SKA EMI/EMC STANDARDS, RELATED PROCEDURES & GUIDELINES

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TABLE OF CONTENTS

1 INTRODUCTION 5
1.1 Context 5
1.2 Purpose 6
2 DOCUMENTATION 7
2.1 Reference 7
2.2 Terms, Acronyms & Abbreviations 7
3 SCOPE 9
3.1 Equipment affected 9
3.1.1 Sub-system Applicability 10
4 SKA THRESHOLDS OF INTERFERENCE HARMFUL TO OBSERVATIONS 11
4.1 SKA Thresholds of Harmful Interference 11
4.1.1 Continuum 11
4.1.2 Spectral Line 12
4.1.3 Limits on Impulsive Emissions 12
4.2 Electromagnetic Susceptibility 13
5 RELATED PROCEDURES 14
5.1 EMC Control Plan (EMCCP) 14
5.1.1 Non-compliance issues 14
5.2 Post installation verification/qualification 14
5.3 Approved Established Traceable Standards 15
6 SUMMARY OF INTENT 16
7 GUIDELINES FOR INTERPRETATION OF INTENT RELATED TO EMCCP EVALUATION 17
7.1 Distance and Affected Antennas 17
7.1.1 Free space path loss 17
7.1.2 Antenna 'gain' 18
7.1.3 Interferometric effects 18
7.2 Shielding 18
7.3 Measurement 18
7.3.1 Measurement Frequency Range and Spectral Resolution of EMI Measurements 18
7.4 Special Cases 19
7.5 Interpretation of Traceable Established Standards 19
7.5.1 CISPR-22 19
7.5.2 MIL-STD-461F 20
8 DECISION-TREE APPROACH TO EMI CONTROL 21
8.1 Best Practices in EMI-Robust Electrical and Electronics Design 26
8.2 Test and Verification Measurements 26
8.3 Facilities 26
8.4 Field-Strength Emissions Measurements 26
8.5 Shielding Measurements 27
9 NOTES ON SOME ESTABLISHED TRACEABLE STANDARDS 28

9.1 Emissions 28
9.1.1 IEC 61000 Series on EMC 28
9.1.2 Other Relevant Established Standards 28
9.2 Shielding 29
9.2.1 IEEE 299-2006 30
9.2.2 IEEE 299.1-2013 31
10 SAMPLE ELECTROMAGNETIC COMPATIBILITY CONTROL PLAN (EMCCP) 32
10.1 Minimum requirements of an EMCCP 32
10.2 Example EMCCP Structure 32
10.2.1 OVERVIEW 32
10.2.2 DESCRIPTION OF EQUIPMENT OR SYSTEM 32
10.2.3 PROGRAMME ORGANISATION & RESPONSIBILITIES 32
10.2.4 TECHNICAL PROGRAM 33
10.2.5 CONTROL PLAN REVISIONS 34

LIST OF FIGURES

Figure 1: A first level decision tree for items proposed for SKA site installation. 22
Figure 2: Second stage decision tree 23
Figure 3: Decision tree for COTS equipment 24
Figure 4: Third stage decision tree 25

LIST OF TABLES

Table 1: CISPR-22 Class B Electric Field Emission Limits 28
Table 2: MIL-STD-461F Electric Field Emission Limits 29

1 Introduction

1.1 Context

SKA telescopes will have to cope with many aspects of Radio Frequency Interference (RFI)[1]. The challenges of constructing radio telescope equipment to meet the very low levels of emissions detectable by radio telescopes are well known. For most previous telescopes, it has been necessary to limit emissions only within relatively narrow receiving bands (although the JVLA telescope is a relatively recent exception). The SKA sites have been specially selected to be as free as possible of external terrestrially generated RFI over significant bandwidths and will be maintained as such via the establishment of Radio Quiet Zones (RQZs). Additionally, we expect that other telescopes operating over a wide range of frequencies will be hosted on the SKA sites. RQZ legislation for both sites provides legal requirements for limitation of levels of RFI from any source on the sites over a frequency range from 70 MHz to 25.25 GHz in Australia and 100 MHz to 25.5 GHz in South Africa[2].

In the context of the SKA telescope, RFI is defined as all unwanted, non-astronomical electromagnetic signals received by the telescope that are sufficiently strong to have the potential of creating false detections of astronomy signals or even influence the telescopes' design. This includes licensed or unlicensed telecommunications signals and also the unintentionally generated signals emitted from any electrical equipment as it operates. Equipment to be used in SKA telescopes must be designed to appropriately limit self-generated RFI that may interfere with nearby telescopes or other sensitive equipment located on the SKA sites. Because self-generated RFI is by definition unlicensed and unintentional, this source of RFI will be denoted simply as 'EMI' in this document.

