Culprit and victim management RFI environment for a radio astronomy site

by
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Declaration

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Abstract

A methodology is developed to manage the large number of RFI Culprits on a new Radio Telescope location such as the South African site being developed in the Karoo, both during construction and ongoing operations. The requirement for RFI control is presented, with brief reference to the more traditional methods used by other Radio Telescope observatories. The new approach is then presented, based on methods used in the engineering field of Logistic Engineering. Three case studies are used to illustrate how the approach can be applied. Finally, recommendations are made on how the approach can be implemented for new Radio Telescope projects.

Opsomming

‘n Metodolgie word ontwikkel vir die beheer van die groot aantal Radiofrekwensiesteurings oortreders by ‘n nuwe Radio Teleskoop terrein, soos die Suid Afrikaanse terrein wat huidiglik in die Karoo ontwikkel word. Die metodolgie geld beide gedurende konstruksie en gedurende bedryf. Die behoefte vir RFS beheer word aangebied, met kortlikse melding van die meer tradisionele metodes wat ander Radio Teleskoop Sterrewagte gebruik. ‘n Nuwe aanslag, gebaseer op die metodolgieë van Logistieke Ingenieurswese, word dan aangebied. Drie gevallestudies wys hoe hierdie nuwe aanslag toegepas kan word. Laastens word aanbevelings gemaak om hierdie nuwe aanslag met nuwe Radio Teleskoop projekte te implimenteer.

Acknowledgements

Foremost, I would like to thank my supervisor Prof. Howard C. Reader, whose technical insight in the field of RFI as well as his motivation and encouragement was key to this work and to getting it completed. I have learned a lot from Professor Reader and hope to continue a long-lasting working relationship. Secondly, thanks to my wife Kobie for not only having patience when I stared into the distance and my answers to her questions were non-committal, but also for doing the technical editing on this document. Then thanks to my colleagues and specifically to Richard Lord, for valuable discussions as well as for the availability of his calculation spreadsheet. Gideon Wiid helped with practical measurements in the field and Tracy Cheetham has my gratitude for her encouragement and for allowing me to focus on this document when I needed to do so.

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Contents

List of Abbreviations

Abbreviation	Definition	Abbreviation	Definition
AGA	Astronomy Geographic Advantage Act	GHz	Gigahertz
ALMA	Atacama Large Millimeter/sub-millimeter Array	GIS	Geographic Information System
BMS	Building Management System	GLS	General Lighting Service
BW	Band Width	GMRT	Giant Metrewave Radio Telescope
C-BASS	C Band All Sky Survey	GPS	Global Positioning System
CFL	Compact Fluorescent Light	GSM	Global System for Mobile Communications: originally from Groupe Spécial Mobile
CISPR	Comité International Spécial des Perturbations Radioélectrique (Special International Committee on Radio Interference)	HartRAO	Hartbeeshoek Radio Astronomy Observatory
CRETE	Common Range Electronic Test Equipment	HPS	High Pressure Sodium
dB	Decibel	i.e.	That is
dBm	Decibel referenced to 1 milliwatt	IF	Intermediate Frequency
DME	Distance Measuring Equipment	ITU	International Telecommunications Union
eg.	For example	Jy	Jansky (unit of measure)
EMC	Electro Magnetic Compatibility	KAT-7	Karoo Array Telescope with 7 Antennas
EMI	Electro Magnetic Interference	LAC	Logistic Analysis Candidate
EN	European standards maintained by CEN (European Committee for Standardization)	LAN	Local Area Network
etc	Etcetera (And so forth)	LED	Light Emitting Diode
FCC	Federal Communications Commission	lm	lumen
FMECA	Failure Mode, Effects and Criticality Analysis	LPDA	Log Periodic Dipole Array
GBT	Green Banks Telescope	LSA	Logistic Support Analysis

Abbreviation	Definition	Abbreviation	Definition
MeerKAT	Expanded Karoo Array Telescope with 64 antennas		
MHz	Megahertz		
NRAO	National Radio Astronomy Observatory (in the USA)		
OEM	Original Equipment Manufacturer		
PAPER	Precision Array for the Probing of the Epoch of Re-Ionisation		
PSU	Power Supply Unit		
RA	Radio Astronomy		
RAMLOG	Brand name of software package used for RFI database		
RFI	Radio Frequency Interference		
RQZ	RFI Quiet Zone		
S/N	Signal to Noise Ratio		
SARAAA	South African Radio Astronomy Advantage Area		
SARAS	South African Radio Astronomy Service		
SKA-SA	Square Kilometer Array Africa		
SoP	Standard Operating Procedure		

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CHAPTER 1 INTRODUCTION

1.1 Research Motivation

Science and engineering of Radio Astronomy in South Africa is experiencing a growth phase with the establishment of the Radio Astronomy Advantage Area and the bid for the Square Kilometre Array (SKA). Radio Frequency Interference (RFI) is one of the key issues for Radio Telescopes, as it has direct impact on the operational performance. The support from the international community to locate systems such as PAPER, C-BASS and possibly SKA in South Africa is due to our relatively radio-quiet environment, when compared to that of countries in Europe and North America.

The RFI environment of a Radio Astronomy site includes the inherent environment (used as a criterion for selecting the site) as well as the induced environment, due to the introduction of Radio Telescope equipment and supporting infrastructure (such as Electrical Power systems) on the site. If a relatively quiet environment is selected initially, the induced RFI can be the dominating source and, if not managed properly, can become a severe limitation to the performance of the Radio Telescope.

This thesis develops management methodologies and tools which may be used to control the induced RFI environment, to ensure that the equipment introduced does not degrade the site.

1.2 Background

Effort has been invested to characterize the RFI environment of the South African Site by Manners [1] ,and also by researchers preparing the South African SKA proposal to host the SKA site [2]. This defines what we have.

Tiplady [4] specified a strict South African Radio Astronomy Service (SARAS) standard and Lord [7] developed a standard method for calculating threshold levels. This defines where we want to be.

A new approach is proposed which can be used to manage the equipment introduced on site to ensure the SARAS standard [4] is maintained. This defines how we get to where we want to be.

This work is based on the experience of the author with the design and development of electronic systems for submarines (Culprit and Victim methodology) as well as the development of various logistic support systems (Logistic Support Analysis or LSA).

In the Radio Telescope environment, the Radio Telescopes (Receivers) are seen as the victims and all the equipment introduced on site (Radio Telescope electronics, power systems, vehicles etc) as culprits for RFI. The logical approach to analysis of systems used in LSA was adapted and applied to the analysis of the RFI Culprits.

1.3 Objective of this Study

The scope (or parameter space) of the RFI on a Radio Astronomy site is substantial and includes:

a. A significant number of systems from various technologies such as RF, digital electronics, power systems, industrial systems, vehicles and domestic equipment.

b. Equipment in various stages of their life-cycles including; planned, in-design, off-the-shelf procurement, being installed, commissioned and in operation.

c. A large geographic area with several sites is planned, including the antenna area, the site complex and the support base, and the surrounding community (farms).

d. The various frequencies of the telescopes.

The management of these issues, given an application of limited resources (people, equipment, time and money), is the challenge which was addressed in the development of the new approach to RFI management.

The intention is to develop a logical, traceable approach where the scope of the RFI issues can be narrowed. The critical issues will be concentrated on, limited resources focused, records maintained and progress of achievements and future tasks reported on.

1.4 Overview of this Work

1.4.1 Overview of the Document

The thesis consists of the following Chapters:

a. Chapter 1: Introduction

   This chapter gives the background to the work, as well as an overview of the process developed.

b. Chapter 2: Literature Study

   This chapter includes documents which define the requirement for the control of a radio quiet area, documents which define the level of radio interference in the radio quiet area before any new Radio Telescopes and related infrastructure are deployed, documents which define the typical standards for radio frequency emissions which commercial-off-the-shelf equipment meets and documents which describe the approach to controlling RFI by Radio Telescope observatories in other parts of the world.

c. Chapter 3: Requirement and Challenge

   This chapter defines the requirement and the challenge, including the scope (both width and depth) of the possible RFI on a Radio Astronomy Site.

d. Chapter 4: Developed Methodology and Process

   This chapter describes the solution which was developed to manage the requirement of RFI on a Radio Astronomy Site.

e. Chapter 5: Case Studies

This chapter demonstrates, by examples and case studies, how the methodologies described in the previous chapters can be used to manage RFI on a Radio Astronomy Site. The following three case studies are presented; Case Study 1: Farm Equipment, Case Study 2: Voltage Regulators and Case Study 3: Lights.

f. Chapter 6: Conclusions and Recommendations

This chapter gives the conclusions and recommendation of where the process developed may be applied.

1.4.2 Summary of new Process developed for this Thesis

Figure 1-1 gives an overview of the approach developed for this thesis:

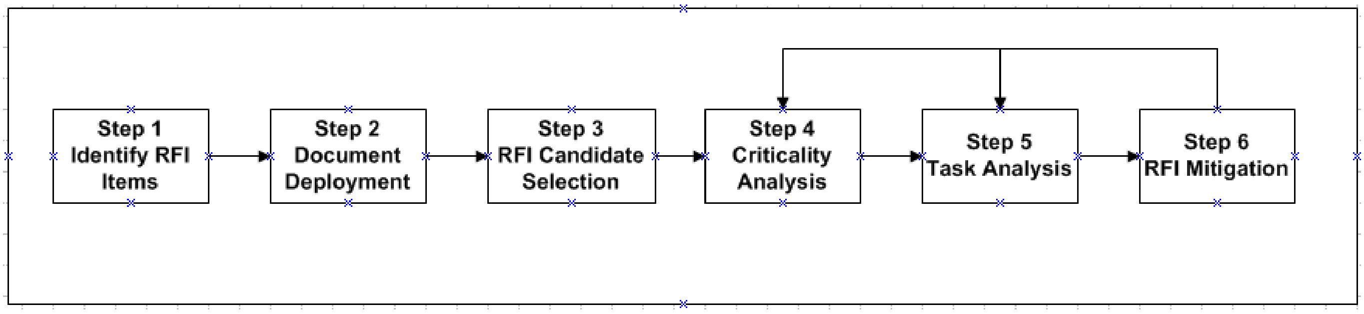


Figure 1-1: Overview of developed approach for RFI Management

A low RFI environment is essential to meet the Radio Telescope requirements of high sensitivity and wide bandwidth. Once a suitable site has been selected (such as the South African Radio Astronomy Advantage Area or SARAAA), it is important not to 'degrade' the site due to introduction of the telescope itself or its support and ancillary equipment.

The scope of possible RFI Sources on such a site is very wide. The traditional approach to control RFI is to measure each item (e.g. in an EMC test facility) and to ensure that the design meets a specific standard. The equipment is then modified and re–tested until it meets this standard. This approach is not advisable for the wide range of commercial-off-the-shelf and other equipment deployed to the SARAAA, as it would be prohibitively expensive, and often overkill.

An alternative methodology has been developed to manage the problem by focusing resources on high risk issues. This methodology was based on the LSA process, as this approach was found to be well suited for the management of RFI, with a few adaptations.

Step 1: Identify the RFI Items

This includes all the Victims (Receivers) and Culprits (Transmitters) and may be done during design/planning phases, as the equipment is deployed to site, or by surveys of existing installations.

Step 1 is similar to the development of the product breakdown structure in LSA.

Step 2: Document the Deployment Plan

This includes the locations of equipment and deployment dates.

Step 2 is similar to deployment plan in LSA.

These first two steps already enable some basic management decisions.

Step 3: RFI Candidate Selection

Front-end analysis, using whatever information is available on the equipment (standards, test results, engineering judgment) is done. This analysis considers the criticality of possible RFI from the Culprit for each possible Victim, taking into account deployment, frequencies, radiated power levels and the effect of the terrain.

Step 3 is similar to Logistic Analysis Candidate (LAC) selection in LSA.

After this step, a many items may be identified as of low risk. These items are logged and monitored, but no further resources are used, i.e. available resources may be focused on the higher risk items.

Step 4: RFI Criticality

The candidates selected in Step 3 are now subject to RFI analysis. This includes identification of RFI Modes and Criticality analysis.

Step 4 is similar to Failure Mode Analysis in LSA.

Step 5: Task Analysis

Task are defined, including additional tests, design modifications and additional screening. Resource allocation to these tasks is defined (facilities, people and procedures).

Step 5 is similar to Maintenance Task Analysis in LSA.

Step 6: Manage RFI Mitigation

The results of Step 4 can be used to initiate and manage mitigation actions. Once the results of these actions (e.g. additional testing) are available, the process can be refined.

The advantages of this approach are:

a. It can be followed at any stage of the life-cycle of equipment; in early design and planning, during or after deployment.

b. A wide range of items may be managed by focusing resources in critical areas.

c. Refinement may be made as additional information about items becomes available.

d. The effect of decisions made may be monitored.

e. Suitable mitigation strategies can be developed, including design changes, operating procedures (when and what to switch off), etc.

1.4.3 Summary of the Case studies demonstrating the application of the new Process

Three case studies are described in Chapter 5 to illustrate the application of the developed process. These case studies are:

a. Case Study 1: Farm Equipment (see paragraph 5.2)

Farm equipment are potential RFI Culprits, and include equipment for power generation, kitchen use, entertainment and communications on the farms surrounding the site. Measurements were made by a MESA team including the author [14], and the results of these measurements were used to develop the analysis process. The results from the analysis may be used to develop equipment guidance to farmers.

b. Case Study 2: Voltage Regulators (see paragraph 5.3)

The designed 22 / 33 kV grid line includes voltage regulators to compensate for the voltage drop due to the large distance of the core site from the ESKOM substation. These voltage regulators are potential RFI Culprits and were subjected to RFI analysis. The design for the grid line was changed as a result of this analysis and the position of the voltage regulators changed.

c. Case Study 3: Lights (see paragraph 5.4)

The buildings at the site complex require lighting. This ranges from high level lights for the construction shed and electronic racks in the data centre area to domestic lights in the office and accommodation area. Various types of lights were tested and analyzed, using the techniques developed in Chapter 4. The results from the analysis may be used to give guidelines to the building designers.

CHAPTER 2 LITERATURE STUDY

This chapter reviews:

a. Documents which define the requirement for the control of a radio quiet area, the various areas where such control is applicable, as well as the levels of radio quietness required for a Radio Telescope to perform well.

b. Documents which define the level of radio interference in the radio quiet area before any new Radio Telescopes and related infrastructure are deployed.

c. Documents which define the typical standards for radio frequency emissions which commercial-off-the-shelf equipment must meet. This includes specific documents for the case studies in Chapter 5.

d. Documents which describe the approach to controlling RFI by Radio Telescope observatories in other parts of the world.

2.1 The Astronomy Geographic Advantage act, 2007 (Act No 21 of 2007) (AGA act) [6]

The AGA act gives the Legal requirement and authority for the protection of the Astronomy Advantage Area. It gives the Minister of Science and Technology powers to declare protection areas.

A more accessible overview of the act is given in the document “Overview of Radio Astronomy Protection in the Northern Cape Province” by Smuts and Tiplady [13]. The AGA act [6] also defines the areas that are to be controlled. These areas are the Core, Central and Co-ordinated areas.

The following three figures from [6, 13] shows the three control areas:

a. Core Area.

b. Central Area.

c. Co-ordinated Area.

a. <u>The Core Area from the AGA act [6, 13]</u>

The major and critical components of the MeerKAT and the SKA telescopes will be located within this area (see Figure 2-1). This is where the overall protection scheme will be centred. No radio communication stations will be permitted in this area, whether they are fixed, mobile, portable, short range devices or any device with an EMC impact, unless authorized by the operating authority of the Radio Astronomy facility. Authorisation will be obtained only by compliance with stringent EMC requirements. Access control to the area will be enforced.

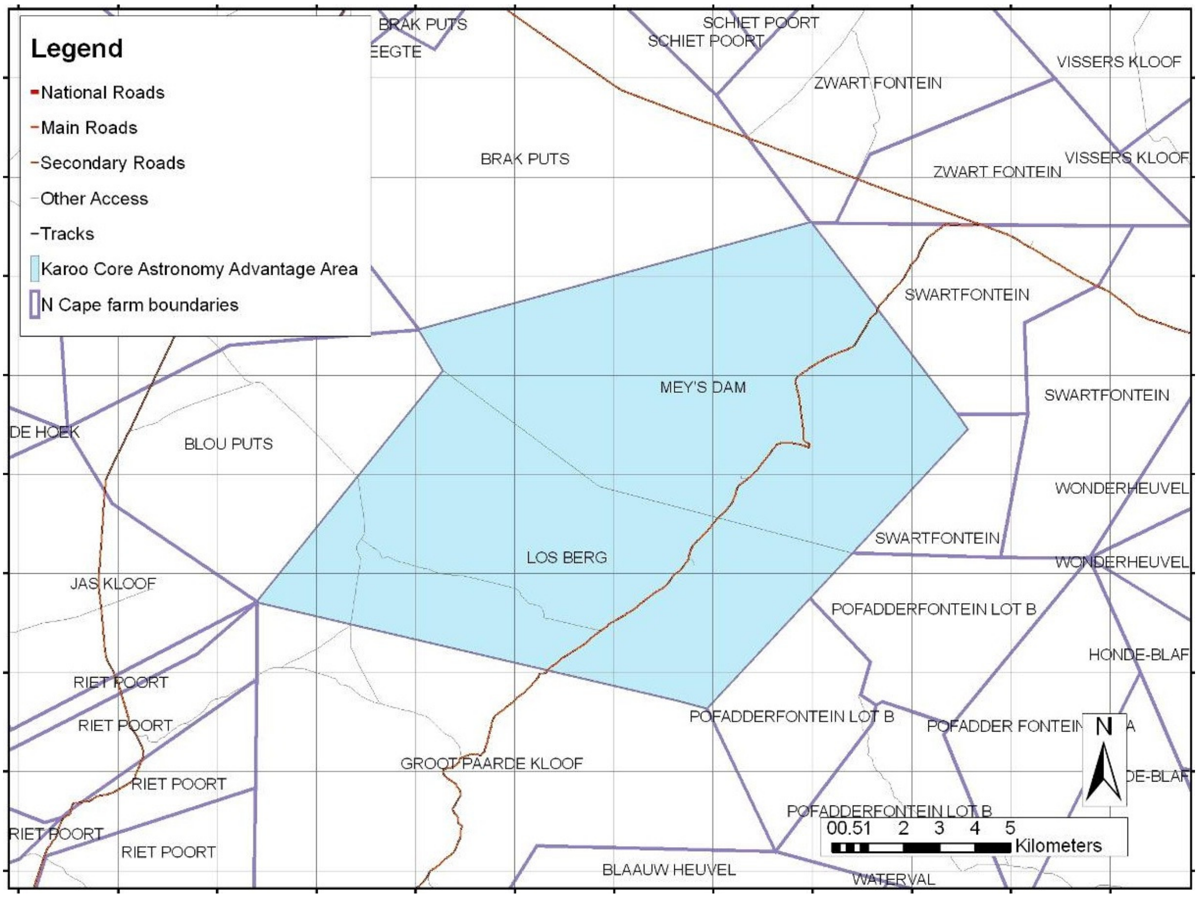


Figure 2-1: The Core Area as defined in the AGA act, consisting of the two farms Losberg and Meysdam, shaded in blue [6,13]

b. The Central Area from the AGA act [6, 13]

Three partly overlaying central astronomy advantage areas will be declared for the purposes stated in section 7(2) of the AGA act (see Figure 2-2). The act provides that declared activities listed in section 23(1) may be restricted or may only be conducted according to standards and conditions prescribed through regulations. The protection of the areas will be related to the SKA Radio Telescope, and each will be linked to a part of the SKA operating frequency spectrum and their propagation characteristics, as listed below:

i. KCenAAA 1 for frequency spectrum from 70 to 1 710 MHz.

ii. KCenAAA 2 for frequency spectrum from 1 710 to 6 000 MHz.

iii. KCenAAA 3 for frequency spectrum from 6 000 to 25 500 MHz.

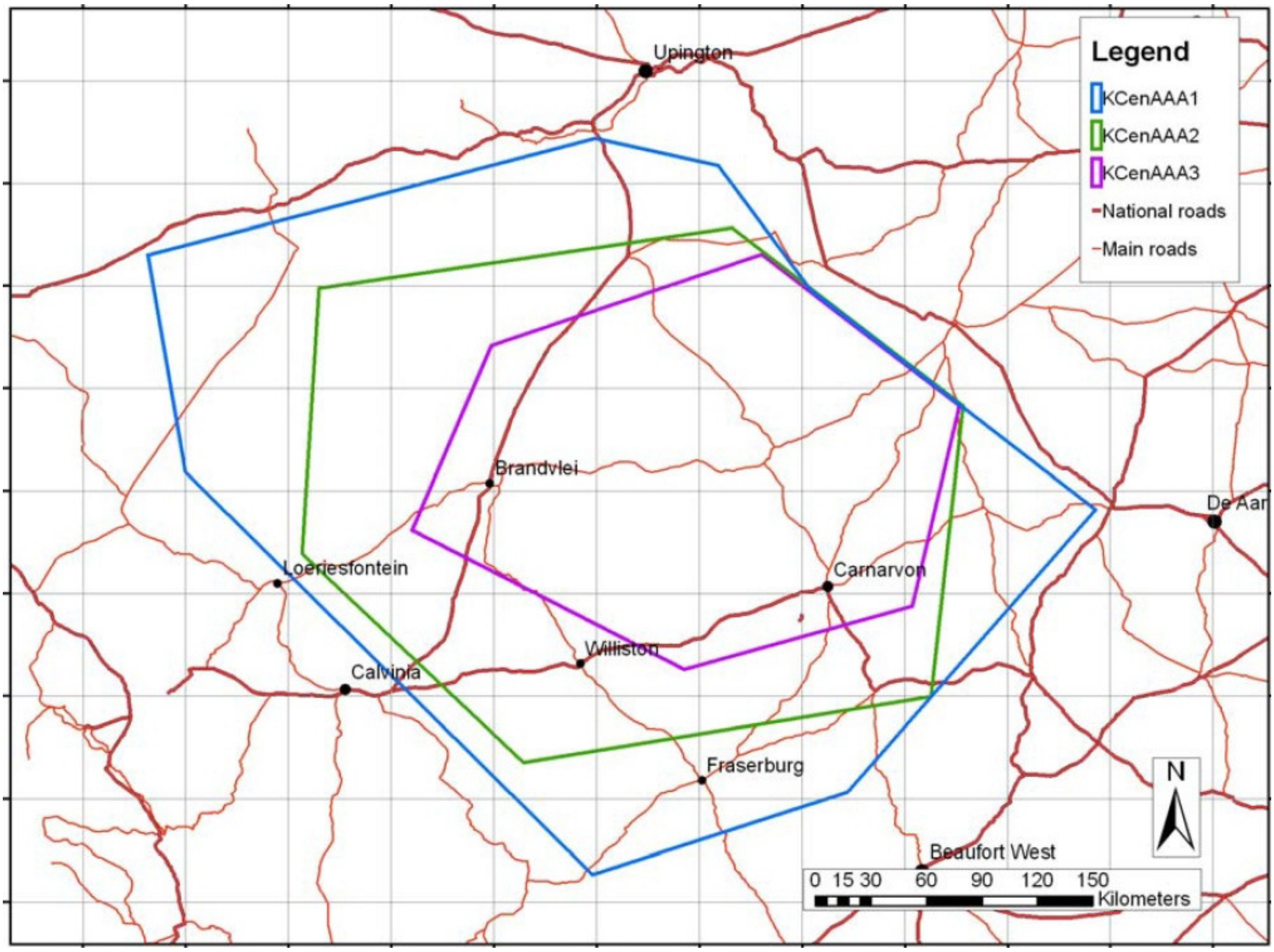


Figure 2-2: The Central area as defined in the AGA act. Area AAA1 is for frequencies between 70 MHz and 1 710 MHz, Area AAA2 is for frequencies between 1 710 MHz and 6 GHz and Area AAA3 is for frequencies between 6 GHz and 25 GHz [6, 13]

c. The Coordinated Areas from the AGA act [6, 13]

The Karoo Coordinated Astronomy Advantage Areas (KCoorAAAs) (see Figure 2-3) will be declared for the purposes stated in section 11(3) of the AGA act. Activities in these areas (in certain categories as prescribed in section 24(2) of the AGA act) which may cause RFI to Radio Astronomy and may have a detrimental effect, will be declared as identified activities. Identified activities may only be undertaken according to prescribed standards and conditions.

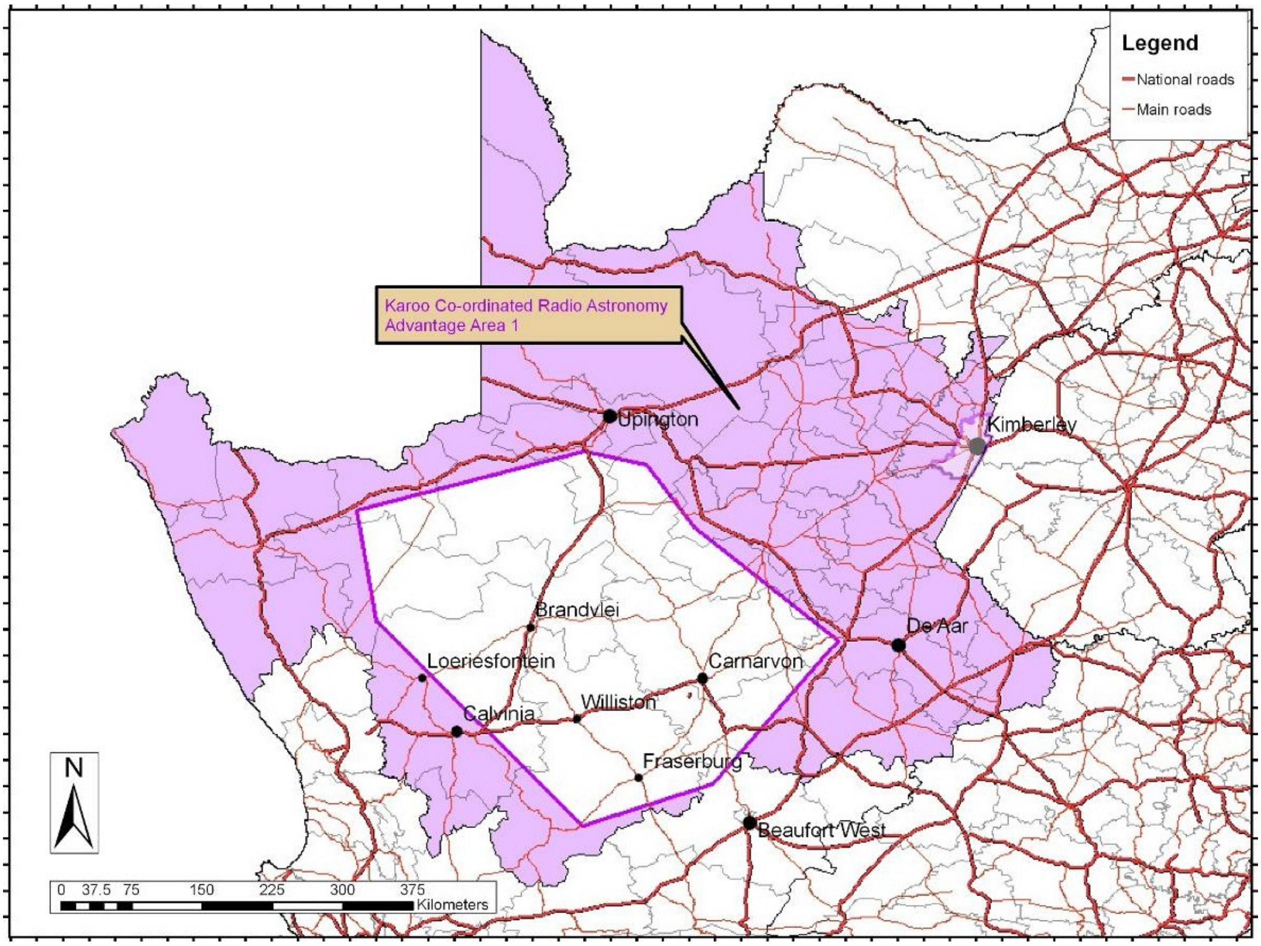


Figure 2-3: The Co-ordinated area as defined in the AGA act. This includes the complete province of the Northern Cape [6, 13].

d. Conclusion and Applicability of AGA act [6, 13]

The act defines the control of RFI in 'legal' terms, but it is not very specific on how such control should be performed. The approach developed in this thesis intends to contribute a more focused engineering management approach to the control of RFI, in the areas defined in the Act.

2.2 South African Radio Astronomy Service (SARAS) Protection Levels [4]

The SARAS Protection levels [4] were developed by Tiplady [4] as a South African extension to the International Telecommunications Union (ITU) standard ITU-R RA.769-2 [3]. The SARAS memorandum gives the level of emissions permissible at the Radio Telescope, attributable to an RFI Source.

The SARAS memorandum makes the following two assumptions:

a. Integration time of 2 000 s.

b. Bandwidth of 10% of the observing frequency.

