risk has a high severity rating, it is important to get the probability as low as possible. Table 31 shows how the probability, consequence and severity are rated between 1 and 5.

Table 31: Component risk analysis evaluation table.

RR	**Probability (P)**	**Consequence (C)**	**Severity (S)**
1	Rare	Material Failure	Insignificant
2	Unlikely	Component Failure	Minor
3	Possible	Module Failure	Moderate
4	Likely	Sub-System Failure	Major
5	Almost Certain	System Failure	Catastrophic

A RR is calculated for every risk by multiplying the probability, consequence and severity values. The risks are ranked according to Table 32 between low, moderate, high or extreme. For most cases, a low to moderate risk would be acceptable. High risks are components with a high likelihood to fail and cause system failures. These risks have a high priority and must be managed first. An extreme risk is a component that has already caused the radar system to fail on numerous occasions and will continue to do so until the component has been repaired or replaced.

Table 32: Component risk analysis priority table.

Risk Rating	**Low**	**Moderate**	**High**	**Extreme**
	1 - 12	13 - 30	31 - 64	65-125

For the first risk analysis, Figure 41 shows the block diagram of the transmitter section only. Each block represents a component with a functional unit (FU) number. The electrical cables are represented by the thinner lines and the EM waveguides by the thicker lines. The waveguide and antenna are included in the analysis as they form part of the process to transmit a signal. As seen from the diagram, the transmitter is made up of 16 functional units. The FMEA of the component risk analysis before the re-engineering is shown in Table 33.

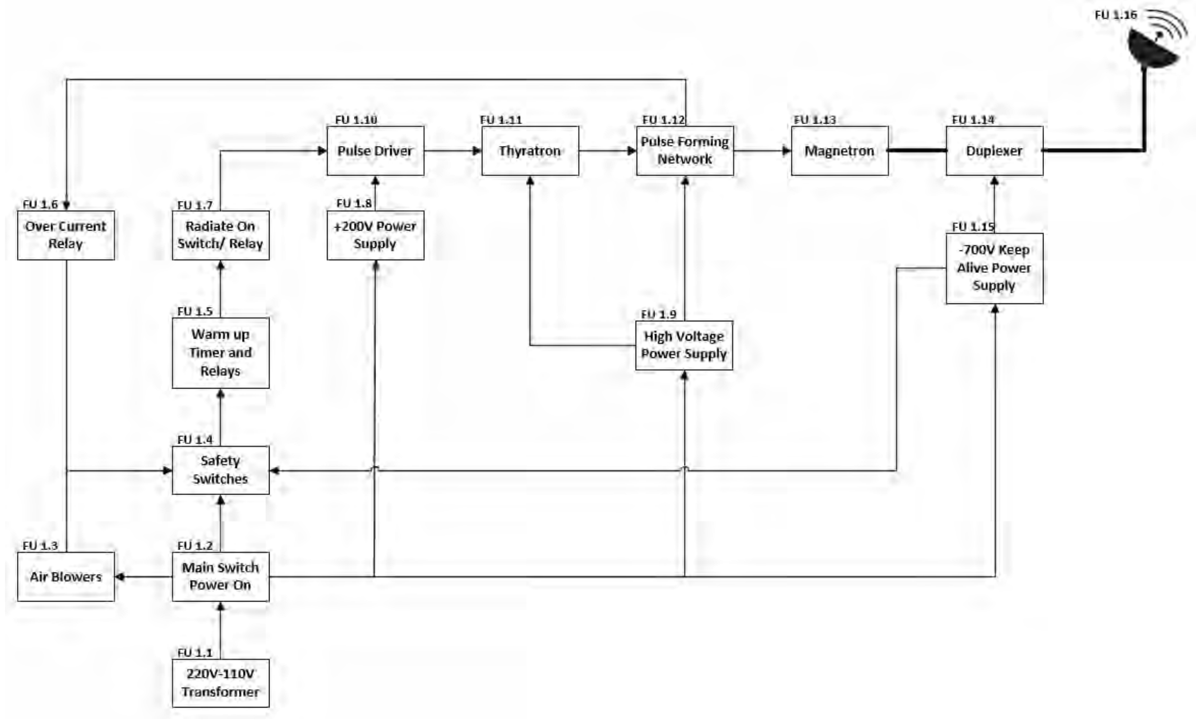


Figure 41: Transmitter functional unit layout before modifications.

Table 33: Component FMEA table before the re-engineering process.

FU	Component	Possible Cause of Failure	Consequence	P	C	S	RR
FU 1.1	220V-110V Transformer	Power supply failure; Overload	System Failure	1	5	2	**10**
FU 1.2	Main Switch Power on	Component failure; Loose connection	System Failure	1	5	1	**5**
FU 1.3	Air Blowers	Motor failure; blown fuse	Transmitter Failure	2	3	2	**12**
FU 1.4	Safety Switches	Interlock failure; Connection failure; Component failure	Transmitter Failure	2	4	1	**8**
FU 1.5	Warm-up Timer Relay	Safety switch failure; Component failure	Transmitter Failure	5	4	4	**80**
FU 1.6	Over Current Relay	PFN failure; Component failure	Magnetron over power	2	4	4	**32**
FU 1.7	Radiate On Switch	Warm-up timer failure; Safety switch failure; Component failure	Radiate Failure	2	3	1	**6**
FU 1.8	+200V Power Supply	Power supply failure; Component failure	Transmitter Failure	2	3	3	**18**
FU 1.9	High Voltage Transformer	Power supply failure; Overload	Transmitter Failure	1	3	2	**6**
FU 1.10	Pulse Driver	Radiate enable failure; Power supply failure; Component failure	Transmitter Failure	3	3	3	**27**
FU 1.11	Thyratron	Pulse driver failure; Component failure	Transmitter Failure	4	3	4	**48**
FU 1.12	Pulse Forming Network	Component Failure	Transmitter Failure	2	3	3	**18**
FU 1.13	Magnetron	Modulator failure; Component failure	Transmitter Failure	3	4	5	**60**
FU 1.14	Duplexer	Keep alive failure; Component failure	Transmitter Failure	2	4	3	**24**
FU 1.15	-700 Keep Alive Power Supply	Power supply failure; Component failure	Transmitter Failure	2	3	4	**24**
FU 1.16	Antenna	Waveguide failure; Power failure; component failure	Transmitter Failure	1	4	4	**16**
	Cables	Cable Failure; Connection failure	System Failure	2	4	1	**8**
	Waveguides	Moisture in waveguide; Arching; Damaged sections	Transmit/Receive Failure	1	5	1	**5**
						Total RR	**407**

After the transmitter system had been re-engineered the same risk analysis as before was conducted on the system. Figure 42 shows the functional block diagram of the modified transmitter. All the components that had been modified or newly installed have a number beginning with 2. A second FMEA was conducted as in the previous analysis, as shown in Table 34.

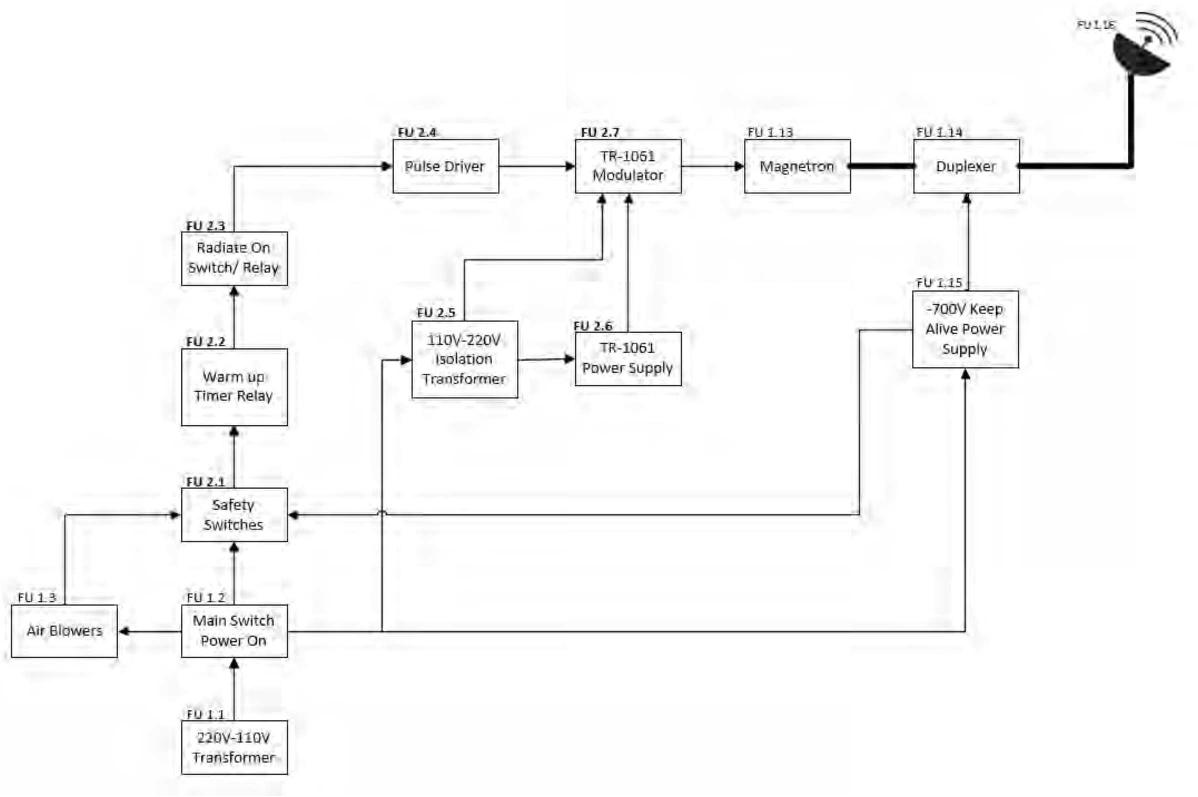


Figure 42: Transmitter functional unit layout after the modifications.

It is evident from the above analysis that the re-engineering process on the transmitter alone had a major impact with a reduction in risk from 407 to 265. While these values are relative, the improvement is around 35%.

Table 34: Component FMEA table after the re-engineering process.

FU	Component	Possible Cause of Failure	Consequence	P	C	S	RR
FU 1.1	220V-110V Transformer	Power supply failure; Overload	System Failure	1	5	2	**10**
FU 1.2	Main Switch Power on	Component failure; Loose connection	System Failure	1	5	1	**5**
FU 1.3	Air Blowers	Motor failure; blown fuse	Transmitter Failure	2	3	2	**12**
FU 1.13	Magnetron	PFN failure; component failure	Transmitter Failure	3	4	5	**60**
FU 1.14	Duplexer	Keep alive failure; Component failure	Transmitter Failure	2	4	3	**24**
FU 1.15	-700 Keep Alive Power Supply	Power supply failure; Component failure	Transmitter Failure	2	3	4	**24**
FU 1.16	Antenna	Waveguide failure; Power failure; component failure	Transmitter Failure	1	4	4	**16**
FU 2.1	Safety Switches	Interlock failure; Connection failure; Component failure	Transmitter Failure	2	4	1	**8**
FU 2.2	Warm-up Timer Relay	Safety switch failure; Component failure	Transmitter Failure	2	4	2	**16**
FU 2.3	Radiate On Switch	Warm-up timer failure; Safety switch failure; Component failure	Magnetron over power	2	4	1	**8**
FU 2.4	Pulse Driver	Radiate enable failure; Power supply failure; Component failure	Radiate Failure	3	3	3	**27**
FU 2.5	220V-110V Isolation Transformer	Power supply failure; Overload	Transmitter Failure	1	3	2	**6**
FU 2.6	TR-1061 Power Supply	Power supply failure; Component failure	Transmitter Failure	1	4	5	**20**
FU 2.7	TR-1061 Modulator	Power supply failure; Component failure	Transmitter Failure	1	4	5	**20**
	Cables	Cable Failure; Connection failure	System Failure	1	4	1	**4**
	Waveguides	Moisture in waveguide; Arching; Damaged sections	Transmit/Receive Failure	1	5	1	**5**
				Total RPN			**265**

3.4 CONCLUSION

The methodology used in this research project was defined in this chapter. The methods focused on radar installation, re-engineering and risk analyses of the radar system. It is clear that, apart from providing a functional radar using outdated and new components, a significant improvement in transmitter module risk was achieved. The use of risk analyses and management allowed the identification of the most risky section of the radar, namely the transmitter, and allocated budget and effort to the replacement of that section. This shows that risk management is effective for directing re-engineering effort.

Table 35 shows the summary of which methodologies contributed to a specific research solution. From this table, it is evident that the methodology that was followed to re-engineer the radar contributed to address the research problem. An operational analysis, radar site selection process, radar deployment, risk analyses (at different levels) both before and after re-engineering, and a good understanding of the operational environment all contributed towards a research solution. A less informed approach (i.e. without risk analyses) would have left the engineer without decision support information, which is clearly a less effective approach. Finally, the documented process and risks above provides a baseline framework to support and guide future research.

Table 35: Research solutions addressed by the project methodology.

Research Solutions / **Project Methodologies**	Familiarize and understand the radar environment	Follow available procedures and acquire additional advice from experts	Follow an integrated systems approach	Follow a proactive risk management approach	Make use of validated, available risk tools and techniques	Create a base of knowledge and skills
Define radar system AS-IS	X				X	X
Understand the operating environment	X		X		X	X
Select best fit for purpose site		X			X	X
Prepare site and deploy radar system		X			X	X
Test and evaluate radar system	X	X	X			X
Conduct risk analysis before re-engineering			X	X		X
Perform re-engineering concept design	X	X	X		X	X
Follow re-engineering process	X	X	X		X	X
Test and evaluate re-engineered radar system	X	X	X			X
Conduct risk analysis after re-engineering			X	X		X

CHAPTER 4: RESULTS AND EVALUATION

This chapter provides the results obtained in this study for the deployment, re-engineering process and risk analyses. The results are divided into four sections namely radar deployment, re-engineering results, risk analysis results and data comparison. The first three sections are the results of their corresponding sections in the methodology Chapter 3. The fourth section evaluates the data collected by the radar and in some cases compares it to a second weather radar. This section serves to validate the research in terms of radar functional capability after re-engineering (i.e. a functional radar), verification evidence in the form of risk reduction, and finally, research validation by showing that this research contributed to the knowledge base by providing a re-engineering case study on weather radar.

4.1 RADAR DEPLOYMENT

4.1.1 Weather radar Installation

According to the methodology described in Chapter 3, the deployment of a weather radar starts with finding the best fit for purpose site location. Because of the nature and characteristics of a radar, the location plays a major role in the data quality and success of the project. The siting of a radar consists of two main criteria, namely strategic and logistical requirements. The strategic criterion looks at what the purpose of the radar is and the logistical criterion focuses on what is required to make this project sustainable (hence, operationally maintainable). The two criteria are used to establish an evaluation table to compare sites with one another shown in Table 6 (Chapter 2.6). Using these criteria and evaluation method, the Lekwena Wildlife received the second-highest fit for purpose score, but was selected due to disqualification of the NWU site – the radar was thus installed on the Lekwena estate. To further evaluate the site, each of the 9 criteria is briefly described.

1) Coverage of populated areas and **2) cover the NWU's rain gauge network**

The radar's scan radius is 200 km and covers almost the entire Gauteng Province, that is, all the highly populated areas in the region. Also, the radar covers the entire NWU rain gauge network. However, there is a significant loss of coverage within

20 km of the radar due to the typical operational setup resulting in a ‘cone of silence’ around the radar site. Figure 43 shows the radar’s coverage over the Gauteng Province. Each ring represents a 50 km radius from the radar. The pins represent the rain gauges forming part of the NWU rain gauge network.

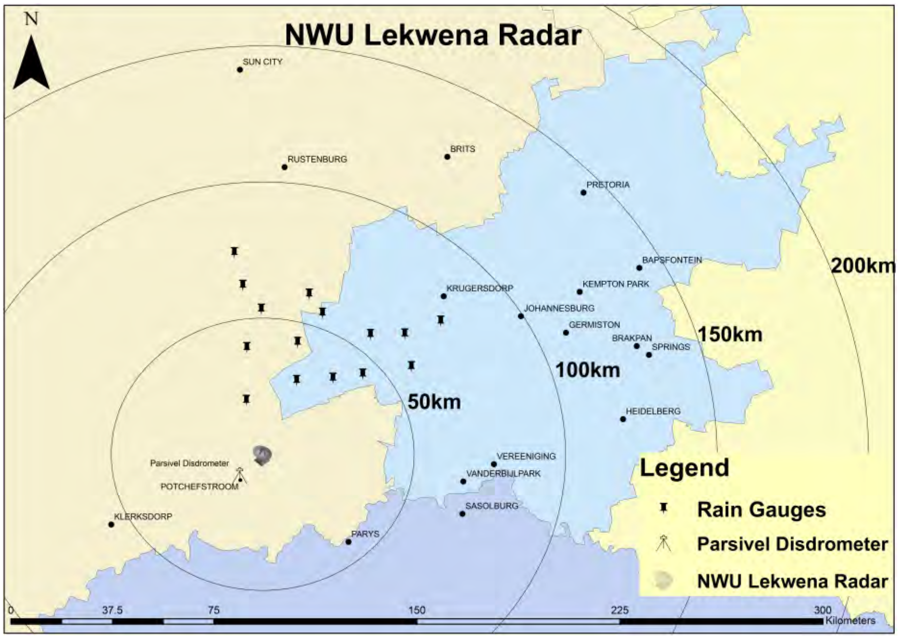


Figure 43: NWU-Lekwena weather radar coverage towards Gauteng including the rain gauges forming part of the NWU rain gauge network.

3) Overlap with the nation weather radar network.

The radar overlaps with three (Irene, Ottosdal and Bethlehem) other radars forming part of the national weather radar network. Figure 44 illustrates the position of the four radars and how they overlap. The Irene and Ottosdal radars are in close proximity to the NWU-Lekwena radar while the Bethlehem radar is further away. Although all three radars could have been used as reference for rain data comparison (and functional capability validation of the Lekwena-NWU radar), the Irene radar recently collected data, so this data was used.

4) Within close proximity

The radar is located roughly 20 km from the NWU by road, making it an ideal distance. It is still close enough to visit when needed but far enough to be out of sight and away from any populated areas.

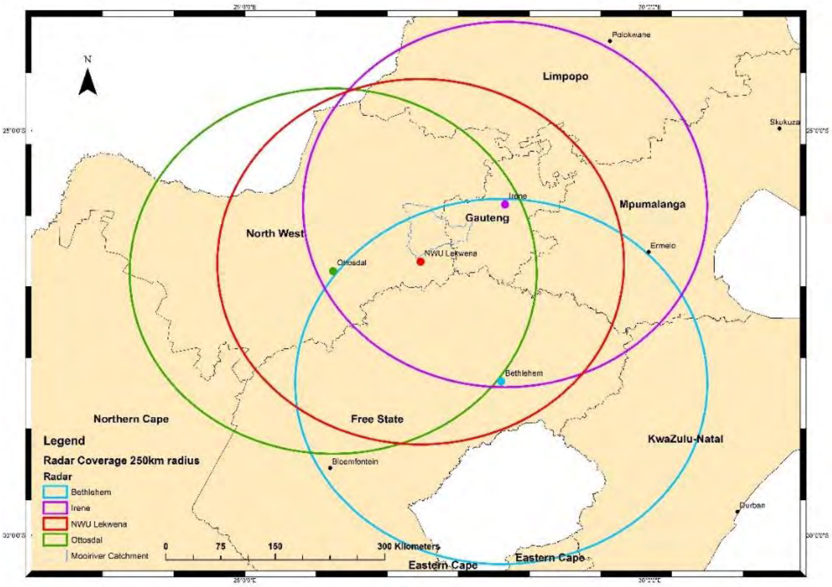


Figure 44: Illustrates how the NWU Lekwena (RED), Ottosdal (Green), Irene (Purple) and Bethlehem (Blue) weather radars overlap

5) Easy access to the site

Because the radar is situated on private property, access to the radar is limited and controlled by the landowner. At the moment the radar be accessed at any time but it is important to keep up a good relationship with the owner.

6) Constant power supply

A good and stable power supply is available from a distribution board at the base of the hill via two transformers. The transformers are used to ensure minimum voltage drop over the power transmission distance. In addition to the primary power supply, two UPS systems and a backup diesel generator will provide sufficient power when the primary power supply fails. The two UPS system also guarantee a good and stable power supply by filtering out any voltage spikes, drops and doing phase correction when needed.

7) Communication link

A communication link between the radar and the NWU was established via a wireless communication network. Because there is no line-of-sight between the radar and the NWU, a repeater consisting of two antennas was installed on the Tiger

Brand silo in Potchefstroom. The one antenna faces the radar while the second antenna faces towards the NWU. The distance between the radar and repeater is roughly 10 km, on the limit of the communication range. Due to the large distance, the communication link was not as reliable as expected and a better solution is needed. Figure 45 shows the two antennas on the Tiger Brand silos used as a repeater (left side) and the antenna installed at the radar site (right side).

Figure 45: Two WIFI antennas used as a repeater for the communication link between the radar and NWU (left) and the WIFI antenna at the radar located on the left side of the platform (right).

8) Annual cost

An agreement was reached with the landowner not to pay any annual fee except the electricity bill. In addition, the radar data should be freely available to the company and the NWU must be willing to show guests the radar upon request.

The second radar siting criteria considered the logistical requirements for the system, such as what might be required to deploy, operate and maintain the radar. Each of the criteria will briefly be described.

9) Infrastructure

The infrastructure consists of two sections, the container housing the radar equipment and the platform to elevate the antenna above the surroundings. The container was placed on a concrete slab to ensure a level and stable foundation. Inside the container, all the radar equipment such as the transmitter, receiver, antenna control, computer, UPS, calibration equipment, spares and manuals are kept. The container is also well insulated and equipped with an air conditioning unit. The container has proved to be very effective and would be recommended for similar projects in the future.