The purpose of this document is to facilitate control of emissions generated on the SKA sites by equipment under the control of the SKA project. The designs of the SKA telescopes that will be built on the sites in Australia and South Africa will be based initially on the current SKA baseline design [1]. This may change as the detailed design and costing process proceeds. In addition, there are precursor telescopes under construction on the site, as well as smaller facilities.

Threshold levels of interference harmful to radio astronomy observations are highly dependent on the specific nature of the observational parameters employed, such as: frequency, observing bandwidth, integration time, system temperature, etc. These set the sensitivity of the telescope under those specific conditions. For that particular sensitivity, the threshold of harmful interference can then be determined by considering the potential error induced by an interfering signal power that cannot be tolerated for that observation. Clearly, there are a substantial range of observational and processing strategies available to astronomers; this leads to significant differences in levels of interference that might be considered to be harmful.

For the practical development of the SKA project, limits for received power from interferers considered harmful to observations are needed to facilitate the engineering design process dealing with Electromagnetic Compatibility (EMC) issues. These limits for radiated emissions are detailed in Section 4 of this document. Inevitably, this means that for some observations the thresholds may appear to be unnecessarily stringent, but equally that for a number of planned observations, the thresholds will be insufficient for complete protection. Designers are urged to try to deliver better performance than the limits provided in Section 4 whenever practicable. The project's procedural requirements to ensure that SKA equipment meets these standards are stated in Section 5.

[1] Radio Frequency Interference - degradation of the reception of a wanted signal caused by radio frequency disturbance [13].

[2] Since this legislation was introduced, the SKA operational frequency range has been extended from 70 to 50 MHz at the low frequency end. This is needed to enable observations to detect red-shifted atomic hydrogen lines associated with the epoch of re-ionisation (EoR), a key science objective. At present there are no plans to seek to extend the regulations.

1.2 Purpose

The purpose of this document is to:

1. Set thresholds of allowable emission levels for equipment located on SKA sites referred to the guided wave input of the telescope antennas.
2. Establish procedures for the monitoring and control of EMC issues as the project progresses.
3. Provide *guidelines* for interpretation of this document, its associated procedures, measurement, and verification requirements.

2 Documentation

2.1 Reference

[1] P.E. Dewdney, "SKA1 System Baseline Design V2", SKA Document SKA-TEL-SKO-DD-002, Rev 04, March 19, 2016.

[2] Recommendation ITU-R RA.769, "Protection Criteria Used for Radio Astronomical Measurements", 2003.

[3] "SKA ECP-140009 – Higher Spectral Resolution over Limited Bandwidth for SKA1-mid and SKA1-survey".

[4] "SKA ECP-140012 – Spectral Zoom Mode SKA1-low".

[5] ACMA, RALI MS 32, "Coordination of Apparatus Licensed Services within the ARQZWA", Canberra, December 2014.

[6] ACMA, "Radiocommunications (Mid-West Radio Quiet Zone) Frequency Band Plan 2011", Canberra, July 2011.

[7] "Regulations on Radio Astronomy Protection Levels in Astronomy Advantage Areas Declared for the Purposes of Radio Astronomy", Staatskoerant, Feb. 10, 2012, No. 35007, No. R. 90.

[8] "Information Technology Equipment – Radio Disturbance Characteristics – Limits and Methods of Measurement", International Special Committee on Radio Interference, CISPR 22, IEC publication, Edition 6.0, 2008-09.

[9] "Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-1: Radio disturbance and immunity measuring apparatus - Measuring apparatus", International Special Committee on Radio Interference, CISPR 16-1-1:2010, IEC publication, Edition 3.0, 2009.

[10] "Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment", Department of Defence Interface Standard, US Dept. of Defence, MIL-STD-461F, Dec. 10, 2007.

[11] "IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures", IEEE STD 299-2006, IEEE Electromagnetic Compatibility Society, Dec. 29, 2006.

[12] "IEEE Standard Method for Measuring the Shielding Effectiveness of Enclosures and Boxes Having all Dimensions between 0.1 m and 2 m", IEEE STD 299.1-2013, IEEE Electromagnetic Compatibility Society, Oct. 31, 2013.

[13] "IEC International Electrotechnical Vocabulary".

[14] "Approved National & International Standards for Referencing in SKA Project EMC Documentation" SKA-TEL-SKO-0000691.