Figure 2-4 gives the protection levels in the SARAS memo:

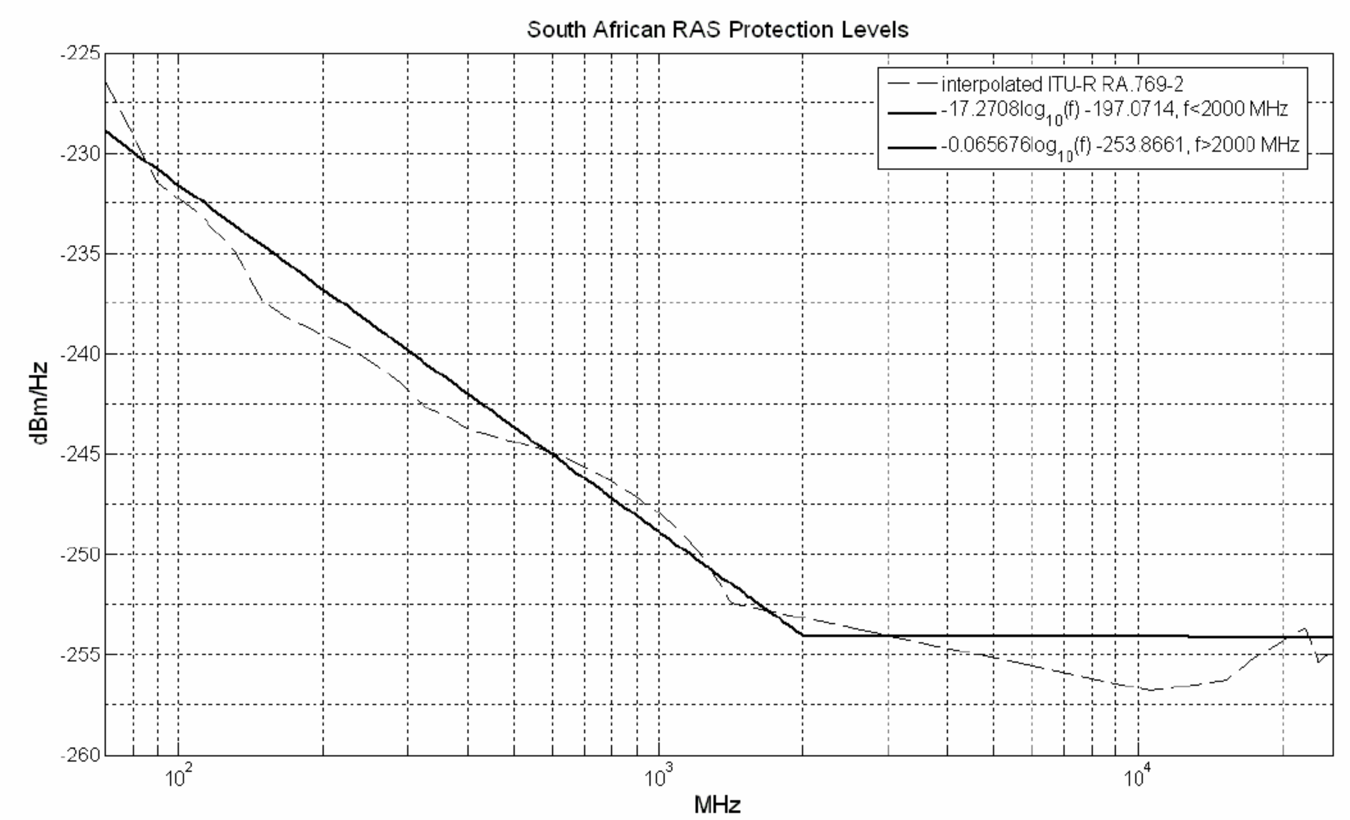


Figure 2-4: SARAS Protection levels indicating the maximum signals permissible at a Radio Telescope due to an interfering RFI Source [4]

Conclusion and Applicability of [4]:

The SARAS protection levels are used as the target to be achieved in the control of RFI. These levels are useful when processing the results of a survey done at the planned location of the future Radio Telescope. A limitation of this document is that it specifies the levels at the Telescope (Victim). When investigating the RFI from a specific Culprit, it is preferable to take measurements close to the source (Victim). To do that, conversion of the SARAS levels are required to take propagation losses into account. This is done in the Calculation Standard by Lord [7].

2.3 SKA SA Standard for Calculating RFI Threshold Levels [7]

The Calculation Standard [7], with its easy-to-use spreadsheet model, was developed by Lord [7] as a tool to investigate the predicted RFI level at the Radio Telescope (Victim), from a RFI Source (Culprit), given the following parameters:

a. Source level of the RFI Source, including the reduction due to special screening measures.

b. Distance between the Radio Telescope and RFI Source. This is used to calculate the free space loss.

c. Height above ground of the Radio Telescope and RFI Source. This is used to calculate the land propagation loss.

d. Test equipment measurement distance when converting from dBm/(Hz.m^2) to dBuV/(Hz.m^2).

The model calculates and displays a graph which defines the level which can be measured at the equipment to meet the SARAS protection levels.

Figure 2-5 gives the maximum radiation levels for a RFI Source 5km away from the Radio Telescope, calculated using the Calculation Standard [7]:

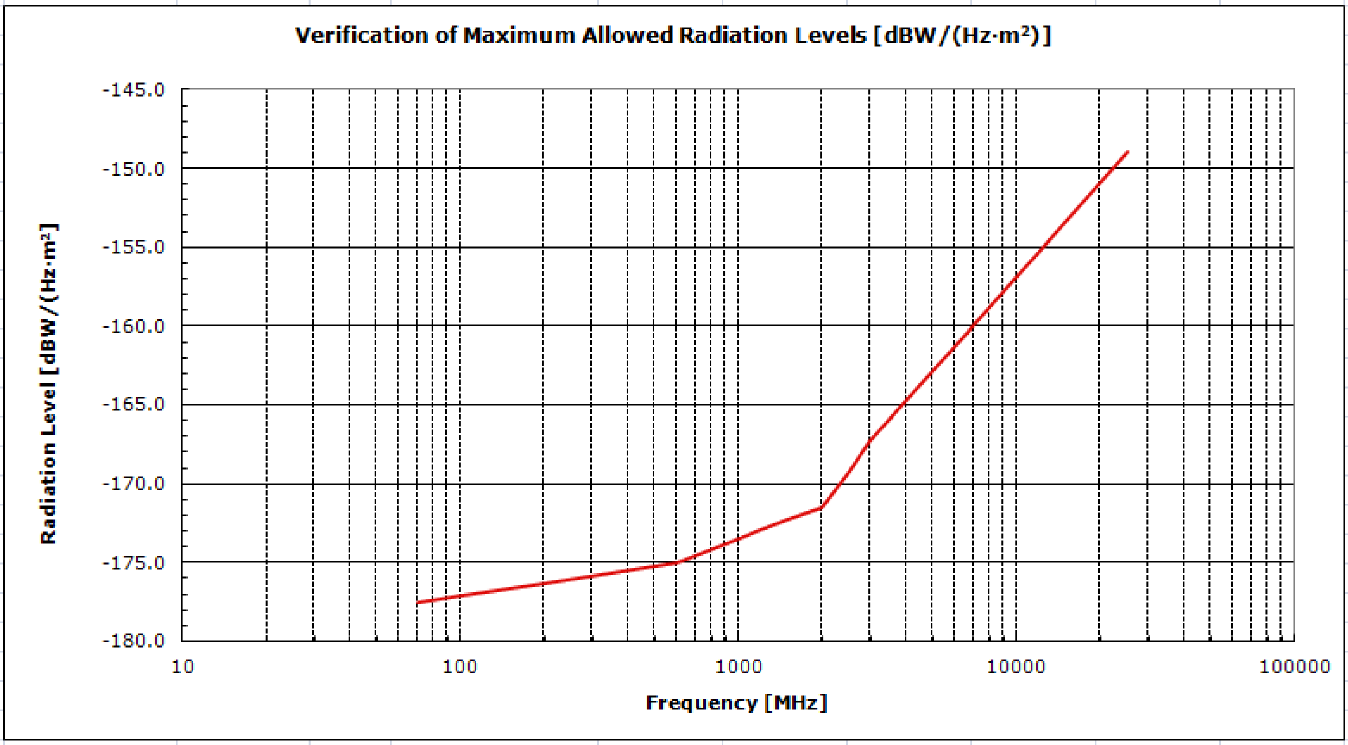


Figure 2-5: Maximum allowed radiation levels from a RFI Source 5 km away from a Radio Telescope using the Calculation Standard [7]

Figure 2-6 shows the maximum allowed radiation levels for a RFI Source 5 km away from the Radio Telescope when measured by a test antenna and test Receiver such as a spectrum analyzer at 10 m from the RFI Source:

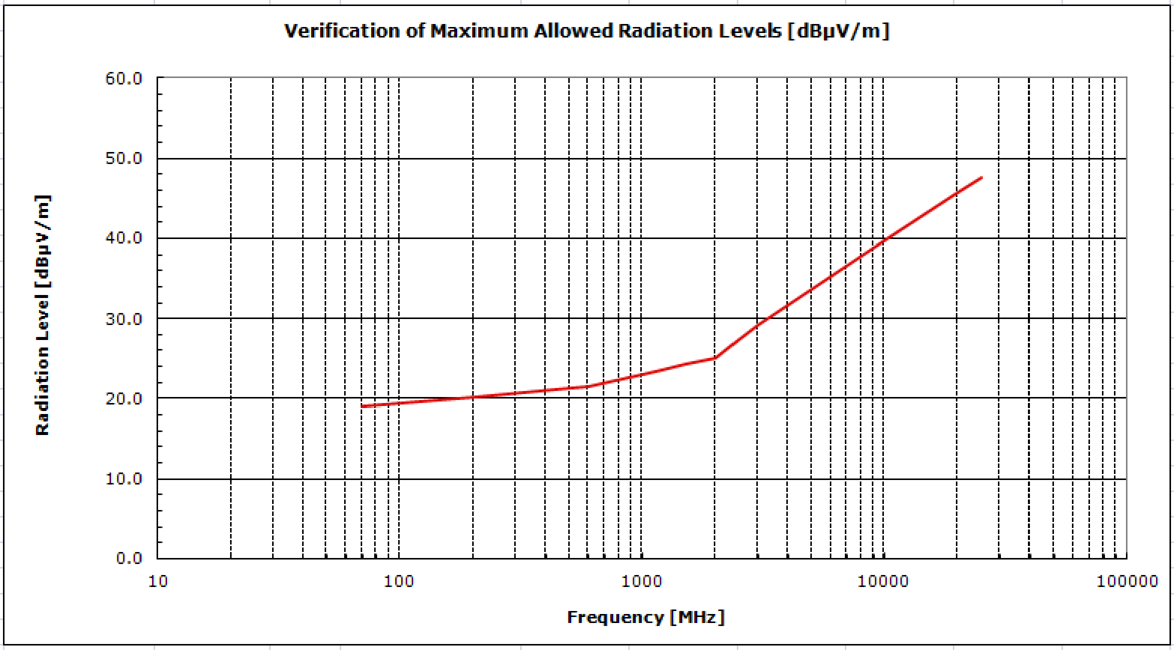


Figure 2-6: Maximum allowed radiation level from RFI Source 5 km from Radio Telescope when measured by test antenna 10 m away from RFI Source

Figure 2-7 shows the noise floor of a typical test instrument, the Rohde and Schwarz spectrum analyser FSH8, compared to the maximum allowed radiation level for a RFI Source 5 km away from the Radio Telescope. In this case, the FSH8 may be used as a measurement Receiver since its noise floor is below the allowed signal level.

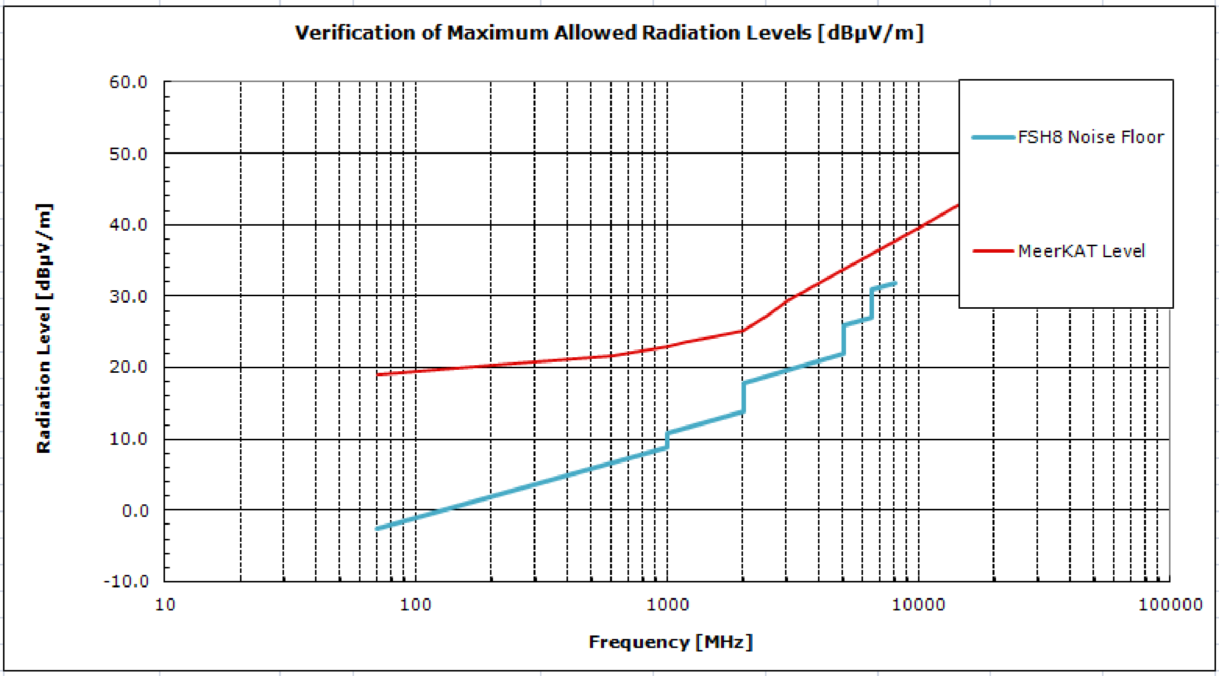


Figure 2-7: The noise floor of a typical test instrument such as the FSH8 compared to the calculated level for a Source 5 km away from the Radio Telescope

Conclusion and Applicability of [7]

The Calculation Standard [7] is a useful tool and was used extensively in the development of the RFI database – see Chapters 4 and 5 for details.

Lord has generated a number of useful documents related to the control of RFI in the Radio Telescope environment and one which may be used as an introduction to this important subject is [9] "RFI and Radio Astronomy - Why the Fuss?"

2.4 Measuring the RFI Environment of the South African SKA Site [1]

The MSc thesis by Manners [1] describes the survey of RFI present at the South African site. It includes:

a. The measurement protocols based on the SKA Memorandum [8].

b. The specialised measurement equipment used.

c. How this measurement equipment was screened against RFI generated by itself.

d. The results of the survey for various modes and frequencies.

Figure 2-8 shows the measurement system developed and used for the RFI survey [1].

Figure 2-8: RFI Measurement System developed for the RFI Environmental Survey [1]

Figure 2-9 from [1] shows the measured environment from 70 MHz to 2 000 MHz.

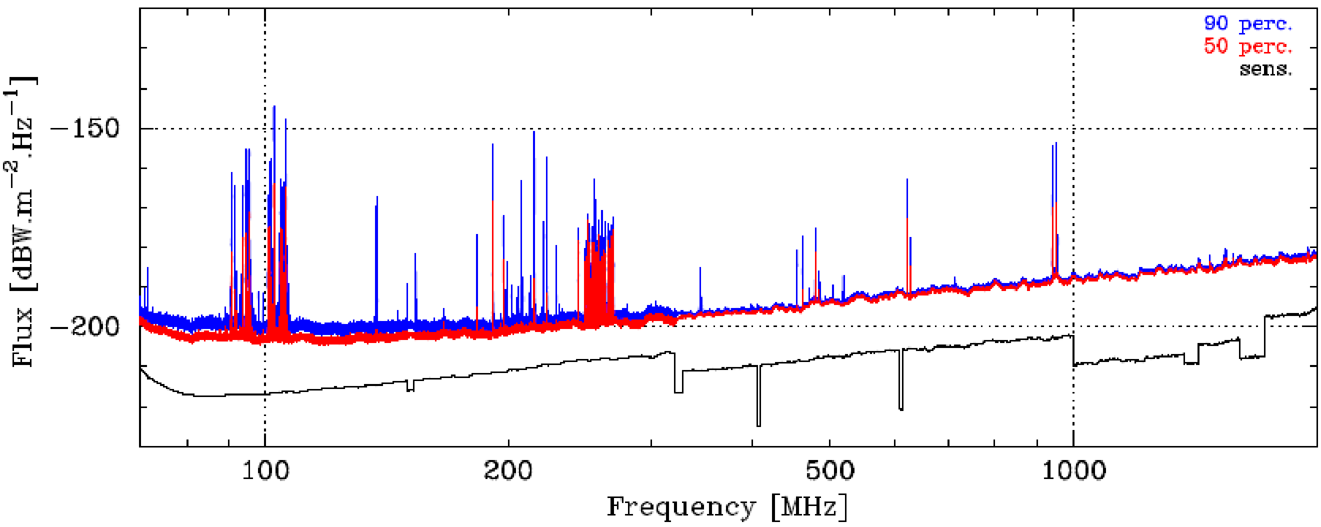


Figure 2-9: Results of RFI Survey for frequencies from 70 MHz to 2 000 MHz. The strong signals in this plot are from commercial and other radios, TV and Cellphones.

Conclusion and Applicability of [1]

The thesis by Manners [1] established a baseline Radio Astronomy site management. It defined the RFI environment before the Radio Telescope and related ancillary equipment deployment. It also identified all the commercial transmitters (radio, cellphone, TV) which require management in terms of the AGA act [6]. An unintended but valuable result of the work done for this survey was to understand the severe screening requirements needed to have equipment meet the SARAS protection requirements [4], including the measurement limitations of existing facilities such as the EMC test facility at Houwteq.

2.5 Generic and Product Standards on Emissions

An important tool in the control of RFI due to electrical and electronic equipment deployed close to a Radio Telescope is the generic standards on emissions, commonly referred to as EMC standards. Ensuring that Culprit equipment meets one of the emission standards does not necessarily imply that the Culprit will not interfere with the Radio Telescope, as other factors such as distance from the telescope, and additional screening must be taken into account. However, knowing if a potential Culprit was qualified to an EMC standard is a good starting point. In addition, the compliance to a known EMC standard makes testing in a qualified EMC facility easier, as such facilities are familiar with such standards. Once such an EMC test reports are available, like may be compared with like and potential problem areas considered.

Special RFI requirements may be specified for equipment developed for a Radio Telescope. However, for commercial-off-the-shelf (COTS) ancillary and other support equipment, special standards cannot apply. Qualification to an EMC standard could be used to influence the selection of COTS equipment.

A good overview and definition of the various EMC standards is given by Williams [15], including an overview and applicability of the EN55xxx series, as well as the equivalent standards.

Figure 2-10 from [15] gives the radiation emission limits of their various EN (CISPR) as well as FCC standards:

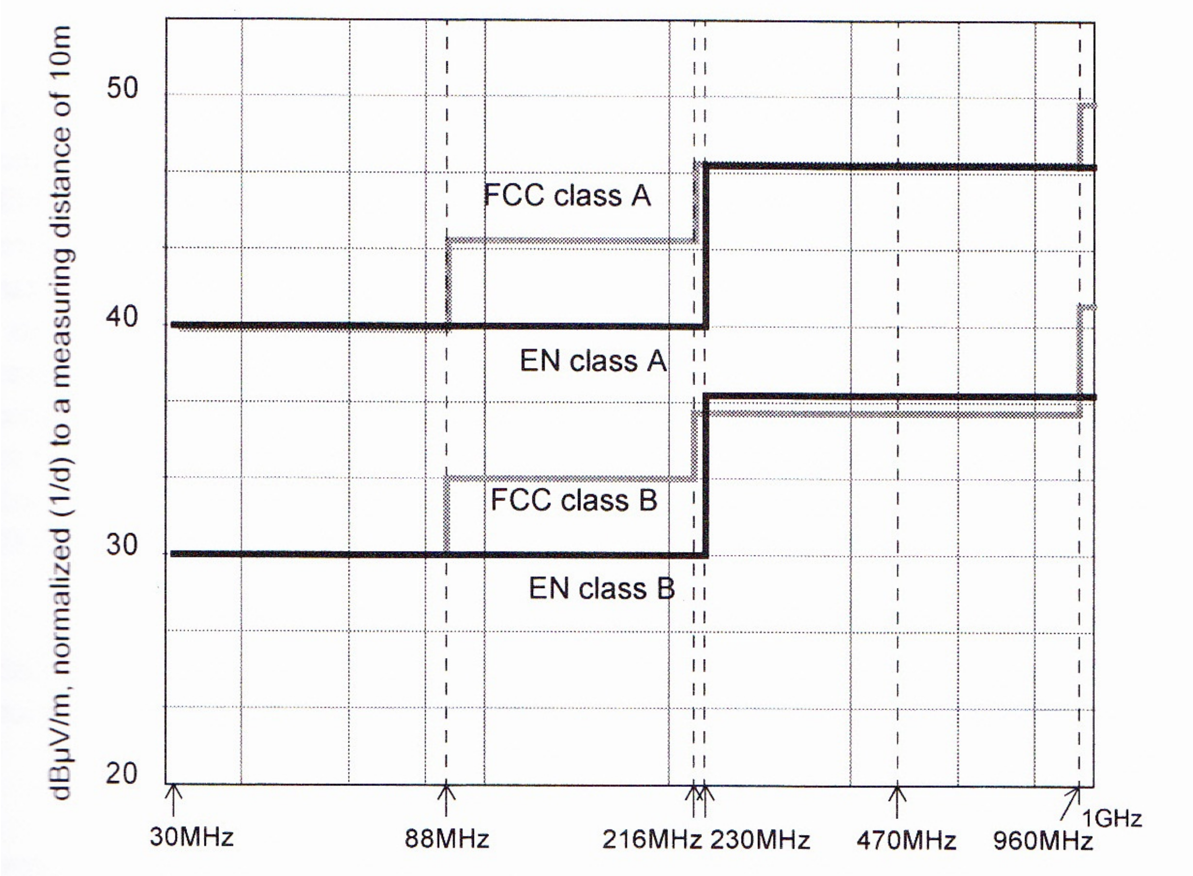


Figure 2-10: Graph (from [15]) showing the radiated emission levels of various EN (CISPR) as well as FCC Standards

Table 2-1 gives various general and equipment standards and the applicability to the control of RFI in the Radio Telescope environment:

Table 2-1: General and Equipment Product Standards that are applicable to the control of RFI in the Radio Telescope environment

Standard	Scope	Applicability in RFI Control
EN 55011 (CISPR 11)	Industrial, scientific and medical (ISM) radio frequency equipment	Applicable standard for any scientific equipment, such as Radio Telescopes which are deployed to the site
CISPR12	Automotive emissions e.g. vehicles. Applicable to off-board Receivers.	All public as well as project vehicles deployed to site
EN 55014-1 (CISPR14)	Household appliances, electric tools and similar equipment. Main functions performed by motors and switching or regulating devices.	Applicable standard for accommodation, water systems and tools deployed to the site
EN 55022 (CISPR22)	Information technology equipment. Primary function data entry, storage, display, retrieval, transmission, processing, switching or control.	Applicable standard to most of the electronic systems not part of the telescope, such as the data communications network, LAN, and personal computers
EN 61000-6-3	General emission standard: Residential, commercial and light industrial.	Refers to EN 55022 for emissions
EN 61000-6-4	General emission standard: .Industrial environment.	Refers to EN 55011 for emissions
FCC Rules Part 15	Unintentional radiators including radio and TV equipment as well digital devices	Similar to EN 55022, applicable to ancillary equipment deployed to site
FCC Rules Part 18	Unintentional radiators including industrial, scientific and medical devices	Similar to EN 55011, applicable to Radio Telescope equipment deployed to site
MIL STD 461 RE 102	Standard use to qualify military equipment, also the baseline used by some of the EMC test facilities	Not applicable to the Radio Telescope, but test reports from EMC test facilities might use this standard

Note that the above table is for the emission standards (for the RFI Culprit) and excludes all the standards related to immunity (of the RFI Victim). In the case of the Radio Telescope, the SARAS standard defines the requirement for the Victims.

Figure 2-11 was generated using [7] and shows a comparison between the EN55022 (CISPR22) [19] Class B, FCC Part 15 Class B and MIL STD 461 radiation levels.

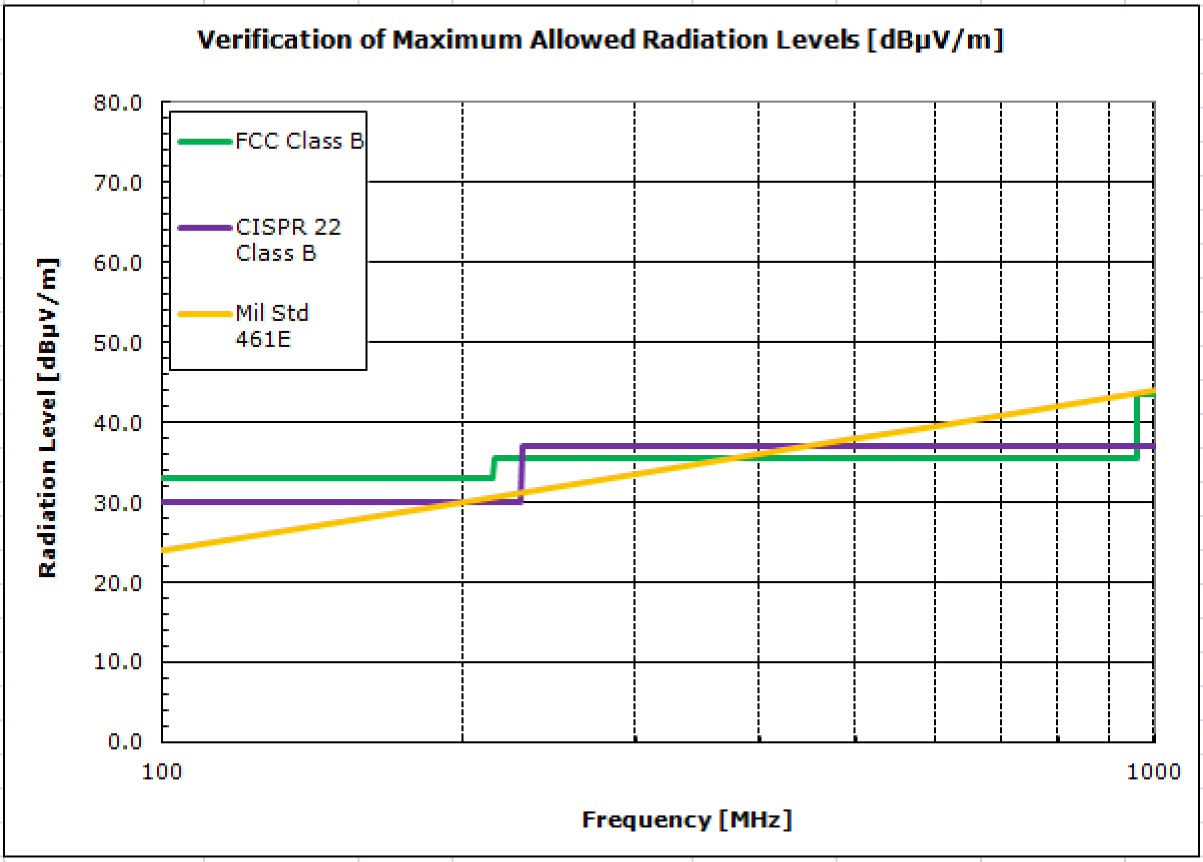


Figure 2-11: Comparison between EN 55022 Class B, FCC Class B and MIL STD 461 Emission levels, generated using the Calculation Tool [7]

<u>Conclusion and Applicability of [15]</u>

There are only minor differences between the limits in the EN (and related CISPR standards), the FCC rules and MIL STD 461 and as such, qualification to any of these standards is acceptable input into the RFI analysis process.

CISPR 22 [19] is the applicable standard for infrastructure and ancillary equipment typically industrial and IT equipment, whereas CISPR11 [20] is applicable to Telescope equipment which is specifically developed for the scientific environment.

There is, however, a 10 dB difference between class A and class B for both standards (CISPR and FCC), and thus it make sense to use the Class B standards in the Radio Astronomy environment.

2.6 Logistic Support Analysis Process

The RFI Culprit analysis process developed in this thesis was based on the background the author had with the Logistic Support Analysis Process (LSA process), including the variations used in the SA Navy environment.

LSA is one of the tools used by Logistic Engineers to analyse complex systems, such as a Naval ship or Submarine and to determine the Logistic Support Requirements, i.e. which support tasks are required, who must perform these, what training is required and what tools and support and test equipment are required. One of the first steps in this LSA process is the so-called FMECA, or Failure Mode, Effects and Criticality Analysis.