The antenna platform design was simplistic, but the installation proved to be more challenging than expected. The structure, made from steel I-beams, consists of fou\r posts with supports at the top from side to side, forming a box. Supports are installed in the middle of the box to carry the weight of the antenna. Steel sheets were placed on top of the I-beam box to create a solid platform. Water drainage was added to the structure by drilling small holes around the radome – showing that, throughout, it was important to consider weather conditions and the environment. The second concern involved sealing the container. A comprehensive sealing-off procedure was required and completely prevented water from seeping in after a number of trial-and-error iterations.

During initial testing of the infrastructure, it was found that when the wind blew, a slight movement of the antenna platform was noticed. This seemed insignificant, but any small movement has a major influence on the accuracy of the data. This was improved by installing support beams between the antenna platform and container. Because both the container and platform are currently fixed with reference to the ground, it minimized the movement of the antenna platform.

The radar site is fairly secured because it is on a security estate, however, the people living in the estate have access to the radar. Therefore, the container, radome access, and generator are access controlled at all times. Warning signs have been put up on the container sides to warn the public against high radiation and to prevent people from climbing on top of the antenna platform, especially while transmitting.

It is relatively easy to access the site by dirt road but one is generally advised to do so with a suitable vehicle, such as a normal utility vehicle. An effort was made to obscure or hide the road to the radar site.

The above results show that all initial criteria had been addressed by this research project. Experiential learning highlighted pitfalls and provide guidelines for future research.

4.1.2 Radar calibration results

The importance of keeping a radar system well calibrated was clearly stated. Calibrating a weather radar consists of calibrating three individual sections, namely the transmitter, receiver and antenna systems. Even though the calibration can be seen as three separate parts, all three play an important role in the overall calibration. The radar was calibrated using the tools and techniques as described in Chapter 2.1.5. For this research, the calibrations were kept to the basic level. A more complete calibration process is described in the radar manuals. The following calibration instruments as shown in Table 36 were used throughout the three calibrations.

Table 36: Calibration equipment used throughout the calibrations.

Equipment Required	**Description**
Power meter	HP Hewlett-Packard 435A
Power meter sensor	HP Hewlett-Packard 8483A
Oscilloscope	Tektronix TDS 1001C-EDU
50 Ω Load terminator	
Crystal detector	
Signal generator	HP 8684B Hewlett-Packard
Cavity meter	
RDAS2k	
RDAS2k Software	

4.1.2.1 Transmitter calibration

The transmitter calibration is relatively straightforward as it mostly consists of measuring specific parameters to use with the receiver calibration. The following parameters were measured as described in the literature, namely the transmitter frequency, peak output power, pulse width (PW), pulse repetition frequency (PRF), duty cycle (DC), and voltage standing wave ratio (VSWR). All the losses in the cables and wave guide are factored into the calibration values. Table 37 shows the summary of the values measured.

Table 37: Transmitter parameters measured during the calibration procedure.

Transmitter calibrations		
Parameters measured	**Value**	
Frequency	5560	MHz
Peak Output Power	152,026	kW
Pulse width	3,75	uSec
Pulse repetition frequency	267	pps
Duty cycle	30,069	dB
Voltage standing wave ratio	1:1,049	

The peak output power was measured as $152\ kW$ instead of $250\ kW$. This is due to the age of the transmitter and avoiding to overdrive the magnetron. The transmitter's pulses also create high noise levels at a higher output power. This can be the result of the old components still being used, such as dried out capacitors. The magnetron's year of manufacture and operating hours are unknown but it is expected to be close to its end of life.

The magnetron's frequency, as it was sent from the USA, was measured to be 5560 MHz, which falls within the magnetron's range but when the NWU received their licence the frequency needed to be adjusted. The licence was approved for a frequency between 5600 – 5650 MHz. The magnetron's frequency was therefore shifted to 5620 MHz by means of adjustment of the cavity knob at the back of the magnetron. The cavity knob mechanically changes the cavity size within the magnetron and its corresponding resonant frequency.

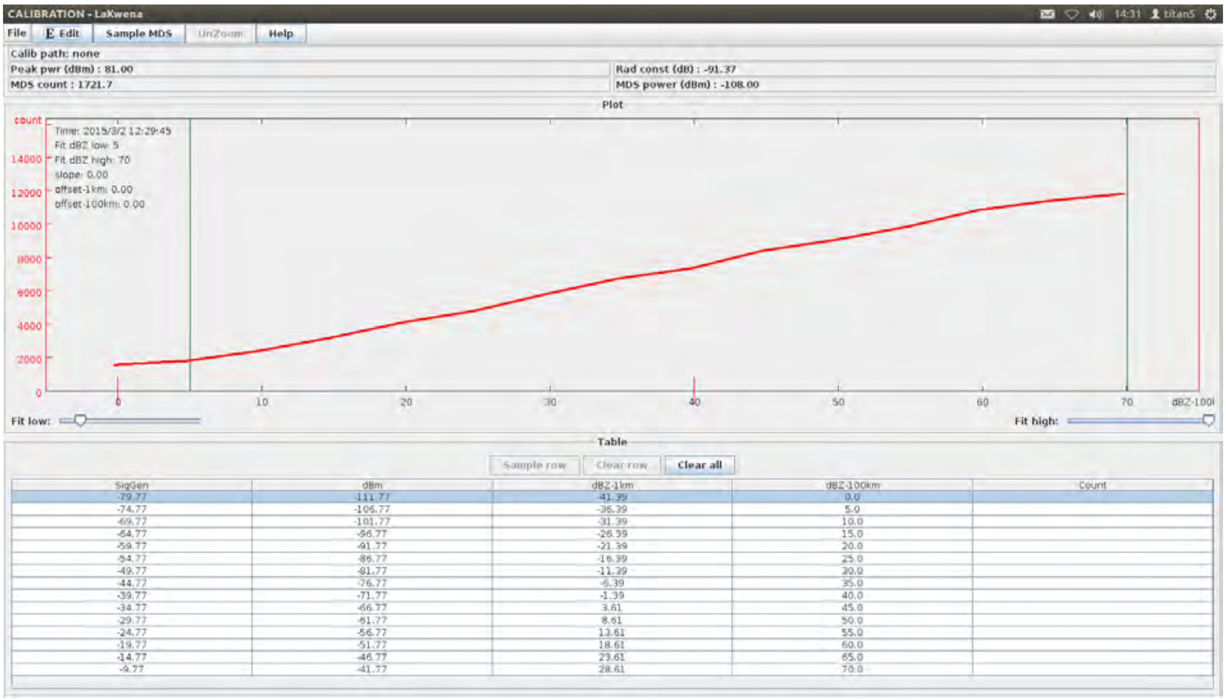
4.1.2.2 Receiver calibration

The main purpose of calibrating the receiver is to establish the response curve that relates the value measured (sample counts) by the receiver to a dBZ value. Before the response curve can be calibrated, the Minimum Detectable Signal (MDS) is measured using a signal generator as described in the methodology. The MDS for this receiver was measured to be -108.00 dBm with a sample count of 1721. The MDS is acceptable but the sample counts according to the calibration manual should be between 350 and 450. This is due to a very high base level caused by noise from external factors such as the DC power supplies. The software package generates a set of power settings from low to high. The signal generator's output power is adjusted to the required setting and the frequency peaked through the manual frequency control. This process was repeated for each power setting until a clear response curve was generated. Figure 46 shows the response curve as generated by the software.

The table below in Figure 46 shows the power setting input at the signal generator starting at the lowest setting of -79.51 dBm. Because the signal is injected through the forward coupler with an attenuation of -31.25 dB, the actual power level is the combined power as shown in the table's second column.

4.1.2.3 Antenna calibration

The third calibration is the antenna's alignment to true North in order to synchronise the antenna direction with collected data. The antenna is calibrated according to the methodology described in the literature chapter. Two methods are commonly used to verify the radar's alignment namely, a fixed location with a known echo or tracking the sun. The first method is used if the position of a known echo is known. The second method uses the sun's radiation as a reference signal. The sun radiates electro-magnetic pulses that can be picked up by the receiver if the antenna is pointed directly at the sun. This phenomenon is known as a "solar spike" and occurs during the early morning or late afternoon. The RDAS2k software has a built-in function showing the position of the sun and has the capability to track it. This is very useful to check the calibration of the antenna by comparing the antenna's position to that of the sun. The sun's position is mathematically determined and serves as a very accurate reference.



Calib path: none
Peak pwr (dBm) : 81.00
MDS count : 1721.7
Rad const (dB) : -91.37
MDS power (dBm) : -108.00

Time: 2015/3/2 12:29:45
Fit dBZ low: 5
Fit dBZ high: 70
slope: 0.00
offset-1km: 0.00
offset-100km: 0.00

SigGen	dBm	dBZ-1km	dBZ-100km	Count
-79.77	-111.77	-41.39	0.0	
-74.77	-106.77	-36.39	5.0	
-69.77	-101.77	-31.39	10.0	
-64.77	-96.77	-26.39	15.0	
-59.77	-91.77	-21.39	20.0	
-54.77	-86.77	-16.39	25.0	
-49.77	-81.77	-11.39	30.0	
-44.77	-76.77	-6.39	35.0	
-39.77	-71.77	-1.39	40.0	
-34.77	-66.77	3.61	45.0	
-29.77	-61.77	8.61	50.0	
-24.77	-56.77	13.61	55.0	
-19.77	-51.77	18.61	60.0	
-14.77	-46.77	23.61	65.0	
-9.77	-41.77	28.61	70.0	

Figure 46: The response curved generated by the RDAS2k software during the receiver calibration.

4.1.3 Weather radar data results

After deploying and calibrating the radar, it was operated for a couple of months, collecting valuable data on a number of storms. The data was analysed and proved to be very useful. Certain concerns and constraints became apparent that limited the radar's capabilities. The beam blockage or ground clutter was more extensive than simulated in Chapter 3. The radar also experienced high levels of external noise that needed to be processed in the correct manner. Yet, the radar proved to be capable of delivering accurate and high quality data from the measured storms, as presented in the sections that follow

4.1.3.1 Data quality estimation

During radar siting, the data quality estimation (DQE) was simulated for each site using a customized programme. Only the Lekwena Wildlife Estate site will be evaluated. Figure 20 C shows the expected blockages for the site as from the simulation. These simulations are important as they provide an estimation of the expected data quality and information for attenuation correction. To evaluate and determine the accuracy of the simulation, the DQE scan is compared with a data scan showing the ground clutter. Any beam blockage in close proximity to the radar will be analysed as ground clutter. If ground clutter is present, it will not change from one scan to the next scan but the precipitation will change with every scan. Therefore, it is fairly simplistic to distinguish between precipitation data and ground clutter. Figures 47 A and B show two consecutive data scans with precipitation in the area. Comparing the two scans, it can clearly be seen that the precipitation does move from east to west but the ground clutter data surrounding the radar is static. From figures A and B, the ground clutter was identified, enlarged and highlighted as shown in Figure 47 C.

When comparing the DQE from Figure 20 C to the ground clutter scan from Figure 47, it is clear that the DQE predicted some beam blockage or possible ground clutter to the entire eastern side of the radar site. It, however, did not predict any on the western side. As a result, the simulation has missed the beam blockage or ground clutter on the western side of this specific site. The radar was situated within a small gap between two outcrops so the container is not visible form the road and only the antenna is exposed. The simulator does not compensate for the lower radar antenna and nearby trees.

In short, the simulator software can be used as a guideline to determine possible ground clutter, but it cannot identify all obstacles. Therefore, it is the engineer’s responsibility to analyse all the data available and to make an informed decision.

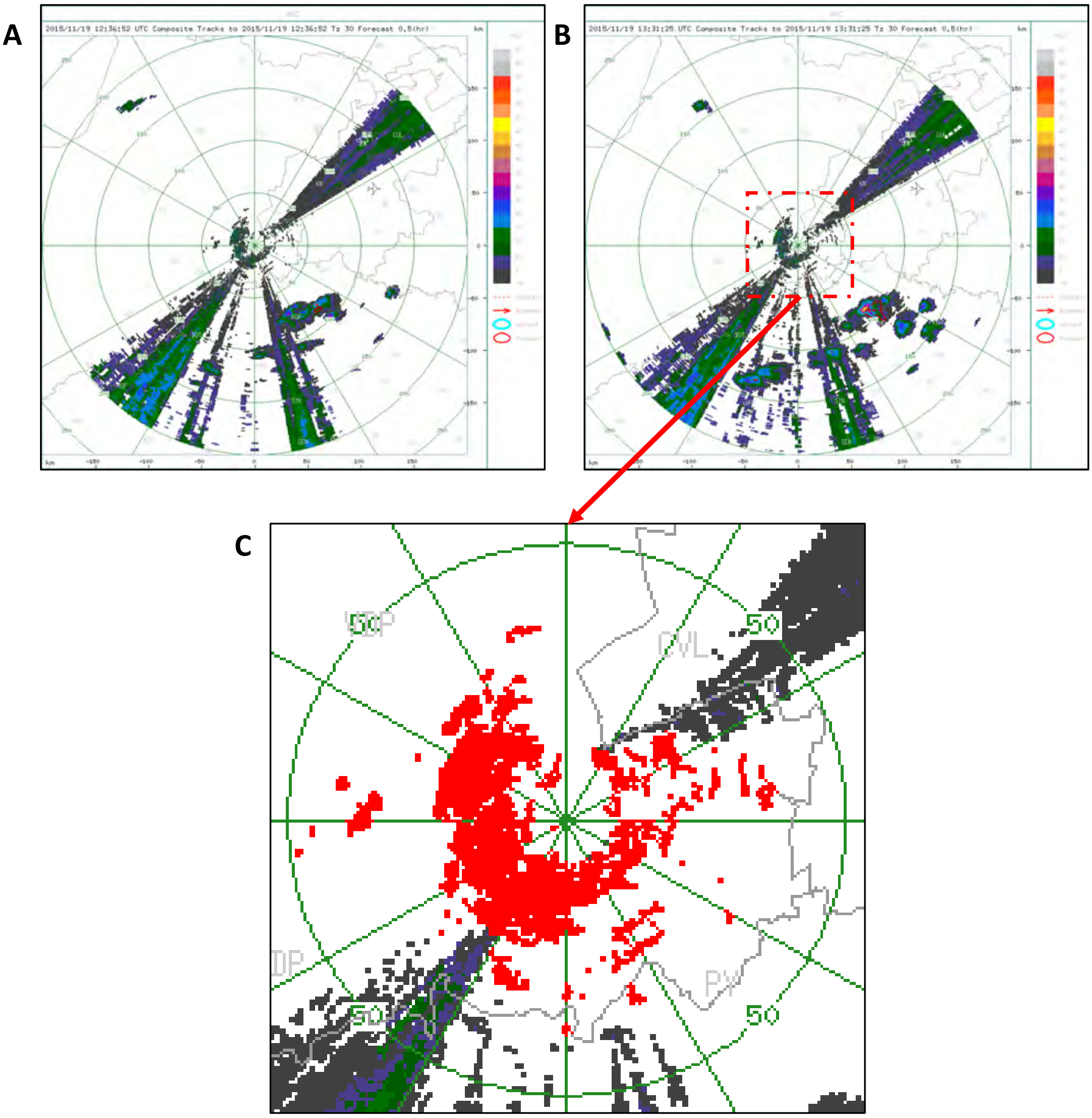


Figure 47: A and B show two consecutive data scans with the ground clutter staying constant. Figure C shows an enlargement of the ground clutter, in red, as identified from B.

4.1.3.2 External interference

A number of months after the radar installation, it was observed that the radar experienced much higher RF noise levels than before. This was most probably due to a new wireless communication device in the area, or existing devices that adjusted their operating frequency to that of the radar's. Because the receiver is very sensitive, it picks up small interference signals (-108 dBm) and processes them as precipitation, effectively blocking any signals indicating precipitation from that direction. Figure 48 shows a scan of a rainstorm on the 28th of September 2014. The interference blocks roughly 30% of the signal and makes it considerably more difficult to distinguish between what is actual precipitation data and man-made interference. From the scan, it can clearly be seen that the interference is caused by an external source as the majority of the spikes cover the entire 200 km range. The noise also has a low elevation compared to the storm on the right-hand side. It is extremely difficult to minimize external noise because the sources are rarely known. It is well-known that C-band weather radars are prone to suffer from external noise because a large number of high speed wireless communication devices operate in the 5 GHz and upwards frequency band.

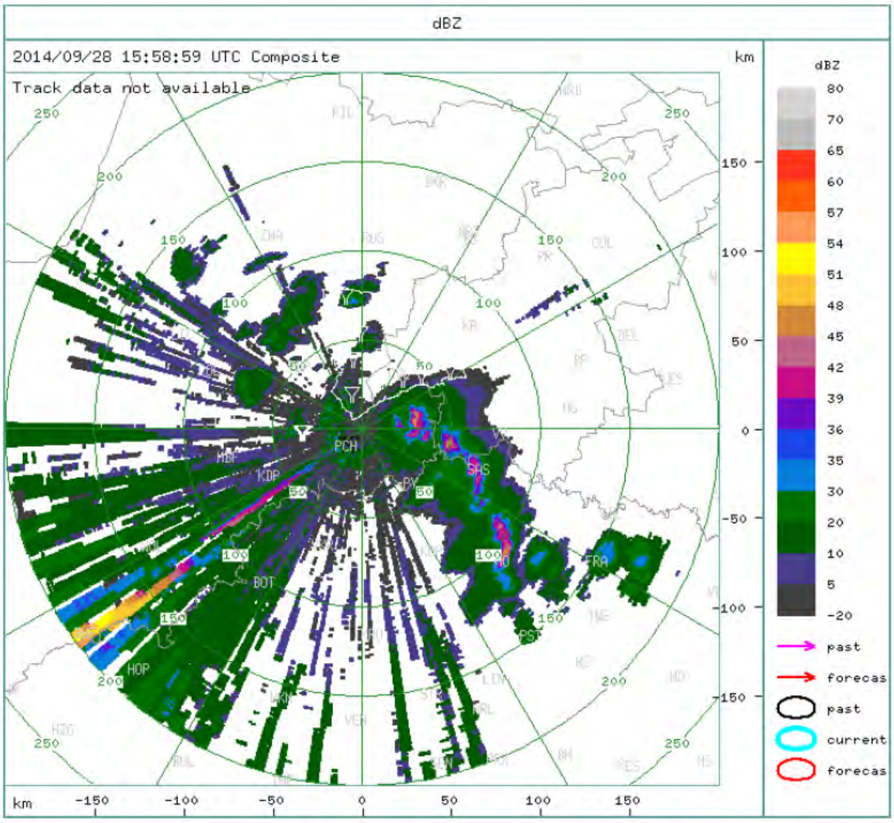
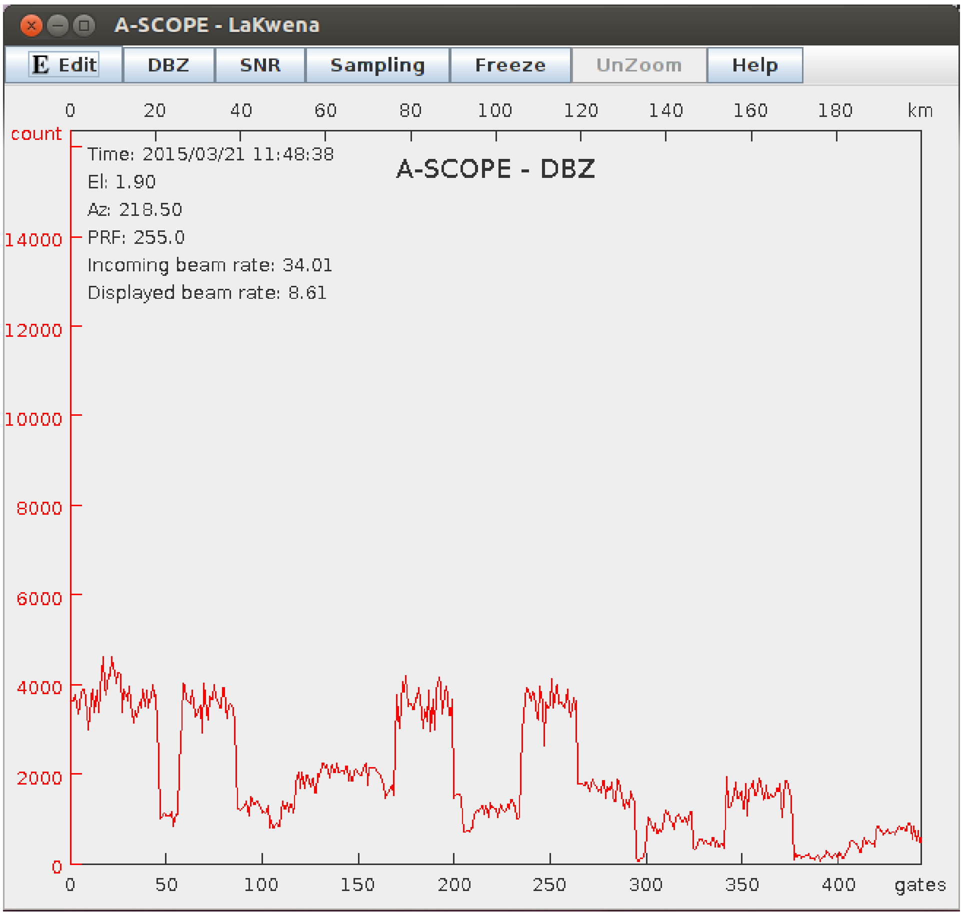


Figure 48: Transmitter functional unit layout before the modifications

Different methods can be used to identify noise sources. One method commonly used to determine the direction of the noise is to turn the receiver on but keep the transmitter off. The antenna is then oriented at a low angle and a 360 degree azimuthal sweep is done. Since the transmitter is off, all external noise will be picked up by the receiver and indicated on the RDAS2k's A-scope. The A-scope is a built-in function in the RDAS2k software showing the receiver's data as received from the antenna. Figure 49 shows an example of external noise pick-up on the 21st of March 2015. The elevation was at 1.9° and the azimuth at 218.50°, facing exactly towards Potchefstroom from the radar. The square pulses show the external noise from other transmitters in that direction. This method only shows that external noise is present and shows its direction relative to the radar.