2.2 Terms, Acronyms & Abbreviations

AUS	Australia
CISPR	Comité International Spécial des Perturbations Radioélectriques
DUT	Device under test
EMI	Electromagnetic Interference
EMC	Electromagnetic Compatibility
ITU	International Telecommunications Union
ITE	Information Technology Equipment
RFI	Radio Frequency Interference
SA	South Africa
SKA	Square Kilometre Array

Spfd	spectral power flux density
TBC	To be confirmed
AC	Alternating Current
CE	Conducted Emissions
COTS	Commercial Of The Shelf
CS	Conducted Susceptibility
EFT	Extremely Fast Transients
EMC	Electromagnetic Compatibility
EMCCP	Electromagnetic Compatibility Control Plan
EMI	Electromagnetic Interference
ESD	Electrostatic Discharge
IE	Induced Emissions
IEC	International Electrotechnical Commission
IS	Induced Susceptibility
RE	Radiated Emissions
RF	Radio Frequencies
RS	Radiated Susceptibility
EUT	Equipment Under Test
RAS	Radio Astronomy Service

3 Scope

Overall Electromagnetic Compatibility (EMC) consideration covers the potential of an electrical or electronic system to:

- Source radiated emissions (RE) and be itself susceptible to radiated emissions (RS)
- Source conducted emissions (CE) and be itself susceptible to conducted emissions (CS)
- Source induced emissions (IE) and be itself susceptible to induced emissions (IS) (usually from close-coupling effects)
- Be susceptible to electrostatic discharge (ESD)

The scope of this document is to establish a key parameter for Electromagnetic Compatibility (EMC) analysis within the SKA project specifically covering radiated emissions, by setting thresholds of allowable emission levels for equipment located on SKA sites referred to the guided wave inputs of the telescope antennas. This document concerns radiated interference only and there are caveats in the text associated with near-field effects. It is not specifically appropriate for conducted or induced interference, nor does it cover susceptibility to ESD. A separate standard for conducted interference may be produced, which will be written so that the effect of conducted interference on the signal chain will be limited to that no greater than for radiated interference.

This document establishes initial procedures for the overall control and management of EMC issues as the project progresses. Where possible the procedures are based on widely accepted industry standards, modified to meet radio astronomy requirements.

The document also provides some guidelines for interpretation of use of the threshold levels in associated EMC control procedures, such as performance verification, measurement, etc.

3.1 Equipment affected

The equipment intended to be covered by EMC requirements in this document is that within all products that constitute the operational radio telescopes, are identified in the SKA product tree, and are operated within the observatory. It also applies to all extraneous support equipment that is used on the SKA sites whilst observations are being conducted by any telescope. It is accepted that this creates a number of complex control issues, particularly during construction phases. It is anticipated that such issues will be highlighted and dealt with within the related procedures for EMC control and non-compliance (see Section 5).

Note that by virtue of their intended function, it is anticipated that application of the strict SKA emission standards in Section 4 will not be necessary for sub-systems housed in formally designated SKA large scale shielded buildings, as the shielding of these facilities will have been designed to cope with emissions at normal commercial levels for the equipment expected to be contained therein (e.g. such as those seen in [8] & [10]). However, sub-systems housed in such facilities must not generate such high levels of emissions (either radiated or conducted), that they interfere with the operation of other sub-systems or equipment. Established traceable international standards already exist for these situations, and they are accepted for the SKA.

3.1.1 Sub-system Applicability

From the perspective of protecting the SKA telescopes and the sites, it is practical only to set limits on emissions from systems or assemblies that are sufficiently isolated that they can be measured as a whole. Examples are entire dishes, buildings, cabinets, cable assemblies and power lines from which it is possible to measure or model emissions in their entirety from a reasonable physical distance. It is not practical to set standards for sub-systems situated right next to each other or inside larger systems. This standard should not be applied directly to items such as individual modules inside enclosures. EMI problems related to these must be solved by the designers of these systems in the context of their overall EMCCP.

Within tightly connected sub-systems or assemblies, there is a significant risk of conducted interference. Although the methods adopted for this standard do not necessarily apply, the allowable levels in telescope signal chains from conducted interference must be no more than that allowed for radiated interference.

4 SKA Thresholds of interference harmful to observations

The International Telecommunications Union (ITU) has developed Recommendation ITU-R RA.769 [2] (hereafter referred to as 'RA.769') as the basis for the determination of levels of interference detrimental to radio telescopes in the frequency bands in which radio astronomy has protected status. This Recommendation is widely accepted within the international community and provides the basis for many national and international regulations. The national regulations of both Australia and the Republic of South Africa covering acceptable levels of RF signals within both radio quiet zones of the SKA sites [5, 6, 7] are derived mainly from this ITU Recommendation. Naturally, equipment installed on the SKA sites must also comply with thresholds of interference described in any relevant applicable national regulations.