The handbook Logistic Engineering and Management by Blanchard [16] is considered one of the major reference works for Logistic Engineers and Figure 2-12 from [16] illustrates the traditional FMECA process:

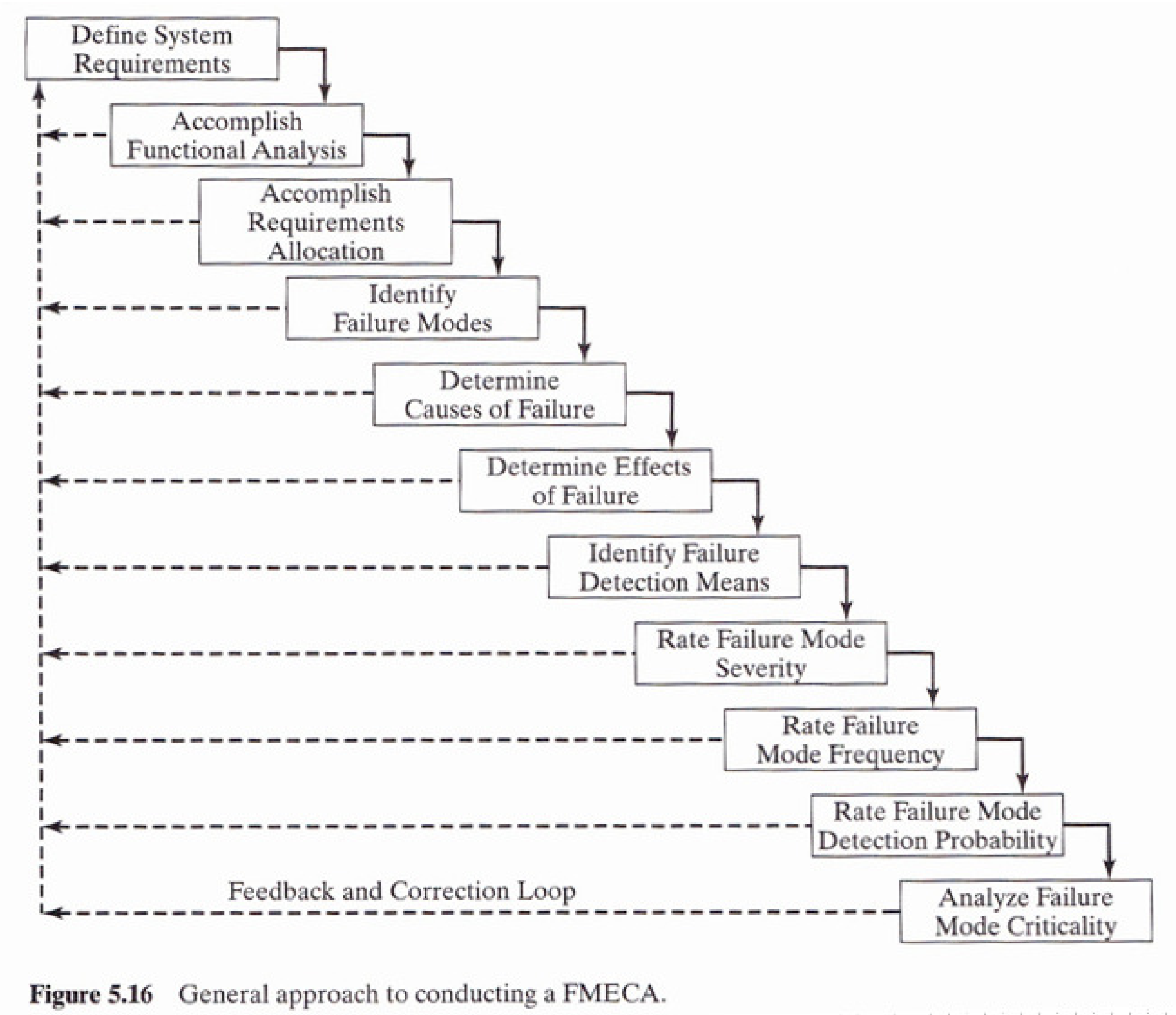


Figure 2-12: Traditional Failure Mode, Effects and Criticality (FMECA) Analysis process as used by Logistic Engineers [16]

In the FMECA process, each failure mode is analysed in terms of criticality. Criticality is a combination of the severity of the failure (i.e. the effect of the failure) and the probability of the failure (i.e. the failure rate) and based on the criticality, the failures are then rated; typically as unacceptable, undesirable and acceptable.

Figure 2-13 is from the SA Navy ILS guide [17] and shows the traditional criticality ratings used by Logistic Engineers:

			Severity			
			1	2	3	4
			Catastrophic	Critical	Marginal	Minor
Probability	A	Frequent	Severe	Severe	Severe	High
	B	Often	Severe	Severe	High	High
	C	Occasional	Severe	High	High	Low
	D	Remote	High	High	Low	Low
	E	Unlikely	High	Low	Low	Low

Criticality	
Severe	Unacceptable Failures (Redesign)
High	Undesirable Failures
Low	Acceptable Failures

Figure 2-13: Criticality Matrix from SA Navy ILS Guide [17] showing the traditional definitions of Severity, Probability and Criticality

<u>Conclusion and Applicability of [16] and [17]</u>

The traditional LSA process in [16] is where a failure mode is defined to indicate an equipment failure which will impact the performance of the system and requires repair and maintenance tasks. This was adapted for RFI analysis by developing a new definition for a failure mode. An RFI failure mode is defined as equipment (Culprit) radiating RFI which can impact the performance of a Radio Telescope (Victim) and will require RFI mitigation tasks – see Chapter 4 for detail.

The criticality definitions, including severity and probability, in [17] were also redefined to be applicable to RFI analysis – see Chapter 4 paragraph 4.2.4.1.

The use of a process similar to the LSA to analyse RFI Culprits made it possible to use an off-the-shelf software package called RamLog to develop the RFI database.

2.7 Typical RFI Control Measures used by Radio Telescope Observatories

Radio Telescope Observatories over the world share the threat of RFI interference and have developed various control measures, including:

a. Legal control of the Spectrum.

b. Legal control of emission limits in RFI Quiet Zones (RQZ).

c. Detection of RFI Culprits using surveys.

d. Investigation of specific RFI Culprits.

e. Co-existence with RFI.

2.7.1 Legal control of the Spectrum

The NRAO states “RFI is what happens when spectrum management fails” [24]. In the USA, the FCC is the vanguard of the ongoing process to shape the use of the electromagnetic spectrum. In Europe and other countries with Radio Telescopes; including South Africa, the legislation is based on the ITU-R (the Radio Bureau of the International Telecommunications Union, a UN agency in Geneva) and specifically ITU-R RA.769-2 “Protection criteria used for radio astronomical measurements” [3].

2.7.2 Radio Quiet Zones

A typical approach in controlling RFI is to define a Radio Quiet Zone (RQZ) where the requirements of spectrum management limitations can be strictly enforced. Examples of this include:

a. The South African AGA act [6] which defines Core, Central and Co-ordinated zones in the Northern Cape, South Africa – see paragraph 2.1 for detail.

b. The West Virginia Zoning Act [22] which defines a ten mile and two mile zone around the Green Bank Radio Telescope, West Virginia, USA.

c. The Mid-West Radio Quiet Zone [25] which defines an inner (70 km) and outer (70-150 km) RQZ.

2.7.3 RFI Surveys and Detection of Culprits

Radio Telescope Observatories can measure the RFI received at the sites by performing surveys. Examples of this include:

a. The survey done of the Karoo site [1] and [2] – see paragraph 2.4 for detail.

b. An RFI survey of the ALMA site at Chajnantor [23].

c. Monitoring the RFI environment at the GMRT [18].

These surveys focus on the frequencies applicable to the telescopes at these sites. The South African survey focused on the frequencies between 70 MHz and 25 GHz [1], as this is the required frequency range of the SKA Bid. The ALMA survey was done from 10 MHz to 18 GHz [23], as this covers the IF range of the ALMA Telescope (the ALMA Telescope operational frequencies are 30 to 950 GHz , but there are no RFI sources in that range). The GMRT frequency range is from 150 MHz to 1 420 MHz and that is the range that is monitored at GMRT [18].

Figure 2-14 shows the results of a RFI survey done at GMRT [18]:

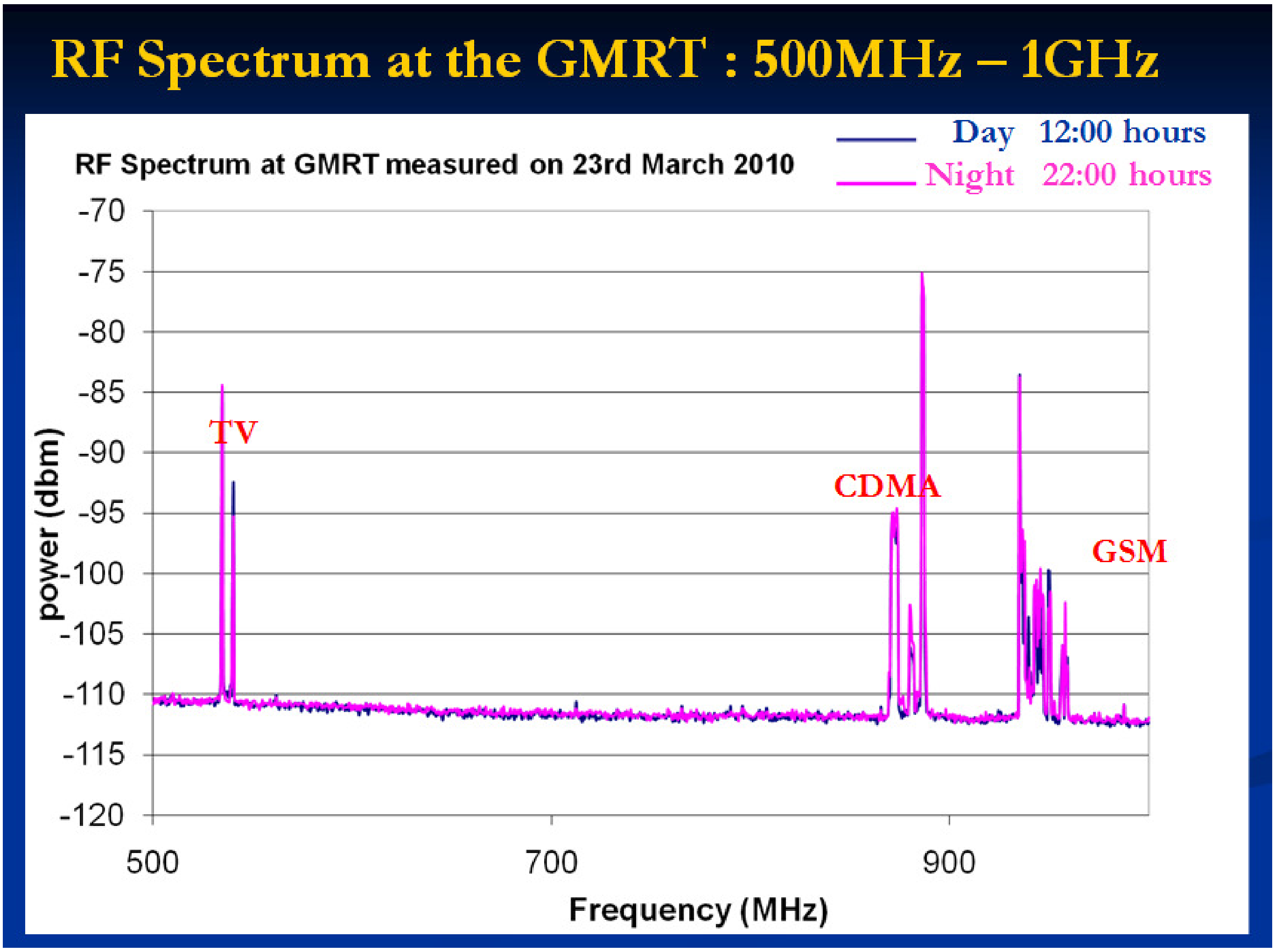


Figure 2-14: Results of the typical RFI survey done at GMRT [18] showing interference from RFI Culprits such as TV and Cellphones

2.7.4 Investigating specific RFI Culprits

Radio Telescope Observatories investigate specific known RFI Culprits and typical examples are:

a. Power Line and Cable TV at GBT [27].

b. Digital Cameras at GBT [26].

c. TV Boosters, Cellular Telephones and Power Lines at GMRT [18].

Figure 2-15 shows the solution to a typical problem at GMRT, where the saturation and oscillations of amplifiers in TV boosters were causing RFI:

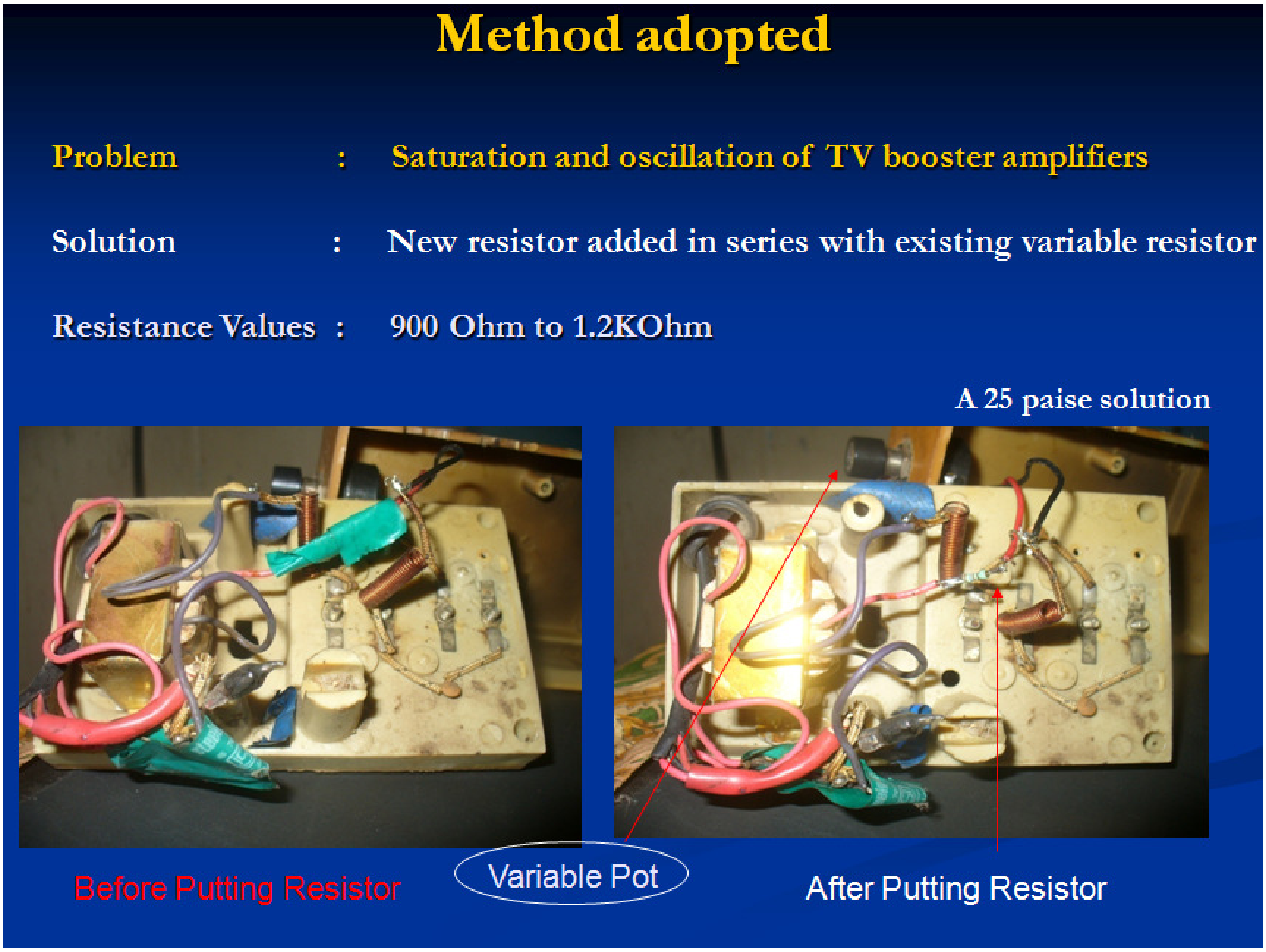


Figure 2-15: Cost effective solution (25 paise – Indian coin of about 5c ZAR) to a RFI Culprit at GMRT, TV boosters which saturate / oscillate and cause RFI [18]

2.7.5 Co-existence with RFI

Radio Telescope Observatories, such as HartRAO, Green Banks, GMRT etc, have to operate in spite of proximity to populated areas with RFI. A part of the function of the observatory is to educate and sensitise people to the issue of RFI. This is focused on internal staff and on outsiders as part of outreach programmes. Examples are:

a. RFI Policy – What Every Green Bank employee needs to know [21].

b. Radio Interference Control at HartRAO [28].

2.7.6 Conclusions and Applicability

Most of the Radio Telescope Observatories are existing facilities and have limited control over RFI introduced. The developed approach may supplement the traditional RFI control methods as described and will be specifically useful where a new facility is being developed, such as the South African site in the Karoo. It includes the control of RFI during construction of additional facilities on site at the same time as the operation of an existing Telescope.

CHAPTER 3 REQUIREMENT AND CHALLENGE

3.1 Introduction

The requirement, and the challenge, including the scope (both width and depth) of the possible RFI on a Radio Astronomy site are now introduced.

3.2 Radio Telescope Performance Requirements

3.2.1 High Sensitivity

Figure 3-1: Radio Telescopes in the Karoo which will be used to detect signals for galactic sources such as stars and pulsars

Radio Telescopes detect and image the signals from galactic sources such as stars, pulsars and even inter-galactic material and gas at radio frequencies of between 70 MHz to 22 GHz [8]. In order for a Radio Telescope to detect these small signals it must be a very sensitive instrument. The sensitivities required are described in layman's terms in [9], and in greater scientific detail in [10].

One way to get an idea of the sensitivity of a Radio Telescope is to look at the unit used by radio astronomers to measure signal levels – the Jansky. The Radio Astronomy community uses a unit of measure for the electromagnetic flux density of Jansky (Jy) – named after pioneering US radio astronomer Karl Guthe Jansky, where

$$1 \text{ Jy} = 10^{-26} [\text{Watt/m}^2\text{Hz}] \quad (3.1)$$

The flux density of traditional radio emitters are measured in 10^{-3} [Watt/m^{2}Hz], where

$$10^{-3} \text{ Watt} = 0 \text{ dBm} \quad (3.2)$$

$$1 \text{ Jy} = -230[\text{dBm/m}^2\text{Hz}] \quad (3.3)$$

From this it may be seen that Radio Telescopes measure signals that are in the order of 230 dB less than traditional radio signals.

Figure 3-2 shows a typical Radio Astronomy image [11]. The colour scaling on the right hand side indicates the signal strength in Jansky.

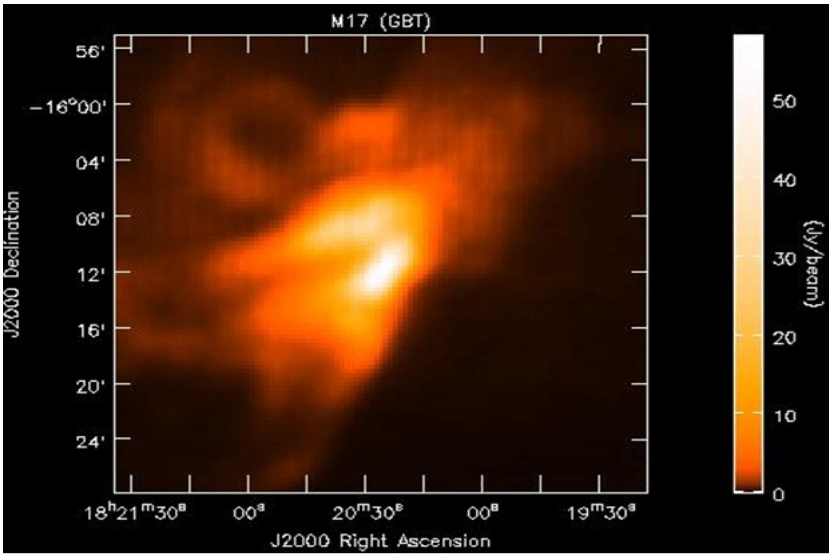


Figure 3-2: Typical Image generated for the signals received by a Radio Telescope. The colour codes define the signal strength using the Jansky unit.

3.2.2 Large Bandwidth

In order for a Radio Telescope to be able to detect the small signals discussed above, it requires a favourable signal to noise ratio (S/N).

Traditionally, good S/N ratios are achieved by having a very small bandwidth, as the noise reduces as bandwidth is reduced. Unfortunately, the Radio Astronomy requirement is for high sensitivity and wide bandwidth. This high sensitivity can be achieved by building a telescope with large collecting area and a low internal Receiver noise (e.g. by cryogenic cooling of the Receiver).

The requirement for wide bandwidth comes from the signal characteristics in the galactic sources. Some of the signal is essentially noise itself and therefore wide band, and some of the signals are Doppler shifted (due to the expansion of the universe) and therefore not only at one specific frequency. See Table 3-1 for examples for frequencies emitted by galactic sources:

Table 3-1: Frequencies of typical galactic sources which will be measured by a Radio Telescope [8]

Galactic Source	Frequency Range (GHz)
Hydrogen (Epoch of Re-ionization)	0,100 – 0,200
Hydrogen (no red shift)	1,370 – 1,427
OH	1,606 – 1,723
CH	3,300 – 3,400
H_2C0	4,800 – 5,000
CH_3OH	6,600 – 6,700 12,100 – 12,200
C_3H_2	18,300 – 18,400

The problem with a wide bandwidth Receiver is that it not only receives the 'wanted' signals but also all the unwanted signals (RFI). This effect is increased by the long integration times used in Radio Telescopes. The ITU standard [3] specifies an integration time of 2000 s, but for some surveys integration times of days or even weeks are used.

The only solution for the combined requirement of high sensitivity and wide bandwidth is to build the telescope in an area with low RFI. This implies an area with low population density. An area in the Northern Cape Province of South Africa has been selected to be the SARAAA, due to its low population density and is now protected by the AGA act [6]. The Northern Cape covers around 40% of the area of South Africa but contains only about 5% of the population and has much less man made RFI noise than other more highly populated areas, such as Gauteng.

Figure 3-3 and Figure 3-4 show a comparison between the RFI measured in Gauteng (at HartRAO) and in the Karoo [1] [2], in the frequency ranges of 300 MHz to 800 MHz. Note the large number of RFI sources in Figure 3-3 (Gauteng) and the small number of RFO sources in Figure 3-4 (Karoo).

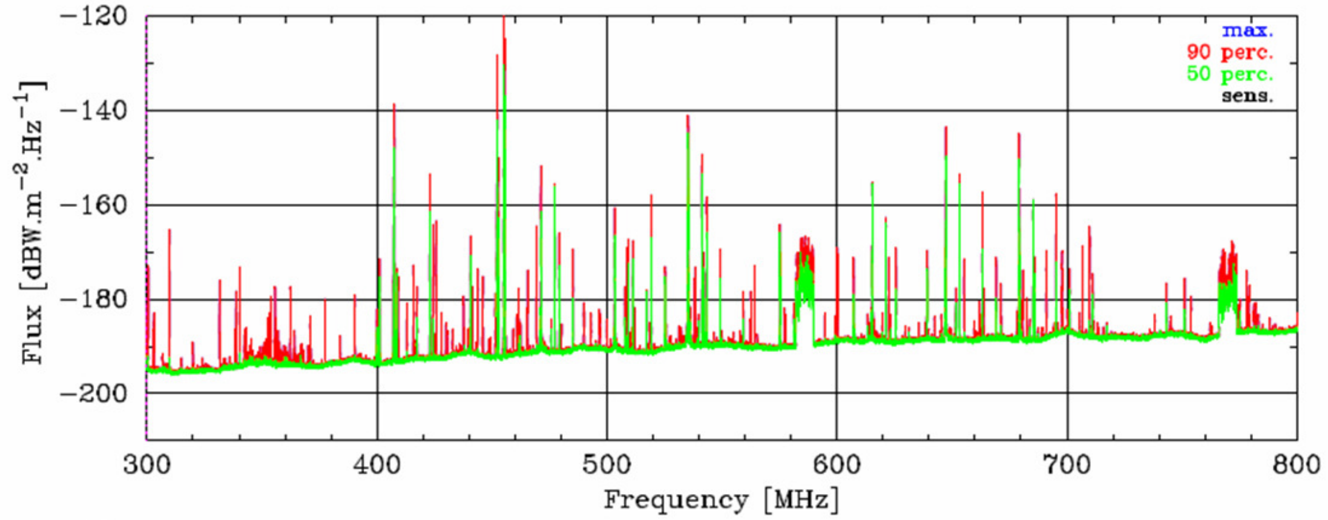


Figure 3-3: RFI Environment in Gauteng with large number of RFI Sources

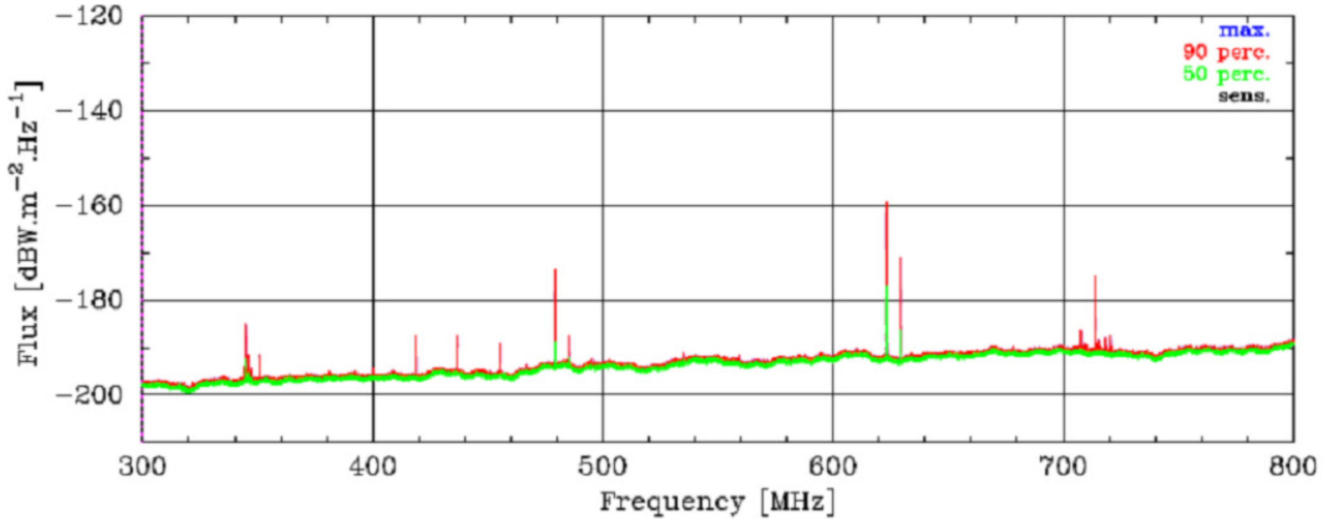


Figure 3-4: RFI Environment in the Karoo showing only a small number of RFI Sources

3.3 Scope of RFI

The scope of the RFI to be managed on a Radio Astronomy site is wide. The following paragraphs give some detail on:

a. The types of RFI (sources of RFI).

b. The distance of the emitters from the Radio Telescope Receivers.

c. The time sequence of the RFI.

d. The life cycle of RFI generating equipment.

3.3.1 Types of RFI

RFI is caused by transmitters such as radio, TV, data links, cellular telephones or from EMI sources such as electrical and electronic equipment.

For simplicity, this thesis will henceforth refer to both RFI (typically narrow band) and EMI (typically wide band) sources as 'RFI'.

RFI that can impact the S/N ratio of a Radio Telescope can be caused by:

<u>Space and airborne Transmitters:</u>

a. Navigation satellites (1,2 to 1,6 GHz band).

b. Communications satellites (12 GHz band).

c. Aircraft DME equipment (1 GHz to 1,2 GHz band).

d. Aircraft weather radars (5 GHz band).

e. Aircraft radio communications (120 MHz band).

<u>Terrestrial Transmitters:</u>

a. Cellphones (900 MHz and 1 800 MHz bands).

b. TV (200 MHz, 600 MHz and other bands).

c. Radio (100 MHz band).

d. Data links (3 GHz, 5 GHz and other bands).

e. Radio links (450 MHz and other bands).

f. WiFi (2,4 GHz and 5,4 GHz bands).

Terrestrial Equipment:

a. Power lines and related equipment.

b. Farming equipment (electric fences, wind chargers, etc).

c. Household equipment (domestic appliances, electronic equipment and power supply units – PSUs).

d. Vehicles (ignition systems, remote control systems).

e. Computers and electronics (digital electronics, switch mode power supplies).

f. Telescope ancillary equipment (cooling systems etc).

g. Telescope electronic systems.

The above lists are not comprehensive, but give the scope of possible RFI. From these lists it may be seen that a site such as the Karoo Astronomy area has a wide range of possible RFI sources and therefore the management of these risks needs careful attention.

3.3.2 RFI Generating Activities

One way to look at the RFI is as RFI generating activities. These maybe defined as layers of activities, related to its distance from the telescope as show in Figure 3-5 below:

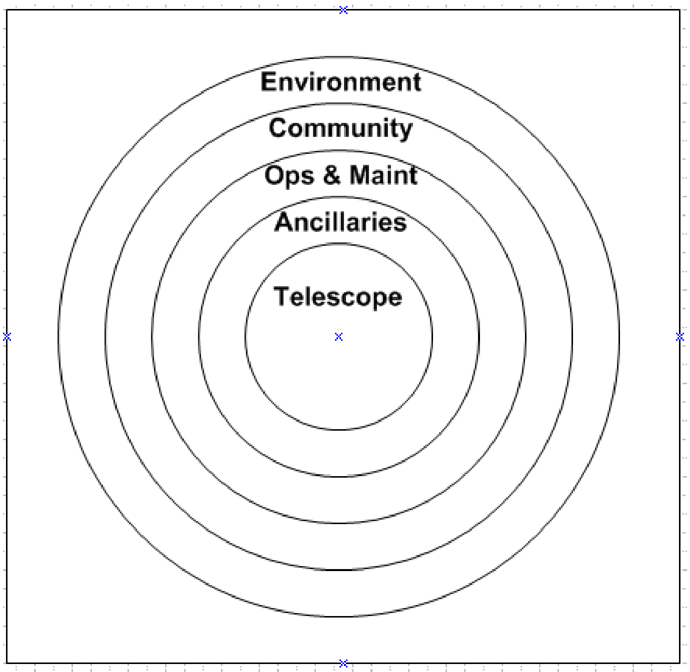


Figure 3-5: Typical activities which may cause RFI in relationship to its distance from the Radio Telescope

<u>RFI from Telescope Equipment</u>

The telescope can be its own worst enemy, since any RFI from the telescope itself is close (within metres) to the receiving elements. This can include power supplies, cooling equipment, digital equipment and local oscillators. Fortunately, the design of this equipment can be optimized to reduce the RFI from this source.