Time: 2015/03/21 11:48:38
El: 1.90
Az: 218.50
PRF: 255.0
Incoming beam rate: 34.01
Displayed beam rate: 8.61

Figure 49: External RF interference detected on the receiver's digital A-scope

To further assist in identifying external noise sources, a wireless communication antenna such as a Ubiquiti transmitter/receiver was used. The Ubiquiti software has a built-in function known as a "Discovery tool" that scans for other devices on the same frequency. The software gives a list of every other device's frequency, strength, noise level and its Service Set Identifier (SSID). The SSID shows the name given to the device during set-up. If the device is high-powered it must be registered with ICASA.

The most effective way to minimize external RF interference is to involve ICASA. Because ICASA has the equipment to detect the interference and the authority to instruct an operator to change its operating frequency they can fairly easily trace the interference to its origin. Throughout this project ICASA was called-out twice and both times they managed to detect and minimize the interference.

An alternative method can be used, such as adjusting the receiver's filters, installing additional filters to better shape the receiver's bandwidth, or changing the radar's frequency. Changing the receiver's filters is a quick and effective method, but the approach has its limits as one can only change it within certain filter performance limits.

Figure 50 shows a data scan from the 19th of November 2015 with high RF interference after which ICASA was called out to assist with the problem. Comparing this data scan with Figure 51 (after ICASA intervened) there is a significant improvement. The external noise has been lowered to a single spike, making the precipitation data much clearer. It would be ideal not to have any external interference, but the data quality as shown in the figure is acceptable.

Data was collected for a number of months with minimal interference but gradually new interferences were picked up from time to time. This is probably caused by new wireless communication devices not aware of the radar's frequency or old devices that have been changed back to original settings. Figure 51 shows a data scan collected on 19 November 2015 showing again the severity of external noise. This highlights the main problem and constant battle with a C-band weather radar.

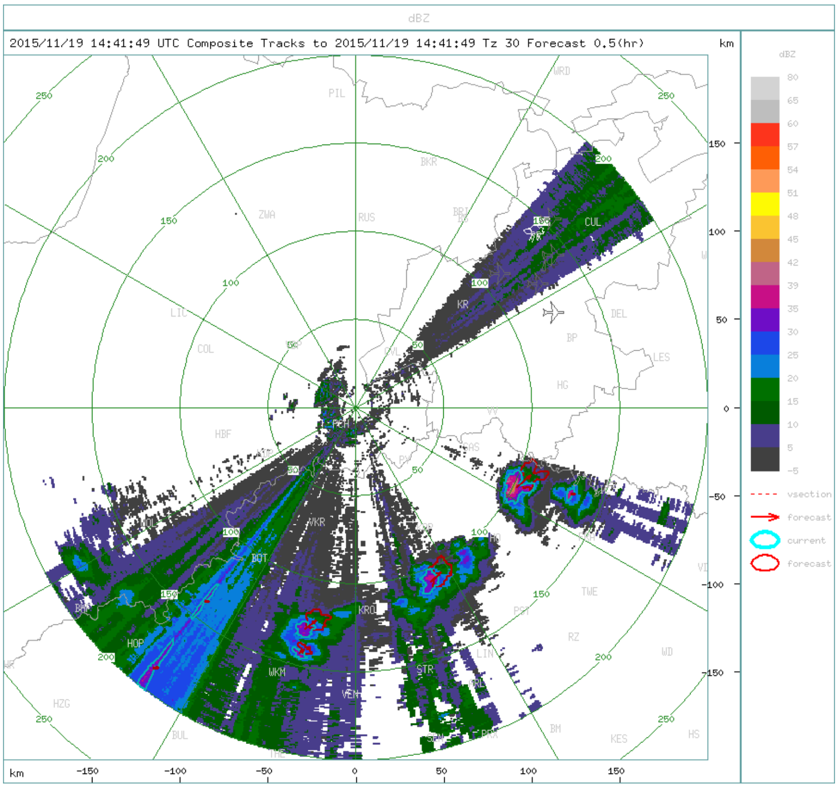


Figure 50: Data scan on the 19th of November 2015 with new RF external noises.

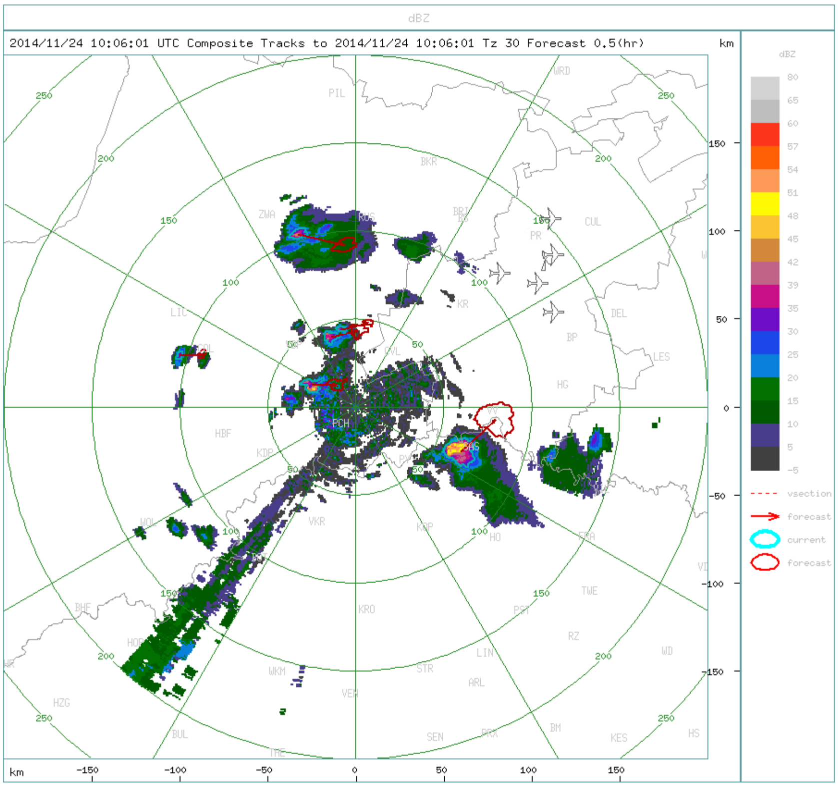


Figure 51: Data scan on 24 November 2014 after ICASA lowered the RF external noise

4.1.3.3 Severe hailstorm data

On 24 November 2014 a severe hailstorm caused serious damage to Klerksdorp, 50 km south-west of Potchefstroom. According to a local newspaper article shown in Appendix D.1 the hail was the size of golf balls. Local residents measured the rainfall to be in the region of 80 mm to 100 mm within an hour. During this storm, the Lekwena weather radar was switched on and collected data as shown in Figure 52. The data scan shows the extent of the storm stretching from Wolmaransstad to Heidelberg. At that point in time, the high-intensity storm was developing near Klerksdorp with another high intensity storm already having developed to the north between Klerksdorp and Ventersdorp. Figure 53 shows two pictures taken by local community members on the day of the storm. This case study proves the importance of having a high quality weather radar to give an early warning to the local community so that preventative action can be taken to minimize damage caused by the storm. The data also contributes to the validation and important role played by the Lekwena weather radar.

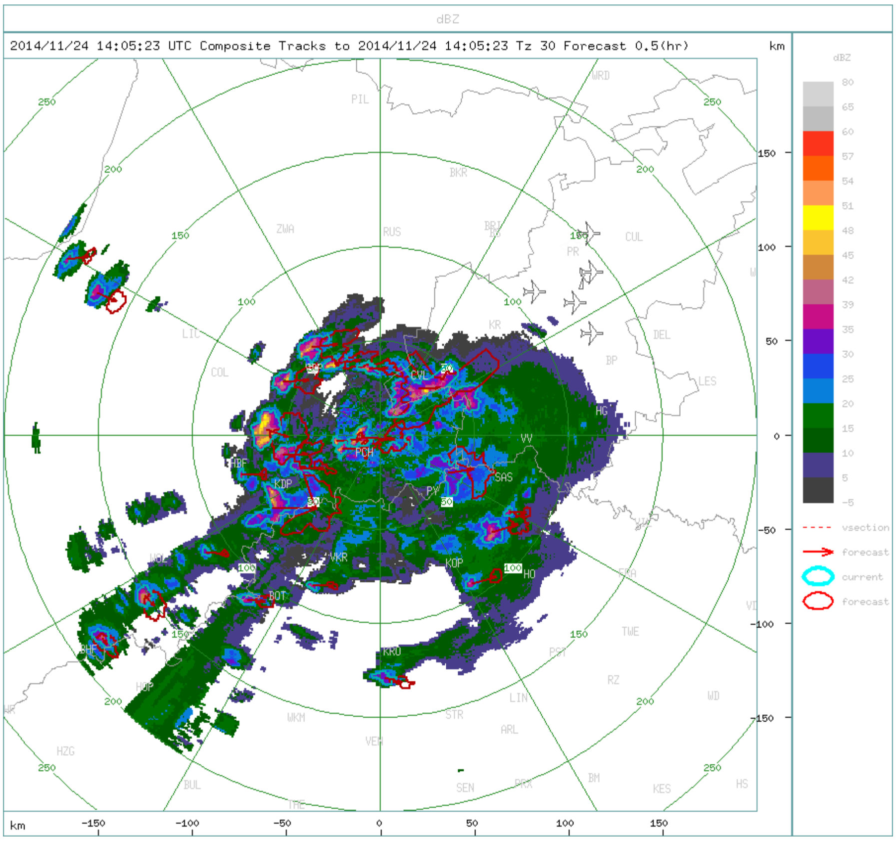


Figure 52: Hail storm on 24 November 2014, causing severe damage in Klerksdorp

Figure 53: Pictures of the hailstorm on 24 November 2014 taken by local residents.

4.2 RE-ENGINEERING RESULTS

The purpose of re-engineering the radar was to improve the radar's performance, extend its lifecycle, reduce the risks and provide the possibility to further upgrade the radar to Doppler or dual polarization later on. It also served as a case study to generate meta-artefacts from the design-science research study. The re-engineering process consists of four phases, namely identifying the re-engineering section, understanding the operational environment, re-engineering the system and implementing all modifications. Each result from the listed phases will be described in summary.

4.2.1 Transmitter re-engineering results

With the first phase it became clear that the old transmitter was plagued by technical difficulties and posed a high risk of failure. After a high-level risk analysis, it was decided to first replace the transmitter with a new state-of-the-art system from Pulse Systems Inc. In due time, as resources and funding are obtained, the receiver and antenna sections will also be upgraded. However, these upgrades did not form part of this research project.

With the transmitter upgrade, the receiver's DC power supplies were replaced to ensure a more stable baseline, improving the data quality. To better understand the re-engineering environment, the radar was divided into 16 functional blocks. Each block represented a sub-unit as shown in Figure 24 (Section 3.2.2). This method gave a better understanding of how the radar operates and which areas needed to be addressed. The re-engineering process ensured that the new transmitter is compatible with the rest of the radar system and defined the procedures needed to install the transmitter. The final phase of the re-engineering process was to implement the new transmitter.

The process started by first removing all transmitter components from the radar enclosure. Certain modifications were made to the box to accommodate the new transmitter setup. The new components were installed, according to the manufacturer's manual, as shown in Figure 34. Additional safety systems were implemented to protect both the equipment and the user from potential damage. Table 15 shows a summary of the components removed, re-used or modified.

With the initial testing of the transmitter, the high voltage (HV) power output was set to 0 on the adjustable knob located on the power supply. After waiting the required time for the magnetron to warm up, the HV output was increased steadily. Two magnetrons were tested, but a severely limited output level was attained, showing that the fault had to be with the transmitter's modulator. A high voltage probe (1:1000) and oscilloscope were used to measure the output pulse at the modulator's cathode. Figure 54 shows the pulse measured on the oscilloscope. According to Pulse Systems Inc. the pulse is supposed to be square with minimum ripple voltage.

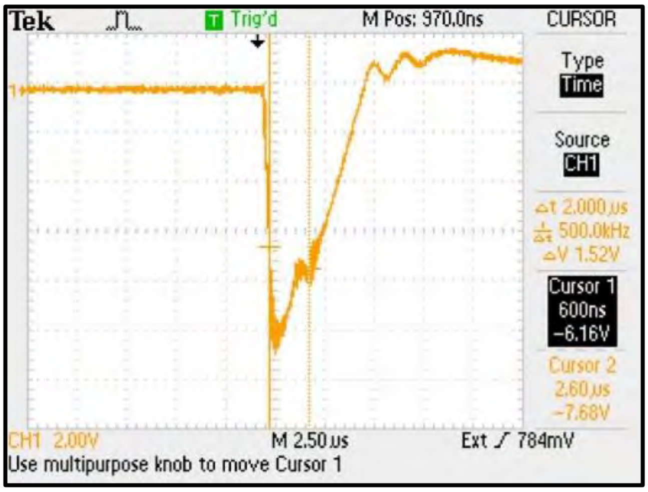


Figure 54: Transmitter modulator high voltage output pulse with second order ringing.

To further test the modulator without the influence of the magnetron, the output was connected to a resistor bank instead. Figure 55 is a circuit diagram of the resistor bank configuration. The resistor bank comprises a $10\,\Omega, 50\,W$ resistor between the anode and cathode terminal representing the magnetron’s heater and a $1000\,\Omega, 300\,W$ resistor to ground representing the magnetron pulse load. The resistors used are carbon based to provide a resistive load with very low impedance, and this test should show the true output pulse. It is important to take extra precautions when testing with the resistor bank since the resistors will most likely be assembled outside the hotbox.

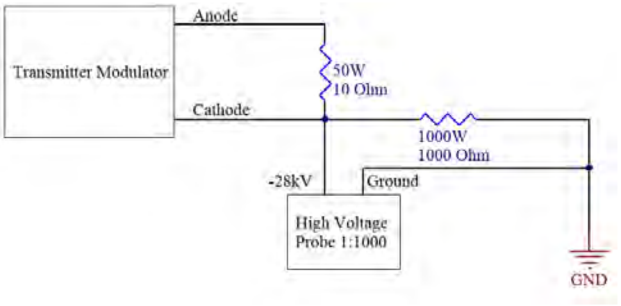


Figure 55: Transmitter modulator test circuit diagram using a resistive load.

The modulator generates a high-powered pulse up to $28\,kV$, therefore the resistors had to be well insulated from each other and from any person in close proximity. If the resistor has a metal casing or stand on either end, arcing between the resistor terminals and casing can be expected. To minimize the arcing the metal casing can be removed if possible and the resistor can be placed flat on an insulated platform. Figure 56 shows how the resistors and high voltage probe were connected for the test.

The initial test was repeated with the resistive load instead of the magnetron. Because the modulator sends out high-power pulses, the resistors also made a buzzing sound similar to the sound that the magnetron made. Above 75% of output power, the pulse started to smooth out into a square wave. Figure 57 shows the pulse as measured on the cathode using a high voltage probe.

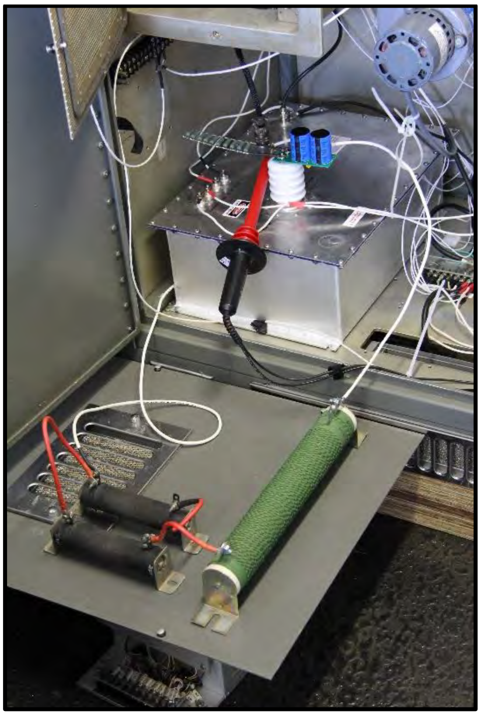


Figure 56: Transmitter modulator test circuit using a resistive load

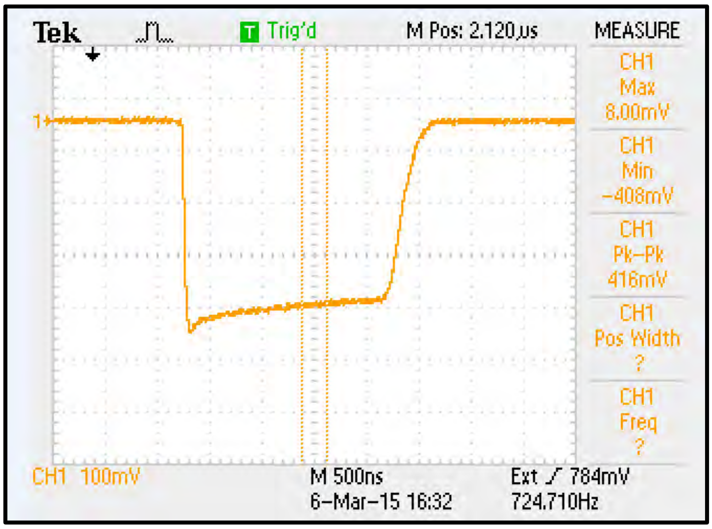


Figure 57: Transmitter modulator high voltage output pulse without second order ringing

The magnetron was reconnected and tested again at 75% of power level and the magnetron pulse was square, similar to the pulse measured using the resistive loads. The power was increased until 83.5 dBm was reached, equivalent to $223\ kW$. The magnetrons that were used had been in use for a significant number of hours, therefore the output power was set just below its rated value of 250 kW, not to overstress the magnetron.

4.2.2 Transmitter comparison

Table 38 below shows the comparison of the transmitter section before (Table 14) and after (Table 15) the re-engineering process. From the table it can be seen that the new transmitter has significantly improved the transmitter's performance. The output power is the biggest benefit to the system. It increased the output capacity with 67%, even though the magnetron has remained the same. The new system is more reliable since newer technology is used, and has less chance of damaging the magnetron or causing a system failure. Another advantage is that the pulse width can be set to 0.5 us, 0.8 us, 1.0 us and 2.0 us. With the new transmitter system, the radar system can be upgraded to a Doppler radar and even dual-polarization radar when needed.

Table 38: Transmitter upgrade comparison.

NWU Lekwena Weather Radar re-engineering comparison		
	Parameters	
Description	**Before**	**After**
Frequency Band	C-Band	C-Band
Magnetron frequency	5560 MHz	**5620 MHz**
Output power	81,8 dBm	**83,8 dBm**
Output power	150 kW	**250 kW**
Duty Cycle	3,75 ms	3,75 ms
Pulse width	3,75 us	**2,0 us**
Pulse repetition frequency	266,67 pps	266,67 pps
Maximum range	±150 km	**200 km**

4.3 RISK ANALYSIS RESULTS

The purpose of the risk analysis was to assist in identifying potential failures before they occur so that the necessary mitigating actions can be taken in advance. The study therefore derives a continuous process for any business or physical project to effectively anticipate all risks, and specifically those risks that have a critical impact on the success of the project.

For this case study, the risk analysis was divided into three levels, namely operational, modular and component level. These analyses evaluated the entire system at different levels to identify the known risks and to manage them as best as possible. Results from each of these analyses are discussed in the sections that follow.

4.3.1 Operational risk analysis

The first risk analysis focussed on the operational side of the project. This analysis was further divided into two sections, namely installation risk and project risks. Each section was represented by a cause-and-effect diagram shown in Figure 39 and Figure 40 respectively.

For the radar installation risk, the "effect" is the failure of successfully installing the radar system and the "causes" are the events that can contribute to the failure. The causes were divided into five main roots, namely logistics, legalisation, procedures, resources, and hazardous conditions. The probability (P) of a risk materializing is scaled from 1 to 5 with 1 being the least likely and 5 being the most likely. Consequence (C) of a risk materializing is scaled from 1 to 5 with 1 being the lowest consequence and 5 being the highest consequence. The Risk Rating (RR) is calculated by multiplying the P and C values with one another giving single value out of 25, representing both the P and C.

Table 39: Summary for the radar installation operational risk analysis.

Area of Risk	P	C	RR
Radar Installation Risks			
Logistics	4	4	**16**
Legalisation	3	3	**9**
Resources	4	4	**16**
Hazardous Conditions	2	5	**10**
Procedures	4	3	**12**

The "Logistics" and "Resources" causes had the highest risk rating with a score of 16 out of 25. This project had various logistical concerns and risks due to the nature and location of the radar site that was selected. The power supply point is roughly 700 m away at the base of the hill therefore requiring additional transformers to minimize cable cost. There is also no line-of-sight between the radar and NWU for wireless communication. Because the radar was ±40 years old, much of the original documentation had been lost or had not been updated through the years. The project also had a restricted budget and limited resources available.

The second analysis focussed on the overall project risks with the “effect” - the failure of successfully maintaining a radar system and the “causes” being the events that could contribute to failure. The causes were divided into 5 main roots namely resources, environment, people, hardware and software. Each root cause was further defined as shown in Figure 40. Every cause was evaluated using the Table 4 and given a risk rating. Table 40 shows a summary of the radar risk analysis.

Table 40: Summary of the radar project risks part of the operational risk analysis.