RA.769 derives threshold of harmful interference levels by consideration of radio telescope sensitivities separately for both continuum and spectral line observations. A threshold is defined as the interference power within the chosen bandwidth that would produce an error of 10% in the smallest power that can be detected by the receiver (which is derived from the radiometer equation). An integration time of 2000 seconds is used together with internationally agreed appropriate values for antenna noise temperature and receiver noise temperature at the frequencies under consideration. For continuum observations the calculations assume bandwidths for each frequency that range between 0.4% and 9%. Threshold levels calculated for spectral line observations utilise much narrower representative bandwidths, based on consideration of a Doppler shift corresponding to 3 km/s at the frequency of the observation.

The threshold levels specified in RA.769 (under regular review), were last formally revised in 2003. Since that date, there have been competing arguments furnished by various stakeholders that the thresholds should be made more stringent (by virtue of improvements in receiver sensitivity, etc.) and, at the same time, less stringent (by virtue of improvements in signal processing, etc.). No side has provided a compelling argument that there should be change. Consequently, owing to the almost universal acceptance of this Recommendation both inside the radio astronomy community and outside in the telecommunications industry, the methodology encapsulated Recommendation ITU RA.769 is chosen as the basis for derivation of the SKA EMI thresholds of harmful interference.

4.1 SKA Thresholds of Harmful Interference

SKA thresholds of harmful interference at the guided wave input of the telescope antennas are generated based on RA.769 methodology and expressed below in Power Spectral Density (PSD) terms independently for continuum and spectral line observations. For the purposes of this document, bandwidths broadly compatible with SKA operations and the RA.769 methodology are defined. Power limits to verify compliance with emission levels for both types of observation can be calculated using the bandwidths stated in the equations given below.

4.1.1 Continuum

A bandwidth ratio of 1% of observing frequency is adopted (the average up to 23.8 GHz in the RA.769 recommendation), although the bandwidths appropriate for SKA continuum observations could in principle be much higher. Verification measurements for continuum should be carried out against a power level threshold at the antenna guided wave input calculated using a bandwidth of 1% of the centre frequency applied to the following equation:

$$PSD\left(\frac{dBm}{Hz}\right) = -17\log(f) - 192 \quad \text{for } f < 2 \text{ GHz.}$$
$$PSD\left(\frac{dBm}{Hz}\right) = -249 \quad \text{for } f \geq 2 \text{ GHz.}$$

Where '*f*' is the chosen centre frequency of operation in MHz.

E.g. For a measurement at 5 GHz & 1% bandwidth of 50 MHz [Logarithmic representation of this BW is 10 $\log_{10}(50000000)$]

Maximum acceptable interference power in BW = -249 + 10 $\log_{10}(50000000)$
(at the antenna guided wave input) = -249 + 77
= -172 dBm (-202dBW)

4.1.2 Spectral Line

A bandwidth corresponding to 0.001% of the observing frequency is chosen (equivalent to a Doppler resolution of 3 km/s). Verification measurements for spectral line should be carried out against a power level threshold at the antenna guided wave input calculated using this bandwidth applied to the following equation:

$$PSD\left(\frac{dBm}{Hz}\right) = -17\log(f) - 177 \quad \text{for } f < 2 \text{ GHz.}$$
$$PSD\left(\frac{dBm}{Hz}\right) = -234 \quad \text{for } f \geq 2 \text{ GHz.}$$

Where 'f' is the chosen centre frequency of operation in MHz.

E.g. – For a measurement at 100 MHz & 0.001% bandwidth of 1 kHz [Logarithmic representation of this BW is 10 $\log_{10}(1000)$]

Maximum acceptable interference power in BW = -17 $\log_{10}(100)$ – 177 + 10 $\log_{10}(1000)$
(at the antenna guided wave input) = -34 – 177 + 30
= -181 dBm (-211 dBW)

In summary, verification procedures must ensure that peak EMI emissions are lower than the continuum and spectral line limits at the distance of the nearest affected receiver input from the source of the emission when measured with the required bandwidths over the frequency range 50 MHz to 20 GHz.

4.1.3 Limits on Impulsive Emissions

Much SKA science will involve searches for and observations of pulsars and transient emissions, the SKA standard must protect against impulsive disturbances potentially generated by interfering devices. Impulsive RFI is very prevalent now, since many devices employ digital processors which generate impulsive emissions**. Thus the SKA thresholds set out above apply to peak emissions from devices.** This issue should be particularly noted when interpreting the performance of equipment to traceable established standards.