<u>RFI from Ancillary Equipment</u>

The ancillary equipment includes the power distribution and backup power systems, the data communications equipment and the various buildings and vehicles. These are located within tens of metres from the telescopes to within a few kilometres. This equipment is mostly commercial off-the-shelf equipment, but careful consideration to RFI issues are given, such as the location and special screening to minimize the RFI risks.

<u>RFI from Operations and Maintenance Activities</u>

The RFI sources from operations and maintenance activities include computer equipment, test equipment and vehicles. This equipment is mostly commercial off-the-shelf equipment, but only need to be used close to the telescopes for limited time periods (i.e. scheduled maintenance tasks).

<u>RFI from the Community</u>

This includes RFI (EMI) from the farms around the telescope site, the roads and the towns. This equipment is COTS equipment (i.e. no specific RFI minimization) but is located kilometres away from the telescope. The site was selected to be in a sparsely populated area to reduce the RFI risk from this source. The location of the mountains and hills (koppies) also assists with screening the telescopes from these sources.

RFI from the Environment

This includes the RFI from the transmitters in the environment around the site, including cellphones, TV, radio as well as the airborne and satellite transmitters. The site was selected to be in an area with minimum transmitters and this is managed with the provisions in the AGA act.

The methodologies described in this document were developed specifically for the RFI from the ancillary layer, but these methodologies can also be applied to the other sources of RFI.

3.3.3 Time Sequence of RFI Activities

Another dimension related to RFI activities is time. Some activities are long term sources of possible RFI (e.g. operations and maintenance), but some activities are only short term sources (e.g. construction). Figure 3-6 gives an overview of typical activities, relative levels of RFI and time sequencing.

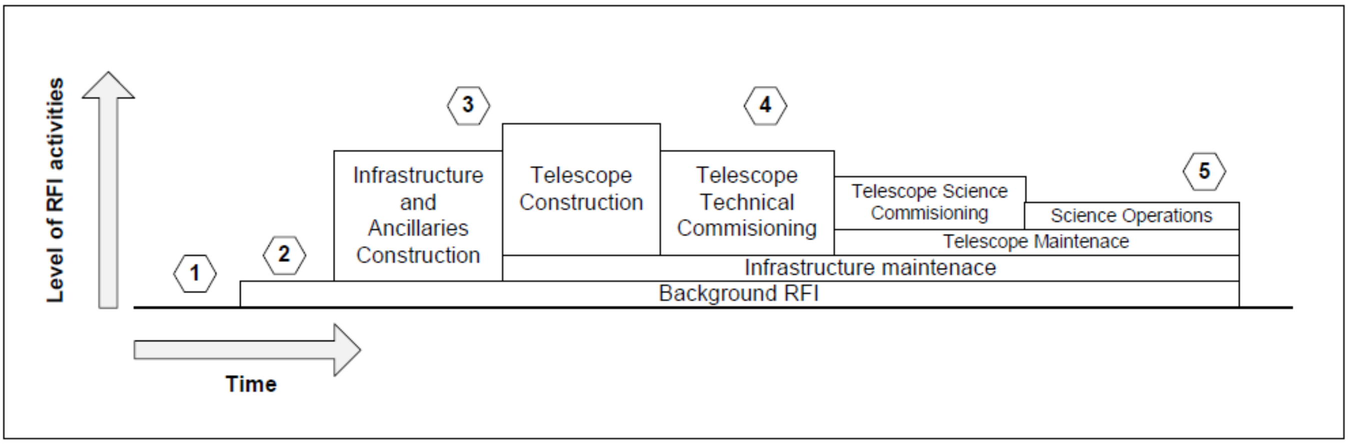


Figure 3-6: Time Sequence of Activities that can generate RFI on a Radio Telescope site

Item 1 is the noise floor (i.e. the lowest possible noise level with zero RFI).

Item 2 is the background noise at the site, as measured during the various RFI surveys. This RFI is due to satellites such as GPS, terrestrial transmitters such as GSM, TV and radio (from outside the area) and any other man-made noise due to towns, cars etc.

Item 3 is the short term increase of the RFI due to the construction activities, initially of the infrastructure but then for the actual telescope. Some management may be done to limit the duration (in time) and overall level of these (e.g. by positioning activities with high RFI levels behind hills etc), but it will be prohibitively expensive if the construction activities must meet the full RFI standard.

Item 4 is the reduction of the RFI due to construction due to the completion of the construction activities. This can be managed in terms of phasing out activities.

Item 5 is the long-term or 'residual' RFI after construction, due to the introduction of new equipment (both ancillaries and telescope) on the site. This introduction must be carefully managed and designed to ensure an RFI level as close to the background RFI levels (or better than even the RFI standard) as possible. The ultimate would be if the increase is zero, but without careful management it can easily pose a high risk to the telescopes.

The focus of this thesis is on the management of the short-term RFI, to ensure that the residual RFI is controlled, rather than on specific design issues of the telescope (or ancillaries).

3.4 Summary

It can be seen that the scope of the RFI to be managed on a Radio Astronomy site is wide, both in terms of the Radio Telescope Receivers (Victims) and the various emitters (Culprits).

Given limited resources, some management is required. The methodology developed is given in the next chapter.

CHAPTER 4 RFI VICTIM AND CULPRIT ANALYSIS PROCESS

4.1 Introduction

This chapter describes the solution that was developed to manage the requirement or challenge as defined in the previous chapter. The next chapter will show how this process has been applied to the examples and case studies.

4.2 Culprit and Victim Analysis Process

In order to manage the RFI items, a Culprit and Victim analysis process has been developed, consisting of the following steps:

a. Step 1: Identify the RFI Items (see paragraph 4.2.1).

b. Step 2: Document the Deployment Plan (see paragraph 4.2.2).

c. Step 3: Select RFI Candidate(s) (see paragraph 4.2.3).

d. Step 4: Analyze RFI Criticality (of selected Candidates) (see paragraph 4.2.4).

e. Step 5: Analyze Tasks (of critical Candidates) (see paragraph 4.2.5).

f. Step 6: Manage RFI Mitigation (see paragraph 4.2.6).

The process was found to be very similar to the LSA process as described in paragraph 2.6 and the RamLog software tool was found to be suitable to document the results of the RFI analysis process.

Figure 4-1 gives an overview of this process and the interaction with the RFI database (RamLog).

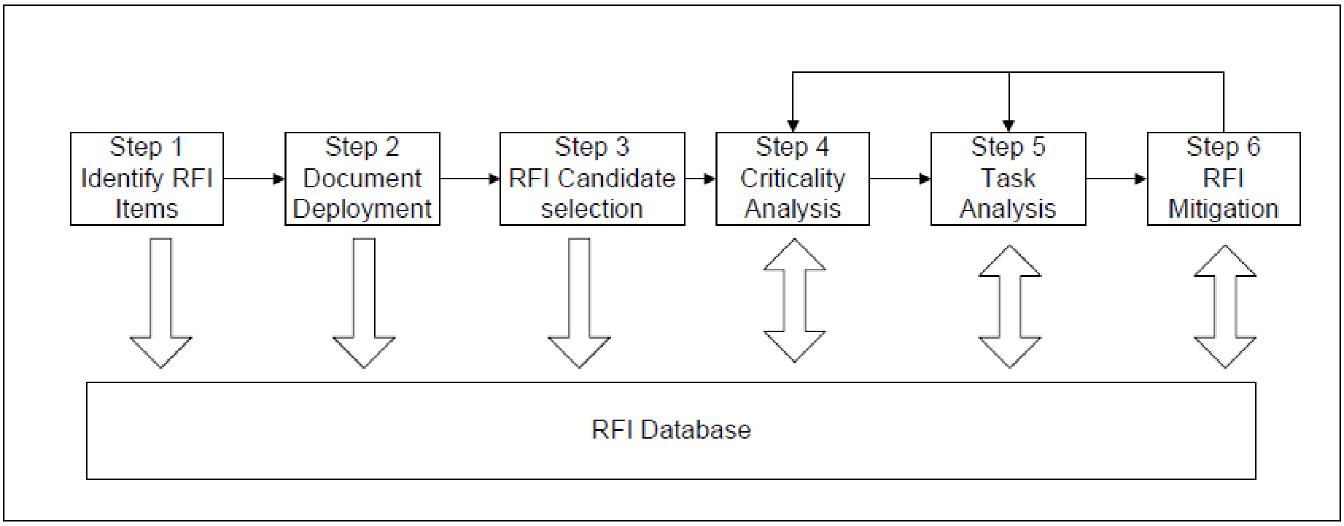


Figure 4-1: The RFI Analysis Process and the use of the RFI Database

4.2.1 Step 1: Identify the RFI Items

This step consists of the following sub-steps:

a. An RFI item newly introduced on site or planned to be introduced on site is identified.

b. The item is digitally photographed.

c. The item is listed on the RFI database and a RFI Culprit number is allocated.

d. The RFI item is added to the RFI database in the RamLog software package.

e. Figure 4-2 shows an example of an RFI item on the RFI database:

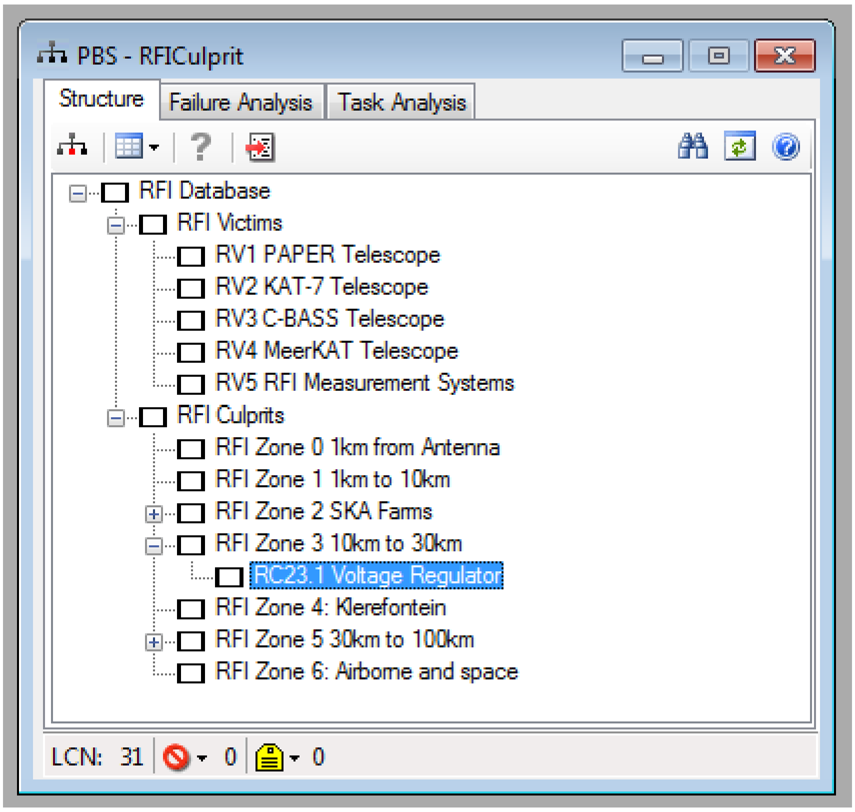


Figure 4-2: An example of an RFI Item on the RFI Database

4.2.2 Step 2: Document the Deployment Plan

A control permit form was developed to document the deployment of an RFI item to the site – see Appendix A for the control permit template.

The control permit captures the following information:

a. Part 1: Description of RFI source / Culprit.

b. Part 2: Usage of RFI source / Culprit.

c. Part 3: Time on site.

d. Part 4: Location of RFI source / Culprit.

e. Part 5: Relevant contact person.

f. Part 6: Additional information.

Figure 4-3 shows the control permit developed to capture the deployment information:

SKA AFRICA	South African Radio Astronomy Reserve Control Permit	Permit No	
		Date Issued	
		Photo File name	

PART 1: Description of RFI Source / Culprit

1.1 Short description of equipment	
1.2 Equipment Make and Model number	
1.3 Equipment Type	

	Computer		Generator (alternator)		TV		Cell phone
	LCD Monitor		Static Inverter		DSTV Encoder		WiFi
	Printer		Wind Charger		Microwave oven		Data Link
	UPS		Solar Charger		HiFi		Cordless phone
	Switch/Router		Power Tools		Geyser		Radio Transmitter
	eNET Convertor		Petrol Vehicle		Heater		Satellite Phone
	Controller		Diesel Vehicle		Air Con		VSAT / VB SAT
	Access control		Electric motor/pump		Lights		Remote control
	Other (specify):						

PART 2 : Usage of RFI source / culprit

2.1 What will the equipment be used for?				
2.2 Duty Cycle	Always on	Day time only	Night time only	Short duration
	Other(Describe)			

PART 3 : Time on Site

3.1 Will the equipment be Permanent or Temporary only?	
3.2 Date deployed to site	
3.2 Date to be removed from site (if applicable)	

PART 4 : Location of RFI source / culprit

4.1 Where will the equipment be located?			
	Zone 0: Within 1 km from antenna		Zone 1: Between 1km and 10 km
	Zone 2A: SiteComplex		Zone 2B: Losberg Construction camp
	Zone 2C: Mesydam construction camp		Zone 3: Between 10km and 30km
	Zone 4: Klerefontein		Zone 5: Between 30km and 100km
4.2 GPS Co-ordinates (if known)	LAT	LONG	

PART 5 : Contact person

Name		Company	
Tel		eMail	

PART 6 : Additional Information (If available)

6.1 Have this equipment been EMC qualified?	Yes	No
6.2 If Yes please provide the EMC standard? (e.g CISPR-XX)		
6.3 Other / Notes		

PART 7 Signatures

Requested By	Site Manager
Name (Print)	Name:
Organization: Position:	Organization:
Signature:	Signature:
Date:	Date:

Figure 4-3: Control Permit used to capture Deployment Information

4.2.3 Step 3: Select RFI Candidate

A front-end analysis is done, using whatever information is available on the equipment (standards, test results, engineering judgment). This analysis considers the criticality of possible RFI from the Culprit for each possible Victim, taking into account the deployment, frequencies, radiated power levels and the effect of the terrain.

Step 3 is similar to Logistic Analysis Candidate selection in LSA.

The following front-end (quick view) method has been developed.

a. An expected radiation level is defined for the identified item. This can be from test results (if available), published standards, or comparison to items of similar technology.

b. The CISPR-22 Class B standard is used as the comparison basis. The estimated radiation is converted to CISPR-22 format (e.g. adjusted for measurement distance, if required).

c. The position of the item is compared to the developed CISPR-22 contours, using the Deployment Plan (see Step 2 above).

d. An item is selected for RFI analysis using the CISPR contours as well as allowing for additional reduction in signal levels due to the terrain (koppies).

e. The item is selected even if there is any doubt about its eligibility from the method steps above. This step is to exclude obvious 'non candidates' and focus resources.

f. Note that this is a quick front-end decision only and after a more detailed analysis (in the next step), more items may be excluded as not being of high risk.

Figure 4-4 shows the CISP-22 Class B contours developed for use for the front-end analysis and selection of RFI candidates.

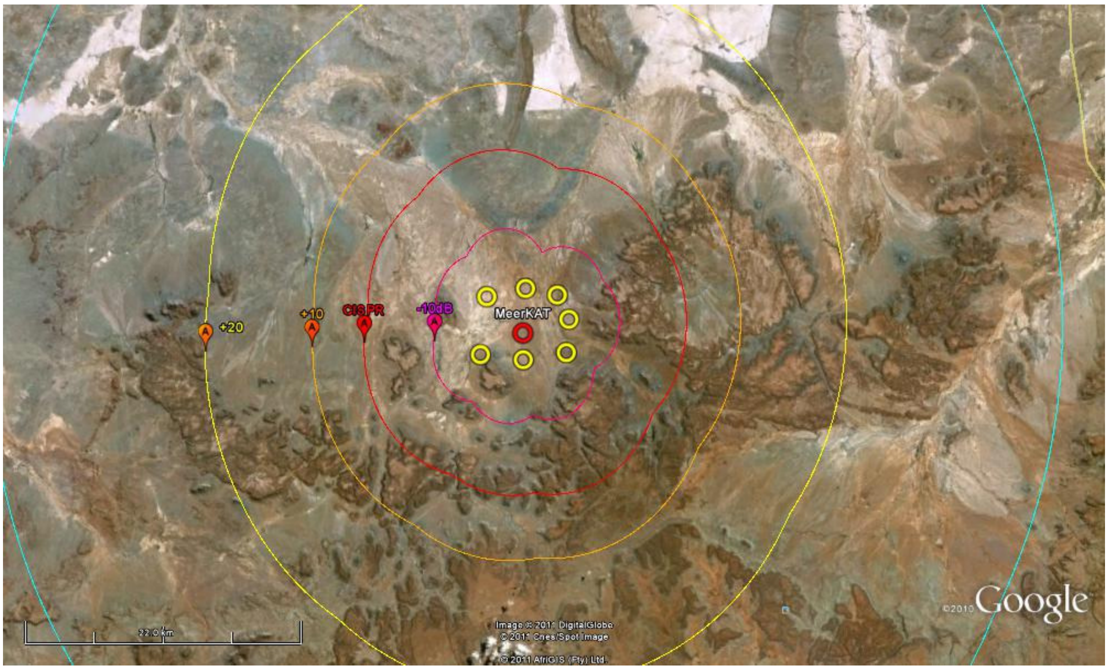


Figure 4-4: CISPR 22 Class B Contours developed for front end analysis and RFI Candidate selection

Once an item is identified as a candidate for RFI analysis, the LAC box is ticked in the RFI database. Figure 4-5 shows an example of the LAC tickbox:

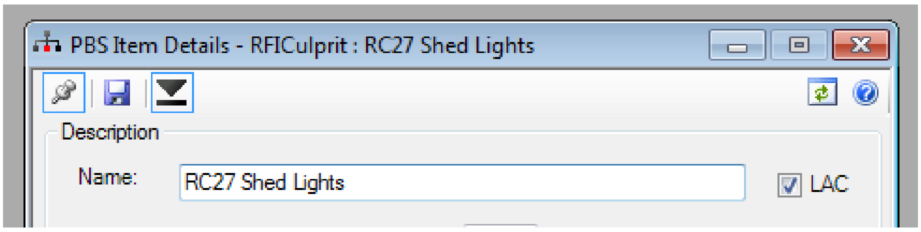


Figure 4-5: LAC box ticked in the RFI database to indicate a Candidate for RFI Analysis

Once the LCA box is ticked, a red icon is displayed on the structure tree in the Failure Analysis view to indicate that the item is a candidate for RFI analysis. Figure 4-6 shows an example of the red icon:

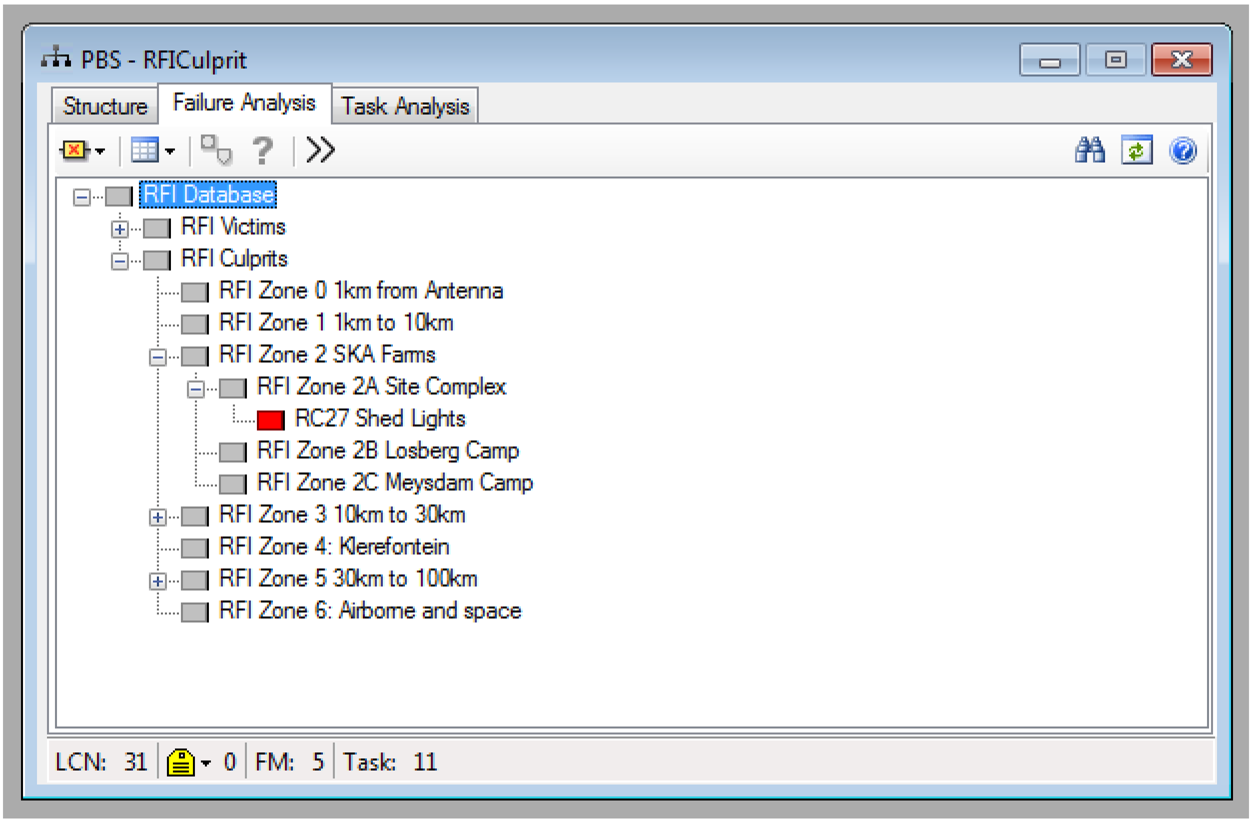


Figure 4-6: Red icon – candidate for RFI Analysis

4.2.4 Step 4: Analyze RFI Criticality

The candidates selected in Step 3 are now subject to RFI analysis. This includes identification of RFI modes and criticality analysis.

Step 4 is similar to Failure Mode Analysis in LSA.

The following definitions are applicable to the criticality analysis of the RFI Culprits:

a. Criticality of RFI.

b. Probability of RFI.

c. Severity of RFI.

The relationships between criticality, probability and severity of RFI are given in Table 4-1:

Table 4-1: The Criticality Analysis Matrix with the combination of Severity and Probability

Probability	**A Saturate Receiver**	**4A** Unacceptable	**3A** Unacceptable	**2A** Unacceptable	**1A** Unacceptable
	B Detectable Strong	**4B** Acceptable	**3B** Mitigation Plan	**2B** Mitigation Plan	**1B** Unacceptable
	C Detectable Medium	**4C** Acceptable	**3C** Mitigation Plan	**2C** Mitigation Plan	**1C** Mitigation Plan
	D Detectable Low	**4D** Acceptable	**3D** Acceptable	**2D** Acceptable	**1D** Mitigation Plan
	E Detectable Unlikely	**4E** Acceptable	**3E** Acceptable	**2E** Acceptable	**1E** Acceptable
		4 Outside Band	**3 Short time**	**2 Narrow Band Continues**	**1 Wide Band Continues**
		Severity			

The Criticality analysis is done for the following RFI Victims, i.e. Radio Telescopes (named operational modes in the database):

d. K for KAT-7 Telescope.

e. P for PAPER Telescope.

f. C for C-BASS Telescope.

g. M for MeerKAT Telescope.

Figure 4-7 shows an example of the criticality analysis results for each Operational Mode (RFI Victim) in the RFI database:

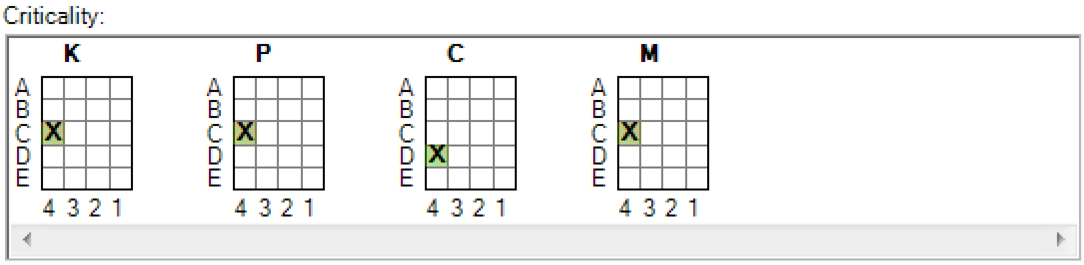


Figure 4-7: RFI Database Criticality Display for each RFI Victim

Once an item has been analyzed, a yellow icon is added to the red icon in the structure of the RFI database in the Failure Analysis view, to show that analysis is available for that item. Figure 4-8 shows an example of the yellow icon:

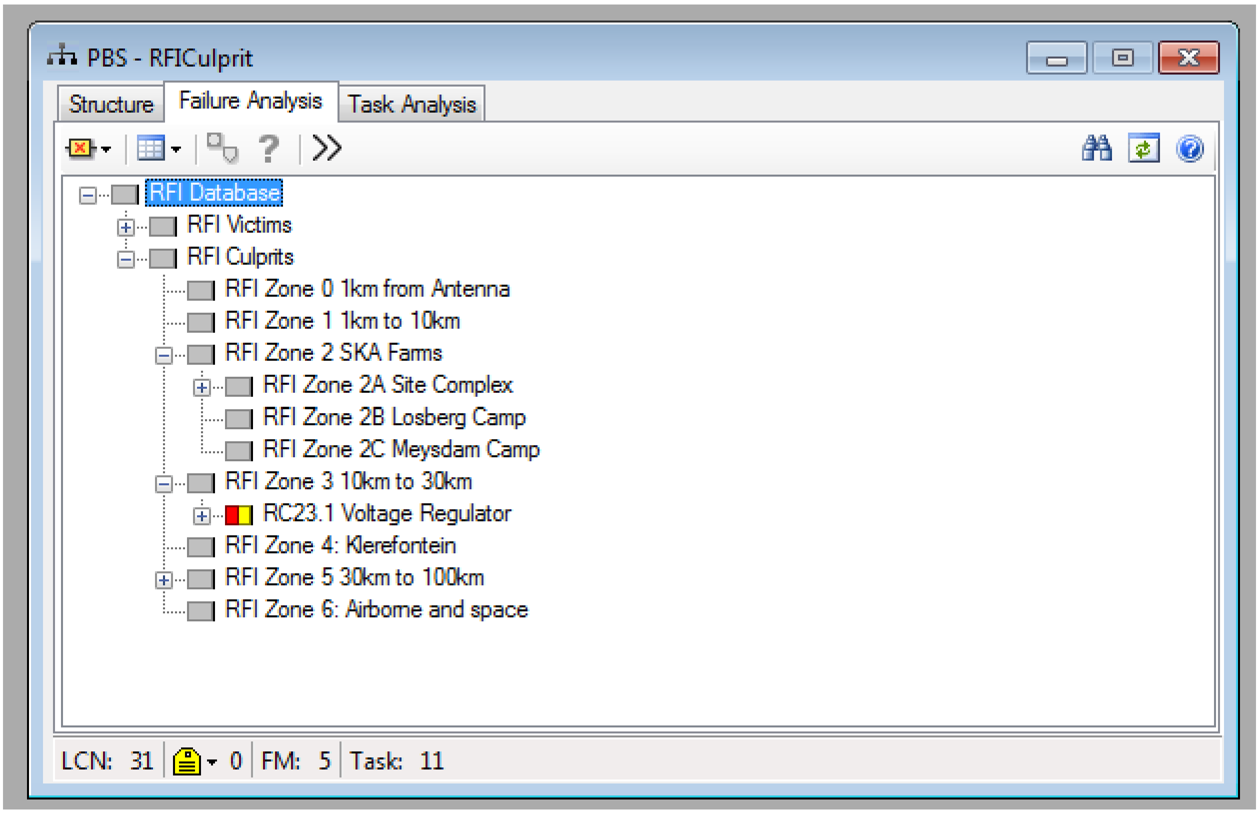


Figure 4-8: Yellow icon – analysis data is available for the RFI Item

4.2.4.1 Definition of Criticality

Criticality is a combination of the probability and severity of the RFI. Three levels of criticality are defined (refer to Table 4-1):

a. **Critical (red).** A rating of Critical means that the RFI from the Culprit will have a severe impact on the performance of the Radio Telescope (the Victim). Any RFI rated as Critical is classified as unacceptable and effort must be taken to reduce the criticality of the RFI. If required, the authority of the AGA act [6] can be used to enforce such a reduction.

b. **Major (yellow).** A rating of Major means that the RFI from the Culprit will cause the loss of some data, such as some frequency channels. Any RFI rated as Major will require a mitigation policy. See paragraph 4.2.6 for more detail on mitigation policies.

c. **Minor (green).** A rating of Minor means the RFI will NOT impact the performance of the Radio Telescope and no mitigation policy is required. However, the RFI Culprit will be monitored for compliance on a periodic basis.