Radar Project Risks			
Additional Resources	3	4	**12**
Environment	2	4	**8**
People	4	4	**16**
Hardware	5	4	**20**
Software	1	4	**4**

According to the risk analysis, the radar hardware presented the highest risk with a risk rating of 20. The risk has a probability of 5 (almost certain) for occurring and 4 (major) for the consequence if it holds. The hardware had a high rating due to the age of the components, especially those of the transmitter. Most of the components still used had become obsolete and started presenting problems. As it was, the magnetron could only deliver 60% of its rated power and the warm-up timer only engages roughly 40% of the time. A rating of 20 is very high and had to be mitigated as a high priority risk. The second troubling risk was the human element of the project. Because the radar environment was new to the NWU, there was a lack of knowledge and experience in the field that added to the overall risk of maintaining the system (both for this research and in the future, although this project has significantly reduced future project risks)

4.3.2 Modular risk analysis

From the operational risk analysis, it was clear that the system hardware posed the highest risk. To further identify and evaluate this risk, a second analysis was conducted that focussed on system hardware. The main focus area for this analysis was the utilities, transmitter, receiver, antenna, signal processor and computer. Each focus area was further divided into smaller risks. These risks were evaluated using a qualitative risk matrix as shown in Table 27 and a risk rating was allocated to each risk identified. The risk rating was then compared to a second rating (in Table 28) showing the priority of the risk from low to extreme. After identifying and evaluating the risks, they were mitigated by instating appropriate risk controls. The analysis was repeated afterwards to indicate the benefits of managing risks.

Table 29 shows the first risk analysis for the hardware section done according to the Failure modes and effects analysis (FMEA). According to the analysis, the biggest risk was the maintenance of the transmitter with a rating of 16. This was due to the lack of knowledge and available spare parts. The following risks also had a high risk rating namely; surge protection failure, RF interference, receiver maintenance failure and maximum output power failure. The combined risk count for the first analysis was found to be **227**. Figure 58 shows a summary of all the risks and their risk levels according to the evaluation table, Table 28. The majority of the risks were in the medium level, which was acceptable. Four risks (surge protection, maximum output power, RF interference and receiver maintenance) were placed in the high level category and one (transmitter maintenance) in the extreme level. These five risks had the highest priority and posed the biggest threat to the project’s success.

With the risks identified and evaluated, they could be mitigated. To reduce the risk rating, either or both the probability and consequence had to change. Generally the easiest and quickest method to reduce the risk rating is to lower the probability of occurrence. This could be as simple as doing more routine inspections and testing. To change the consequence, the system physically needed to be modified. This was a more permanent solution but could be time-consuming and expensive.

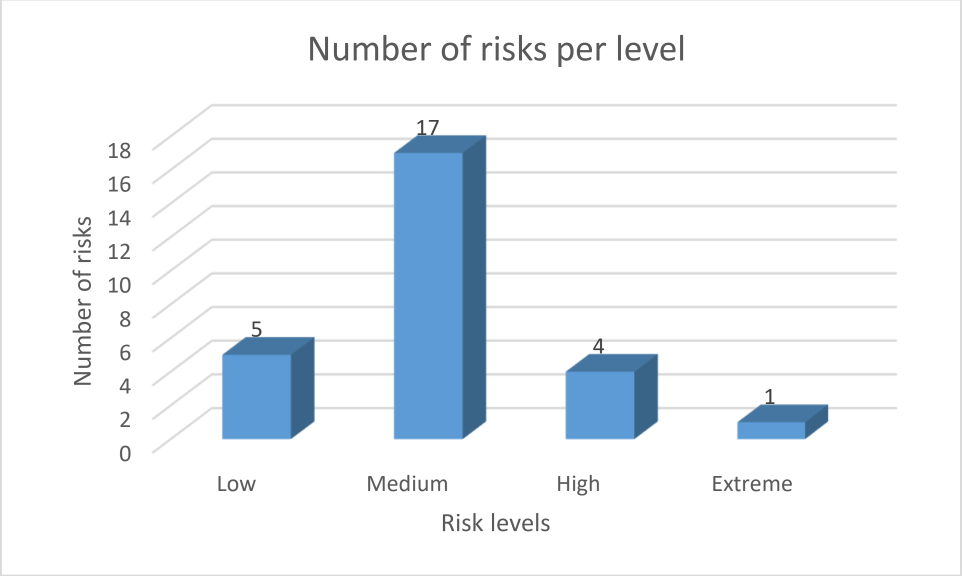


Figure 58: The first functional risk analysis summary graph

After all the risks had been mitigated within budget and time constraints, the risk analysis was repeated. Table 30 included two additional columns, showing how each risk was mitigated and the improvement (Imp) on the risk rating. Figure 59 shows a summary of all the risks and their priority levels before and after the risks had been mitigated. From the graph, it can be seen that the risks have increased in the low and medium categories while it decreased at the high and extreme categories. The system has only two high risks remaining.

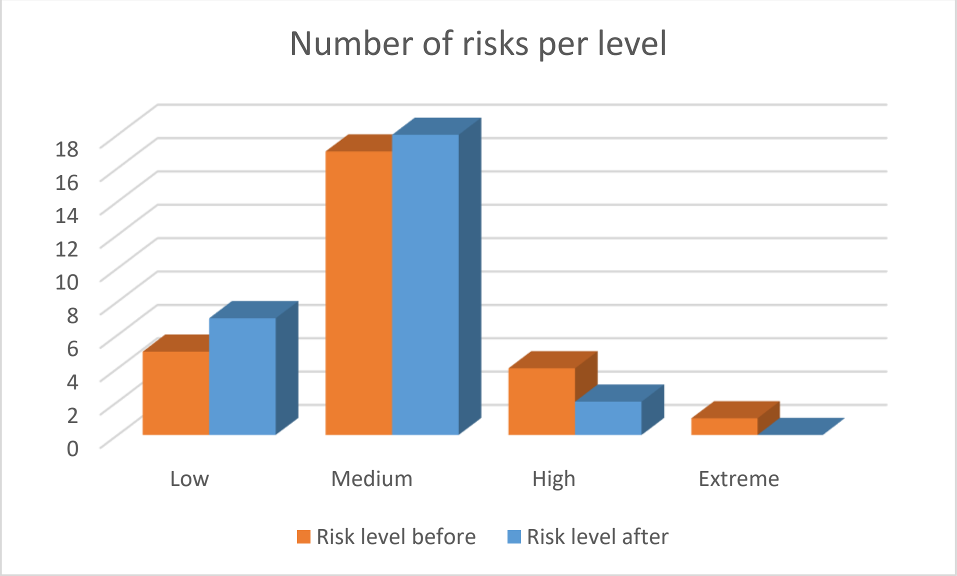


Figure 59: First and second modular risk analysis comparison

From the second analysis, it became clear that managing the basic risks had an influence on the overall system's risk rating, hence its reliability. Fairly easy tasks such as routine inspections and tests lowered the risk rating by four points. However, the more substantial improvement came from replacing high-risk components and re-engineering the transmitter. Replacing the safety switches, installing additional switches, surge protection devices, replacing the receiver power supplies and repairing the radome leakages lowered the risk rating by another 22 points. By re-engineering the transmitter section, the risks were lowered by 17 points, but more importantly also lowered the extreme and high risks, making the system more reliable. This risk analysis has an overall risk rating of 184 which is 18% lower than the original risk,

The two remaining high risks, RF interference and maintenance failure, are both due to the receiver section. These risks can only be lowered by means of installing additional filters or re-engineering the receiver system as was done with the transmitter section.

4.3.3 Component risk analysis

The third risk analysis focussed on re-engineering of the radar system with the purpose of illustrating how the process affected the reliability of the transmitter at component level. As with the modular risk analysis, this analysis was conducted before and after the transmitter system had been re-engineered. By comparing the two analyses, the improvements could be noted.

To help identify risks, a diagram was used to show the functional layout of the transmitter's components as seen in Figure 37 (section 3.3). Every functional unit was evaluated against the probability of the unit failing, resulting in the loss of data. Every risk was evaluated using a Qualitative risk analysis table (Table 31) consisting of three criteria namely; probability, consequence, and severity. Each risk was then given a risk rating and compared with a second analysis (Table 32) showing the risk priority between low and extreme. For the first analysis, a total of 18 risks were identified and evaluated with a relative risk rating of 407. Figure 60 shows a summary of the 18 risks and their priority according to Table 32.

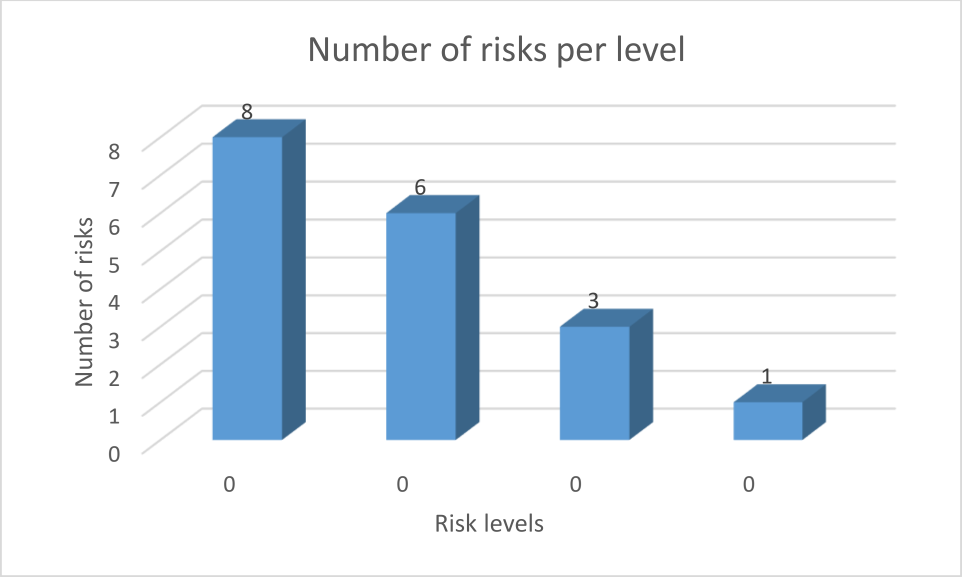


Figure 60: The first component risk analysis summary graph

According to the summary, the majority of risks were in the low to medium risk range with three in the high range and one in the extreme range. The extreme risk was the warm-up timer relay (FU 1.5) used to give the magnetron sufficient warm-up time before it starts radiating. After a certain time, the timer is supposed to engage a safety switch which enables the magnetron to start radiating. However this timer did not always switch on after it was supposed to, therefore not enabling the transmitter to transmit. This timer had a high risk rating because the component has become obsolete and no spare parts are available on the market. The over-current relay (FU 1.6), thyratron (FU 1.11) and magnetron (FU 1.13) have all been given a high risk rating. The overcurrent relay limits the output power of the magnetron to only 200 kW of the possible 250 kW to prevent overstressing. The magnetron was set at a maximum of 125 kW, which was below the value for the overcurrent relay, but it was expected that this relay would start presenting problems in the future. The thyratron has a high risk rating due to the lifespan of the device which is between 1 and 3 years. The thyratron has become difficult to source and very expensive as not many devices are still making use of one. As the radar technology keeps getting older, it will become scarcer and more expensive. The third high risk component is the magnetron. The magnetron has a lifespan of roughly 20 000 hours. The actual operating hours for this magnetron is unknown but it is expected to be close to 20 000. This type of magnetron is still available on the market but is very expensive.

After the transmitter system had been re-engineered and modified, the same risk analysis (Figure 41) was conducted on the system. The same evaluation criteria and risk priority system were used. With the new system a total of 16 risks were identified and evaluated with a total risk rating of **265**. Using the risk rating evaluation table (Table 32) these risks were prioritised between low, medium, high and extreme. Figure 61 shows a summary of all the risks and their priority levels before and after the risks had been mitigated. From the graph, it can be seen that the number of risks increased on the medium priority while it decreased at the high and extreme priorities. The system has one high risk remaining.

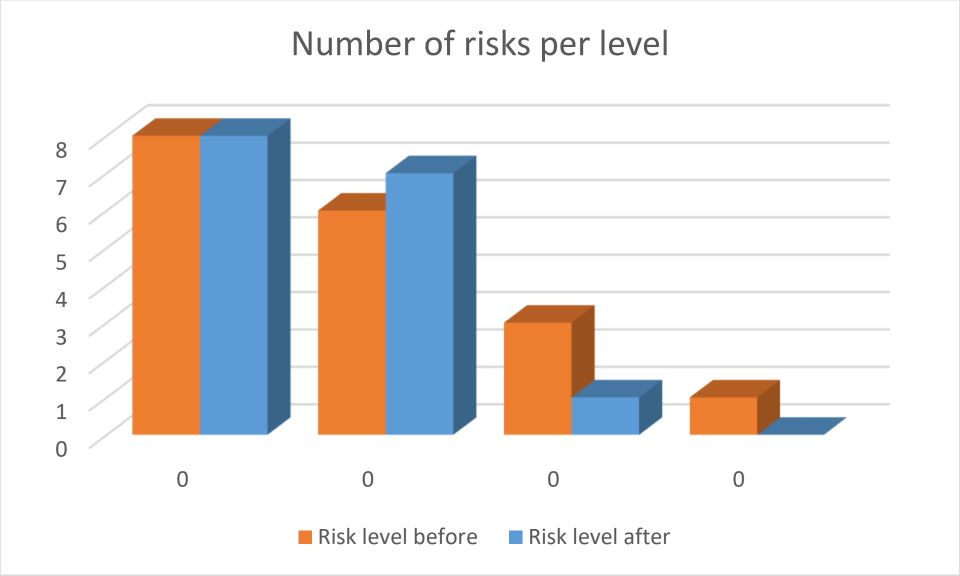


Figure 61: First and second component risk analysis comparison

By comparing the first risk rating with the second risk rating, it can be seen that the modified transmitter has a **35 %** decrease in risk. As with the first assessment, the majority of risks are in the low to medium risk range with one in the high region and none in the extreme. The high risks include the magnetron (FU 1.13) which has not been changed from the first assessment. Other than the magnetron, all the other high and extreme risks have been reduced. This provides clear evidence that re-engineering a system most definitely has a significant positive effect on the risk rating of that section and on the entire system. Moreover, with this knowledge, any new projects following on this research project will have a clear baseline and reference.

4.4 DATA COMPARISON

4.4.1 NWU-Lekwena radar comparison with Irene radar

The NWU-Lekwena radar was installed, set-up and calibrated using the correct procedures but the data first had to be validated before it could be used. One method to validate the data was by comparing a scan from the NWU-Lekwena weather radar with that of another radar in close proximity. This was not a straight forward task. Figure 44 (Chapter 4.1.1) shows three weather radars forming part of the national weather radar network intersecting the NWU-Lekwena radar namely; Irene (Pretoria), Ottosdal, and Bethlehem. For two weather radars to be compared, there are various factors that can influence the comparison, such as:

- Type and operating frequency of the two radars;
- Distance between the two radars;
- Distance and position of a storm relative to the radars;
- Radar data availability;
- Accuracy of both radars;
- Time difference between comparative scans.

To begin with, in order to compare the NWU-Lekwena weather radar with another radar, data on the same storm at roughly the same time from both radars are required. The radar compared with must be well maintained and regularly calibrated. Of the three national weather radars it is known that the Irene radar was the best maintained and kept up-to-date with its routine calibrations. According to Figure 2 (Chapter 1.2.1), the Irene radar has data availability of over 85% while Bethlehem is just below 40% and Ottosdal below 20%. Also, it was noted that the Bethlehem radar was not accurately calibrated causing it to underestimate its values. Therefore, of the three possible radars, the Irene radar would provide the highest probability for data available and accuracy.

The main difference between the NWU-Lekwena radar and Irene radar is the operating frequency. The NWU-Lekwena radar is a C-band, operating on 5.6 GHz while the Irene radar is an S-band operating on 2.9 GHz. Since the C-band radar operates on a higher frequency, this radar is more sensitive to smaller precipitation particles and the signal is attenuated more over large distances.

Two different storms were used to compare the two radars. The first comparison was made observing a storm on 28 September 2014 between Potchefstroom and Johannesburg. Figure 62 shows the scan from the NWU-Lekwena radar at 15:45:19 UTC and Figure 63 shows the scan from Irene radar at 15:45:56 UTC. The storm surrounds Potchefstroom with the highest intensity between 15 km and 30 km north-east of the NWU-Lekwena radar and 110 km to the south-west of Irene radar.

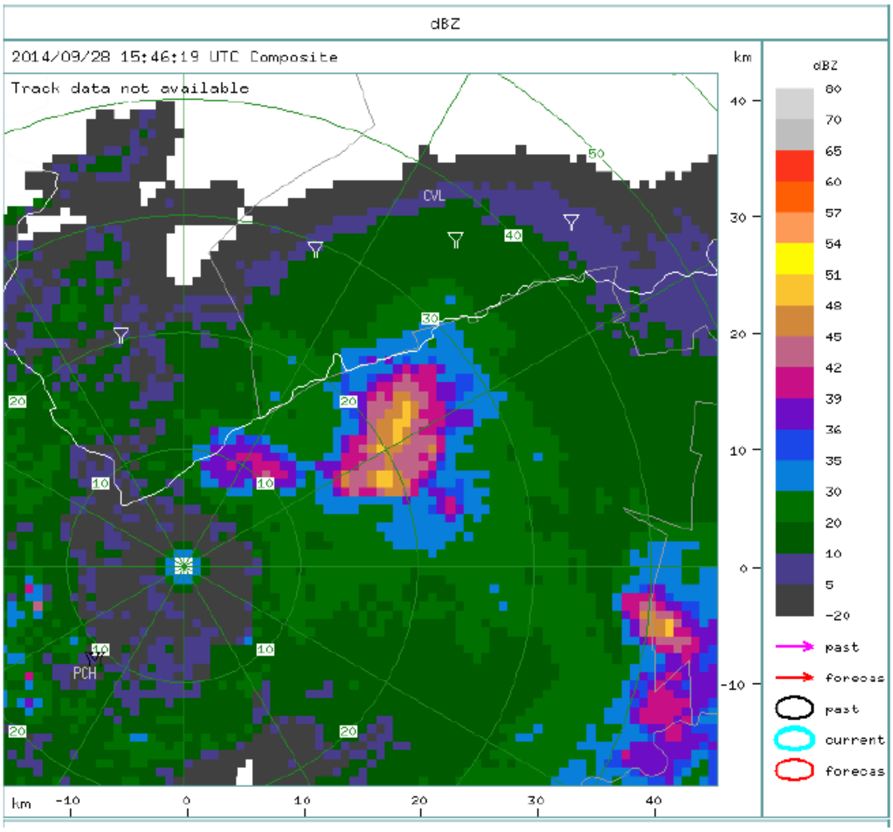


Figure 62: NWU-Lekwena radar scan 28 September 2014 at 15:45:19 UTC

The two scans were taken 23 seconds apart, which is close enough for a good comparison. Comparing the scans, it is clear that there is a strong similarity, as confirmed by Dr Roelof Burger, a weather expert. Both radar scans show roughly the same shape and intensity from 10 dBZ up to 54 dBZ. The area around the NWU-Lekwena radar shows more detail than the Irene radar for a number of reasons. Firstly, the NWU-Lekwena radar is a C-band radar which is more accurate than an S-band radar, therefore it can better measure lower intensity storms. Secondly, the Irene radar is further away from the storm. According to Figure 12 the minimum height Irene would be able to scan at a 1° elevation is about 3 km. Therefore any precipitation below 3 km will not show on the scan.

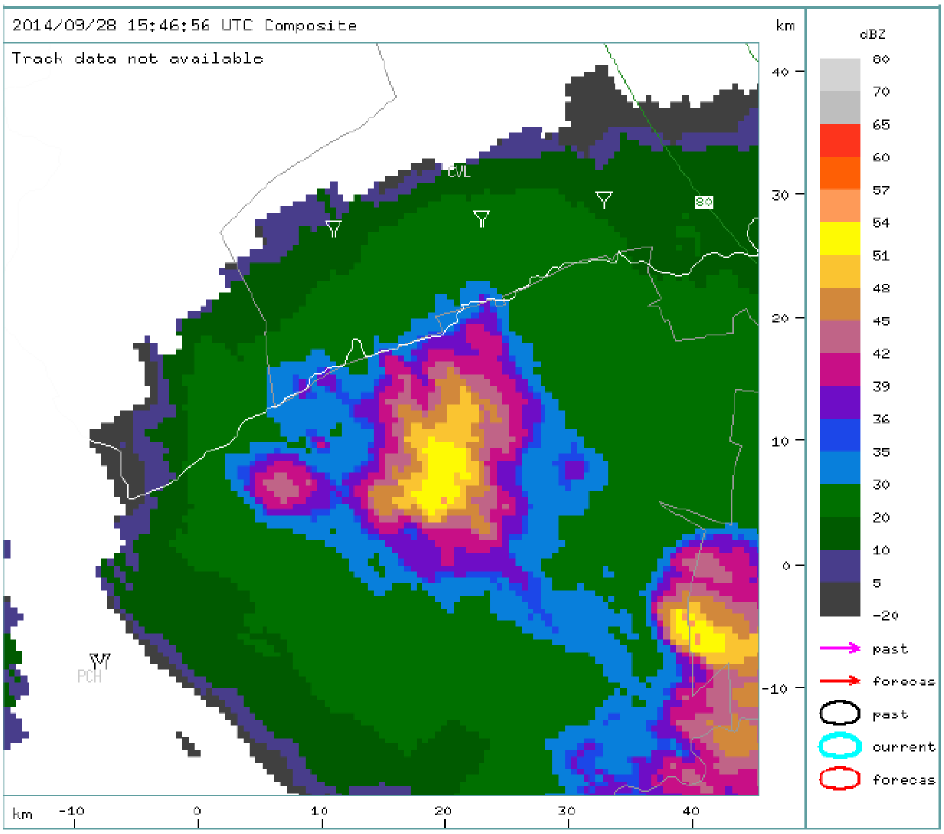


Figure 63: Irene radar scan on 28 September 2014 at 15:46:56 UTC

The second was made observing a storm on 24 November 2014. Figure 64 shows the scan from the NWU-Lekwena radar at 10:34:38 UTC and Figure 65 shows the scan from Irene radar at 10:34:55 UTC. The storm was divided into three sections; the area around Potchefstroom.