4.2 Electromagnetic Susceptibility

This document focuses conceptually on the situation where most of the equipment covered is considered to be a *source* of radiated emissions. A related topic is *susceptibility* of that SKA equipment to electromagnetic interference from either internal or external sources. This is particularly important in cases where safety is involved (i.e. the control of moving machinery or control of large electrical sub-systems may be affected by illumination by strong RFI signals). It is expected that the EMI controls described in this document will also help ensure that such systems meet susceptibility needs, but this is not necessarily always true and established traceable international standards for susceptibility for observatory equipment are accepted for the SKA.

5 Related Procedures

5.1 EMC Control Plan (EMCCP)

Formal consideration of EMC is needed within the SKA Project to ensure that all equipment is electromagnetically compatible with itself and with all other systems in operation in the observatory (observing systems, power, data transfer, communications, etc.). Initial documentation in the form of an EMC Control Plan (EMCCP) shall be submitted by the entity responsible for the product design or manufacture to SKAO for initial approval. Currently this responsibility is assumed to reside at Consortium level. The EMCCP shall be defined at an appropriate level of detail and complexity to reflect the EMC issues faced. The EMCCP is intended to be integrated into the overall routine SKA project review processes to ensure continued oversight and development and will develop as the project progresses. The EMCCP identifies the entity that is responsible for accomplishing and documenting the electromagnetic compatibility programme, the EMI specifications to be adhered to and the conditions for EMI compliance of individual elements of the product tree within that Consortium. It covers all relevant issues: including scope, purpose and requirements; EMC design; EMC safety analysis; emission limits; verification & test plans; and should also include programmatic issues such as organization, schedule and deliverables. Any EMC procedures and testing that will need to be carried out on a routine basis on equipment after qualification testing should also be defined. Sub-contractors and suppliers of electrical and electronic equipment should also submit evidence of compliance to that control plan where appropriate.

A skeleton layout for an EMCCP is suggested in Section 10.

5.1.1 Non-compliance issues

Following approval of the initial EMCCP, it is anticipated that the programme defined in it will be managed and operated by the entity responsible, with routine SKAO oversight via scheduled reviews. However, the design & development process will occasionally throw up issues of equipment or systems that exhibit some level of non-compliance with the requirement. It is assumed that many issues of this kind will be solved via the normal iterative design process, but where such issues cannot or are unlikely to be resolved internally (e.g. significant cost vs. performance trade-offs, fundamental issue identified, etc.) the issue should be reported to SKAO (with appropriate supporting documentation). On a case-by-case basis SKAO will then institute an appropriate procedure towards resolution; acceptance of non-compliance under certain defined conditions may be established.

5.2 Post installation verification/qualification

The EMCCP and associated process should deliver verification methods needed to qualify devices to a sufficient degree that they may be delivered to the SKA sites. Once installed, it is possible that emissions will still generate EMI effects in telescope data due to unforeseen interactions with other equipment or those undetected in the earlier phase, although the EMCCP process should ensure that these are rare cases. The post installation verification and qualification phase will be a major exercise in itself and hence require an appropriate planning process with inputs from all stakeholders. This plan is yet to be developed.

5.3 Approved Established Traceable Standards

A separate SKA document [14][3] is available containing a list of SKA approved established traceable standards related to EMC.

For the purposes of the EMCCP & related review procedures, individual devices or test methods indicating compliance with SKA approved established traceable standards may be discussed and referenced in EMCCPs and project documentation without the need for extensive further description of emission levels or test detail if the levels or methodologies specified in those standards are used as basic input benchmarks for the evolution of more complex verification & planning strategies.

In any documentation where specific devices are stated as having better EMI performance than laid down in an approved standard, or if a device has not been tested to comply with an SKA approved standard, a fully documented verification of the stated EMI performance must be provided.

[3] On release of –this- document SKA-TEL-SKO-0000202 (MAR17), document [14]- (SKA-TEL-SKO-0000691) contains only the established traceable standards related to EMC that are cited in Section 9 of SKA-TEL-SKO-0000202, which by implication are approved.