4.2.4.2 Detail Definition of Probability of RFI

The probability of RFI is defined as a signal level relative to the SARAS standard [4], taking into account the reduction in signal due to distance from the receiver, using the calculation spreadsheet [7]. Table 4-2 gives the definition of the probability levels:

Table 4-2: Definition of Probability Levels for the RFI Analysis

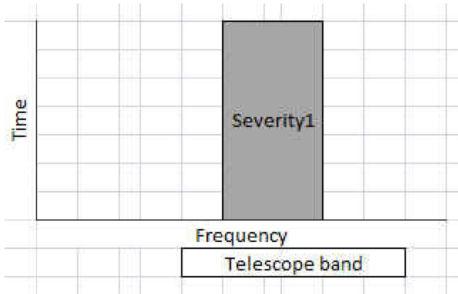
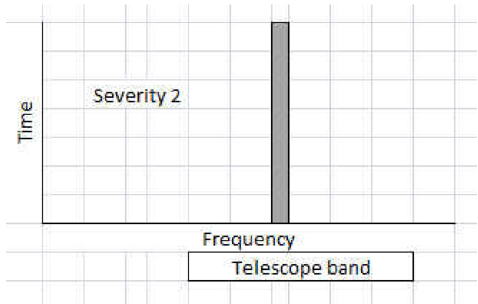
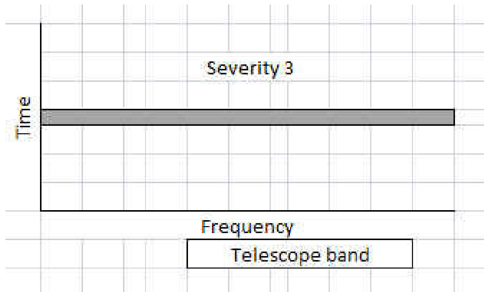
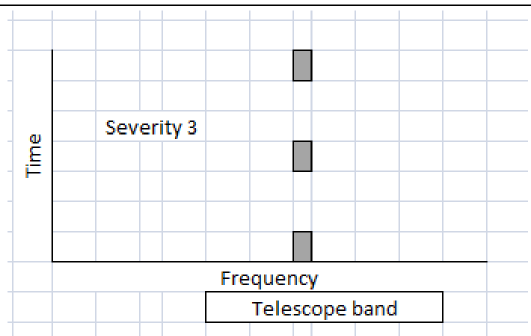
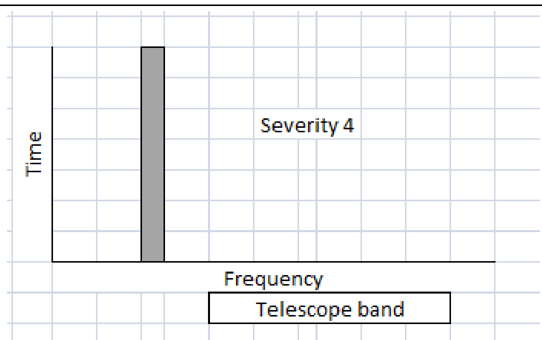
Probability Code	Definition	Signal Level
A	Saturate Receiver	60 dB or more above standard (contour)
B	Detectable Strong	30 to 59 dB above standard (contour)
C	Detectable Medium	10 to 29 dB above standard(contour)
D	Detectable Low	0 to 9 dB above standard (contour)
E	Detectable Unlikely	Signal below standard (contour)

Note that the above definitions were developed for the purpose of this thesis and used in the case studies. These definitions will need review and agreement before they may be used on a specific project, such as MeerKAT.

4.2.4.3 Detail Definition of Severity of RFI

Table 4-3 gives a detailed definition of the RFI severity codes used in the criticality analysis:

Table 4-3: RFI Severity Codes as sued in the RFI Analysis

Severity Code	Definition	Graphic
1	Inside Frequency band Wide band Continuous	
2	Inside Frequency band Narrow band Continuous	
3	Inside Frequency band Wide band Short time	
3	Inside Frequency band Narrow band Short time	
4	Outside Frequency band	

Note that signals which are outside the band of the Telescope can also saturate the Receiver if they are strong enough and such signals must also be classified using the above definitions.

4.2.4.4 Examples of Criticality

Table 4-4 gives some examples of the various criticality ratings. Note that this table is not a comprehensive list of RFI Culprits. Its aim is to illustrate the definitions used in the matrix given in Table 4-1:

Table 4-4: Examples of Criticality Rating as a result of the RFI Analysis

RFI Culprit RFI Victim	Severity	Probability	Criticality	Typical Mitigation
Power line arcing, close to antenna	1 Wide band Continuous (inside band)	A Saturate Receiver 60 dB or more above standard	1A **Red** Unacceptable (Critical)	Change design of power line to prevent arcing
Arc welding close to antenna	3 Wide band Short time (inside band)	A Saturate Receiver 60 dB or more above standard	3A **Red** Unacceptable (Critical)	Ensure no arc welding is done close to antenna
Strong cell phone signal at antenna	2 Narrow band Continuous (inside band)	B Strong signal 40 to 59 dB above standard	2B **Red** Unacceptable (Critical)	Reduce cell phone signal towards the antenna to reduce the level
High power lights when switched on in construction shed	3 Wide band Short time (inside band)	C Medium signal 20 to 39 dB above standard	3C **Yellow** Mitigation Plan (Major)	Influence design to remotely monitor and control switch on of lights
Microwave oven at site complex	4 Narrow band Short time (inside band)	B Strong signal 40 to 59 dB above standard	4B **Yellow** Mitigation Plan (Major)	Allow use of microwave during construction only, but switch off when operation begins
Microwave oven at support base	4 Narrow band Short time (inside band)	D Low signal 0 to 19 dB above standard	4D **Green** Acceptable (Minor)	Allow use of microwave but monitor radiation levels on periodic basis
Low powered data link with shaped antenna beam, far from the site	2 Narrow band Continuous (inside band)	E Detection unlikely Signal below standard	2E **Green** Acceptable (Minor)	Allow use of data link but monitor radiation levels on periodic basis

4.2.5 Step 5: Analyze Tasks

Tasks are now defined from the results of the criticality analysis in the previous step. These can include:

a. RFI testing.

b. Design modifications required.

c. Additional screening to be fitted.

d. Operations procedures to be developed.

e. Recording on RFI database.

Step 5 is similar to Maintenance Task Analysis in LSA.

The tasks are listed on the RFI database and are indicated with a yellow icon on the structure in the 'Task Analysis' view. Figure 4-9 shows an example of such tasks in the structure:

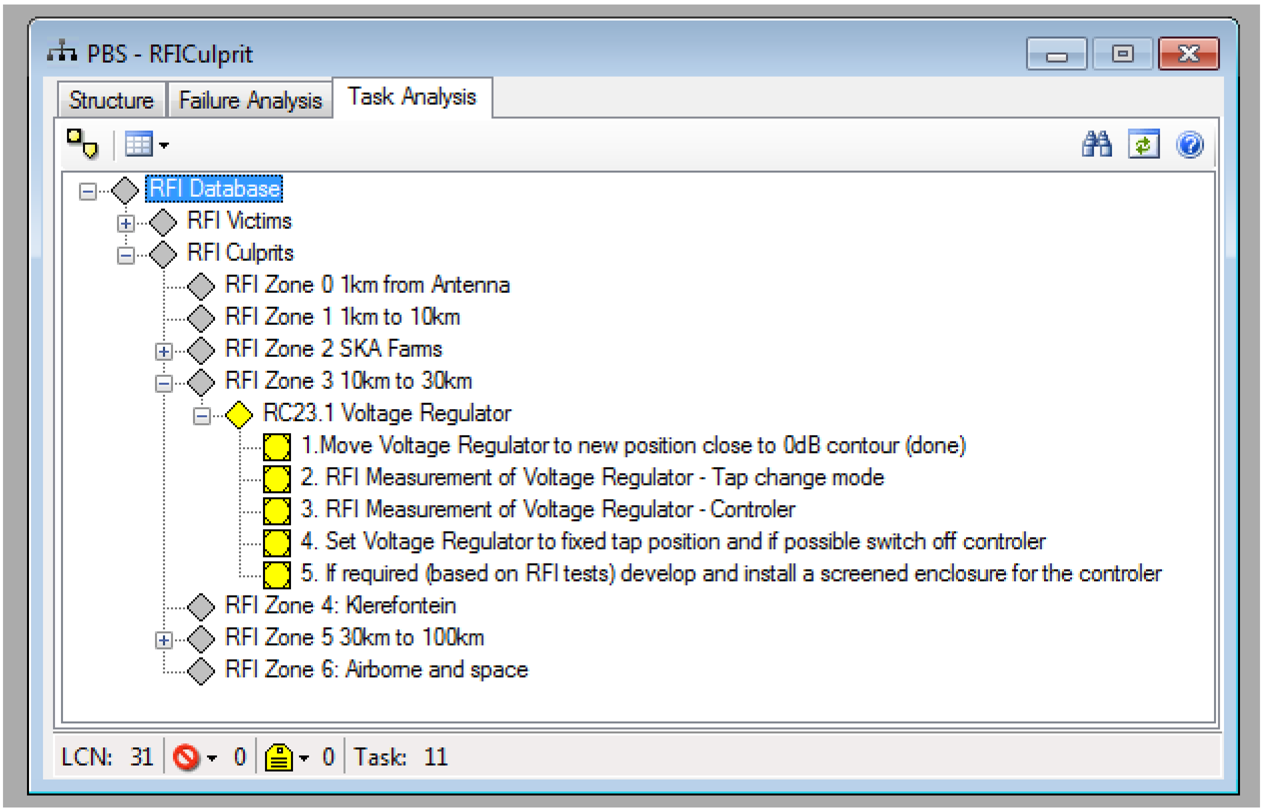


Figure 4-9: Example of Task Analysis on the RFI Database

4.2.6 Step 6: Manage RFI Mitigation

The tasks defined in Step 5 can now be developed into mitigation plan for each item, using one or more of the following mitigation policies:

a. Additional RFI Testing.

   This policy is to perform additional RFI testing in order to improve the analysis results. This can include testing of units of a similar type in a lab environment (such as at Houwteq) or on-site testing of the installed items.

b. Design Change – remove item / change technology.

   This policy removes the Culprit from the site by removing its function from the design, or replacing its function with an item using a less interfering technology (e.g. gas stove in place of microwave stove).

c. Design Change – move position of item

   This policy aims to reduce the radiated RFI level by moving the Culprit:

   i. Away from the Radio Telescope.

   ii. Closer to the ground.

   iii. Behind some natural screening e.g. a koppie.

d. Design Change – additional screening

   This policy aims to reduce the radiated RFI level by adding additional screening to the Culprit. Typical examples include a screened container for the KAT-7 electronic equipment.

e. Design Change – frequency

   This policy aims to change the frequency of the radiations from the Culprit to be outside the band of the Victims. Typical examples include the use of a 66 MHz radio system for communications, instead of the 900 MHz GSM system.

f. Operational Procedures

   This policy aims to reduce the time that the Culprit is radiating by introducing standard operating procedures. Typical examples include allowing interfering activities only during specific periods / time of day.

g. Record in the RFI Database

   The policy aims to have record of all electrical and electronic items deployed to site and the identified RFI Culprits, as well as test results and analysis.

The mitigation plan includes the definition of the following task resources:

h. People and Skills.

i. Facilities and Tools (e.g. RFI test equipment).

j. Documentation (procedures, etc.).

Once a mitigation plan has been developed, it is initiated and managed via the normal project management process, using the RFI database as a tool.

4.3 Summary

The new process developed for RFI analysis and related definitions for criticality may now be used to manage the wide scope of RFI Culprits on a Radio Astronomy site. The following chapter gives three examples on how this may be done.

CHAPTER 5 CULPRIT MEASUREMENTS (CASE STUDIES)

5.1 Introduction

This chapter demonstrates, by examples and case studies, how the methodologies described in the previous chapters may be used to manage RFI on a Radio Astronomy site. The following three case studies are presented here:

a. Case Study 1: Farm Equipment (see paragraph 5.2)

Farm equipment, such as equipment for power generation, kitchen use, entertainment and communications on the farms surrounding the site are potential RFI Culprits. Measurements were made by a MESA team (including the author) and the results were used to develop the analysis process. The results from the analysis may be used to develop equipment guidance to farmers.

b. Case Study 2: Voltage Regulators (see paragraph 5.3)

The designed 22 / 33 kV grid line includes voltage regulators to compensate for the voltage drop due to the large distance of the core site from the ESKOM substation. These voltage regulators are potential RFI Culprits and were subjected to RFI analysis. The design for the grid line was changed as a result of this analysis and the position of the voltage regulators changed.

c. Case Study 3: Lights (see paragraph 5.4)

The buildings at the site complex require lighting. This ranges from high level lights for the construction shed and electronic racks in the data centre area, to domestic lights in the office and accommodation area. Various types of lights were tested and analyzed using the techniques developed in Chapter 4. The results from the analysis may be used to give guidelines to the building designers on the type of lighting to use.

5.2 Case Study 1: Farmstead Power Generation and Other Equipment

5.2.1 Introduction

This case study is based on the investigation into typical farmstead power generating and other equipment as potential RFI Culprits. Tests were done by the author and MESA Solutions on 22 and 23 March 2011 on three farms in the Carnarvon Area. The MESA report [12] provides further detail on the measurements done.

5.2.2 Step 1: Identify the RFI Items

The following potential RFI Culprits were identified:

a. Power generation equipment, such as solar panels, wind charger, diesel generators.

b. Power storage and conversion equipment, such as batteries and static invertors

c. Domestic equipment, such as microwave ovens, TV and DStv receivers.

d. Radio communications equipment (Marnet system).

The identified equipment were given RFI identification numbers and logged on the RFI database (RamLog) – see Figure 5-1:

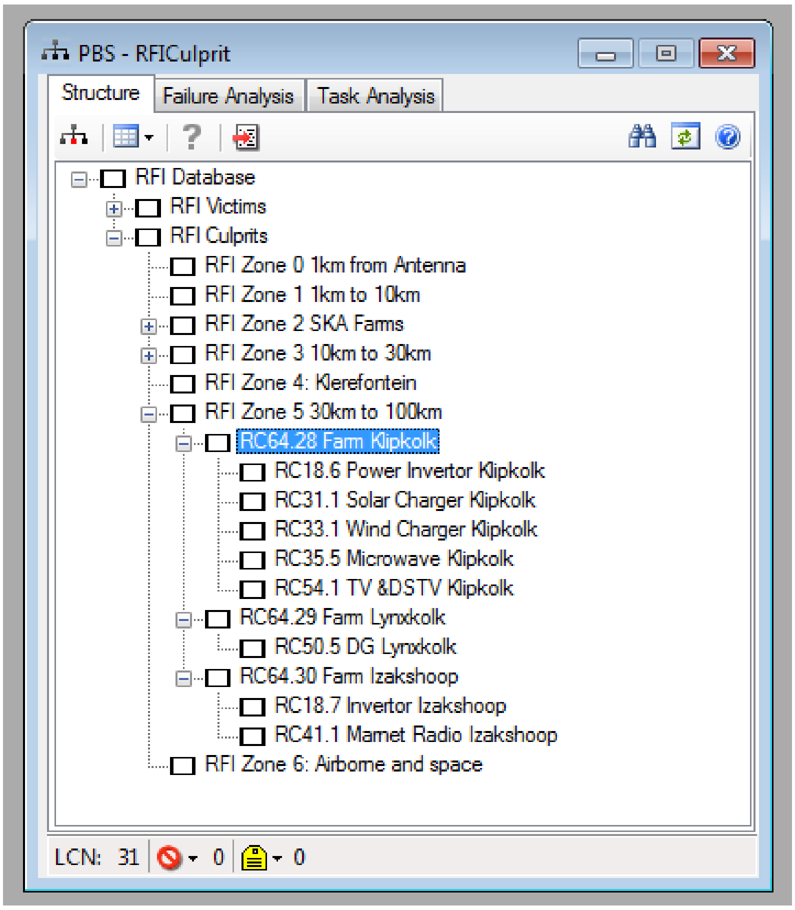
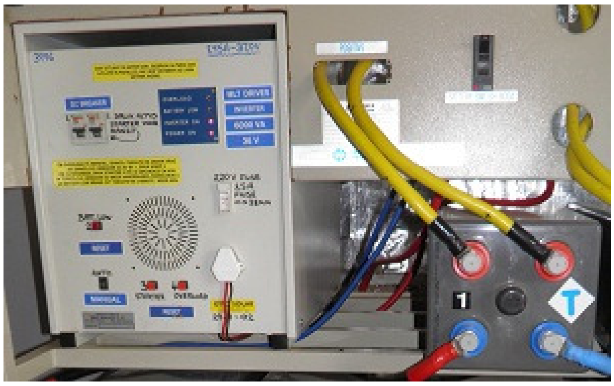
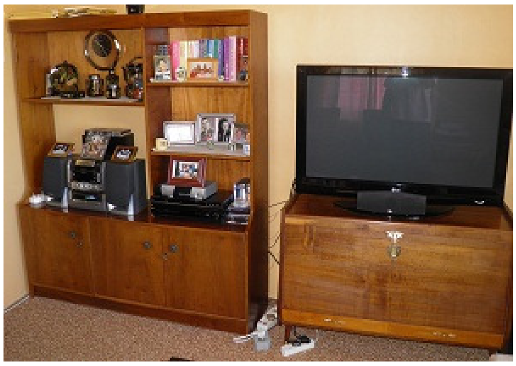


Figure 5-1: RFI Identification of Farmstead Culprits

The RFI Culprits identified at the three farmsteads are shown in Table 5-1:

Table 5-1: RFI Culprits at Farmsteads

Culprit ID No	Culprit	Photo
RC31.1	Solar Charger	
RC33.1	Wind Charger	
RC18.6	Power Invertor Type 1	
RC50.5	Diesel Genset	

Culprit ID No	Culprit	Photo
RC18.7	Power Invertors Type 2	
RC35.5	Microwave	
RC54.2	TV and DStv	
RC41.1	Marnet Radio	 

5.2.3 Step 2: Document the Deployment Plan

Figure 5-2 shows the how the newly developed RFI control form has been used to document the deployment of equipment at the farm Klipkolk:

SKA Africa	South African Radio Astronomy Reserve Control Permit	Permit No	2011-001
		Date Issued	22 March 2011
		Photo File name	

PART 1: Description of RFI Source / Culprit

1.1 Short description of equipment	General domestic and farm power generation equipment on Klipkolk farm
1.2 Equipment Make and Model number	
1.3 Equipment Type	

	Computer		Generator (alternator)	X	**TV**		Cell phone
	LCD Monitor	X	**Static Inverter**	X	**DSTV Encoder**		WiFi
	Printer	X	**Wind Charger**	X	**Microwave oven**		Data Link
	UPS	X	**Solar Charger**		HiFi		Cordless phone
	Switch/Router		Power Tools		Geyser		Radio Transmitter
	eNET Convertor		Petrol Vehicle		Heater		Satellite Phone
	Controller		Diesel Vehicle		Air Con		VSAT / VB SAT
	Access control		Electric motor/pump		Lights		Remote control
	Other (specify):						

PART 2 : Usage of RFI source / culprit

2.1 What will the equipment be used for?
Solar and wind charger is used to generate power for use in Farmhouse
TV & DSTV is used for leisure and entertainment
Microwave is used in Farm kitchen in addition to Gas cooking appliances

2.2 Duty Cycle	Always on	Day time only	Night time only	Short duration
	Other(Describe): Microwave is only on for very short periods Solar charges is always on (but only charges in day time) Wind charge is always on but only charges if the wind is blowing Static invertors is always on TV & DSTV is mostly used late afternoon and early evening			

PART 3 : Time on Site

3.1 Will the equipment be Permanent or Temporary only?	Permanent
3.2 Date deployed to site	Currently on site
3.2 Date to be removed from site (if applicable)	

PART 4 : Location of RFI source / culprit

4.1 Where will the equipment be located?

	Zone 0: Within 1 km from antenna		Zone 1: Between 1km and 10 km
	Zone 2A: SiteComplex		Zone 2B: Losberg Construction camp
	Zone 2C: Mesydam construction camp		Zone 3: Between 10km and 30km
	Zone 4: Klerefontein	X	**Zone 5: Between 30km and 100km Distance to core iste is 37km**

4.2 GPS Co-ordinates (if known)	LAT	**30°24'59.20"S**	LONG	**21°16'9.80"E**

Figure 5-2: Klipkolk RFI Control Form

Table 5-2 shows the location of the RFI Culprits at the various farmsteads and the farmstead distance to the centre of the MeerKAT core site:

Table 5-2: Deployment of RFI Culprits on Farms close to the Site

RFI Culprit ID	RFI Culprit	Farm Name	Farmstead distance to Site
RC18.6	Power Invertor Type 1	Klipkolk	37 km
RC31.1	Solar Charger	Klipkolk	37 km
RC33.1	Wind Charger	Klipkolk	37 km
RC35.5	Microwave	Klipkolk	37 km
RC54.2	TV and DStv	Klipkolk	37 km
RC50.5	Diesel Genset	Lynxkolk	29 km
RC18.6	Power Invertor Type 2	Izakshoop	39 km
RC41.1	Marnet Radio	Izakshoop	39 km

Figure 5-3 shows the location of the three farmsteads in relationship to the MeerKAT (M), PAPER (P) and KAT-7 (K) Radio Telescopes:

Figure 5-3: Location of farmsteads in relation to Core Site

5.2.4 Step 3: Select RFI Candidates

The RFI candidates were selected by comparing the measured radiated levels with contours developed based on the CISPR 22 Class B standard. The concept is that equipment below the contour level for its location poses a low risk (and thus NOT a candidate for further analysis) and equipment above or close to the contours pose a higher risk and is therefore a candidate for analysis.

The contours shown in Figure 5-4 were calculated as distances from the core site for a Transmitter (Culprit) radiating at CISPR 22 Class B Levels, to meet the SARAS levels [4] at the Radio Telescope Receiver (Victim).

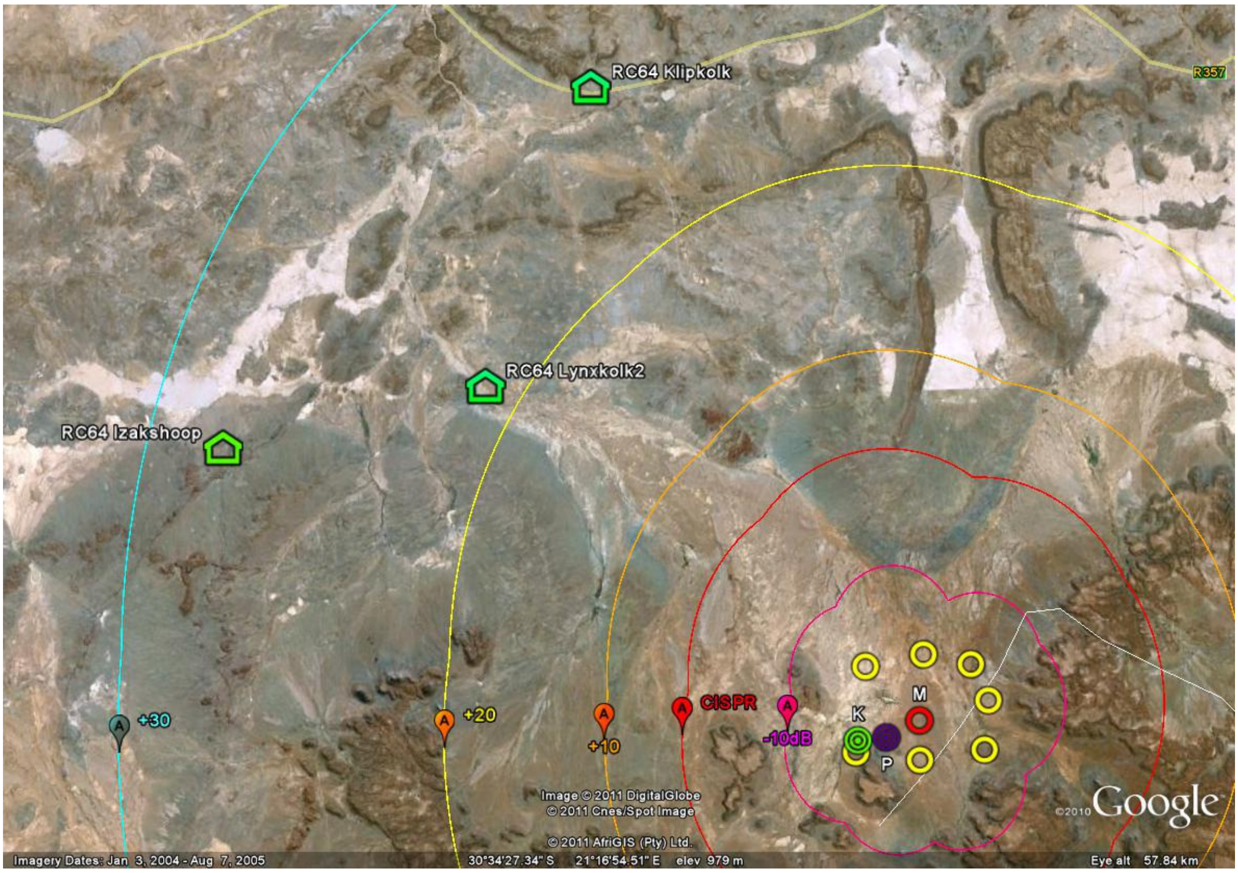


Figure 5-4: Contours for CISPR 22 Class B Levels

From Figure 5-4 it can be seen that:

a. Lynxkolk is close to the CISPR +20 contour.

b. Izakshoop is close the CISPR +30 contour.

c. Klipkolk is at about the CISPR +25 contour.

The levels measured for the RFI Culprits were adjusted to be in line with the CISPR 22 Class B standard in terms of bandwidth and distances from the unit under test and then compared with the CISPR levels.

Results are shown in Table 5-3:

Table 5-3: Comparison of measured results relative to CISPR Levels in order to identify RFI Candidates

Culprit		Location	Relative to CISPR22	Comment	RFI Candidate
RC18.6	Power Invertor	Klipkolk	-20	Well below +25 contour for Klipkolk	No
RC31.1	Solar Charger	Klipkolk	-12	Well below +25 contour for Klipkolk	No
RC33.1	Wind Charger	Klipkolk	-12	Well below +25 contour for Klipkolk	No
RC35.5	Microwave	Klipkolk	+49	Above +25 contour for Klipkolk	Yes
RC54.2	TV and DSTV	Klipkolk	-17	Well below +25 contour for Klipkolk	No
RC50.5	Diesel Genset	Lynxkolk	+6	Below +20 contour for Lynxkolk	Yes
RC18.6	Power Invertor	Izakshoop	-21	Well below +30 contour for Izakshoop	No
RC41.1	Marnet Radio	Izakshoop	+70	Above +30 contour for Izakshoop	Yes

Based on the above, the following RFI candidates were identified for criticality analysis; the microwave oven (at Klipkolk), the Marnet radio (at Izakshoop) and the diesel Genset (although not exceeding the contours) at Lynxkolk. Note that similar equipment closer to the site may present a problem.

Figure 5-5 shows the RFI database screen where the RFI candidates have been identified:

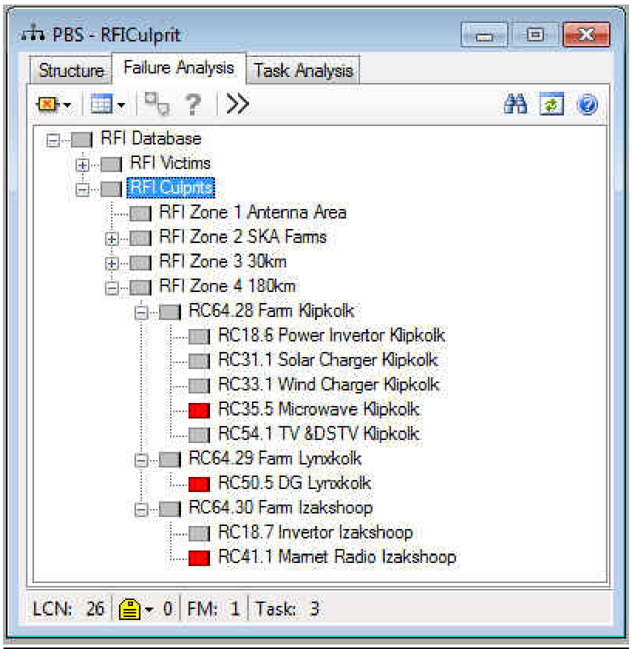


Figure 5-5: Identified RFI Candidates on the RFI Database (red icons)

5.2.5 Step 4: Analyze RFI Criticality

The RFI candidates identified in the previous step have been analyzed using the criticality definitions in paragraph 4.2.4.1.