The two scans were taken 17 seconds apart, which is very close and good for a comparison. When comparing the scans, the three different storms can clearly be identified with a similar shape and intensity. As seen on the previous scans, the area around the NWU-Lekwena radar is scanned in more detail compared to the scans from the Irene radar. This could be because the storm was below the Irene radar scans or the precipitation particles were too small to detect.

From both these comparisons, it is clear that there is a strong correlation between the NWU-Lekwena radar and the Irene radar. This validates the statement that the NWU-Lekwena radar produces accurate and valuable data that can be used for both weather forecasting and research purposes.

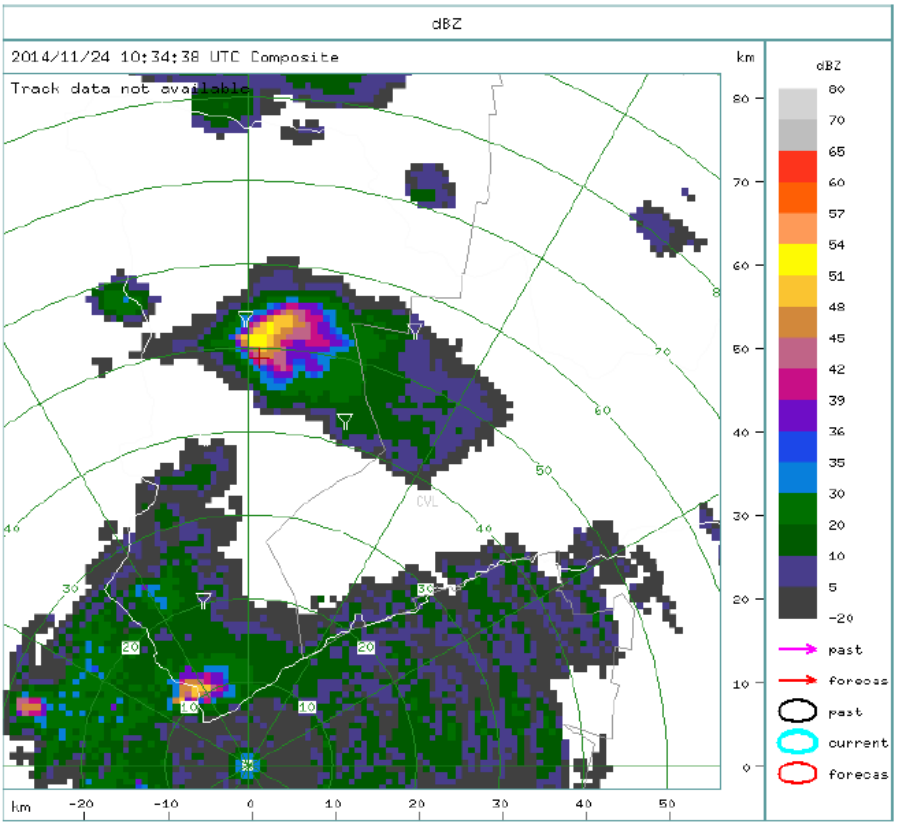


Figure 64: NWU-Lekwena radar scan on 24 November 2014 at 10:34:38 UTC

4.5 CONCLUSION

This section discussed the results of this research project based on the methodology described in Chapter 3. From the results it is clear that the radar system was successfully installed and upgraded by following a re-engineering process.

Furthermore, the risk analysis study evaluated the radar system and highlighted areas posing a risk. Extreme risks were mitigated and a risk reduction of 35% was achieved with limited funds and resources.

The data collected was compared with another radar to evaluate the data quality and accuracy and was found to correlate well with an existing, calibrated radar. Currently the system is providing valuable data used in other research projects.

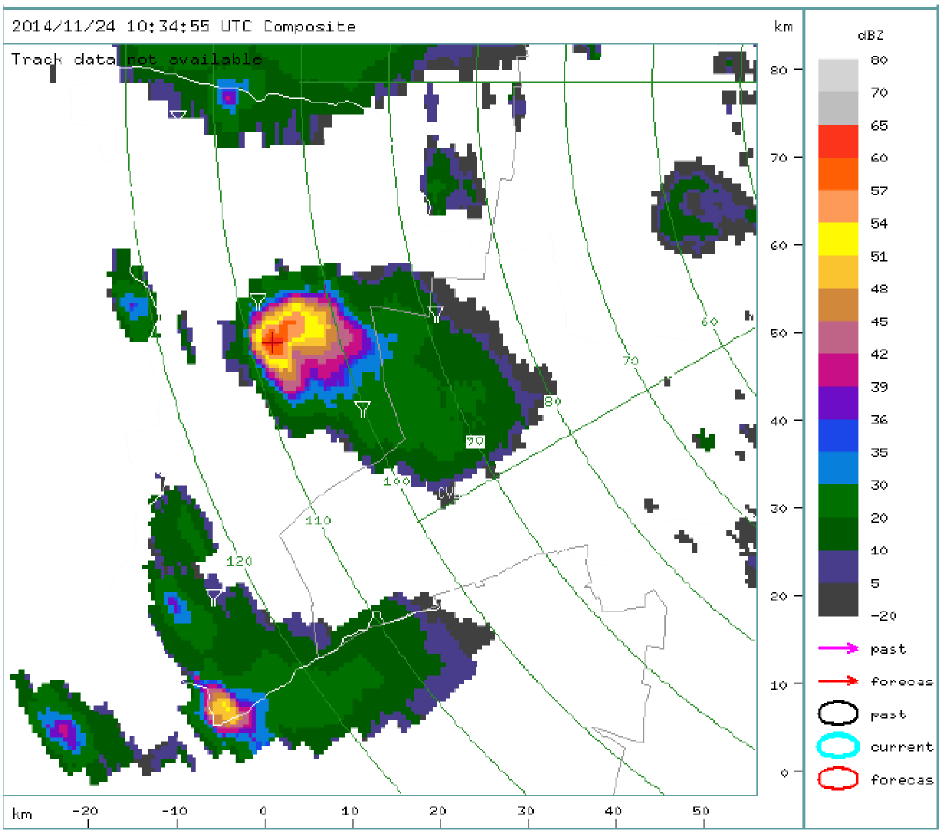


Figure 65: Irene radar scan on 24 November 2014 at 10:34:55 UTC

CHAPTER 5: CONCLUSION

This conclusion chapter provides a summary of what has been achieved through the project, the experiential lessons learned (to be presented in the form of guidelines) and what lies ahead following the completion of this research project.

A weather radar is definitely a valuable tool for providing high spatio-temporal data over large areas to study storms and precipitation. The national weather radar network of South Africa is a world-class asset with enormous potential to provide real-time, high resolution data for various departments and research facilities. Unfortunately, the SAWS has tremendous challenges regarding the maintenance of the entire system. The system has been plagued by technical problems mainly due to budget cuts, the loss of skilled experts and limited resources.

This study focussed on building much needed, capacity in South Africa in the weather radar environment. The research was conducted within the design science research (DSR) framework to ensure that a well-structured research method was followed. A complete problem analysis, project statement, research approach and project objectives were listed in Chapter 1.

A literature study (Chapter 2) was conducted on related literature specified by the research challenges. The focus area in this literature study comprised weather radar background, designs, operations, different types of radars, derived products from data collected, calibration procedures, risk analysis methodologies and techniques, and finally re-engineering processes and techniques. The literature showed ample literature available on radar background, designs, data processing, products, risk analyses methodologies and the re-engineering process. However, there was a significant lack of literature on the radar model in question, calibration procedures, site selection process and requirements, and risk analysis case studies based on weather radars. Additional literature and advice were used from different sources such as Mr. Farren Hiscutt (an expert) and the SAWS to supplement literature where needed. From the literature, valuable information was obtained as the research challenges were successfully translated to research solutions.

The methodologies used throughout this project were discussed in Chapter 3. This chapter described the process and procedures followed to select the best-fit site, how to deploy the radar, and how to test the radar. Furthermore, it describes the process followed to partially re-engineer the radar and in doing so, also upgrade the transmitter to a state-of-the-art solid-state transmitter. The chapter also describes the process followed to conduct a risk analysis on the whole project, the radar system and specifically the transmitter.

5.1 DISCUSSION OF RESEARCH RESULTS

From the results in Chapter 4, it is clear that all operational, functional and theoretical requirements set out in the project objectives were met.

The weather radar was successfully deployed and complies with all requirements according to the criteria listed in Chapter 3.1.1. During the initial tests, it became apparent that the radar occasionally suffers from external interferences, causing loss of data. This was corrected by changing the radar’s operating frequency and involving ICASA from a legal perspective. Occasionally, the radar still picks up external interference that causes a loss of data – this must be managed in the future.

Simulations were generated to determine the possible beam blockage and ground clutter that could be expected for the site. The simulations were compared with the actual ground clutter from data scans and proved to be not as accurate as anticipated. The simulations predicted limited ground clutter to the east but did not pick up any clutter on the west. This can be due to environmental factors, the location of the radar, software coding or incorrect topographical data.

For this research project, the time, resources and budget available only allowed researchers to re-engineer one section of the radar. The re-engineering process evaluated the entire radar system by conducting a risk analysis and concluded that re-engineering of the transmitter system would enhance the performance the most. The process consisted of replacing the entire transmitter system with a new state-of-the-art transmitter. The new transmitter was designed to replace the original transmitter with minimal modifications. During the re-engineering process, additional components, not directly related to the transmitter, were also replaced, improving the overall data quality of the receiver. The new system generates 68% more power than before.

A thorough risk analysis study was completed on the project, focussing on identifying and mitigating risks. The analysis was divided into three levels, a study based on the overall project, as well as operating and maintaining a radar (operational level), a modular study focussing on the radar system itself, and a component level focussing on the re-engineering of the radar. The first analysis identified that the hardware section had the highest risk rating and probability to cause a system failure. In the modular risk analysis, the radar received an overall risk rating of 227. With basic improvements such as introducing routine inspections, and by eliminating an extreme risk – the transmitter – the risk rating was lowered by 18%. The third study focused on the risk associated with the radar system on a component level and the effect of re-engineering a component. According to the results, the radar had a high risk rating of 407. This is due to old and obsolete components. After completing the re-engineering process, the risk rating was reduced to 265, showing a 35% improvement. These results validate the benefits of re-engineering a radar system, and using a risk analysis to make decisions. The research contributes to the body of knowledge and will assist in future research.

5.2 VERIFICATION AND VALIDATION

Verification and validation are key factors in the design science research (DSR) process. The DSR methodology consists of a forward and reverse loop. The forward loop links an artefact to a real-world problem. In this case it is to build local capacity in South Africa in the radar environment. The reverse loop is used to evaluate the artefact in the real world through a rigorous process of evaluation and improvement. In the following section the validation of the research problem and solutions are shown in a traceable matrix as shown in Table 41.

The **research problem** was validated from observations in the real-world, confirmation from experts in the field, data availability from other radar sources, available documentation, and published literature. From these sources it was clear that there was a need to build local capacity in South Africa regarding the weather radar environment. Certain focus areas such as the radar site selection process, installation procedures, re-engineering a radar, and risk analysis case studies are very limited. These shortfalls were **translated** into **research challenges** as described in Chapter 1. The top part of Table 41 shows the information contributing to the research problem while the bottom part indicates the derived research challenges. Instances where information contributed to the research challenge is indicated by a downward arrow.

The **research solutions** were defined so that they addressed corresponding research challenges. The **literature study**, Chapter 2, was used to **validate research challenges** and **contribute to research solutions**. The arrows in the table indicate which literature validated and / or contributed respectively, indicated by upwards and downwards arrows. The bottom part of the table indicates which of the methodologies described in Chapter 3 and 4 contributed to the research solutions.

From the research validation table, it is clear that the research problem was a valid problem as it resulted in a number of validated research challenges. Literature confirmed some of these challenges and contributed to research solutions. Finally, the overall research effort resulted in an integrated solution by design, and addressed the initial research challenges as well as the initial research problem, namely to re-engineer and validate the integrated solution by means of risk analysis. The results were shown to be valid by providing a functionally capable, re-engineered weather radar that generates valid data (as verified against the Irene radar). Also, the risk analysis, employing valid risk analysis techniques as from literature, showed a significant decrease in risk and also identified future risks.

Table 41: Research verification and validation.

1. SAWS information	↓	↓				↓
2. Radar documentation	↓	↓				↓
3. Observations and previous case studies	↓	↓	↓	↓	↓	↓
4. Limited resources available	↓	↓	↓	↓	↓	↓
Information Sources **Research Challanges** **Literature Focus Area**	Radar environment and context are unknown	Radar installation and operation procedures	Re-engineering of the radar system	Lack of previous risk analysis on a radar system	Risk analysis is mainly compiled from observations	Limited expert advice and knowledge
1. Weather radar background	↓	↑	↑	↑		↓
2. Weather radar operations	↑↓	↑	↑↓	↑	↑	↑↓
3. Radar logistical and legislative procedure	↓	↑↓		↑	↑	↑↓
4. Risk management framework		↑		↑↓	↑↓	↓
5. Existing risk assessment tools and techniques				↓	↓	↓
6. Re-engineering framework and techniques			↑↓	↑		↑↓
Literature Focus Area **Research Solutions** **Project Methodology**	Familiarize and understand the radar environment	Follow available procedures and acquire additional advice from experts	Follow an integrated systems approach	Follow a proactive risk management approach	Make use of validated, available risk tools and techniques	Create a base of knowledge and skills
1. Define radar system AS-IS	↑				↑	↑
2. Understand the operating environment	↑		↑		↑	↑
3. Select best fit for purpose site		↑			↑	↑
4. Prepare site and deploy radar system		↑			↑	↑
5. Test and evaluate radar system	↑	↑	↑			↑
6. Conduct risk analysis before re-engineering			↑	↑		↑
7. Perform re-engineering concept design	↑	↑	↑		↑	↑
8. Follow re-engineering process	↑	↑	↑		↑	↑
9. Test and evaluate re-engineered radar system	↑	↑	↑			↑
10. Conduct risk analysis after re-engineering			↑	↑		↑

Legend: ↑ - *Element contributes upwards to its linked entity*

↓ - *Element contributes downwards to its linked entity*

5.3 RESEARCH CONTRIBUTION

The reader is kindly referred to the lower section of the validation matrix for an integrated view of research contributions (Table 41). Steps 1 to 10 provide evidence that, apart from individual contributions such as risk analyses and design, the overall re-engineering project is in itself a research contribution in the DSR sense. A discussion on DSR contributions (meta-artefacts such as a knowledge base, and the physically constructed artefact) is provided below.

The purpose of design science research is to provide a research platform for projects to contribute real-world artefacts. The following artefacts resulted from this project:

1. Knowledge base

- Develop a methodology to extend the life of an old C-band weather radar. This would make it possible for the SAWS to redeploy up to 6 radars in strategic places to improve the resilience of the current network as well as to expand the coverage area.
- The methodology of deploying a new radar was developed and documented. The processes followed to select the correct site, site requirements, legislative matters and other procedures were provided;
- Although re-engineering and upgrading of weather radars have been done elsewhere, documented processes to this effect were not available to the research team. In this project each re-engineering step was documented and can be used as a guideline for future work;
- A significant contribution to the knowledge base is the risk analysis conducted on the radar system. Limited literature was available on the risks associated with a weather radar before this research project. This project identified multiple risks posing possible system failures, as well as methods to manage these risks accordingly.

2. Physical artefact

- The main physical contribution of this research is the deployment of an operational weather radar. The radar generates valuable precipitation data for other projects at the NWU. The data will in the near future also be available online for the local community to observe weather related phenomena;

- In providing an operational radar, the overall system has undergone a re-engineering process to upgrade the transmitter system and other smaller sections. This process contributed to the success of the project, improved the radar's performance and lowered the majority of the high risks associated with project. In addition, the re-engineering process made it possible to further upgrade the radar system to Doppler and even dual-polarization in the future.

According the DSR knowledge contribution framework showed in Figure 4 (Chapter 1.3.1) DSR research contributions are divided into four quadrants. Of these four, this research project contributed primarily in the improvement quadrant. One of the main reasons for re-engineering and conducting a risk analysis on the system was to improve the performance and reliability of the system. As stated by the framework, this project had a low solution maturity but a high problem maturity. Although, improvement was the main contribution, this project also contributed to routine design and adaptation.

By contributing to both the knowledge base and delivering a physical artefact, this project assisted in building much needed capacity in the weather radar environment, especially within South Africa. As a result, the objectives of this research project have been addressed.

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APPENDIX A: RECOMMENDATIONS GAINED FROM PROJECT EXPERIENCE

This appendix includes personal guidelines, notes and suggestions as experienced through this project to aid similar projects in the future.

A.1 SITE INSPECTION

- Ensure all the criteria are thoroughly defined before starting the evaluation process;
- Certain topics within the criteria have a higher priority than other and this needs to be factored into the decision making process. An example is that a constant and stable power supply is more important than easy access;
- Do not assume that three-phase power is available. Verify that all the power supplies are active and available to use immediately;
- Install the generator away from the radar site if possible or on rubber mounts to avoid vibrations on the radar system;
- Install a warning system to directly inform the user about abnormal conditions such as a power failure, back-up power failure, radar failure, and high temperature within the building;
- Conduct an RF interference test on every site identified and factor the results into the final decision. A regular WIFI transmitter/receiver with a detection mode, such as the *Ubiquiti Bullet,* can be used. This device will show the frequency, strength and SSID of the interference source. For most cases it is possible to find the interference source, but it is a constant battle as old sources change back to their original frequencies and new sources are regularly added.

A.2 RADAR INSTALLATION

- Comply with all the requirements and regulations before starting with the installation process;
- Plan the installation process beforehand and ensure that all the equipment that needs to be lifted by a crane is already at the site to avoid additional costs;

- Ensure all the radome sides are fixed and fit perfectly together. Use silicon glue between each joint to seal the radome to prevent ingress of water;
- Ensure the structures housing the radar and antenna platform are well anchored to the ground and to one another to minimize any movement;
- Provide a door beneath the antenna platform for easy access to the antenna. Also ensure that the door can be locked to restrict access;
- Place warning signs where needed to warn the public against hazardous conditions such as mechanical moving parts, high voltage, and radiation;
- After installing the radar system, check that all the connections and wires are properly fastened before switching on the system. Something as simple as a loose wire can generate noise on the receiver system.

A.3 POWER CONNECTION

- Provide adequate protection devices against lightning strikes, power spikes and voltage dips;
- Use an inline UPS with active filtering systems to provide a stable power supply to the entire radar system. This is important especially when the power is supplied by a generator for same reason;
- The generator must be capable of supporting the load for at least 12 hours;
- Contract the electrical connections out to a qualified electrician and ensure he provides a certificate of compliance (COC) for the site.

A.4 ACCESS

- Build a good working relationship with the landowner;
- Restrict access to the site if possible;
- Keep the equipment secure and locked when left unattended.

A.5 ICASA

- Ensure the radar is registered at the local government communication offices. In South Africa two licences are needed to register a radar at ICASA, namely a radio communication license, and a frequency spectrum licence. Both these licences will indicate the specific area, range and operating frequency allowed;

- ICASA can assist in finding RF interference on the same frequency as that of the radar and ask them to change their operating frequency;

A.6 LEGISLATION DOCUMENTS

- Ensure all legal documents are in order. Keep the original documents in a safe cabinet and a copied set of all the documents at the radar site itself;
- Keep duplicates of all legal documents off premises as a backup.

A.7 RADAR MANAGEMENT AND MAINTENANCE

- Conduct routine inspections and maintenance on the entire radar system and the generator. With the inspections also verify that the antenna is still aligned by tracking the sun or pointing it at a known obstacle;
- Perform new calibrations when seeing any deviations in the data or data quality;
- If possible, always have spare parts available at the site;
- Ensure that all safety protection devices are operational and within their limits.

A.8 TRANSMITTER RE-ENGINEERING

- Perform a comprehensive analysis to capture the “as is” of the current design and layout before starting the re-engineering process;
- Identify the sections to be re-engineered. In this case it was the transmitter section and the receiver’s power supply;
- Remove all the components of that specific section. Keep the components intact and store them in a safe environment. Some might be re-used or sold as spare parts.

When installing the new transmitter use high quality components such as Teflon wire and proper plugs.

APPENDIX B: PROJECT PHOTOGRAPHS

This appendix includes figures showing the various stages throughout this project.

Figure 66: The weather radar situated in Cotula, Texas USA before it was relocated to South Africa.

Figure 67: Radome, container and site preparation.

Figure 68: Power cable, antenna platform and pedestal installation.