6 Summary of Intent

- In relation to the products that constitute the operational radio telescopes identified in the SKA product tree and operated within the observatory, the standards contained in this document will apply to physically isolated systems or assemblies located within the boundaries of SKA Radio Quiet Zones.
- Methodologies encapsulated in Recommendation ITU-R RA.769 using bandwidths as defined herein form the basis for setting the limits for EMI at the guided wave inputs of the telescope antennas. The resulting SKA EMI standards will be applied over the frequency range 50 MHz to 20 GHz.
- The path to compliance with the SKA Project EMI/EMC requirements must be demonstrated via an EMC Control Plan (EMCCP).
- Equipment on the SKA site must comply with appropriate established international standards on electromagnetic susceptibility.
- Post-installation verification: it is intended that at an appropriate point in the AIV phase of the project the signal chains of all SKA antennas shall be checked for the presence of site-generated EMI above the SKA thresholds as described in this document.
- Designers are urged to try to deliver better performance than the levels given in Section 4 wherever practicable.

7 Guidelines for Interpretation of Intent Related to EMCCP evaluation

Within its scope this document cannot hope to anticipate the almost infinite variations of systems and conditions to be considered for evaluation of compliance to the standard. The project will rely on the professional skills of the engineers concerned to make appropriate decisions on factors affecting the systems that they understand best; a practical design philosophy, erring on the side of conservatism is envisaged. However, some of the factors described below may form part of verification elements detailed in EMCCPs submitted for approval. This section aims to discuss some of these factors and provide guidelines for how these issues might be considered, but only in the context of their assessment within the SKAO EMCCP approval process.

Compliance assessments frequently start with a power & loss budget analysis approach, i.e. the emitter is considered to be a source transmitting at a power determined with reference to the traceable standards with which its components comply; at the other end of the 'path' is the telescope antenna's guided wave input, having a maximum permitted received interference power in a given bandwidth specified by the equations in Section 4. In between the two there are elements such as shielding (screened enclosures, terrain shadow, building penetration loss, etc.), physical separation ('path loss'), etc. that equate to 'loss' in the budget. Occasionally there may also be effects that need to be considered that equate to 'gain', such as the direction in which the antenna is pointing w.r.t. its directivity. Many of these effects themselves are not easily characterised and require analysis, modelling and experimentation to assess their contributions. Some are discussed further in the following sections.

7.1 Distance and Affected Antennas

7.1.1 Free space path loss

Evaluating radiation loss in the space between EMI source and the affected antenna is a complex problem. As a basis for calculations, free-space path loss (fspl) can be assumed for all separation distances exceeding 3 metres, as follows:

$$FSPL\ (dB) = 20\ \log_{10}(d) + 20\ \log_{10}(f) - 27.55$$

Where:

d is the distance of the receiver from the source of emission in metres
f is the signal frequency in MHz

This approach greatly simplifies calculation, but will represent an over-simplification and hence error in some situations. At distances of a few wavelengths the affected antenna may be in the near field of the emitter, and may pick up EMI through electric or magnetic field coupling, even though the emission is not actually radiated. Conversely, in cases where separation distances are likely to be of the order of several hundreds of meters or more it is possible that the actual path loss may exceed that of free space. In these cases, if the locations of the affected antenna and EMI source are known and the path between them can be described accurately in terms of its terrain and clutter, then a more accurate estimation of path loss can be calculated using an internationally recognised propagation model.

For cases that lie in the near field, it may be necessary to utilise near realistic mock-ups for verification by measurement. The ideal measurement distance will be similar to the actual distance between the source and the affected antenna although it is appreciated this may not always be practical.

7.1.2 Antenna 'gain'

For interference calculation purposes the assumption is frequently made (based on the methodology defined in Rec ITU-R RA.769) that the antenna in front of a radio astronomy receiver is equivalent to reception into a side-lobe with gain of 0 dBi over the relevant frequency range. For some situations the *actual* gain (or loss) of the antenna system under those conditions may need to be taken into account. Divergences from the 0 dBi figure in any calculation should be described and justified.

7.1.3 Interferometric effects

The SKA telescopes are designed to be operated as aperture synthesis arrays. When used in imaging applications, especially for small fields of view and long baselines, the outputs of individual interferometers provide rejection of interfering signals if such signals lack coherence between antenna pairs. The degree of rejection is affected by many time-variable factors (e.g. projected baseline length, angular distance from the phase centre, bandwidth, correlator integration time, antenna side-lobes, location and motion of the interfering source). The SKA1 array configuration, which contains many short baselines, may not provide much rejection. Moreover, important observational modes utilise only individual antennas or short-baseline arrays. Thus a conservative approach is to discount the interferometry effect. However, for some specific EMI scenarios there may be a case for including some additional margin to account for this effect. Any assessment contained in an EMCCP that includes additional margins based on anticipated benefits from interferometric effects should be fully described and justified.