Figure 5-6 shows the input screen for the RFI database for the criticality analysis:

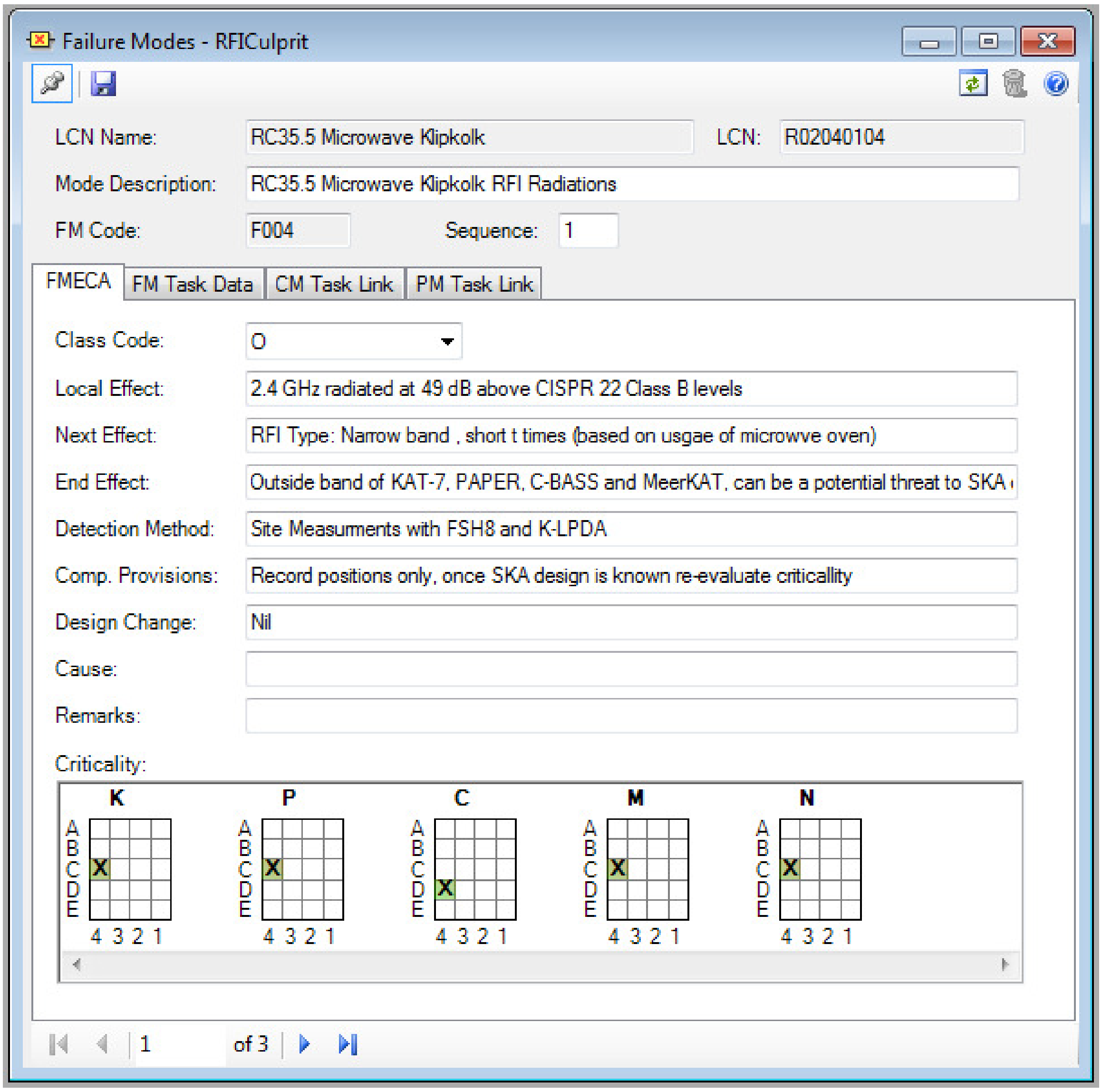


Figure 5-6: Criticality Analysis Input Screen on the RFI Database

The RFI criticality analysis report from the RFI database is shown on the following pages:

Table 5-4: Criticality Analysis report from the RFI Database showing the results of the RFI Analysis

Seq	FM Code	Mode Description	Class Code	Local Effect	Next Effect	End Effect	Comp. Provisions	Criticality M	Criticality S	Criticality P
R02040104		***00***	***RC35.5 Microwave Klipkolk***							
1	F004	RC35.5 Microwave Klipkolk RFI Radiations	O	2.4 GHz radiated at 49 dB above CISPR 22 Class B levels	RFI Type: Narrow band , short t times (based on usgae of microwve oven)	Outside band of KAT-7, PAPER, C-BASS and MeerKAT, can be a potential threat to SKA depending on SKA frequency bands	Record positions only , once SKA design is known re-evaluate criticality	C K M N P	4 4 4 4 4	D C C C C
R02040201		***00***	***RC50.5 DG Lynxkolk***							
1	F006	RC50.5 DG Lynxkolk FAILURE	O	Radiate 6dB above CISPR 22 Class B levels, but at low frequencies (below 30 MHz)	RFI Type: Wide Band continues - when Diesel is running	Outside band of KAT-7, PAPER, C-BASS and MeerKAT	Record all culprits on RFI database	C K M N P	4 4 4 4 4	D C C C C
R02040302		***00***	***RC41.1 Marnet Radio Izakshoop***							
1	F007	RC41.1 Marnet Radio Izakshoop FAILURE	O	Radiate at 70 dB above CISPR 22 Class B levels, Frequency of 76 MHz	RFI Type: Narrow band, short time (only when radio PPT is pressed)	Ourside band on KAT-7, PAPER, C-BASS and MeerKAT, possible Threat to SKA bepending on SKA frequency bands	REcord all positions, re-evaluate when SKA design is clear	C K M N P	4 4 4 4 4	C B B B B

5.2.5.1 Summary of Criticality

Figure 5-7 shows that all the RFI candidates were analyzed (red and yellow icons):

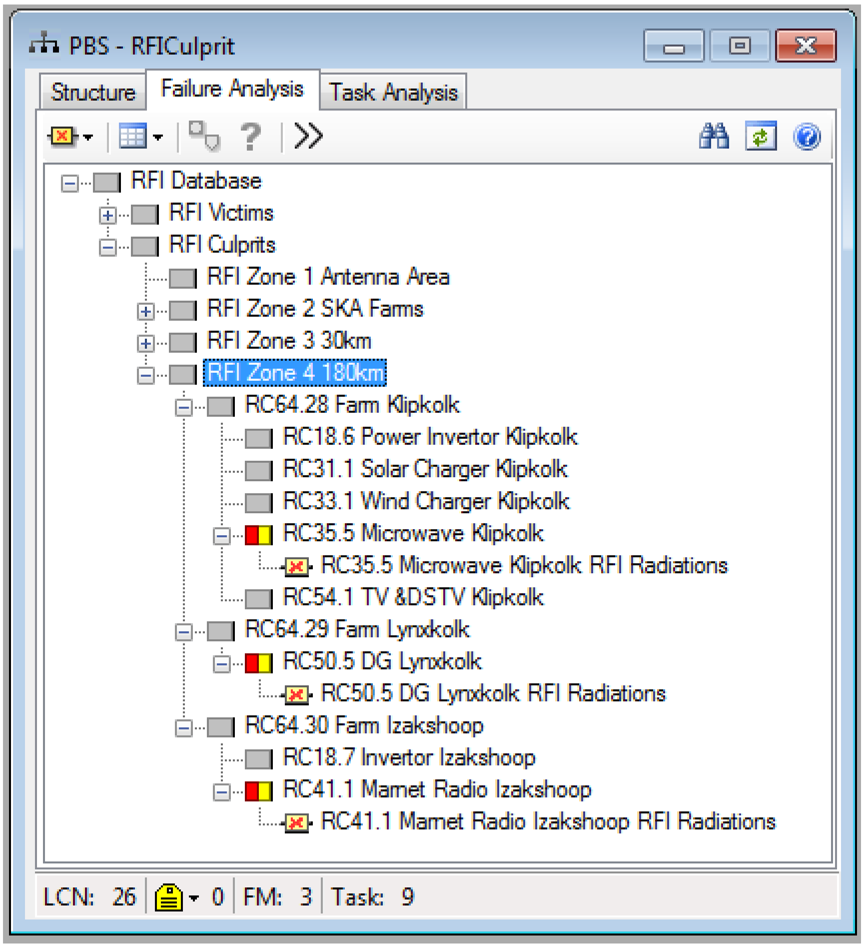


Figure 5-7: Analyzed RFI Candidates (red and yellow icons)

Table 5-5 gives a summary of the worst case criticality of the farmstead equipment (refer to Table 4-1 for the definitions).

Table 5-5: Summary of worst case Criticality for the Farm equipment resulting from the RFI Analysis

RFI Culprit	Severity	Probability	Criticality
RC35.5 Microwave oven	4	C	4C Acceptable
RC50.5 Diesel Lynxkolk	4	C	4C Acceptable
RC41.1 Marnet Radio Izakshoop	4	B	4B Acceptable

5.2.6 Step 5: Analyze Tasks

Based on the criticality analysis in Step 4, tasks were identified and recorded on the RFI database. Figure 5-8 illustrates these tasks:

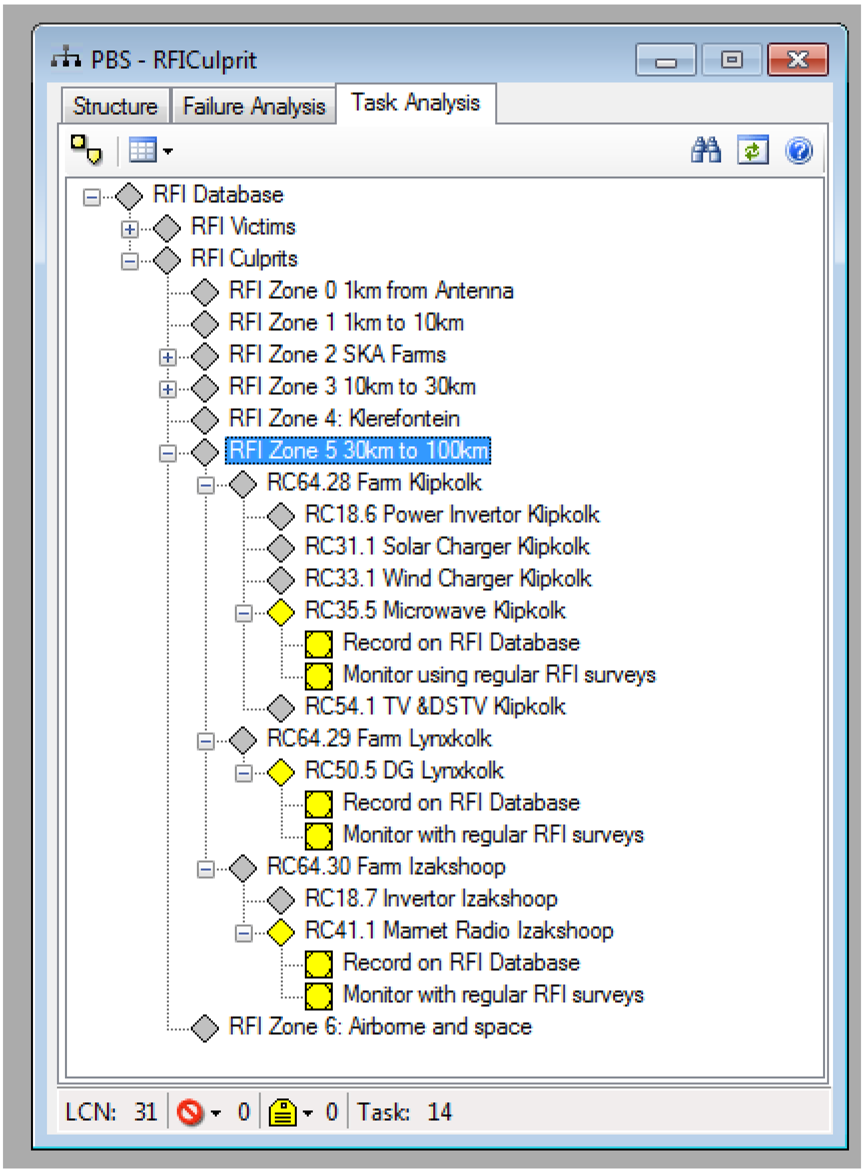


Figure 5-8: Tasks defined for Farm equipment on the RFI Database

5.2.7 Step 6: Manage RFI Mitigation

The following table gives the mitigation plan for farm equipment, based on the tasks identified in the previous step:

Table 5-6: Farm Equipment Mitigation Plan developed as part of the RFI Analysis

Task	Mitigation Policy	People / Skills	Equipment
Microwave oven Klipkolk Record on RFI database	SoP Record on Database	RFI Database manager	RFI Database
Microwave oven Klipkolk Monitor with regular RFI surveys	SoP RFI Surveys	RFI Measurement Engineer	RFI Test equipment or PAPER and KAT-7 Telescopes
Diesel Generator Lynxkolk and Izakshoop Record on RFI database	SoP Record on Database	RFI Database manager	RFI Database
Diesel Generator Lynxkolk and Izakshoop Monitor with regular RFI surveys	SoP RFI Surveys	RFI Measurement Engineer	RFI Test equipment or PAPER and KAT-7 Telescopes

5.3 Case Study 2: 33 kV Voltage Regulators

5.3.1 Introduction

The voltage regulators are large transformers which are fitted to the 22 kV grid power line to compensate for the voltage drop due to the long distance from the Karoo substation to the core site. This case study is an example of how the developed process was used to influence the 'system design' of the grid power line and specifically the location of the voltage regulators.

5.3.2 Step 1: Identify the RFI Items

Figure 5-9 shows the voltage regulators in storage at the site complex:

Figure 5-9: Voltage Regulators in Storage

Figure 5-10 shows the voltage regulators in the structure of the RFI database:

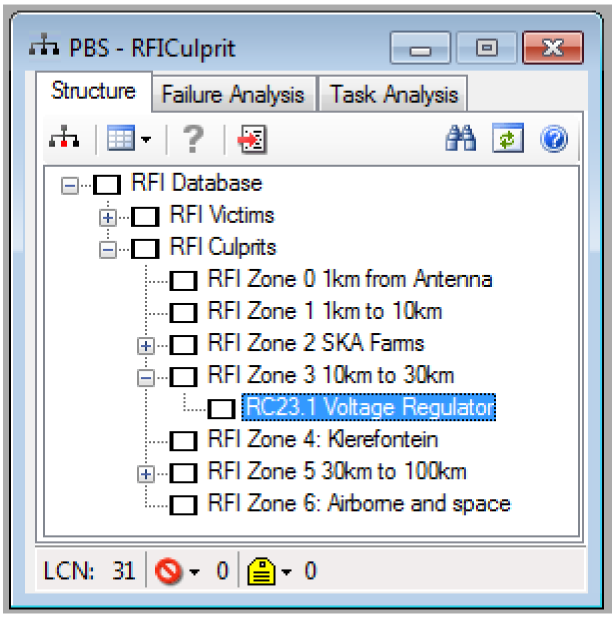


Figure 5-10: Voltage Regulator in the RFI Database

5.3.3 Step 2: Document the Deployment Plan

Figure 5-11 shows the deployment information for the voltage regulators:

SKA AFRICA SQUARE KILOMETRE ARRAY	**South African Radio Astronomy Reserve Control Permit**	Permit No	2011-002
		Date Issued	4 Jan 2011
		Photo File name	

PART 1: Description of RFI Source / Culprit

1.1 Short description of equipment	22kV Grid Line – Voltage Regulator
1.2 Equipment Make and Model number	Cooper Power Systems Type CL6

1.3 Equipment Type

	Computer		Generator (alternator)		TV		Cell phone
	LCD Monitor		Static Inverter		DSTV Encoder		WiFi
	Printer		Wind Charger		Microwave oven		Data Link
	UPS		Solar Charger		HiFi		Cordless phone
	Switch/Router		Power Tools		Geyser		Radio Transmitter
	eNET Convertor		Petrol Vehicle		Heater		Satellite Phone
	Controller		Diesel Vehicle		Air Con		V SAT / VB SAT
	Access control		Electric motor/pump		Lights		Remote control
X	**Other (specify): 22kV Voltage Regulator**						

PART 2 : Usage of RFI source / culprit

2.1 What will the equipment be used for?
Correction of voltage drop on grip Power line, tapping 10% up or down on voltage levels

2.2 Duty Cycle	**Always on X**	Day time only	Night time only	Short duration
	Control circuit always on, powertapping only when ESKOM supply voltage changes			

PART 3 : Time on Site

3.1 Will the equipment be Permanent or Temporary only?	Permanent
3.2 Date deployed to site	Early 2011
3.2 Date to be removed from site (if applicable)	NA

PART 4 : Location of RFI source / culprit

4.1 Where will the equipment be located?

	Zone 0: Within 1 km from antenna	X	Zone 1: Between 1km and 10 km
	Zone 2A: SiteComplex		Zone 2B: Losberg Construction camp
	Zone 2C: Mesydam construction camp		Zone 3: Between 10km and 30km
	Zone 4: Klerefontein		Zone 5: Between 30km and 100km Distance to core iste is 37km

4.2 GPS Co-ordinates (if known)	LAT	**30°43'0.83"S**	LONG	**21°27'53.93"E**

Figure 5-11: Voltage Regulator Deployment Information

Figure 5-12 shows the planned position of the voltage regulator in relationship to the various Radio Telescope antennas (Victims).

Figure 5-12: Position of Voltage Regulator (red) in relation to Radio Telescope Antennas

Table 5-7 gives the distances from the voltage regulator to the Radio Telescopes:

Table 5-7: Distances from Voltage Regulator to Radio Telescopes

Radio Telescope (Victim)	Distance to Voltage Regulator
KAT-7	5,34 km
PAPER	3,74 km
MeerKAT Core	2,02 km

5.3.4 Step 3: Select RFI Candidate

The following figure shows the position of the voltage regulator in relationship to the CISPR 22 Class B contours:

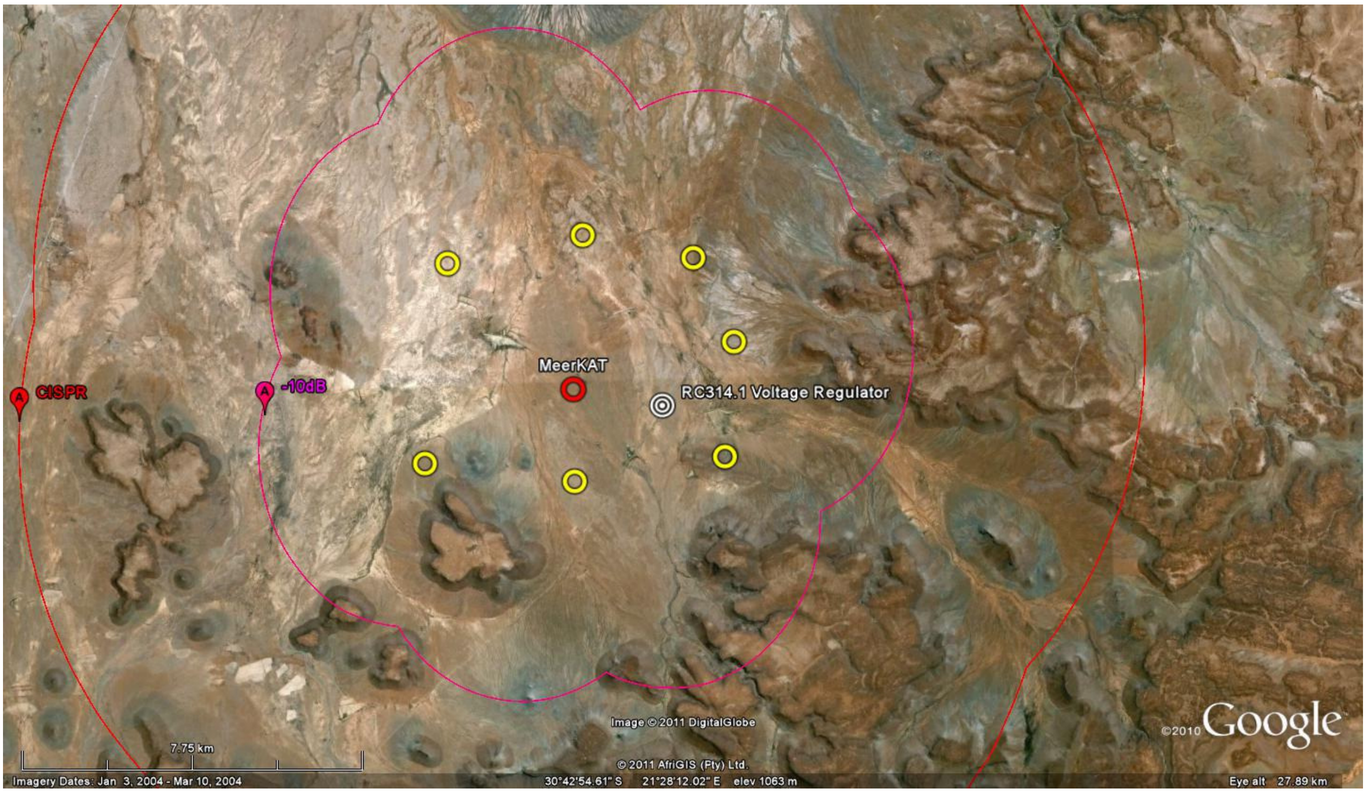


Figure 5-13: Voltage Regulator position in relation to CISPR-22 Contours

No test results or standards very readily available for the voltage regulators. Figure 5-14 shows the results of a visual inspection:

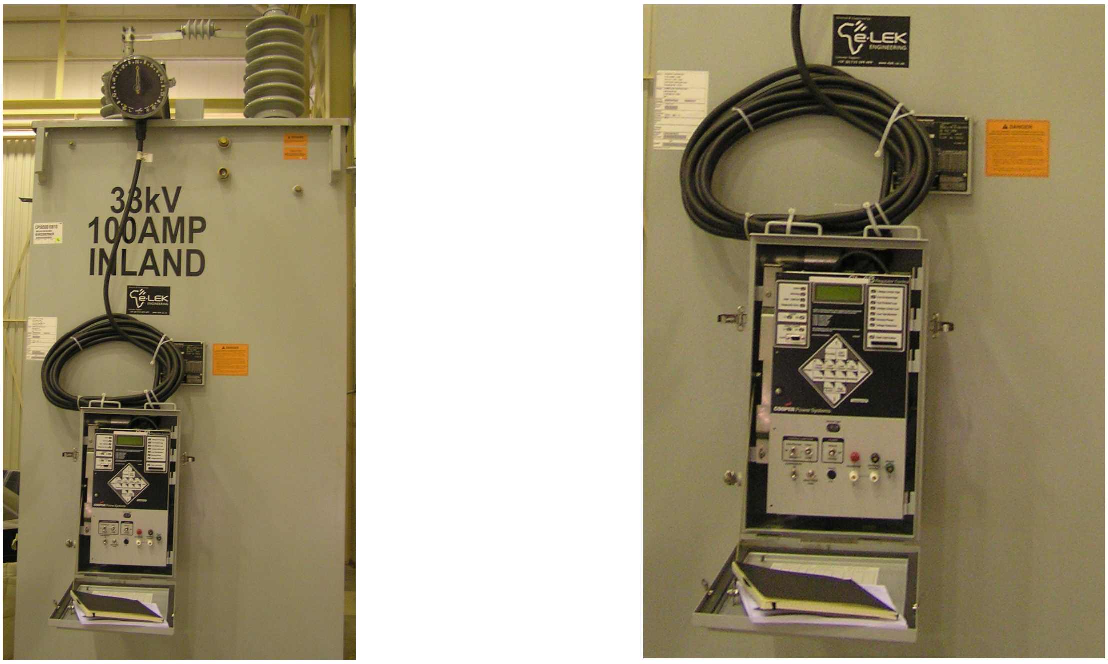


Figure 5-14: Voltage Regulator Visual Inspection

Based on the visual inspection, it was estimated that the voltage regulator will not be much better than CISPR-22 Class B as it did not have any specific RFI screening provisions.

The voltage regulator was classified to be a candidate for RFI analysis.

Figure 5-15 shows the RFI database screen with the voltage regulator indicated as a RFI candidate (LAC ticked):

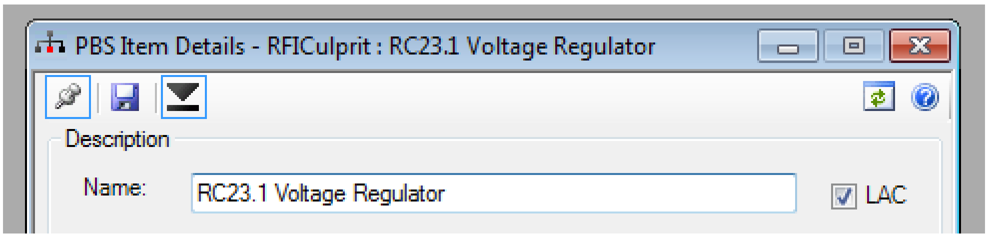


Figure 5-15: Voltage Regulator selected as candidate for RFI Analysis

5.3.5 Step 4: Analyze RFI Criticality

Two RFI modes were identified and analyzed for the voltage regulators. See Figure 5-16, from the RFI database:

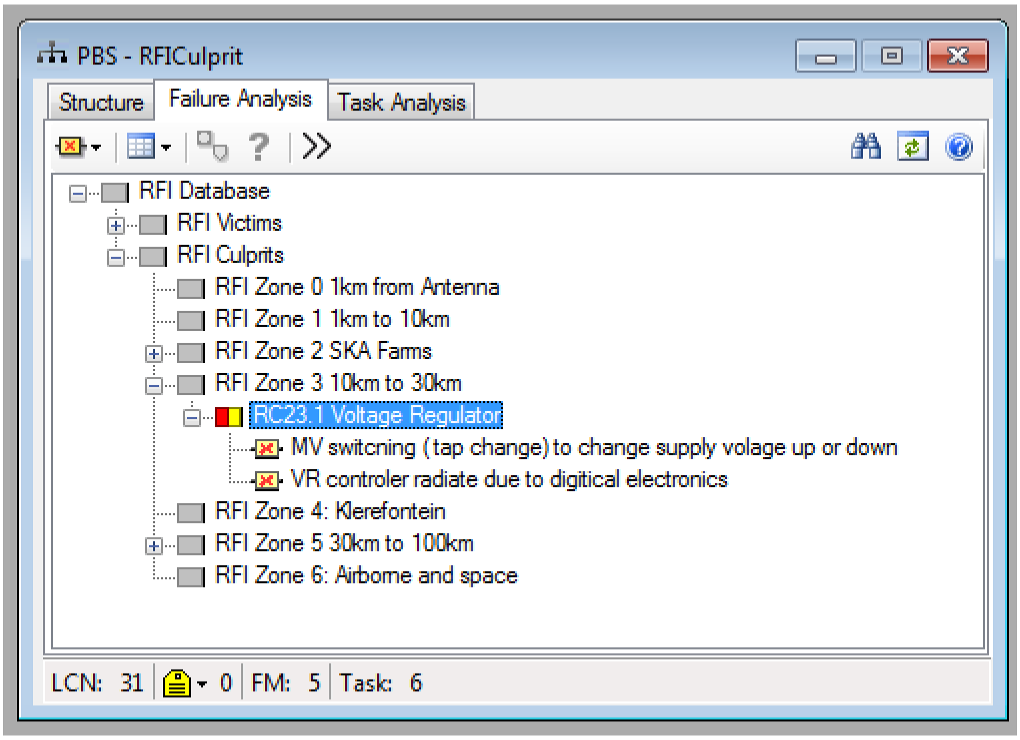


Figure 5-16: Voltage Regulator – RFI Failure modes from the RFI Database

The results of the RFI analysis of the voltage regulators are shown in Table 5-8 below:

Table 5-8: Report from the RFI Database showing the analysis results for the Voltage Regulators

Seq	FM Code	Mode Description	Class Code	Local Effect	Next Effect	End Effect	Comp. Provisions	Criticality M	Criticality S	Criticality P
R020301		***00***	***RC23.1 Voltage Regulator***							
1	F008	MV switcning (tap change) to change supply volage up or down	O	Short duration radiation due to 22/33kV switching inside VR	RFI Type: Wide band , short time	Possible RFI source for PAPER, KAT-7 and MeerkAT, unlikely for C-BASS (due to distance)	Consider setting to fixed tap position i.e. no automatic switching, Consider moving position to CISPR-22 0dB contour	C K M P	3 4 3 3	E B B B
2	F009	VR controler radiate due to digitical electronics	O	Continues emissions due to clock of controler digital electronics	RFI: Type narrow band , continues	Possible RFI source for PAPER, KAT-7 and MeerkAT, unlikely for C-BASS (due to distance)	Consider switching off controler (after setting tap positions),Consider moving position to CISPR-22 0dB contour	C K M P	1 1 1 1	E B B B

Table 5-9 gives a summary of the worst case criticality of the voltage regulators (refer to Table 4-1 for the definitions):

Table 5-9: Worst Case Criticality for the voltage regulators before mitigation

Failure mode	Severity	Probability	Criticality
MV switching (tap changes) to change supply voltage up or down	3	B	3B Mitigation Plan
VR controller radiate due to digital electronics	1	B	**1B** Unacceptable

In order to get rid of the 'unacceptable' criticality, a design change to the Electrical System was initiated and the voltage regulator position was changed to a new position about 12,3 km from the MeerKAT core (close to the CISPR 0 dB contour line) and behind one series of koppies. See the Figure 5-17 for the initial position, as well as the new position:

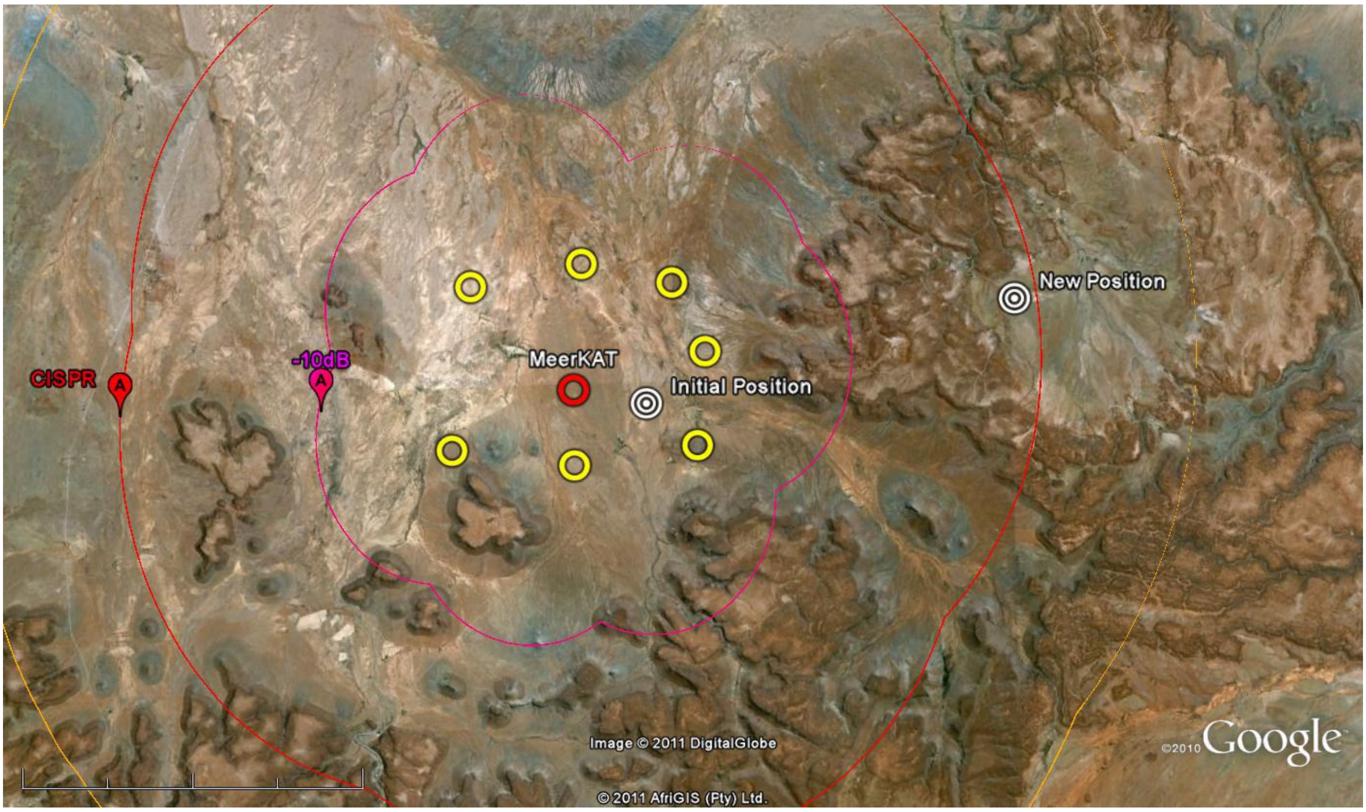


Figure 5-17: Voltage Regulator new position, as a result of the RFI Analysis

As a result of the new positions of the voltage regulators, the criticality was improved to be as per the following table:

Table 5-10: Worst Case Criticality for the voltage regulators after mitigation

Failure Mode	Severity	Probability	Criticality
MV switching (tap changes) to change supply voltage up or down	3	C	3C Mitigation Plan
VR controller radiate due to digital electronics	1	C	**1C** Mitigation Plan

5.3.6 Step 5: Analyze Tasks

Based on the criticality analysis in Step 4, the following five tasks (see Figure 5-18) were defined for the voltage regulators:

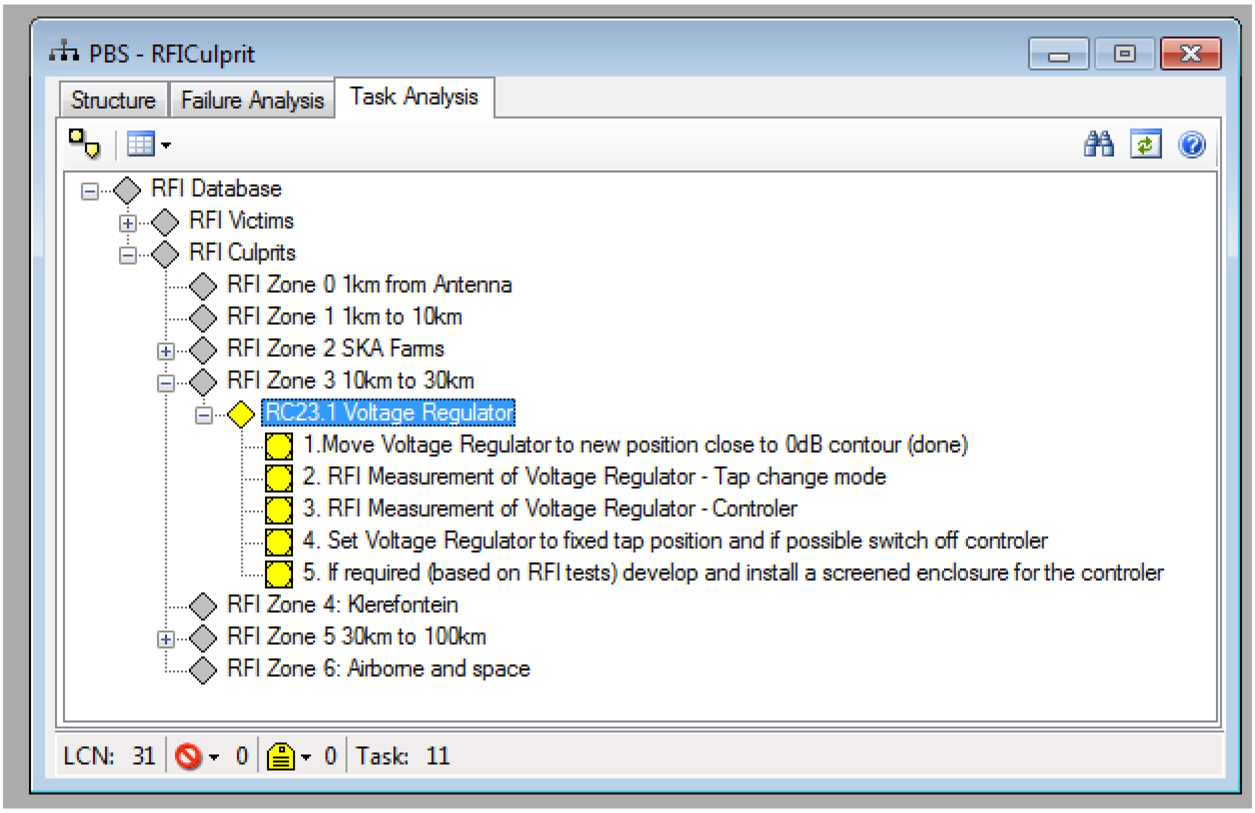


Figure 5-18: Task Definition for the Voltage Regulators

5.3.7 Step 6: Manage RFI Mitigation

Table 5-11 gives the mitigation plan for voltage regulators, based on the tasks identified in the previous step:

Table 5-11: Voltage Regulator Mitigation Plan

Task	Mitigation Policy	People / Skills	Equipment
1. Move Voltage Regulator to new position close to 0dB contour	Design change – Move position of item	Electrical contractor	Contractor equipment
2. RFI Measurement of Voltage Regulator – tap change mode	Additional RFI testing	RFI Measurement engineer	RFI Test antenna RFI Receiver
3. RFI Measurement of Voltage Regulator – controller	Additional RFI testing	RFI Measurement engineer	RFI Test antenna RFI Receiver
4. Set Voltage Regulator to fixed tap position and if possible switch off controller	Operational Procedures	Site electrical technician	CRETE
5. If required (based on RFI tests), develop and install a screened enclosure for the controller	Design change additional screening	Development engineer	Lab / Manufacturing facility

5.4 Case Study 3: Various Light Technologies for the Site Complex

This case study considers the lights to be fitted at the buildings and facilities of the Site Complex, about 5 km from the core of the MeerKAT Radio Telescope. This includes the lights inside the buildings, for general office and domestic use, the lights inside the technical areas (such as the data rack area and electrical facility), the lights inside the dish manufacturing facility (the factory) as well as lights outside the buildings (such as flood lights and street lamps for parking and security).

5.4.1 Step 1: Identify the RFI items

A light, or to use the better term, luminaire; consists of the outside physical enclosure and of a lamp. Figure 5-19 shows the typical parts of a luminaire:

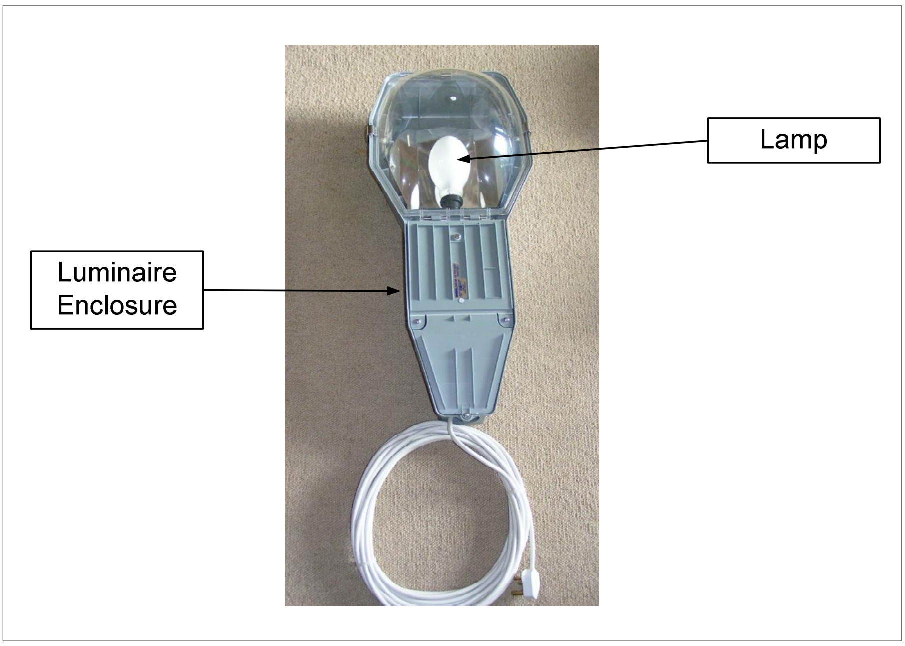


Figure 5-19: Details of a typical Luminaire

There are a number of technologies for the lamp of a luminaire; such as incandescent, various gasses or light emitting diode. The type of technology selected for a specific application is decided by design parameters, including the requirement for light level of the application (measured in Lumens / Lux), energy efficiency (measured in watts per Lumens) and cost.

Figure 5-20 gives an overview of the types of lamp technologies:

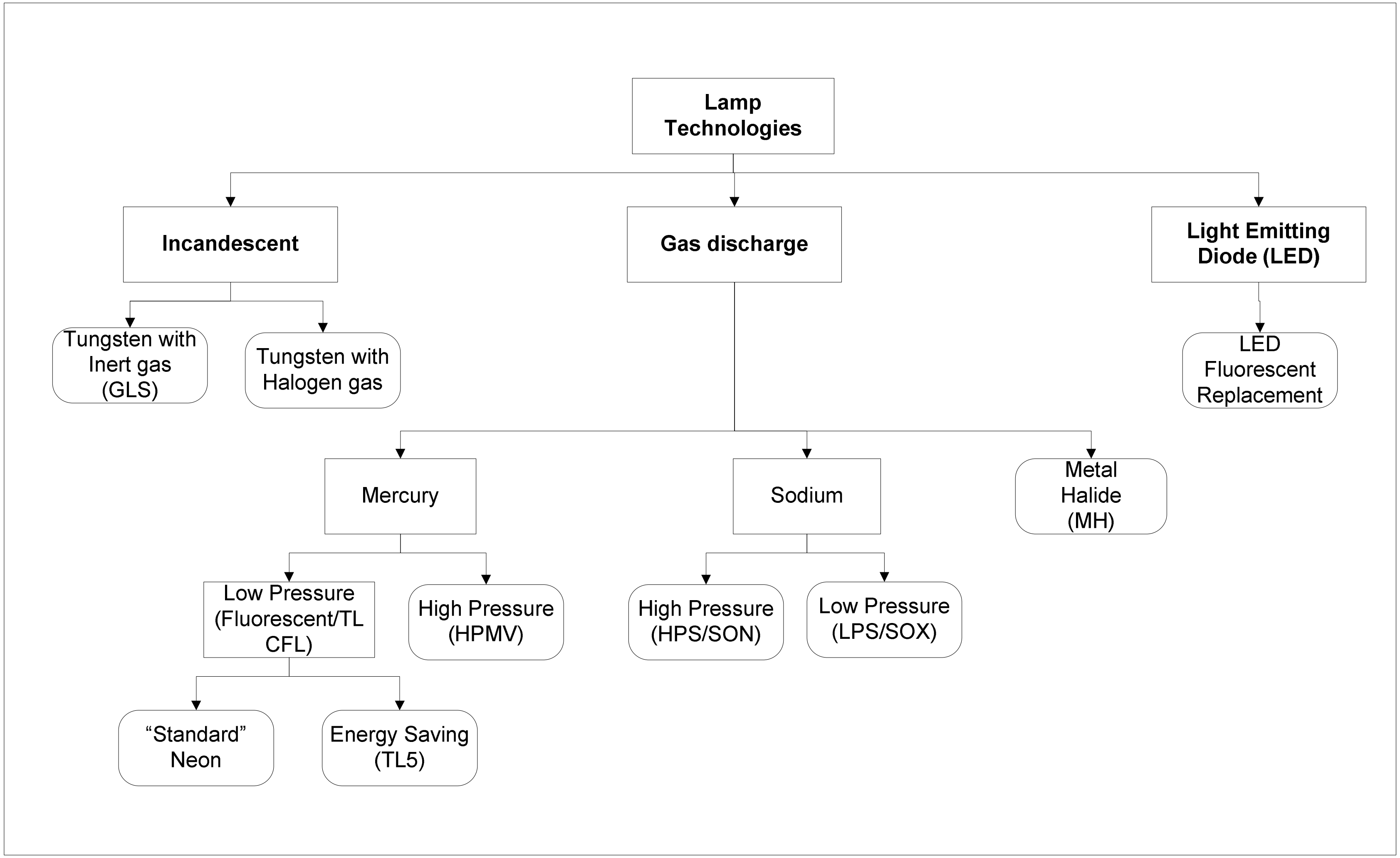


Figure 5-20 : Overview of Lamp technologies used in Luminaires

Table 5-12 gives an overview of the typical design parameters and application of the various lamp technologies:

Table 5-12: Lamp Technology Design Parameters

Lamp Type	Typical Design Parameters				Examples	Typical Application				
	Output [Lumens / Watt]	Lamp Life [hours]	Typical Cost	Wattage Ranges		General Indoor	Data Centre	Factory	Flood Light	Parking and Security
Incandescent (GLS)					Beka Rondo	x				
Compact Fluorescence (CFL)	Medium 65-70	Medium 7500	Low	Low 10-200	Beka Rondo	x				
					Beka Heavy	x	x	x		
					Philips Smartform	x	x	x		
					Beka Lane					x
Light Emitting Diode (LED)	Medium 40-60	High 100 000	Medium	Low 10-200	Philips Power balance	x	x	x		
					Beka with Optotronic PSU	x	x	x		
High Pressure Mercury (MV)	Medium 40-50	High 12000	High	High 50-1000	Beka Bay			x		
Metal Halide (MH)	High 62-112	High 12000	High	High 400-2000	Beka Max				x	x
High Pressure Sodium (HPS)	High 70-130	High 9000	High	High 100-1000	Beka Max				x	x

The various technologies are design parameters for the selection of the lamps for the Radio Telescope application. Product specifications and brochures are not very informative, thus a number of luminaires and lamps were identified as potential RFI Culprits and were investigated by the author. The following figure shows the various luminaires and lamps investigated:

Table 5-13: Typical Luminaires and Lamps planned for use on the Site

No	Luminaire		Lamp
1		Beka Lane	Type: High Pressure Sodium (HPS) Power: 150 W Light: 17 00 lm
2		Beka Lane	Type: Compact Fluorescence (CFL) Power: 57 W Light: 4 300 lm
3		Beka Max	Type: High Pressure Sodium (HPS) Power: 400 W Light: 48 000 lm
4		Beka Rondo	Type: Incandescent (GLS) Power: 100 W Light: 1 360 lm
5		Beka Rondo	Type: Compact Fluorescence (CFL) Power: 18 W Light: 1 200 lm

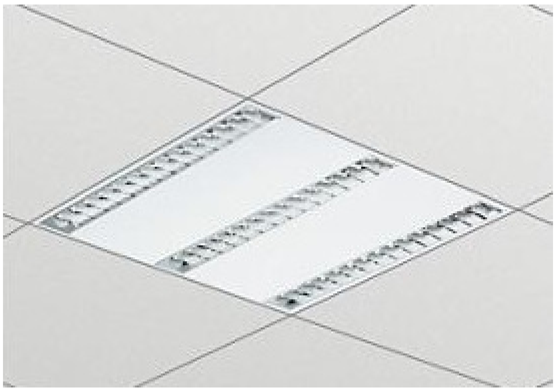
No	Luminaire		Lamp
6		Beka Bay	Type: High Pressure Sodium (HPS) Power: 400 W Light: 48 000 lm
7		Beka Heavy	Type: Compact Fluorescence (CFL) Power: 37 W Light: 5 700 lm
8		Philips Smartform TBS 460- TL5	Type: Compact Fluorescence (CFL) Power: 3x14 W (42 W) Light: 3x 1 200 lm (3 600 lm)
9		Philips Power Balance	Type: Light Emitting Diode (LED) 45 W 3 400 lm
10		Beka with Optotronic PSU	Type: Light Emitting Diode 15 W 1 200 lm

Figure 5-21 shows the lights for the Site Complex on the RFI database:

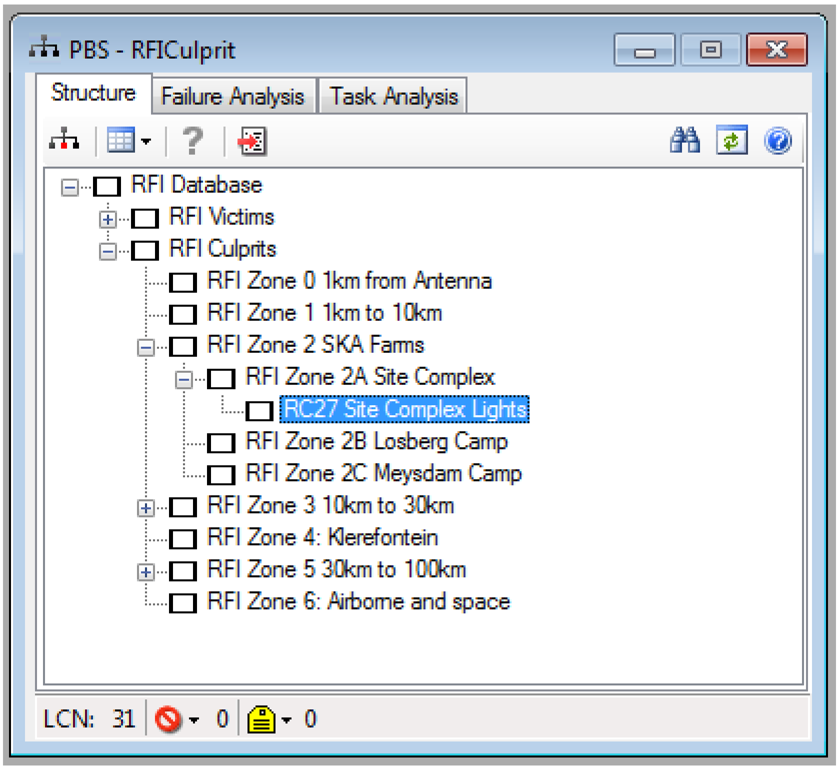


Figure 5-21: Lights at the Site Complex on the RFI Database

5.4.2 Step 2: Document the Deployment Plan

Figure 5-22 shows the RFI control permit for the Site Complex Lights:

SKA AFRICA SQUARE KILOMETRE ARRAY	South African Radio Astronomy Reserve Control Permit	Permit No	2011-003
		Date Issued	4 Jan 2011
		Photo File name	

PART 1: Description of RFI Source / Culprit

1.1 Short description of equipment	Site Complex Lights
1.2 Equipment Make and Model number	Varios

1.3 Equipment Type

	Computer		Generator (alternator)		TV		Cell phone
	LCD Monitor		Static Inverter		DSTV Encoder		WiFi
	Printer		Wind Charger		Microwave oven		Data Link
	UPS		Solar Charger		HiFi		Cordless phone
	Switch/Router		Power Tools		Geyser		Radio Transmitter
	eNET Convertor		Petrol Vehicle		Heater		Satellite Phone
	Controller		Diesel Vehicle		Air Con		VSAT / VB SAT
	Access control		Electric motor/pump	**X**	**Lights**		Remote control
	Other (specify):						

PART 2 : Usage of RFI source / culprit

2.1 What will the equipment be used for?
Lights for the various buildings including Accommodation, Security, Dish Assembly shed. Data Racks Area (Screened) and Power Facility

2.2 Duty Cycle	Always on X	Day time only	**Night time only**	Short duration
	Mostly night time only, but data rack area will also be on during day time as it has no natural light			

PART 3 : Time on Site

3.1 Will the equipment be Permanent or Temporary only?	Permanent
3.2 Date deployed to site	Late 2009
3.2 Date to be removed from site (if applicable)	NA

PART 4 : Location of RFI source / culprit

4.1 Where will the equipment be located?

	Zone 0: Within 1 km from antenna		Zone 1: Between 1km and 10 km
X	Zone 2A: SiteComplex		Zone 2B: Losberg Construction camp
	Zone 2C: Mesydam construction camp		Zone 3: Between 10km and 30km
	Zone 4: Klerefontein		Zone 5: Between 30km and 100km Distance to core iste is 37km

4.2 GPS Co-ordinates (if known)	LAT	**30°45'11.71"S**	LONG	**21°25'44.76"E**

Figure 5-22: RFI Control Permit for the Site Complex Lights

5.4.3 Step 3: Select RFI Candidate

The Site Complex location was selected so that the Losberg hill screens it from most of the Radio Telescope. This is the case for the KAT-7, PAPER and most of MeerKAT antennas; however, some of the MeerKAT antennas are within line of site of the Site Complex. Figure 5-23 shows the location of the Site Complex, within the -10 dB contour lines for CISPR 22 Class B:

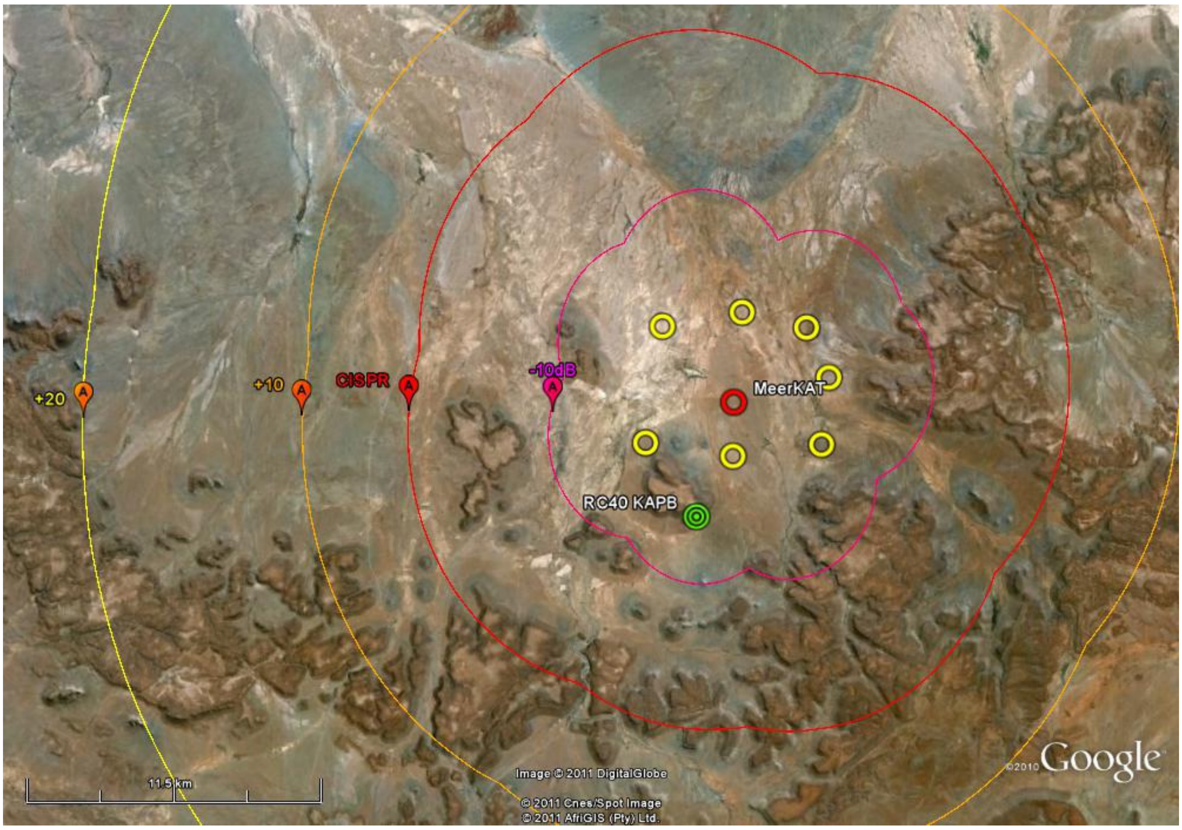


Figure 5-23: Location of the Site Complex within the -10 dB contour line

Because of the location within the -10 dB contour lines, the lights have been classified as candidates for RFI analysis. Figure 5-24 shows the Site Complex lights identified as candidate for RFI analysis:

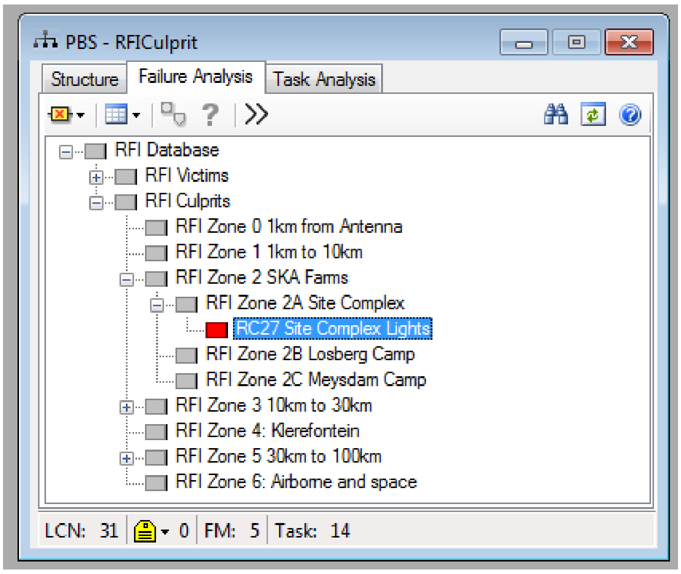


Figure 5-24: Site Complex lights selected as candidate for RFI Analysis

5.4.4 Step 4: Analyze RFI Criticality

As input to the Criticality analysis, the various lights were tested as per Table 5-14:

Table 5-14: Overview of Testing done for Lights

No	Luminaire and Lamp	Test
1	Beka Lane with HPS lamp	Tested at Stellenbosch University June 2008 by author
2	Beka Lane with CLF lamp	Tested at Stellenbosch University June 2008 by author
3	Beka Max with HPS lamp	Tested at Stellenbosch University June 2008 by author
4	Beka Rondo with GLS lamp	Tested at Stellenbosch University June 2008 by author
5	Beka Rondo with CFL lamp	Tested at Stellenbosch University June 2008 by author
6	Beka Bay with HPS lamp	Tested at Stellenbosch University June 2008 and on site February 2010 by author
7	Beka heavy with CFL lamp	Tested at Stellenbosch University June 2008 by author
8	Philips Smartform with CFL lamp	Test results from OEM
9	Philips Power balance with LED lamps	Test results from OEM
10	Beka LED lamps	Tested at Houwteq March 2010 by author

Figure 5-25 shows the testing done in the screened room at Stellenbosch University in June 2008 [14].