Figure 69: Radar setup inside the container

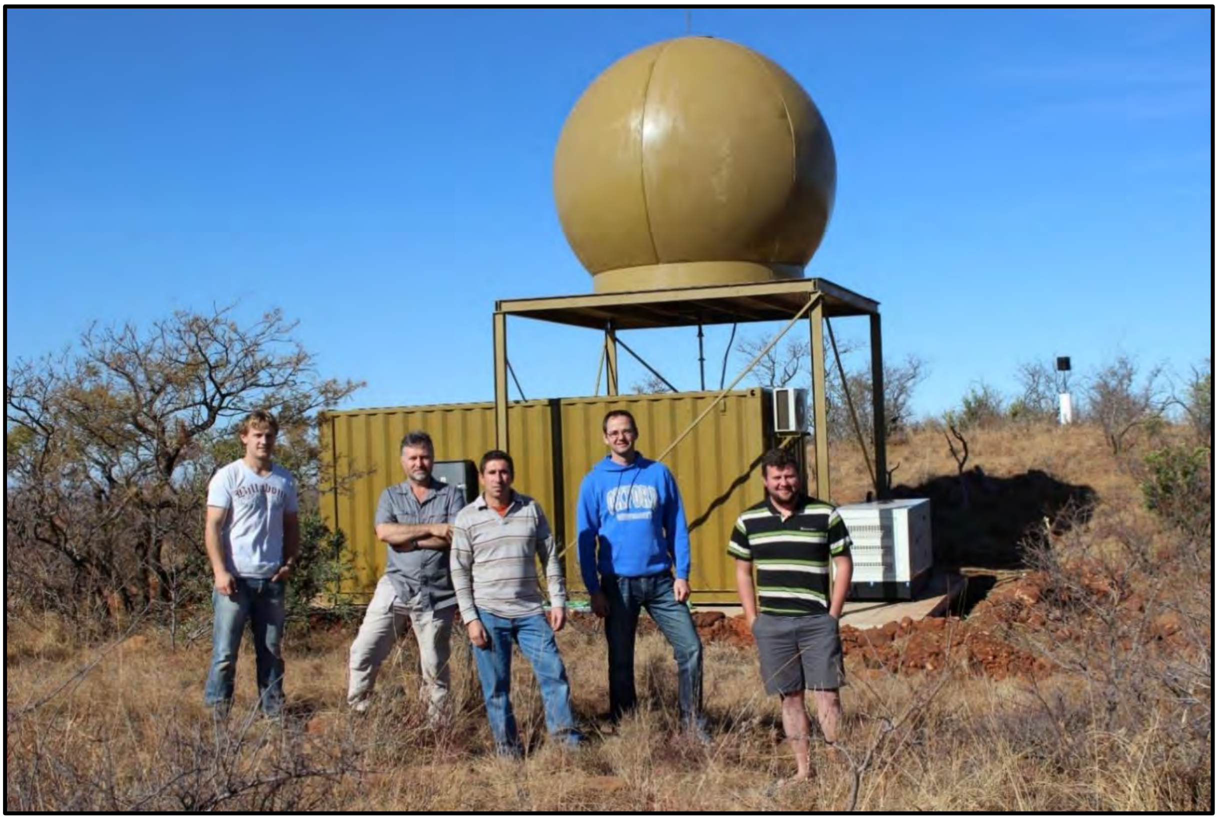
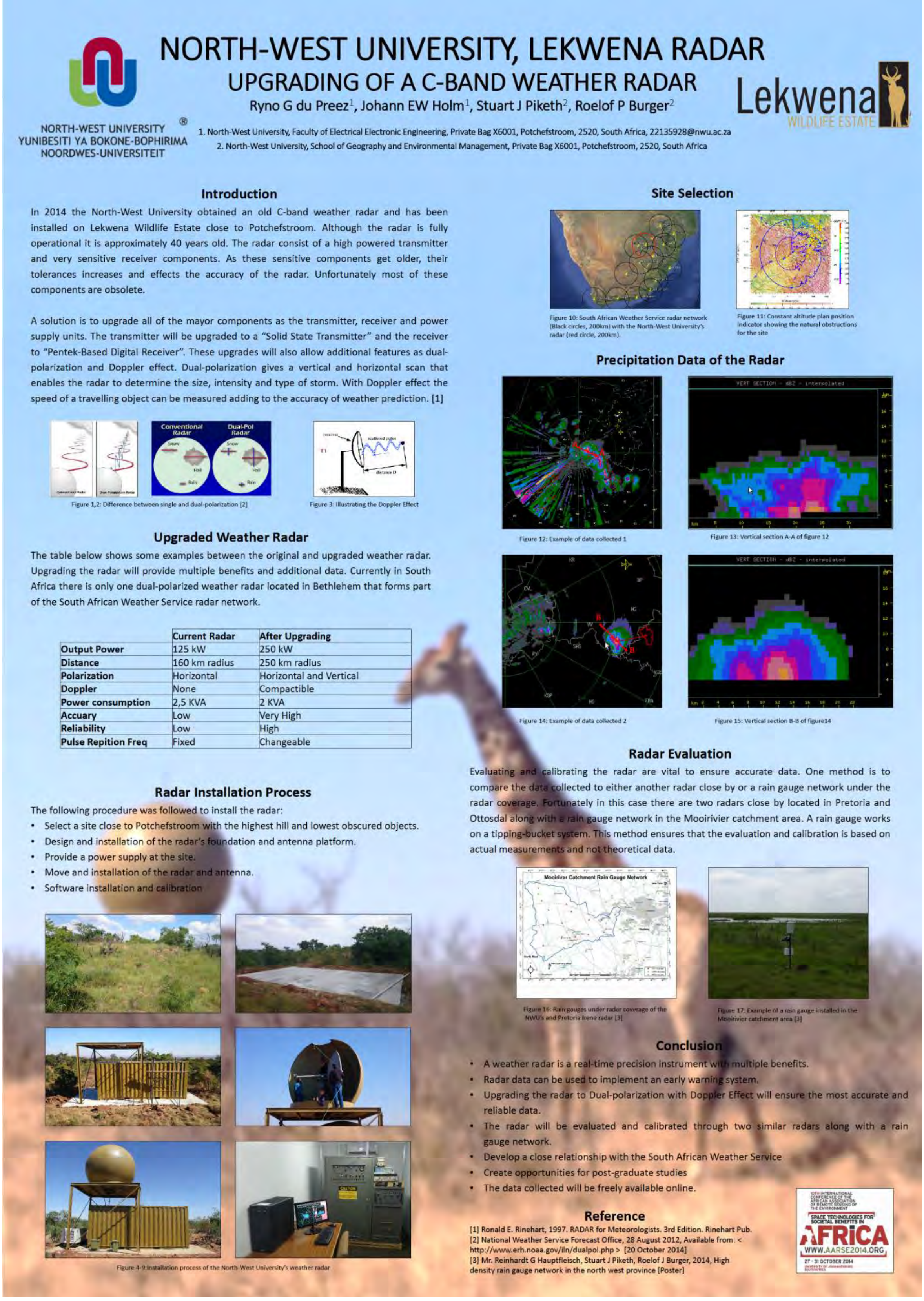


Figure 70: Weather radar and the installation team.

APPENDIX C: CONFERENCE PROCEEDINGS

The poster shown below in figure 71 was presented at the 10th International Conference of the African Association of Remote Sensing of the Environment at the University of Johannesburg between the 27^{th} and 31^{st} of October 2014.



NORTH-WEST UNIVERSITY, LEKWENA RADAR

UPGRADING OF A C-BAND WEATHER RADAR

Ryno G du Preez[1], Johann EW Holm[1], Stuart J Piketh[2], Roelof P Burger[2]

NORTH-WEST UNIVERSITY ®
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT

1. North-West University, Faculty of Electrical Electronic Engineering, Private Bag X6001, Potchefstroom, 2520, South Africa, 22135928@nwu.ac.za
2. North-West University, School of Geography and Environmental Management, Private Bag X6001, Potchefstroom, 2520, South Africa

Lekwena
WILDLIFE ESTATE

Introduction

In 2014 the North-West University obtained an old C-band weather radar and has been installed on Lekwena Wildlife Estate close to Potchefstroom. Although the radar is fully operational it is approximately 40 years old. The radar consist of a high powered transmitter and very sensitive receiver components. As these sensitive components get older, their tolerances increases and effects the accuracy of the radar. Unfortunately most of these components are obsolete.

A solution is to upgrade all of the mayor components as the transmitter, receiver and power supply units. The transmitter will be upgraded to a "Solid State Transmitter" and the receiver to "Pentek-Based Digital Receiver". These upgrades will also allow additional features as dual-polarization and Doppler effect. Dual-polarization gives a vertical and horizontal scan that enables the radar to determine the size, intensity and type of storm. With Doppler effect the speed of a travelling object can be measured adding to the accuracy of weather prediction. [1]

Figure 1,2: Difference between single and dual-polarization [2]

Figure 3: Illustrating the Doppler Effect

Upgraded Weather Radar

The table below shows some examples between the original and upgraded weather radar. Upgrading the radar will provide multiple benefits and additional data. Currently in South Africa there is only one dual-polarized weather radar located in Bethlehem that forms part of the South African Weather Service radar network.

	Current Radar	**After Upgrading**
Output Power	125 kW	250 kW
Distance	160 km radius	250 km radius
Polarization	Horizontal	Horizontal and Vertical
Doppler	None	Compactible
Power consumption	2,5 KVA	2 KVA
Accuary	Low	Very High
Reliability	Low	High
Pulse Repition Freq	Fixed	Changeable

Radar Installation Process

The following procedure was followed to install the radar:

- Select a site close to Potchefstroom with the highest hill and lowest obscured objects.
- Design and installation of the radar's foundation and antenna platform.
- Provide a power supply at the site.
- Move and installation of the radar and antenna.
- Software installation and calibration

Figure 4-9: installation process of the North-West University's weather radar

Site Selection

Figure 10: South African Weather Service radar network (Black circles, 200km) with the North-West University's radar (red circle, 200km).

Figure 11: Constant altitude plan position indicator showing the natural obstructions for the site

Precipitation Data of the Radar

Figure 12: Example of data collected 1

Figure 13: Vertical section A-A of figure 12

Figure 14: Example of data collected 2

Figure 15: Vertical section B-B of figure14

Radar Evaluation

Evaluating and calibrating the radar are vital to ensure accurate data. One method is to compare the data collected to either another radar close by or a rain gauge network under the radar coverage. Fortunately in this case there are two radars close by located in Pretoria and Ottosdal along with a rain gauge network in the Mooirivier catchment area. A rain gauge works on a tipping-bucket system. This method ensures that the evaluation and calibration is based on actual measurements and not theoretical data.

Figure 16: Rain gauges under radar coverage of the NWU's and Pretoria Irene radar [3]

Figure 17: Example of a rain gauge installed in the Mooirivier catchment area [3]

Conclusion

- A weather radar is a real-time precision instrument with multiple benefits.
- Radar data can be used to implement an early warning system.
- Upgrading the radar to Dual-polarization with Doppler Effect will ensure the most accurate and reliable data.
- The radar will be evaluated and calibrated through two similar radars along with a rain gauge network.
- Develop a close relationship with the South African Weather Service
- Create opportunities for post-graduate studies
- The data collected will be freely available online.

Reference

[1] Ronald E. Rinehart, 1997. RADAR for Meteorologists. 3rd Edition. Rinehart Pub.
[2] National Weather Service Forecast Office, 28 August 2012, Available from: < http://www.erh.noaa.gov/iln/dualpol.php > [20 October 2014]
[3] Mr. Reinhardt G Hauptfleisch, Stuart J Piketh, Roelof J Burger, 2014, High density rain gauge network in the north west province [Poster]

10TH INTERNATIONAL CONFERENCE OF THE AFRICAN ASSOCIATION OF REMOTE SENSING OF THE ENVIRONMENT
SPACE TECHNOLOGIES FOR SOCIETAL BENEFITS IN AFRICA
WWW.AARSE2014.ORG
27 - 31 OCTOBER 2014

Figure 71: Poster presented at the 10th International Conference of the African Association of Remote Sensing of the Environment.

APPENDIX D: ADDITIONAL DOCUMENTATION

This appendix lists additional documentation used throughout this research project as newspaper articles, license applications and certification of compliance.

D.1 LOCAL NEWSPAPER ARTICLE

28 NOVEMBER 2014 news • nuus KLERKSDORP RECORD • 3

Hail storm causes serious damage

by Danie Jacobs

Klerksdorp Record, Klerksdorp - The city is slowly returning to normal after a vicious storm struck on Monday 24 November.

At the time of going to press, the damage was still clearly visible after the storm struck just after 14:00 and the city was bombarded with hard rain and hail as big a golf balls.

According to an employee of the SA weather service in Bloemfontein who wants to remain anonymous, 43 mm was measured at the PC Pelser Airport. He said the airport is situated at the edge of the storm. Private readings were taken where the eye of the storm hit (city centre and northern suburbs) of between 80 and 100 mm. According to Jan Botha of Flamieda, he measured 90 mm in his garden and Tanya Havenga measured 80 mm in Irenepark.

A cloudburst is classified as such when 100 mm or more of rain is measured within an hour and according to the weather service it is mostly accompanied by hail.

Flamwood Walk's underground parking took the brunt of the storm. According to Rina Joubert, centre manager, the basement got flooded as the hail blocked the drainage pipes.

Checkers continued trading and she said they have already started with the clean-up to ensure that the parking is open by the weekend.

Readers took to social media such as Facebook to share pictures of the storm. Quickcare 24/7 shared a picture of a rescue from a car's roof after the vehicle got stuck in flood waters next to the Recreation Centre. The police rescued the people. Jonathan de Klewit of Milner High School said many of the staff were unable to leave after school because their cars were stuck in the hail. It took a few hours with spades and a tractor to remove the hail.

Various shops closed in LA Piazza Square and others in Central Avenue closed due to damage sustained as streets were turned into rivers and several shops and homes were flooded.

The Musikon at THS suffered serious damage after ceilings of the auditorium and classrooms collapsed. Various musical instruments were also damaged beyond repair.

According to Sandrie von Deventer, HOD, the school is now closed for the year for repairs.

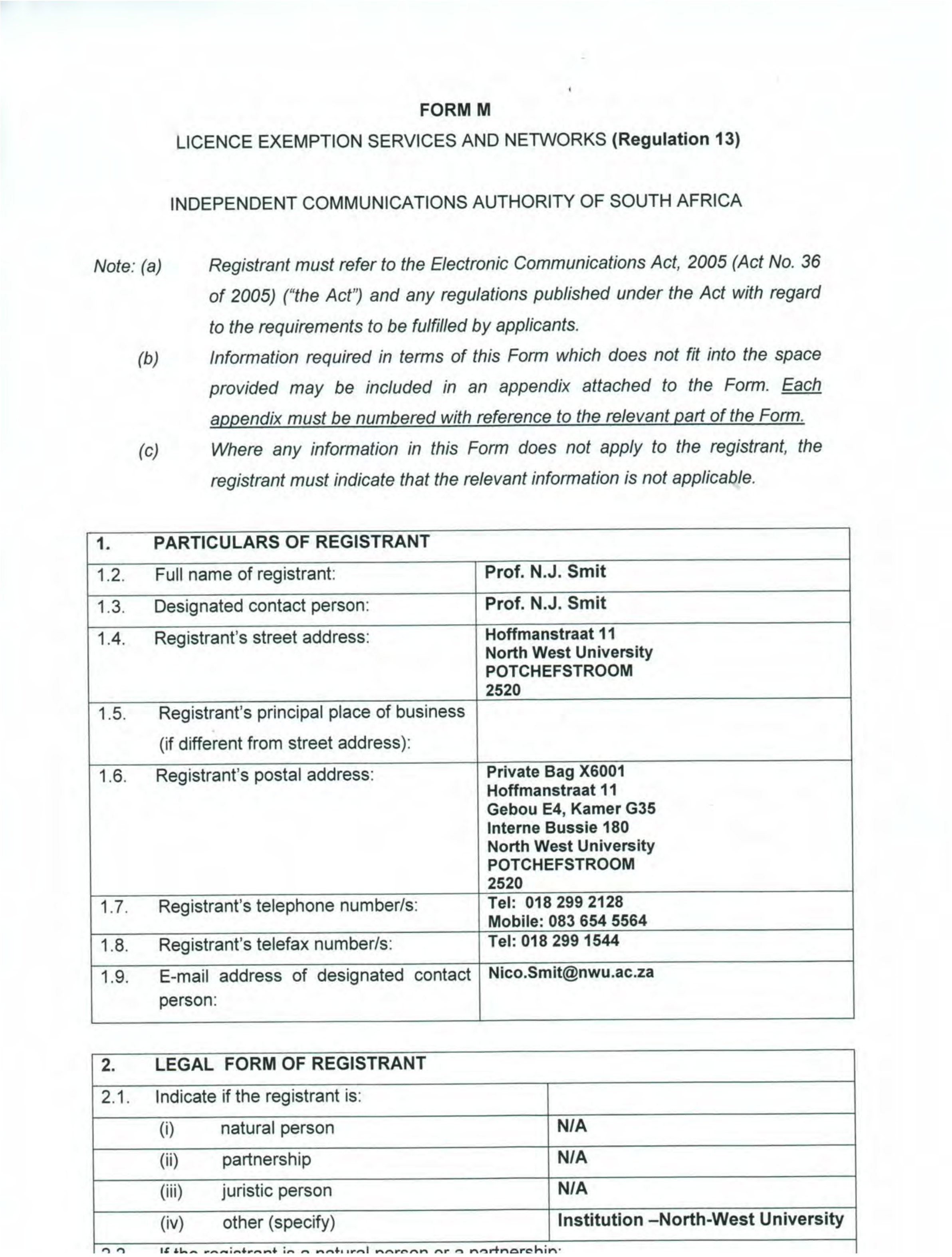
Pick n Pay Hypermarket and Matlosana Mall suffered little damage. The underground parking at City Mall was also flooded and was still closed at the time of going to press.

A section of the ceiling at the AFM Oase Church collapsed as well as the ceiling at the prayer room. Their special Christmas Carols service scheduled for this weekend, will however go on.

No injuries were reported.

Figure 72: Hail storm causing serious damage article from the local newspaper in Klerksdorp.

D.2 ICASA LICENCE APPLICATION



FORM M

LICENCE EXEMPTION SERVICES AND NETWORKS **(Regulation 13)**

INDEPENDENT COMMUNICATIONS AUTHORITY OF SOUTH AFRICA

Note: (a) Registrant must refer to the Electronic Communications Act, 2005 (Act No. 36 of 2005) ("the Act") and any regulations published under the Act with regard to the requirements to be fulfilled by applicants.

(b) Information required in terms of this Form which does not fit into the space provided may be included in an appendix attached to the Form. Each appendix must be numbered with reference to the relevant part of the Form.

(c) Where any information in this Form does not apply to the registrant, the registrant must indicate that the relevant information is not applicable.

1.	**PARTICULARS OF REGISTRANT**	
1.2.	Full name of registrant:	**Prof. N.J. Smit**
1.3.	Designated contact person:	**Prof. N.J. Smit**
1.4.	Registrant's street address:	**Hoffmanstraat 11 North West University POTCHEFSTROOM 2520**
1.5.	Registrant's principal place of business (if different from street address):	
1.6.	Registrant's postal address:	**Private Bag X6001 Hoffmanstraat 11 Gebou E4, Kamer G35 Interne Bussie 180 North West University POTCHEFSTROOM 2520**
1.7.	Registrant's telephone number/s:	**Tel: 018 299 2128 Mobile: 083 654 5564**
1.8.	Registrant's telefax number/s:	**Tel: 018 299 1544**
1.9.	E-mail address of designated contact person:	**Nico.Smit@nwu.ac.za**

2.	**LEGAL FORM OF REGISTRANT**	
2.1.	Indicate if the registrant is:	
	(i) natural person	**N/A**
	(ii) partnership	**N/A**
	(iii) juristic person	**N/A**
	(iv) other (specify)	**Institution –North-West University**
2.2.	If the registrant is a natural person or a partnership:	

2.2.1 Provide the identity number of the registrant or each partner in the registrant:	**N/A**
2.2.2. If the registrant is a juristic person:	
Provide certificate of incorporation	

3 **NATURE OF SERVICES TO BE AUTHORISED**	
3.1 Indicate if the service to be provided is:	
(i) an electronic communications network service	
(ii) an electronic communications service	**X**
3.2 Indicate the form of licence exemption being sought with reference to the categories of licence exemption as set out in the Licence Exemption Regulations. **The license is for a C-band weather radar operating on a fixed frequency 5600-5650 MHz. This is not a communication radar but only transmits to its self.**	
3.3 Provide the description of the service, the manner in which it is to be provided and provide a detailed explanation of the purpose for which the service is to be provided. **The license is for a weather surveillance radar that operates on a fixed C-band frequency (5600-5650 MHz). The radar transmits a pulse and receives echoes from precipitation within the area, 200km radius. It does not sent or receive any communication from another source. The radar transmit and receive the backscattered energy at the same source (S26.61929 E27.16670).**	
3.4 Indicate the geographic area in which the service is to be provided:	
The site is located 10km northeast from Potchefstroom, Tlokwe Municipality, Northwest on Lekwena Wildlife Estate owned by ALS group. The site is on a hill with no residential housing close by. **Position is: S26.61929 E27.16670, approximately 1512m above sea level.**	

4 RADIO FREQUENCY SPECTRUM

4.1 Indicate if the registrant holds any radio frequency spectrum licence in respect of radio frequency spectrum to be utilised for the purpose of providing the services for which authorisation is sought in terms of this registration. Attach a copy of any such radio frequency spectrum licence marked clearly as **Appendix 4.1** of **FORM M**:

The North-West University has applied for the frequency license and paid the full amount for registration.

4.2 Indicate if the registrant applicant has submitted or intends to submit an application for a radio frequency spectrum licence for the provision of the services to which this registration relates. Furthermore, indicate the frequency band which is proposed to be utilised for the purpose of providing the service:

The North-West university has applied for a frequency spectrum license for 5600-5650 MHz in 2014 in the area of Potchefstroom.

5. GENERAL

Attach a resolution authorising the person signing this registration to sign and mark it clearly as **Appendix 5** of **FORM M**.

The person signing the registration on behalf of the applicant must acknowledge as follows:

I acknowledge that the Authority reserves the right to have any authorisation issued pursuant to this application set aside should any material statement made herein, at any time, be found to be false

Signed ....