7.2 Shielding

The effectiveness of shielding solutions is likely to form part of most scenarios. COTS pre-qualified shielding solutions may be referenced in EMCCP documentation via manufacturer's data sheets. Bespoke shielding solutions should be validated by appropriate measurement campaigns and the results included in EMCCP documentation.

7.3 Measurement

Verification by direct measurement of such low levels as required by SKA is one of the most difficult aspects of this topic. It is accepted that typical commercial standards permit much higher emissions and use wider bandwidths for measurement when compared to the spectral line requirements of this document; they therefore facilitate more convenient measurement procedures.

Verification by indirect means where possible, such as measurement of devices outside shielded enclosures, and then installing them in previously qualified shielded enclosures will be accepted. In many situations a prototype or mock-up may be required.

7.3.1 Measurement Frequency Range and Spectral Resolution of EMI Measurements

Currently radio telescopes devote much of their observing time to continuum observations, which for practical purposes are considered to be inherently less sensitive to narrow-band RFI than spectral line

observations. However, much of the SKA key science will also depend on observations of weak spectral lines, particularly the red-shifted line of atomic hydrogen (HI) whose rest frequency is approximately 1420 MHz. The redshift range covers a frequency range from 50 to 1420 MHz. Additional spectral lines at frequencies up to 20 GHz will also be observed. EMI performance verification measurements must cover the entire range of frequencies and applicable bandwidths. However, it is appreciated that measurement campaigns at this level are complex and time consuming, requiring stable facilities and experienced personnel, therefore limiting unnecessary measurements is desirable. It is recognised that typical EMI emission profiles show power levels that tend to roll off as frequency increases. Consequently for practical purposes unless modelling, analysis or known equipment behaviour indicate otherwise, verification measurement frequency range can be appropriately limited if suitably justified.

It is also recognised that in developing the threshold levels of harmful interference, the bandwidths adopted suit radio astronomy purposes but are mostly incompatible with those routinely provided by commercial test equipment. Commercial equipment is frequently designed for automated testing to specific international standards using bandwidths somewhere in between the SKA continuum and spectral line limits. It is accepted that in many cases measurement programmes will need to be carefully designed to reconcile bandwidth issues; for example, it may be possible to verify compliance at wide bandwidths by summing contiguous narrower band measurements. Where particularly significant difficulties exist, for example, when it can be demonstrated that a combination of limited measurement scenarios together with some additional modelling/analysis is the only means of cost-effective verification, this may be proposed. In these cases SKAO should be advised via the EMCCP and involved in a dialogue supported by an adequately documented description.

7.4 Special Cases

A special case of interference may arise if there are devices that employed in large numbers, which individually pass EMI tests, but act coherently in the field. There are unlikely to be more than a few such instances, potentially clock systems for example, and they may have to be handled as special cases.

7.5 Interpretation of Traceable Established Standards

Devices that have qualified to a level of EMI performance specified under a particular traceable standard (and/or associated test procedure) that is not based on peak emissions, but are however likely to generate impulsive emissions, require a thorough understanding of the nature of the emission profile of the devices. This may require a specific measurement programme and verification procedure, which may indicate that additional shielding is required.

Some comments in this respect on ubiquitous industry standards follow.

7.5.1 CISPR-22

For frequencies lower than 1 GHz, devices that have qualified under the CISPR-22 standard will have been based on quasi-peak-detection measurements. In the worst case of reception of a single pulse approximately equal to the inverse bandwidth of the CISPR measurement apparatus registering a

peak-detection just at the CISPR threshold will show a quasi-peak-detection at 32 dB[4] below the threshold.

Similarly, for frequencies higher than 1 GHz, devices that have qualified under the CISPR-22 standard will have been based jointly on peak and average detector measurements (i.e., both must be satisfied). However, the allowed peak measurements are 20 dB higher than the average measurements.

As the SKA standard is based on peak levels, CISPR-22 qualified devices may, require additional shielding (or equivalent increased separation distances if practical) if they produce emissions of a pulsed nature.

7.5.2 MIL-STD-461F

Devices that have qualified under the MIL-STD-461F standard will already conform to the requirement for detector measurements based on peak emissions from devices.

[4] See Table 2 of [9] (Pulse response of quasi-peak receivers).