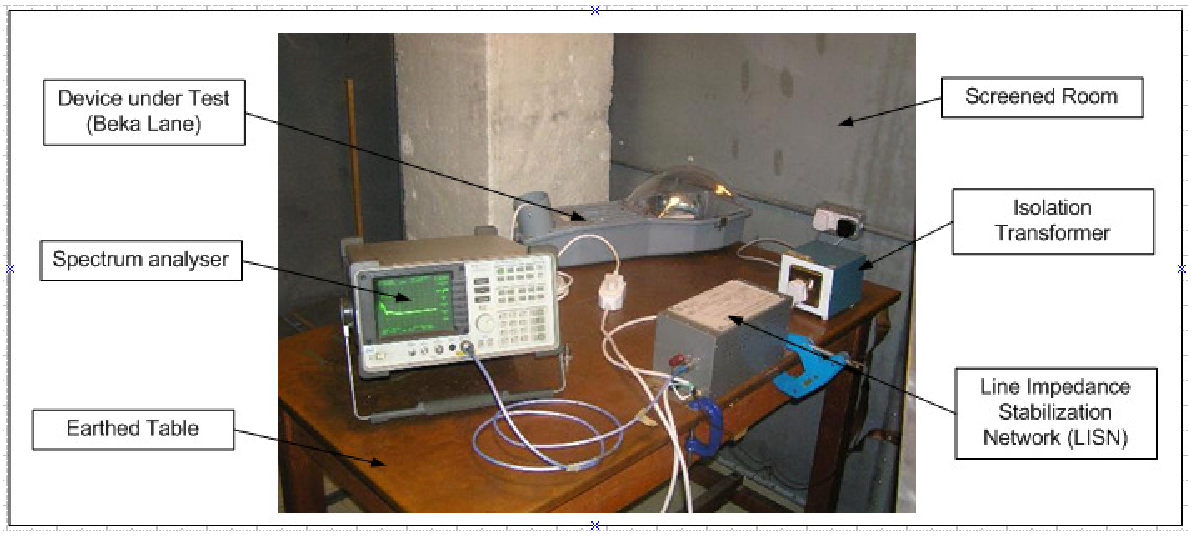


Figure 5-25: Test setup in the screened room at Stellenbosch University

Figure 5-26 shows the test setup used at the Houwteq EMC test facility in February 2010:

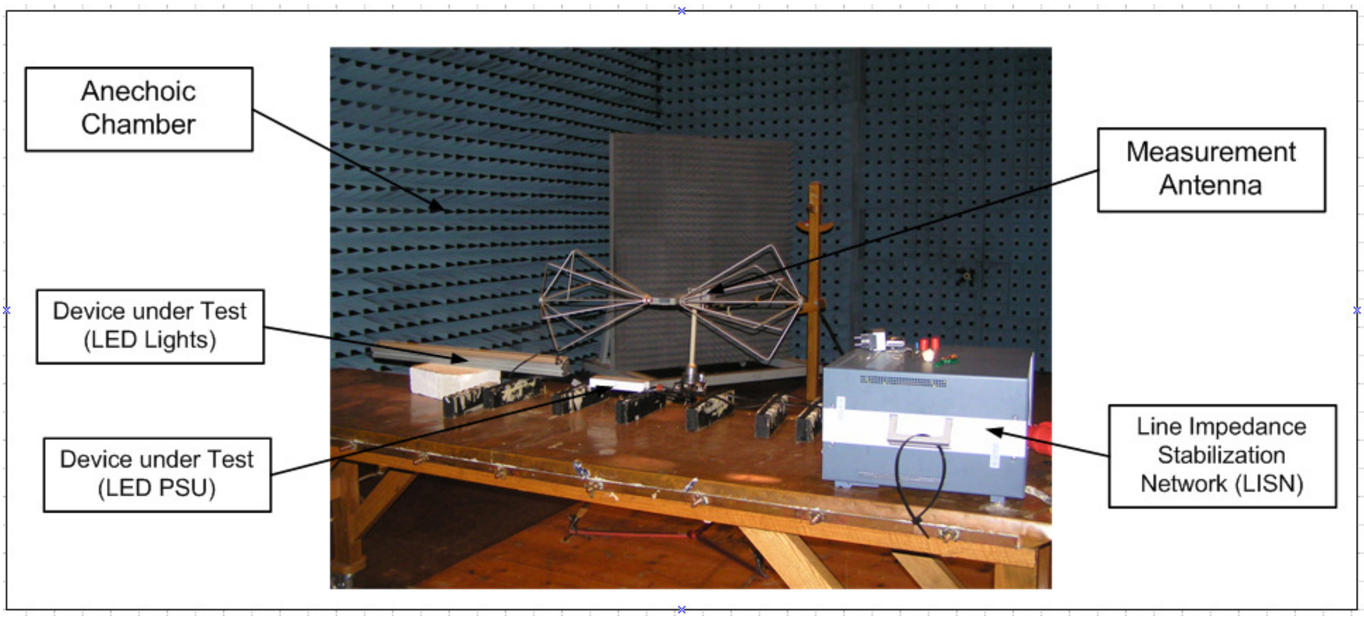


Figure 5-26: Test setup used at the Houwteq EMC Test Facility

Figure 5-27 shows the test setups used at the Site Complex in February 2010:

Figure 5-27: Test setup used at the Site Complex

Conducted measurement of Shed Lights

The following conducted measurement (see Figure 5-27) was done on the lights in the shed at the Site Comlex, using the FSH8 spectrum analyser and the current clamp. The measurement point was the earth wire of the AS-1 distribution board. A resolution bandwidth of 3 MHz was used and the spectrum analyser was set to maximum hold.

a. File Shed 001 – Lights Off.

b. File Shed 002 – Lights switched On.

c. File Shed 003 – Lights On after 1 minute.

Figure 5-28 shows the results of the conducted measurement done on the shed lights:

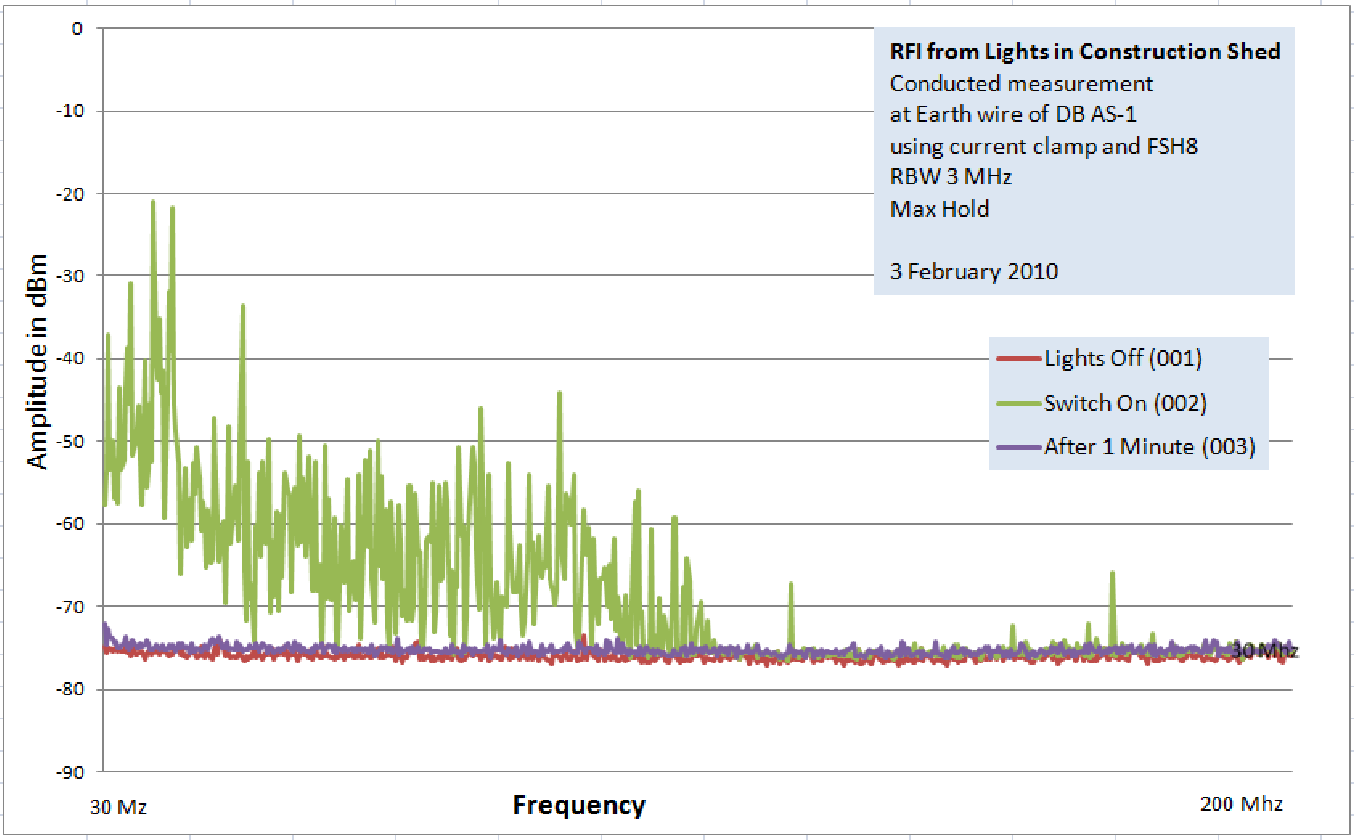


Figure 5-28: RFI from Shed Lights, conducted measurement using current clamp and FSH8 Spectrum Analyser, showing the large signal during switch on

The next measurement was done to confirm the results, measured using the conducted method but also detected when using a radiated measurement.

Radiated measurements of Shed Lights

The following radiated measurement (See Figure 5-27) was conducted on the lights in the shed using the FSH8 spectrum analyser and the dipole antenna. The measurement point was about 10m below the lights in the middle of the shed. A resolution bandwidth of 3 MHz was used and the spectrum analyser was set to maximum hold.

a. File Shed 008 – Lights Off.

b. File Shed 009 – Lights switched On.

c. File Shed 010 – Lights On after 1 minute.

Figure 5-29 shows the results of the radiated measurement done on the shed lights:

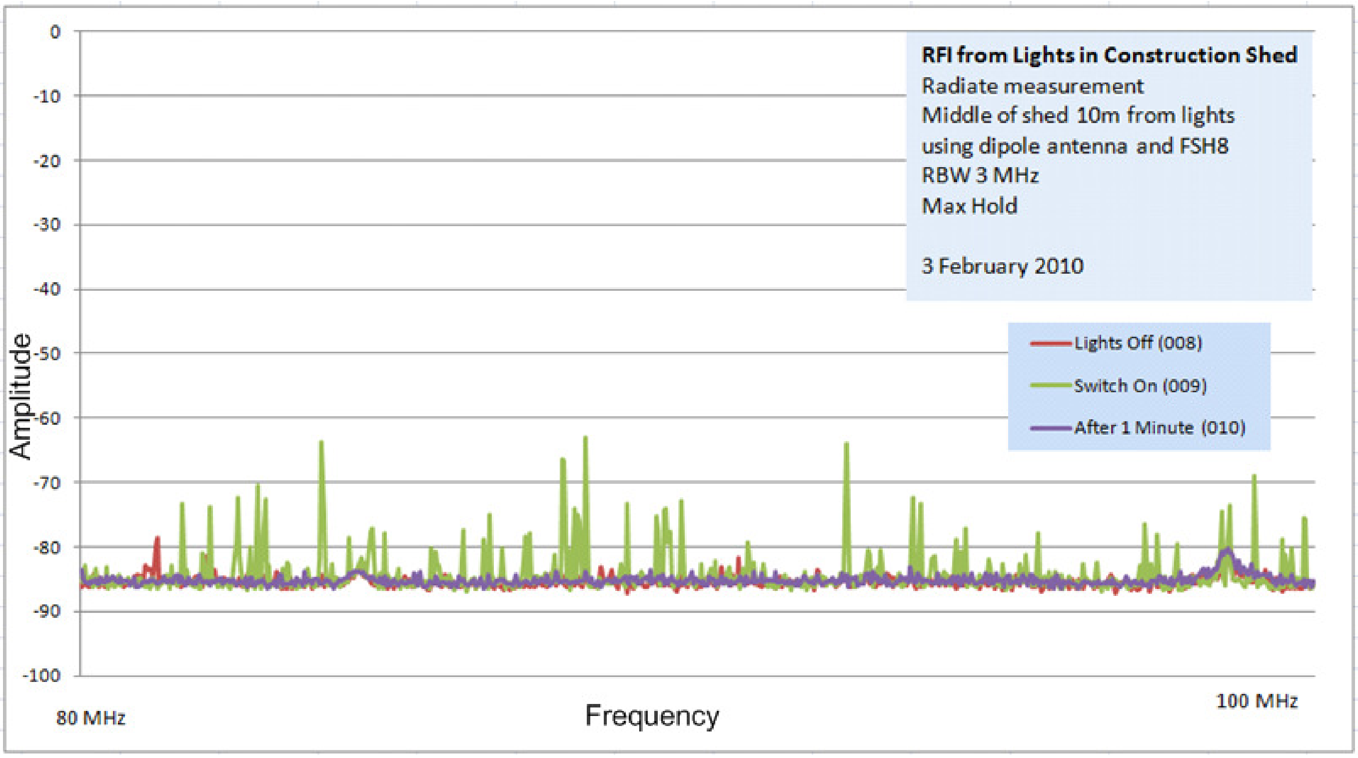


Figure 5-29: Results of conducted RFI measurements of the lights in the shed using the FSH8 and Dipole antenna

Discussion

The result of the conducted and radiated measurements clearly shows a large signal (green series) at switch On of the lights. This reduces (blue series) to very close to the noise floor (red series) after 1 minute. This behaviour of the lights as installed is consistent with the results from the tests at Stellenbosch on a single lamp in the screened room.

Table 5-15 gives an overview of the test results for the various types of lights:

Table 5-15: Overview of Testing done for Lights, with related Probability

No	Luminaire and Lamp	Summary of Test Results (Relative to -10db below CISPR22 Class B)		Criticality
		During switch on and warming up	Continues emissions	
1	Beka Lane with HPS lamp	57 dB above to 20 MHz	12 dB above up to 10 MHz then below noise floor	1D
2	Beka Lane with CLF lamp	37 dB above to 70 MHz	37 dB above at various frequencies	1B
3	Beka Max with HPS lamp	37 dB above to 70 MHz	Below noise floor	1D
4	Beka Rondo with GLS lamp	2dB above up to 100 MHz	2 dB above up to 100 MHz then below noise floor	1E
5	Beka Rondo with CFL lamp	Not tested Expect similar to Lamp 2 and 7	Not tested Expect similar to Lamp 2 and 7	1B
6	Beka Bay with HPS lamp	37 dB above up to 90 MHz	Below noise floor	1D
7	Beka heavy with CFL lamp	37 dB above up to 100 MHz	37 dB above up to 70 MHz	1B
8	Philips Smartform with CFL lamp	Not known	35 dB above up to 100 MHz then 17 dB above up to 300 MHz	1B
9	Philips Power balance with LED lamps	Not known	25 dB above to 100 MHz then 20 dB above to 300 MHz	1C
10a	Beka LED with PSU	Not measured	5 dB above up to 200 MHz	1D
10b	Beka LED without PSU	Not measured	Below noise floor up to 1 GHz	1E

Figure 5-30 shows the RFI database with the RFI modes for the lights at the Site Complex:

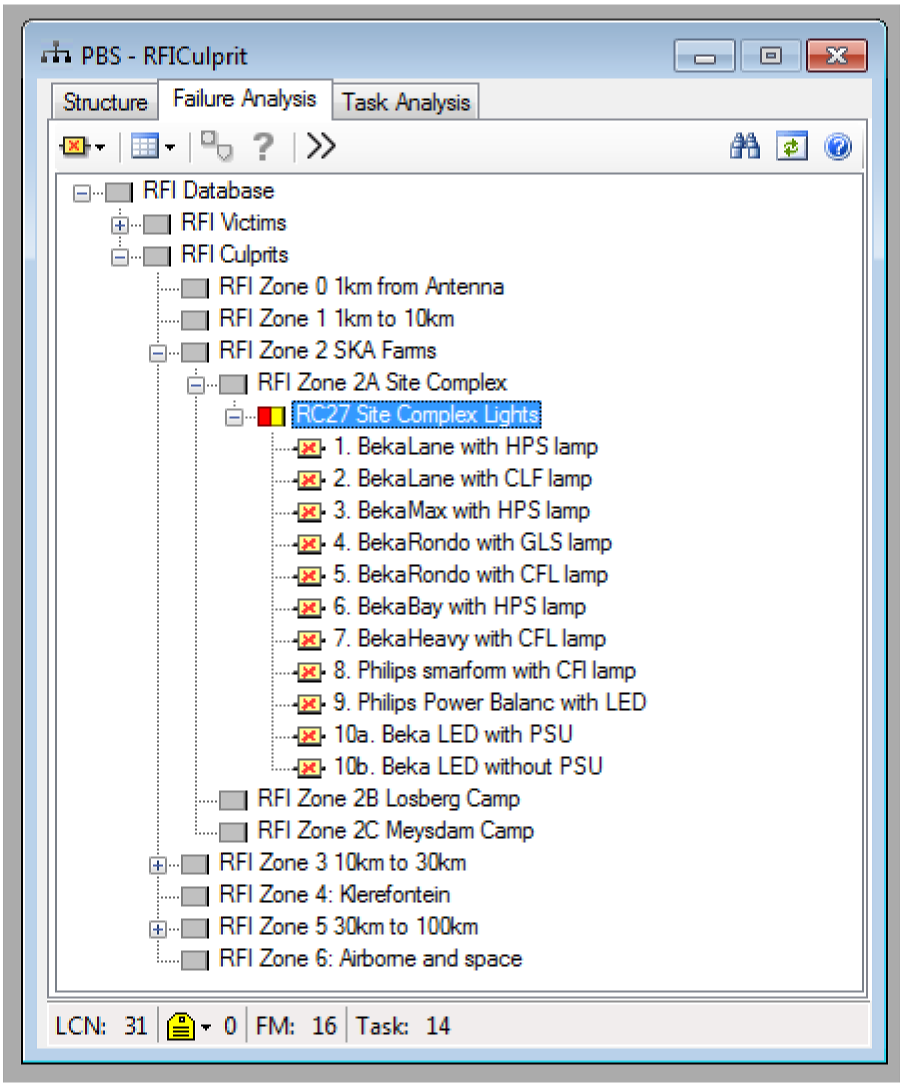


Figure 5-30: RFI database with RFI modes for Lights at Site Complex

The RFI report for the various lights and lamps are given on the following pages.

Table 5-16: Results of RFI Analysis of the Lamps

Seq	FM Code	Mode Description	Class Code	Local Effect	Next Effect	End Effect	Comp. Provisions	Criticality M	Criticality S	Criticality P
R02020101		***00***	***RC27 Site Complex Lights***							
1	F00A	1. BekaLanewith HPS lamp		RFI Level: 12 db above CISPR 22 contour up to 10 Mhz then below noise floor , switch on 57 db above contour	RFI Type: Wide band continues	Possible detection for PAPER, KAT-7 and MeerKAT, none for C-BASS		C K M P	1 1 1 1	E D D D
2	F00B	2. BekaLanewith CLF lamp		RFI Level: RFI 37 dB above CISPR 22 contour levels for various frequencies	RFI Type: Wide band , continues	Strong detection for PAPER, KAT-t and MeeeKAT, unlikely for C-BASS		C K M P	1 1 1 1	E B B B
3	F00C	3. BekaMax with HPS lamp		RFI Level: Below noise floor	RFI Type: Wide band , continues	Possible detection for PAPER, KAT-7 and MeerKAT, none for C-BASS		C K M P	1 1 1 1	E D D D
4	F00D	4. BekaRondo with GLS lamp		RFI Level: RFI below noise floor, some RFI at swith on up to 100MHz	RFI Type: Wide band , continues	Detection unlikely		C K M P	1 1 1 1	E E E E
5	F00E	5. BekaRondo with CFL lamp		Not tested, expect similar to oher CFL lamps (2 and 7)	RFI Type: Wide band , continues	Strong detection for PAPER, KAT-7 and MeerKAT, none for C-BASS		C K M P	1 1 1 1	E B B B

Seq	FM Code	Mode Description	Class Code	Local Effect	Next Effect	End Effect	Comp. Provisions	Criticality M	Criticality S	Criticality P
R02020101		*00*	*RC27 Site Complex Lights*							
6	F00F	6. BekaBay with HPS lamp		RFI Level: RFI below noise floor, some RFI at swith on up to 90 MHz	RFI Type: Wide band , continues	Possible detection for PAPER, KAT-7 and MeerKAT, none for C-BASS		C K M P	1 1 1 1	E D D D
7	F00G	7. BekaHeavy with CFL lamp		RFI Level: RFI 37 dB above CISPR 22 contour levels up to 70 Mhz	RFI Type: Wide band , continues	Strong detection for PAPER, KAT-7 and MeerKAT, none for C-BASS		C K M P	1 1 1 1	E B B B
8	F00H	8. Philips smarform with CFL lamp		RFI Level: RFI 35 dB above CISPR 22 contour levels up to 100 Mhz then 17 db above	RFI Type: Wide band , continues	Strong detection for PAPER, KAT-7 and MeerKAT, none for C-BASS		C K M P	1 1 1 1	E B B B
9	F00I	9. Philips PowerBalanc with LED		RFI Level: RFI 25 dB above CISPR 22 contour levels up to 100 Mhz then 20 db above	RFI Type: Wide band , continues	Possible detection for PAPER, KAT-7 and MeerKAT, none for C-BASS		C K M P	1 1 1 1	E C C C
10	F00J	10a. Beka LED with PSU		RFI Level: RFI 5 dB above CISPR 22 contour levels up to 200 MHz	RFI Type: Wide band , continues	Possible detection for PAPER, KAT-7 and MeerKAT, none for C-BASS		C K M P	1 1 1 1	E D D D
11	F00K	10b. Beka LED without PSU		RFI Level: RFI below noise floor up to 1 Ghz	RFI Type: Wide band , continues	Detection unlikely		C K M P	1 1 1 1	E E E E

5.4.5 Step 5: Analyze Tasks

Figure 5-31 shows the tasks identified for the lights at the Site Complex using the RFI analysis results.

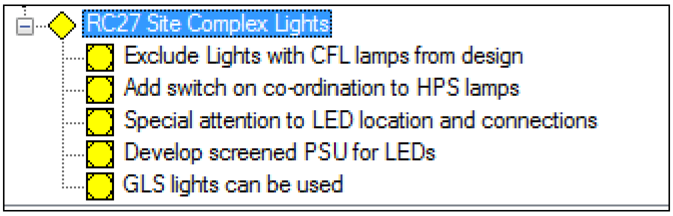


Figure 5-31: Tasks identified for the Lights at the Site Complex

Figure 5-32 shows the identified tasks allocated to each type of light and lamp:

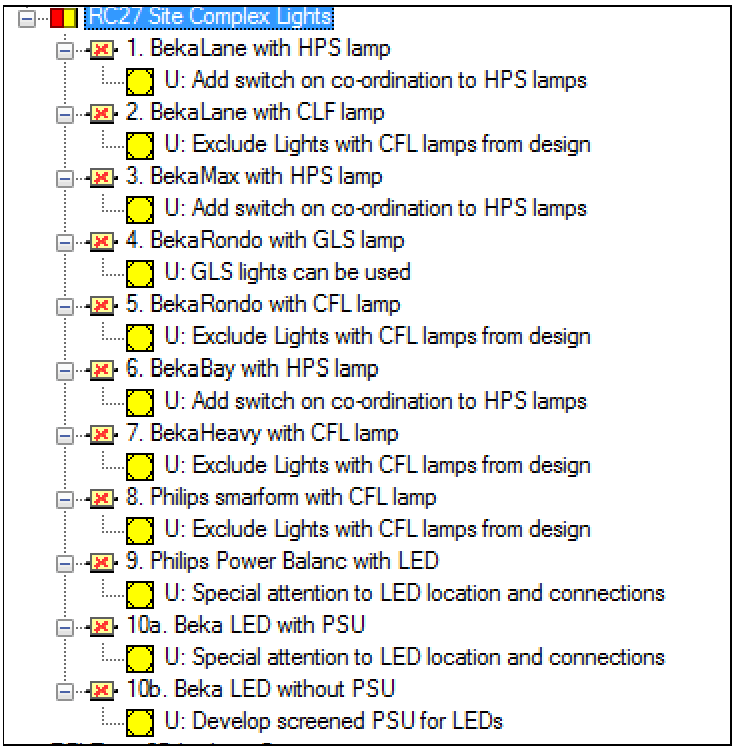


Figure 5-32: Identified Tasks allocated to each type of Light and Lamp

5.4.6 Step 6: Manage RFI Mitigation

Table 5-17 gives the mitigation plan for lights, based on the tasks identified in the previous step:

Table 5-17: Mitigation Plan for Site Complex Lights

Task	Mitigation Policy	People / Skills	Equipment
Exclude lights with CFL lamps from design	Change to difference technology such as LED lamps	Design engineers	Design tools
Add switch on co-ordination for HPS lamps	Add central switch to design and link to BMS Develop Operating procedures	Design engineers (BMS) Site Staff	Design tools
Special attention to LED PSU location and wiring	Additional design effort and verification during construction	Design Engineers	Design tools
Develop screened PSU for LED lights	Additional screening	Screening design and manufacturing	Manufacturing
GLS lights can be used	Nil	Nil	Nil

5.5 Summary of Case Studies

The case studies showed how the equipment is recorded on the RFI database, how an RFI candidate is selected for RFI analysis, the results of the RFI analysis and how the tasks for the mitigation of the RFI are identified and described, including the resources required.

The case studies showed that the process developed can be applied to a wide range of subjects, and with different depths of available information, ranging from very little (Case 2) to relatively good (Case 1 and Case 3):

a. Case Study 1 – Farm equipment, was based on information available from RFI tests done on site.

b. Case Study 2 – Voltage Regulators, was based on engineering judgment and tests done on similar equipment.

c. Case Study 3 – Site Complex lights, based on detailed test results from RFI tests done in special EMC test facilities.

CHAPTER 6 CONCLUSION AND RECOMMENDATIONS

Radio Telescopes are particularly sensitive RF Receivers with wide bandwidths. Selecting and maintaining a low RFI area in which they can operate is essential. Controlling of RFI is done by spectrum management and other legislative measures, including zoning. However, in present day society, the electromagnetic spectrum is one of many scarce resources and it is impossible to allocate the complete spectrum to one group, such as the Radio Astronomers.

The RFI observed by a Radio Telescope is best reduced by locating the Radio Telescope facility as far as practically possible from human settlement (the other users of the spectrum). Radio Telescope facilities are expensive installations and cannot easily be moved once established. Hence, the new SKA facility is planned in a remote area of the southern hemisphere, such as Western Australia or the Karoo region in South Africa.

At a given site, traditional RFI management includes performing RFI surveys, identifying specific RFI Culprits and working on solutions for those Culprits. The only solution may be to co-exist with the RFI Culprits and to flag RFI in the data stream as bad data.

For new Radio Astronomy sites, the control of RFI is complicated by the construction and commissioning activities which co-exist with operational Radio Telescopes. Not all the possible RFI Culprits are equally critical to the Radio Telescope and it make sense to concentrate limited resources to test and solve problems with the more critical Culprits first. Criticality is a function of many parameters of both the Radio Telescope (Victim) and the RFI Source (Culprit), including frequency of the Victim and Culprit, sensitivity of the Victim, source level of the Culprit, relative distance between the Culprit and Victim, height above ground level, duration of interference and other factors.

A methodology was developed which is proposed as the backbone of RFI control of a new Radio Astronomy site. This includes: a database where all potential RFI candidates are recorded, a decision-making process to select RFI candidates and an analysis process to determine the criticality of a particular RFI Culprit. Once the criticality is determined, a suitable mitigation policy may be selected and implemented. This ensures the optimum allocation of the limited resources.

In order to take the developed methodology forward, the following is recommended:

a. The developed techniques are to be applied to a wide number of areas on the Radio Telescope site.

b. An RFI test capability should be established on site and at the base (in Cape Town).

c. A standard test procedure is to be developed.

d. A standard interface between the developed RFI database and the Radio Telescope is to be developed.

e. The contracts for the construction on Site are to include some of the developed procedures, such as the RFI control permits.

6.1 Wide Application of the Developed Methodology

It is recommended that the techniques developed be applied to a wide number of applications on a Radio Telescope project, such as:

a. Infrastructure and ancillaries which are permanently deployed to the site.

b. Telescope equipment which is permanently deployed to the site.

c. Equipment belonging to the communities surrounding the site.

d. Equipment which is temporary deployed to the site during construction and must co-exist with early science from Radio Telescopes operational on the site.

It is recommended that a project wide 'standard' be developed to ensure the application of the developed methodology.

6.2 Establishment of an RFI Test Capability

It is recommended that an RFI test capability be established on site in the Karoo as well as at the telescope development team at the base in Cape Town, in the South African case. This capability should include:

a. RFI test equipment.

b. Standard RFI test procedures.

c. Engineers and technicians trained in performing RFI tests.

The RFI test equipment should include suitable antennas for use in the operational environment, as well as RFI test Receivers able to record data in both the frequency domain (for continuous signals), as well as in the time domain (for pulsed and for very short signals). The test equipment must be calibrated and tested to ensure that it is RFI free.

6.3 Develop Standard Test Procedures

The standard test procedures should be based on the test procedures developed for this RFI analysis and should include set of standard test parameters such as:

a. Distance from source.

b. Resolution bandwidth.

c. Frequency bands, etc.

d. File name of the recorded data for each event.

The standard test procedures should in all cases include measurements with the equipment under test switched on and off, in order to make a positive identification of the signals coming from the item under test.

In order to ensure that data analysis is error free, the standard test procedures should include standard methods for:

e. Naming the files of the stored data.

f. Standard formats for the recorded data.

6.4 Interface between the RFI Database and the Radio Telescope

It is recommended that a standard interface be developed between the RFI database and the various Radio Telescope instruments, such as MeerKAT, PAPER and SKA in the case of South Africa, in order to enable the Radio Telescope to identify RFI originating from know RFI Culprits in the RFI database. This standard interface should be based on the standard data format developed for the standard RFI test procedure. The Radio Telescope can establish zones or frequencies of avoidance (where known RFI Culprits exist), or for more intermitted signals; may use the RFI Culprit data to flag RFI in the Telescope data stream.

6.5 RFI Control during Construction

It is recommended that the various contracts for the construction of the Infrastructure as well as new Telescopes include requirements developed, such the RFI control permits. These permits should be used to record all potential RFI Culprits deployed to the Site. This should include all permanent items as well as all temporary items. The permanent items will be used as input to the RFI management of the long term science on the site; whereas the temporary items will be used to manage the co-existence of the construction and early science on the site.

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