(APPLICANT)

I certify that this declaration was signed and sworn to before me at Potchefstroom on the 22nd day of October 2014, by the deponent who acknowledged that he/she:

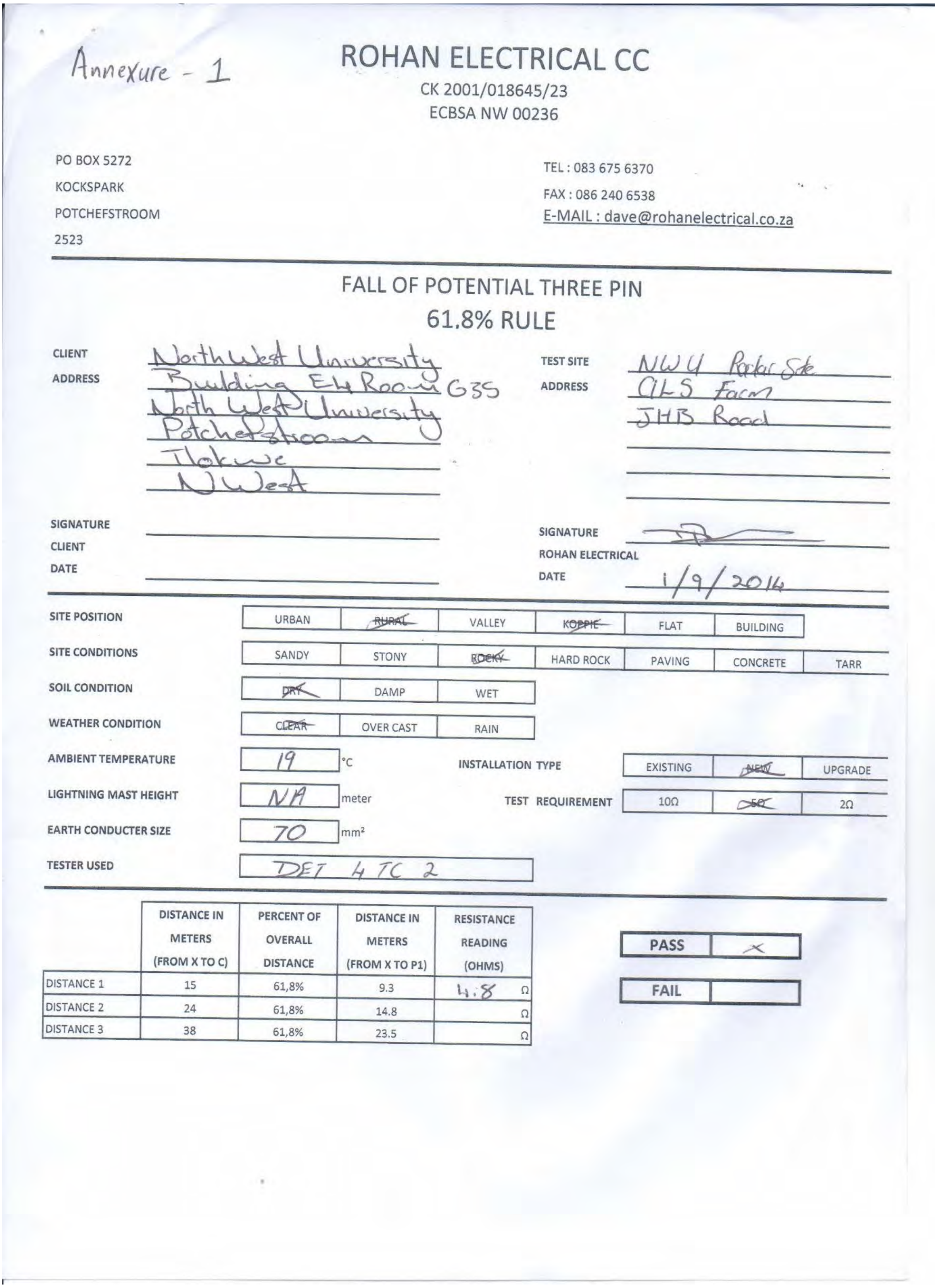
1. knows and understood the contents hereof;
2. has no objection to taking the prescribed oath or affirmation; and
3. considers this oath or affirmation to be truthful and binding on his/her conscience.

Joubert

COMMISSIONER OF OATHS

Name: ADRIANA JOUBERT
COMMISSIONER OF OATHS
Address: EX-OFFICIO: ATTORNEY
Capacity: ORUM, 240 LANGE STREET

D.3 ELECTRICAL CERTIFICATE OF COMPLIANCE (COC)



Annexure - 1

ROHAN ELECTRICAL CC

CK 2001/018645/23
ECBSA NW 00236

PO BOX 5272
KOCKSPARK
POTCHEFSTROOM
2523

TEL : 083 675 6370
FAX : 086 240 6538
E-MAIL : dave@rohanelectrical.co.za

FALL OF POTENTIAL THREE PIN
61.8% RULE

CLIENT ADDRESS North West University
Building E4 Room G35
North West University
Potchefstroom
Tlokwe
N West

TEST SITE ADDRESS NWU Radar Site
CILS Farm
JHB Road

SIGNATURE CLIENT DATE

SIGNATURE ROHAN ELECTRICAL DATE 1/9/2014

SITE POSITION	URBAN	[✓ RURAL]	VALLEY	[✓ KOPPIE]	FLAT	BUILDING	
SITE CONDITIONS	SANDY	STONY	[✓ ROCKY]	HARD ROCK	PAVING	CONCRETE	TARR
SOIL CONDITION	[✓ DRY]	DAMP	WET				
WEATHER CONDITION	[✓ CLEAR]	OVER CAST	RAIN				

AMBIENT TEMPERATURE 19 °C

LIGHTNING MAST HEIGHT NA meter

EARTH CONDUCTER SIZE 70 mm²

TESTER USED DET 4 TC 2

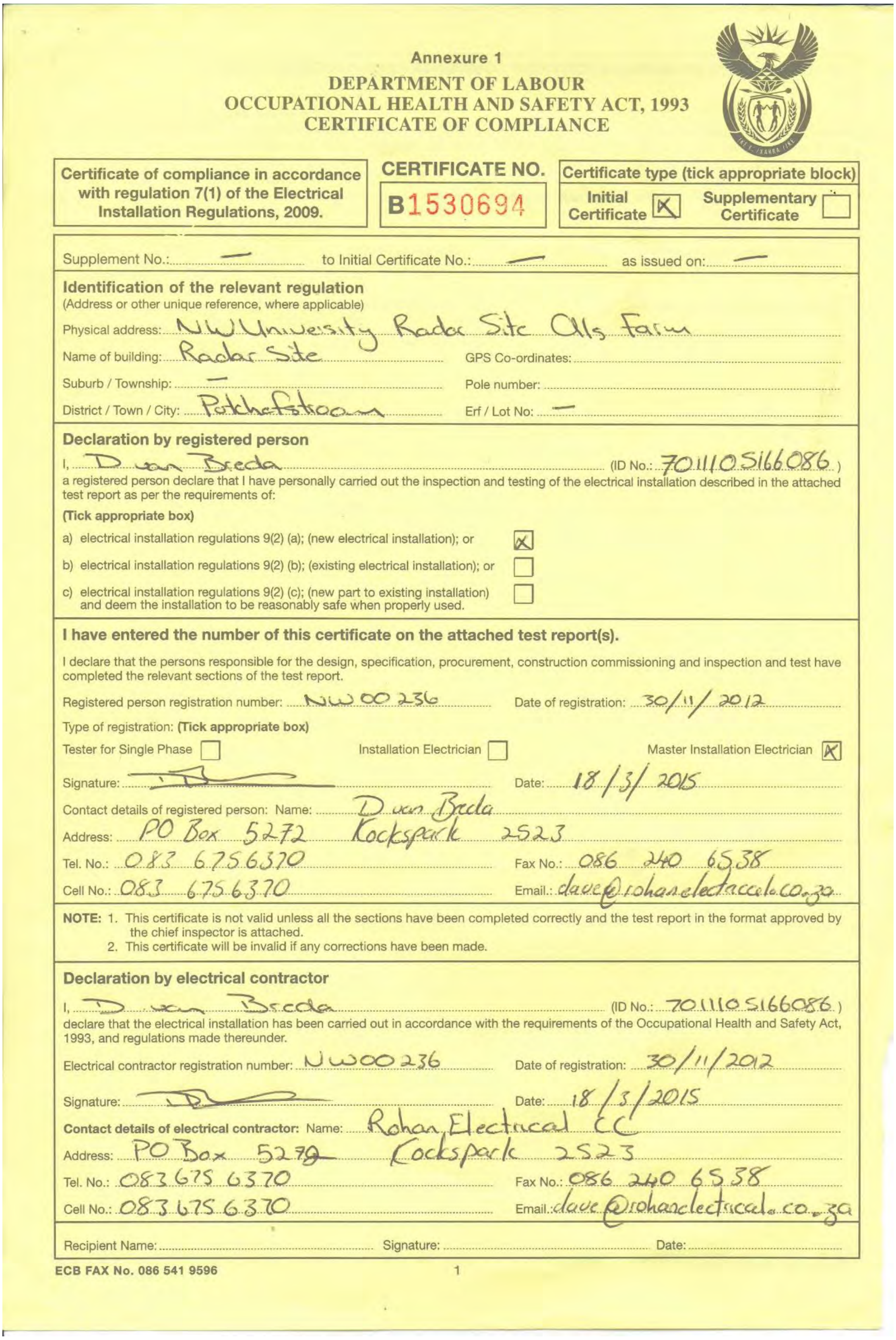
INSTALLATION TYPE EXISTING [✓ NEW] UPGRADE

TEST REQUIREMENT 10Ω [✓ 5Ω] 2Ω

	DISTANCE IN METERS (FROM X TO C)	PERCENT OF OVERALL DISTANCE	DISTANCE IN METERS (FROM X TO P1)	RESISTANCE READING (OHMS)
DISTANCE 1	15	61,8%	9.3	4.8 Ω
DISTANCE 2	24	61,8%	14.8	Ω
DISTANCE 3	38	61,8%	23.5	Ω

PASS ×

FAIL



Annexure 1

DEPARTMENT OF LABOUR
OCCUPATIONAL HEALTH AND SAFETY ACT, 1993
CERTIFICATE OF COMPLIANCE

Certificate of compliance in accordance with regulation 7(1) of the Electrical Installation Regulations, 2009.

CERTIFICATE NO. B1530694

Certificate type (tick appropriate block) Initial Certificate ☒ Supplementary Certificate ☐

Supplement No.: — to Initial Certificate No.: — as issued on: —

Identification of the relevant regulation

(Address or other unique reference, where applicable)

Physical address: NW University Radar Site Olls Farm

Name of building: Radar Site GPS Co-ordinates:

Suburb / Township: — Pole number:

District / Town / City: Potchefstroom Erf / Lot No: —

Declaration by registered person

I, D van Breda (ID No.: 7011105166086)
a registered person declare that I have personally carried out the inspection and testing of the electrical installation described in the attached test report as per the requirements of:

(Tick appropriate box)

a) electrical installation regulations 9(2) (a); (new electrical installation); or ☒

b) electrical installation regulations 9(2) (b); (existing electrical installation); or ☐

c) electrical installation regulations 9(2) (c); (new part to existing installation) and deem the installation to be reasonably safe when properly used. ☐

I have entered the number of this certificate on the attached test report(s).

I declare that the persons responsible for the design, specification, procurement, construction commissioning and inspection and test have completed the relevant sections of the test report.

Registered person registration number: NW 00 236 Date of registration: 30/11/2012

Type of registration: **(Tick appropriate box)**

Tester for Single Phase ☐ Installation Electrician ☐ Master Installation Electrician ☒

Signature: Date: 18/3/2015

Contact details of registered person: Name: D van Breda

Address: PO Box 5272 Kockspark 2523

Tel. No.: 083 6756370 Fax No.: 086 240 6538

Cell No.: 083 6756370 Email.: dave@rohanelectrical.co.za

NOTE: 1. This certificate is not valid unless all the sections have been completed correctly and the test report in the format approved by the chief inspector is attached.
2. This certificate will be invalid if any corrections have been made.

Declaration by electrical contractor

I, D van Breda (ID No.: 7011105166086)
declare that the electrical installation has been carried out in accordance with the requirements of the Occupational Health and Safety Act, 1993, and regulations made thereunder.

Electrical contractor registration number: NW00236 Date of registration: 30/11/2012

Signature: Date: 18/3/2015

Contact details of electrical contractor: Name: Rohan Electrical CC

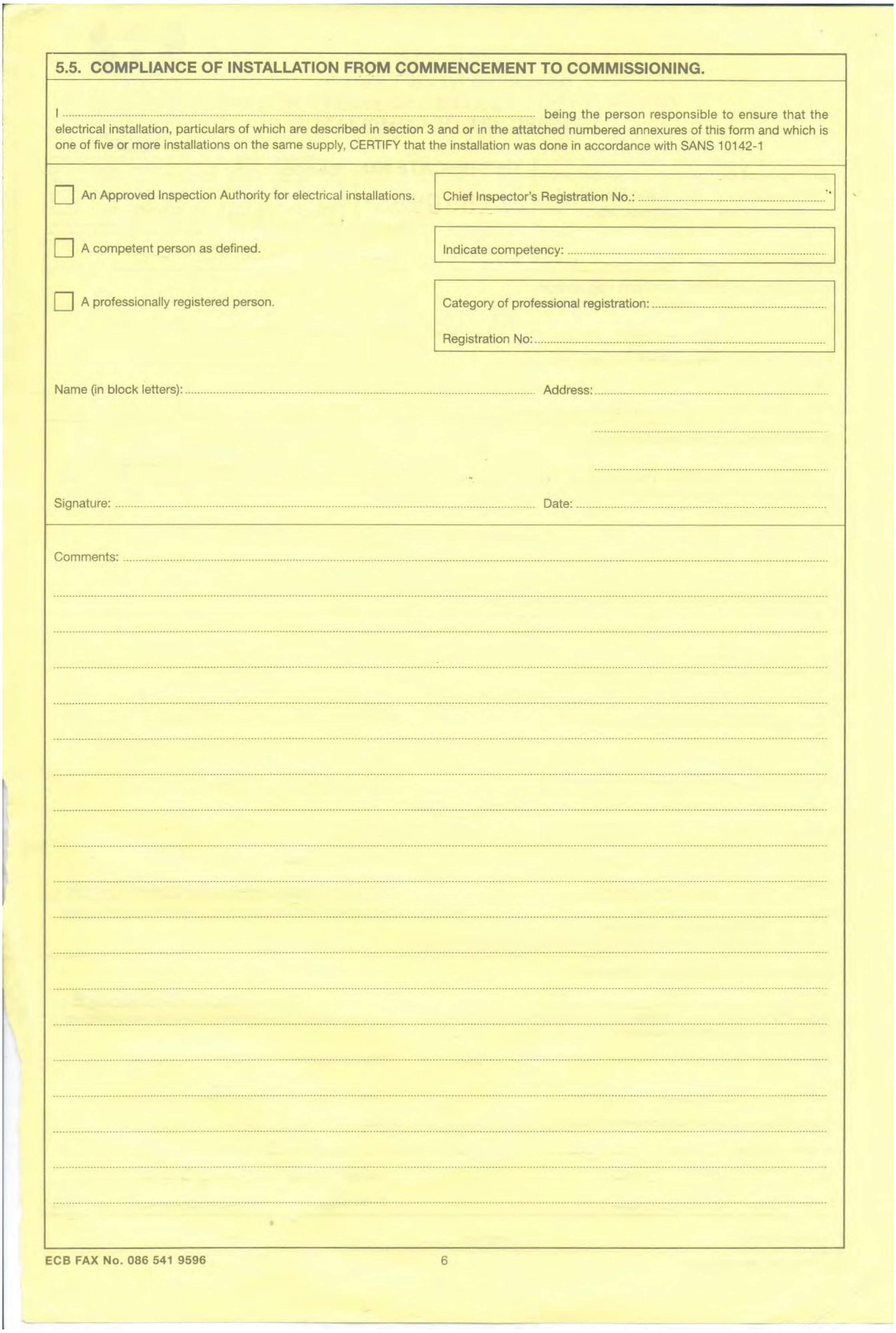
Address: PO Box 5272 Cockspark 2523

Tel. No.: 083 675 6370 Fax No.: 086 240 6538

Cell No.: 083 675 6370 Email.: dave@rohanelectrical.co.za

Recipient Name: Signature: Date:

ECB FAX No. 086 541 9596 1



5.5. COMPLIANCE OF INSTALLATION FROM COMMENCEMENT TO COMMISSIONING.

I .... being the person responsible to ensure that the electrical installation, particulars of which are described in section 3 and or in the attatched numbered annexures of this form and which is one of five or more installations on the same supply, CERTIFY that the installation was done in accordance with SANS 10142-1

☐ An Approved Inspection Authority for electrical installations.	Chief Inspector's Registration No.: ....
☐ A competent person as defined.	Indicate competency: ....
☐ A professionally registered person.	Category of professional registration: .... Registration No: ....

Name (in block letters): .... Address: ....

....

....

Signature: .... Date: ....

Comments: ....

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ECB FAX No. 086 541 9596

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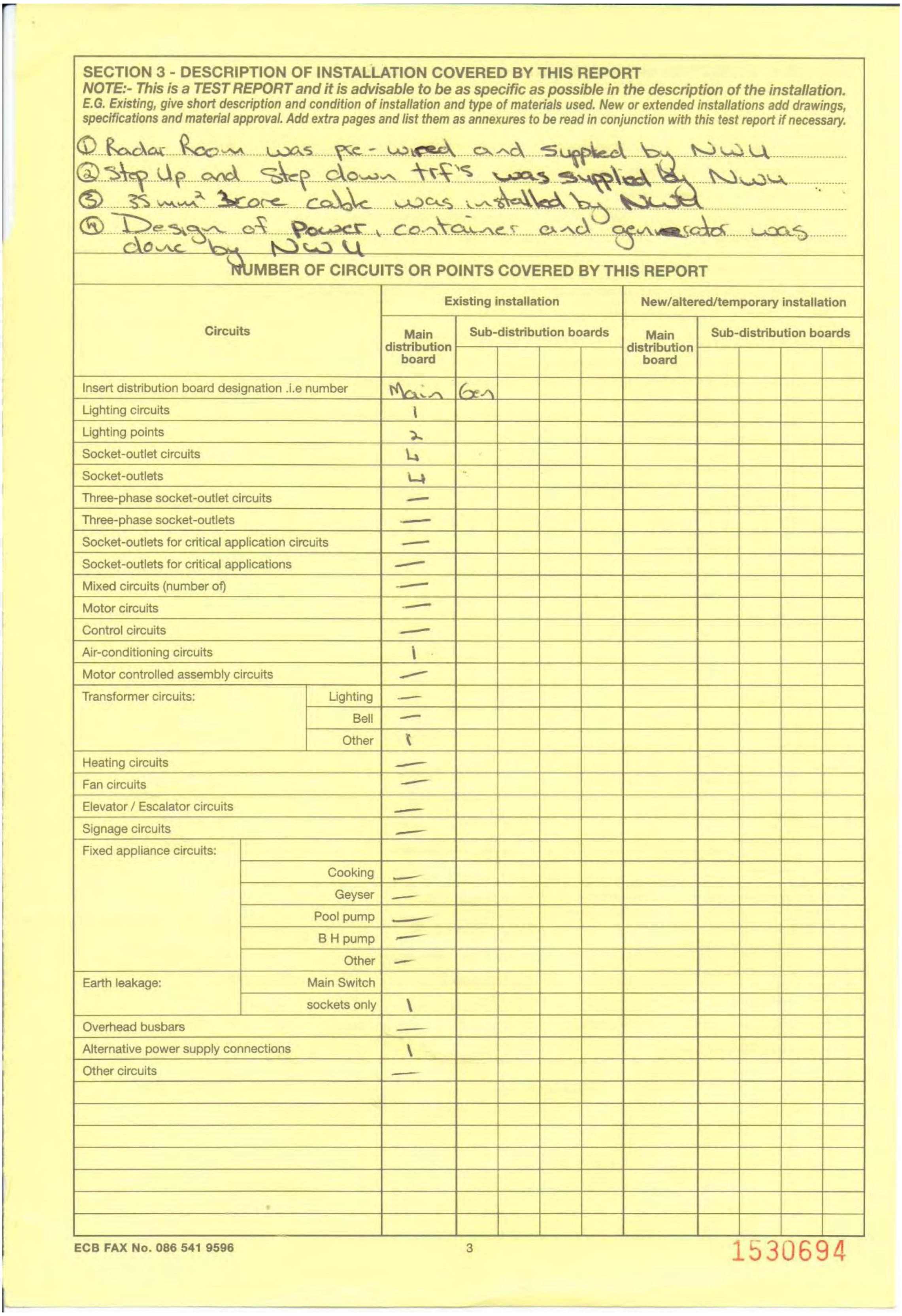


SECTION 3 - DESCRIPTION OF INSTALLATION COVERED BY THIS REPORT

NOTE:- This is a TEST REPORT and it is advisable to be as specific as possible in the description of the installation.

E.G. Existing, give short description and condition of installation and type of materials used. New or extended installations add drawings, specifications and material approval. Add extra pages and list them as annexures to be read in conjunction with this test report if necessary.

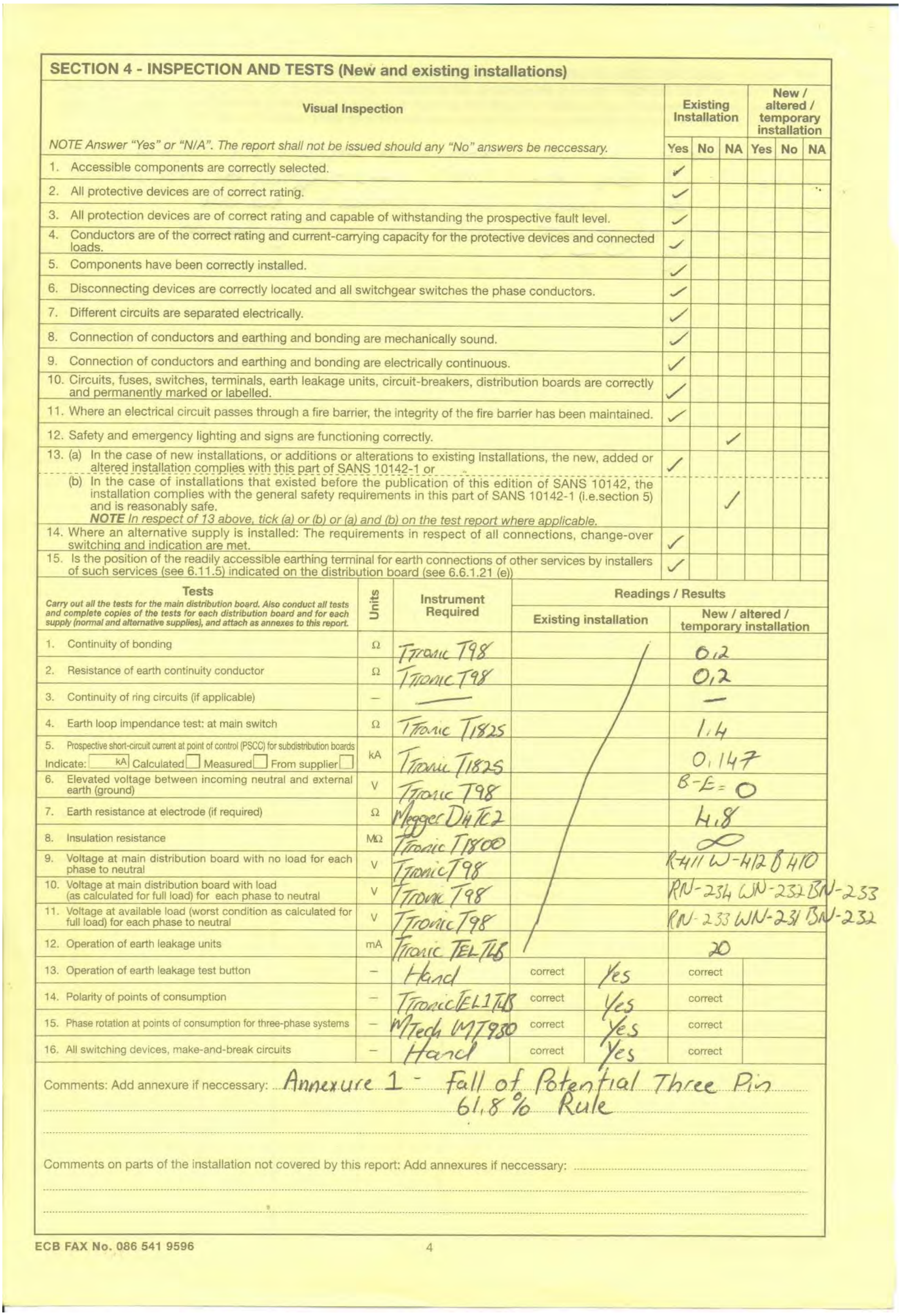
① Radar Room was pre-wired and Suppled by NWU
② Step Up and Step down trf's was supplied by NWU
③ 35 mm² 3core cable was installed by NWU
④ Design of Power, container and generator was done by NWU

NUMBER OF CIRCUITS OR POINTS COVERED BY THIS REPORT

Circuits	Existing installation					New/altered/temporary installation				
	Main distribution board	Sub-distribution boards				Main distribution board	Sub-distribution boards			
Insert distribution board designation .i.e number	Main	Gen								
Lighting circuits	1									
Lighting points	2									
Socket-outlet circuits	4									
Socket-outlets	4									
Three-phase socket-outlet circuits	—									
Three-phase socket-outlets	—									
Socket-outlets for critical application circuits	—									
Socket-outlets for critical applications	—									
Mixed circuits (number of)	—									
Motor circuits	—									
Control circuits	—									
Air-conditioning circuits	1									
Motor controlled assembly circuits	—									
Transformer circuits: Lighting	—									
Bell	—									
Other	1									
Heating circuits	—									
Fan circuits	—									
Elevator / Escalator circuits	—									
Signage circuits	—									
Fixed appliance circuits:										
Cooking	—									
Geyser	—									
Pool pump	—									
B H pump	—									
Other	—									
Earth leakage: Main Switch										
sockets only	1									
Overhead busbars	—									
Alternative power supply connections	1									
Other circuits	—									

ECB FAX No. 086 541 9596

1530694



SECTION 4 - INSPECTION AND TESTS (New and existing installations)

Visual Inspection	Existing Installation			New / altered / temporary installation		
NOTE Answer "Yes" or "N/A". The report shall not be issued should any "No" answers be neccessary.	Yes	No	NA	Yes	No	NA
1. Accessible components are correctly selected.	✓					
2. All protective devices are of correct rating.	✓					
3. All protection devices are of correct rating and capable of withstanding the prospective fault level.	✓					
4. Conductors are of the correct rating and current-carrying capacity for the protective devices and connected loads.	✓					
5. Components have been correctly installed.	✓					
6. Disconnecting devices are correctly located and all switchgear switches the phase conductors.	✓					
7. Different circuits are separated electrically.	✓					
8. Connection of conductors and earthing and bonding are mechanically sound.	✓					
9. Connection of conductors and earthing and bonding are electrically continuous.	✓					
10. Circuits, fuses, switches, terminals, earth leakage units, circuit-breakers, distribution boards are correctly and permanently marked or labelled.	✓					
11. Where an electrical circuit passes through a fire barrier, the integrity of the fire barrier has been maintained.	✓					
12. Safety and emergency lighting and signs are functioning correctly.			✓			
13. (a) In the case of new installations, or additions or alterations to existing Installations, the new, added or altered installation complies with this part of SANS 10142-1 or	✓					
(b) In the case of installations that existed before the publication of this edition of SANS 10142, the installation complies with the general safety requirements in this part of SANS 10142-1 (i.e.section 5) and is reasonably safe. ***NOTE** In respect of 13 above, tick (a) or (b) or (a) and (b) on the test report where applicable.*			✓			
14. Where an alternative supply is installed: The requirements in respect of all connections, change-over switching and indication are met.	✓					
15. Is the position of the readily accessible earthing terminal for earth connections of other services by installers of such services (see 6.11.5) indicated on the distribution board (see 6.6.1.21 (e))	✓					

Tests ***Carry out all the tests for the main distribution board. Also conduct all tests and complete copies of the tests for each distribution board and for each supply (normal and alternative supplies), and attach as annexes to this report.***	**Units**	**Instrument Required**	**Readings / Results** **Existing installation**		**New / altered / temporary installation**	
1. Continuity of bonding	Ω	Ttronic T98			0,2	
2. Resistance of earth continuity conductor	Ω	Ttronic T98			0,2	
3. Continuity of ring circuits (if applicable)	–	—			—	
4. Earth loop impendance test: at main switch	Ω	Ttronic T1825			1,4	
5. Prospective short-circuit current at point of control (PSCC) for subdistribution boards Indicate: ☐ kA Calculated ☐ Measured ☐ From supplier ☐	kA	Ttronic T1825			0,147	
6. Elevated voltage between incoming neutral and external earth (ground)	V	Ttronic T98			B-E = 0	
7. Earth resistance at electrode (if required)	Ω	Megger Di4TC2			4,8	
8. Insulation resistance	MΩ	Ttronic T1800			∞	
9. Voltage at main distribution board with no load for each phase to neutral	V	Ttronic T98			R-411 W-412 B 410	
10. Voltage at main distribution board with load (as calculated for full load) for each phase to neutral	V	Ttronic T98			RN-234 WN-232 BN-233	
11. Voltage at available load (worst condition as calculated for full load) for each phase to neutral	V	Ttronic T98			RN-233 WN-231 BN-232	
12. Operation of earth leakage units	mA	Ttronic TELTLB			20	
13. Operation of earth leakage test button	–	Hand	correct	Yes	correct	
14. Polarity of points of consumption	–	TtronicTEL1TLB	correct	Yes	correct	
15. Phase rotation at points of consumption for three-phase systems	–	MTech MT930	correct	Yes	correct	
16. All switching devices, make-and-break circuits	–	Hand	correct	Yes	correct	

Comments: Add annexure if neccessary: Annexure 1 - Fall of Potential Three Pin 61,8 % Rule

Comments on parts of the installation not covered by this report: Add annexures if neccessary:

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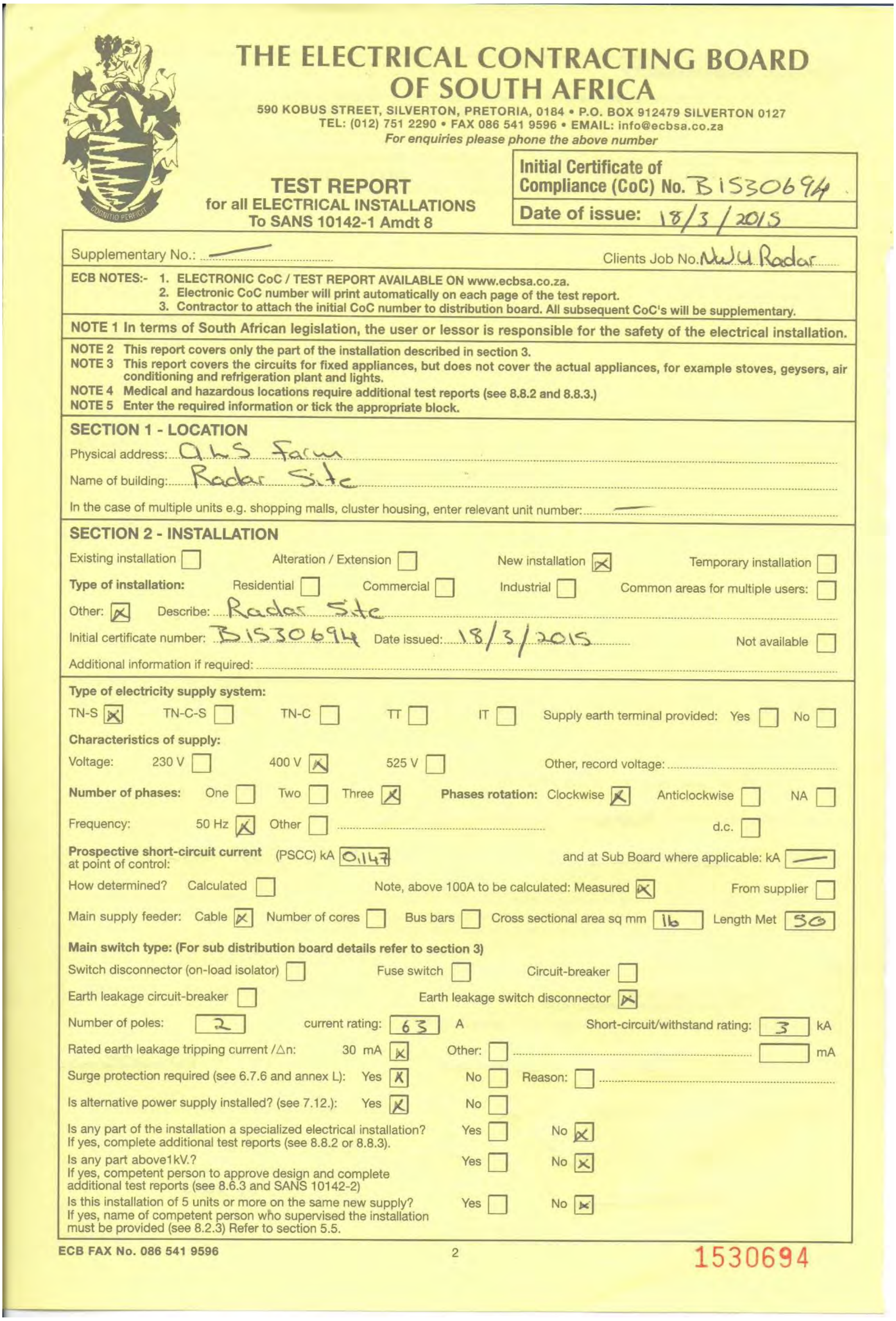

THE ELECTRICAL CONTRACTING BOARD OF SOUTH AFRICA

590 KOBUS STREET, SILVERTON, PRETORIA, 0184 • P.O. BOX 912479 SILVERTON 0127
TEL: (012) 751 2290 • FAX 086 541 9596 • EMAIL: info@ecbsa.co.za
For enquiries please phone the above number

TEST REPORT

for all ELECTRICAL INSTALLATIONS
To SANS 10142-1 Amdt 8

Initial Certificate of Compliance (CoC) No. B1530694

Date of issue: 18/3/2015

Supplementary No.: —

Clients Job No. NWU Radar

ECB NOTES:-
1. ELECTRONIC CoC / TEST REPORT AVAILABLE ON www.ecbsa.co.za.
2. Electronic CoC number will print automatically on each page of the test report.
3. Contractor to attach the initial CoC number to distribution board. All subsequent CoC's will be supplementary.

NOTE 1 In terms of South African legislation, the user or lessor is responsible for the safety of the electrical installation.

NOTE 2 This report covers only the part of the installation described in section 3.
NOTE 3 This report covers the circuits for fixed appliances, but does not cover the actual appliances, for example stoves, geysers, air conditioning and refrigeration plant and lights.
NOTE 4 Medical and hazardous locations require additional test reports (see 8.8.2 and 8.8.3.)
NOTE 5 Enter the required information or tick the appropriate block.

SECTION 1 - LOCATION

Physical address: QLS farm

Name of building: Radar Site

In the case of multiple units e.g. shopping malls, cluster housing, enter relevant unit number: —

SECTION 2 - INSTALLATION

Existing installation ☐ Alteration / Extension ☐ New installation ☒ Temporary installation ☐

Type of installation: Residential ☐ Commercial ☐ Industrial ☐ Common areas for multiple users: ☐

Other: ☒ Describe: Radar Site

Initial certificate number: B1530694 Date issued: 18/3/2015 Not available ☐

Additional information if required:

Type of electricity supply system:

TN-S ☒ TN-C-S ☐ TN-C ☐ TT ☐ IT ☐ Supply earth terminal provided: Yes ☐ No ☐

Characteristics of supply:

Voltage: 230 V ☐ 400 V ☒ 525 V ☐ Other, record voltage:

Number of phases: One ☐ Two ☐ Three ☒ **Phases rotation:** Clockwise ☒ Anticlockwise ☐ NA ☐

Frequency: 50 Hz ☒ Other ☐ d.c. ☐

Prospective short-circuit current at point of control: (PSCC) kA 0,147 and at Sub Board where applicable: kA —

How determined? Calculated ☐ Note, above 100A to be calculated: Measured ☒ From supplier ☐

Main supply feeder: Cable ☒ Number of cores ☐ Bus bars ☐ Cross sectional area sq mm 16 Length Met 50

Main switch type: (For sub distribution board details refer to section 3)

Switch disconnector (on-load isolator) ☐ Fuse switch ☐ Circuit-breaker ☐

Earth leakage circuit-breaker ☐ Earth leakage switch disconnector ☒

Number of poles: 2 current rating: 63 A Short-circuit/withstand rating: 3 kA

Rated earth leakage tripping current /Δn: 30 mA ☒ Other: ☐ mA

Surge protection required (see 6.7.6 and annex L): Yes ☒ No ☐ Reason: ☐

Is alternative power supply installed? (see 7.12.): Yes ☒ No ☐

Is any part of the installation a specialized electrical installation? If yes, complete additional test reports (see 8.8.2 or 8.8.3). Yes ☐ No ☒

Is any part above1kV.? If yes, competent person to approve design and complete additional test reports (see 8.6.3 and SANS 10142-2) Yes ☐ No ☒

Is this installation of 5 units or more on the same new supply? If yes, name of competent person who supervised the installation must be provided (see 8.2.3) Refer to section 5.5. Yes ☐ No ☒

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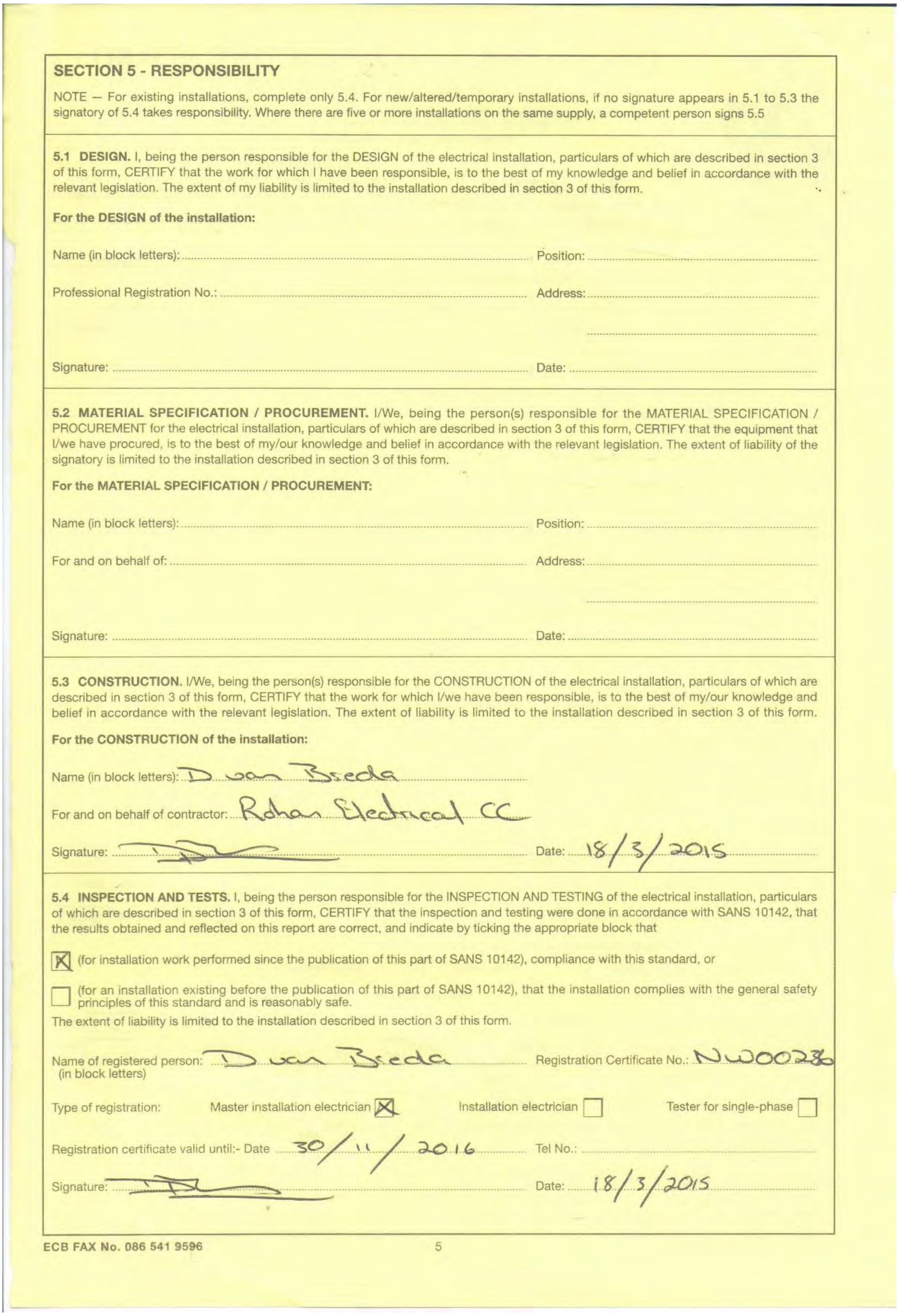

SECTION 5 - RESPONSIBILITY

NOTE — For existing installations, complete only 5.4. For new/altered/temporary installations, if no signature appears in 5.1 to 5.3 the signatory of 5.4 takes responsibility. Where there are five or more installations on the same supply, a competent person signs 5.5

5.1 DESIGN. I, being the person responsible for the DESIGN of the electrical installation, particulars of which are described in section 3 of this form, CERTIFY that the work for which I have been responsible, is to the best of my knowledge and belief in accordance with the relevant legislation. The extent of my liability is limited to the installation described in section 3 of this form.

For the DESIGN of the installation:

Name (in block letters): Position:

Professional Registration No.: Address:

Signature: Date:

5.2 MATERIAL SPECIFICATION / PROCUREMENT. I/We, being the person(s) responsible for the MATERIAL SPECIFICATION / PROCUREMENT for the electrical installation, particulars of which are described in section 3 of this form, CERTIFY that the equipment that I/we have procured, is to the best of my/our knowledge and belief in accordance with the relevant legislation. The extent of liability of the signatory is limited to the installation described in section 3 of this form.

For the MATERIAL SPECIFICATION / PROCUREMENT:

Name (in block letters): Position:

For and on behalf of: Address:

Signature: Date:

5.3 CONSTRUCTION. I/We, being the person(s) responsible for the CONSTRUCTION of the electrical installation, particulars of which are described in section 3 of this form, CERTIFY that the work for which I/we have been responsible, is to the best of my/our knowledge and belief in accordance with the relevant legislation. The extent of liability is limited to the installation described in section 3 of this form.

For the CONSTRUCTION of the installation:

Name (in block letters): D van Breda

For and on behalf of contractor: Rohan Electrical CC

Signature: Date: 18/3/2015

5.4 INSPECTION AND TESTS. I, being the person responsible for the INSPECTION AND TESTING of the electrical installation, particulars of which are described in section 3 of this form, CERTIFY that the inspection and testing were done in accordance with SANS 10142, that the results obtained and reflected on this report are correct, and indicate by ticking the appropriate block that

☒ (for installation work performed since the publication of this part of SANS 10142), compliance with this standard, or

☐ (for an installation existing before the publication of this part of SANS 10142), that the installation complies with the general safety principles of this standard and is reasonably safe.

The extent of liability is limited to the installation described in section 3 of this form.

Name of registered person: D van Breda Registration Certificate No.: NW00236
(in block letters)

Type of registration: Master installation electrician ☒ Installation electrician ☐ Tester for single-phase ☐

Registration certificate valid until:- Date 30/11/2016 Tel No.:

Signature: Date: 18/3/2015