8 Decision-tree Approach to EMI Control

A goal for the application of the SKA standard is to facilitate SKA equipment meeting the required emission levels with a minimum of effort. A decision-tree approach may be used as a way of prioritising effort. This Appendix contains a suggested approach for which the overall key components are:

- Recognise established commercial and military emission standards as much as possible and apply appropriate levels of shielding. (In some cases, no testing will be required if a recognised standard can be combined with a pre-qualified shielding solution.)
- Follow measurement procedures described in recognised standards where possible.
- Develop prototypical shielding solutions that are pre-qualified for shielding applications in which emissions can be safely assumed or calculated.
- Make maximum use of optical communications through shielding walls. In many situations using standard shields, the only viable conducting (electrical) connection will be a filtered power supply.
- Concentrate design and testing effort on EMC cases that involve small numbers of high-value objects (e.g. buildings), large numbers of smaller items (e.g. isolated micro-processors in sub-systems attached to commercial equipment, power switches, etc.), or items of special technical significance and complexity (e.g. dishes). One-off and temporary situations need less attention.
- Take into account site operational factors.

Figures 1-4 are decision trees to provide more specific guidelines to this approach. There will inevitably be situations that do not fit the decision tree. In those cases, in consultation with SKAO a reasonable alternative proposal may be made in the EMCCP.

Figure 1 illustrates the first stage of an approach. Items that will be used in non-site applications need to follow only normal commercial standards.

If further evaluation is needed, then Figure 2 applies. This decision tree provides guidance on how to handle commercial off-the-shelf (COTS) items as distinguished from SKA-specific designs, and whether either will be used in high-value or large-number installations. In this figure a 'traceable EMI/EMC standard' can be CISPR-22[5], MIL-2TD-461F or other agreed standard [14]. Other standards may comply, but if they are referenced in this way, approval from SKAO must be given. Note that a COTS item that does not comply with a traceable commercial standard is treated as if it were an SKA-specific design. Note also that all of the end-points require a post-installation check.

Figure 3 applies to COTS items where commercial standards can be applied. However, where these will be installed in large numbers as stand-alone assemblies (not in shielded facilities), then more care is warranted to ensure that the end result is correct and then minimum resources are expended.

[5] CISPR-22 is based on the measurement methods and standards outlined in CISPR-16-1-1 [9].

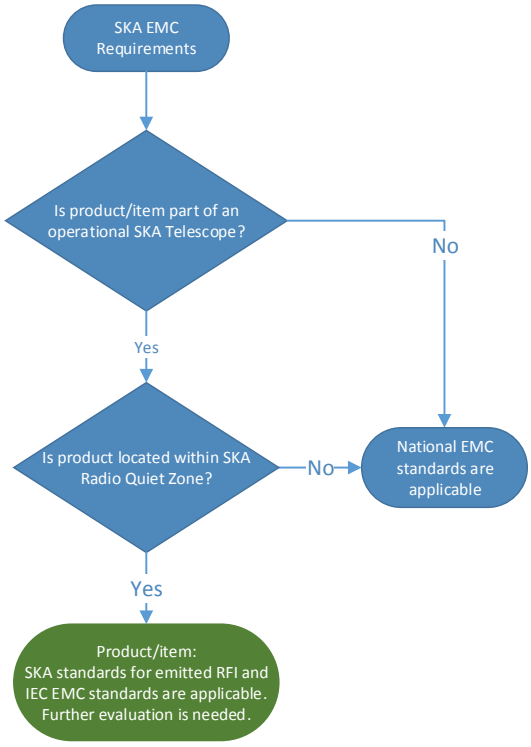


Figure 1: A first level decision tree for items proposed for SKA site installation.

(The dark green box indicates a connection to Figure 2.)

In complex or high-value situations more planning is needed (see Figure 4). In these cases a proposal should be written and reviewed by SKAO. If significant design work is needed, the usual series of design reviews should be carried out (Concept, Preliminary, Critical, and Production Readiness). In some cases, these reviews will be an aspect of the overall design. In the case of dishes, for example, potentially there will be a need for micro-processors for a variety of functions. These would have to be individually shielded or consolidated together in a larger shielded enclosure. (Note the rule on optical-only signal connections). Also dishes are likely to have shielded enclosures with moving mechanical penetrations, such as shaft encoders. Clearly these aspects need to be closely woven into the overall dish design solutions. In Figure 3 and Figure 4, purple boxes indicate that an EMI emissions measurement is required. Light green boxes indicate that a shielding effectiveness measurement is required.

The shielding proposals must take into account the distances to affected antennas on the site. This will require knowledge (prediction) of the site layout in cases where the site layout may not be finalised; nevertheless design work on devices that will create EMI must go ahead. In these cases a conservative approach is required – estimate the shielding effectiveness required for the minimum expected distance.



Figure 2: Second stage decision tree

(The light orange box indicates connection to Figure 3. The dark orange box indicates connection to Figure 4.)

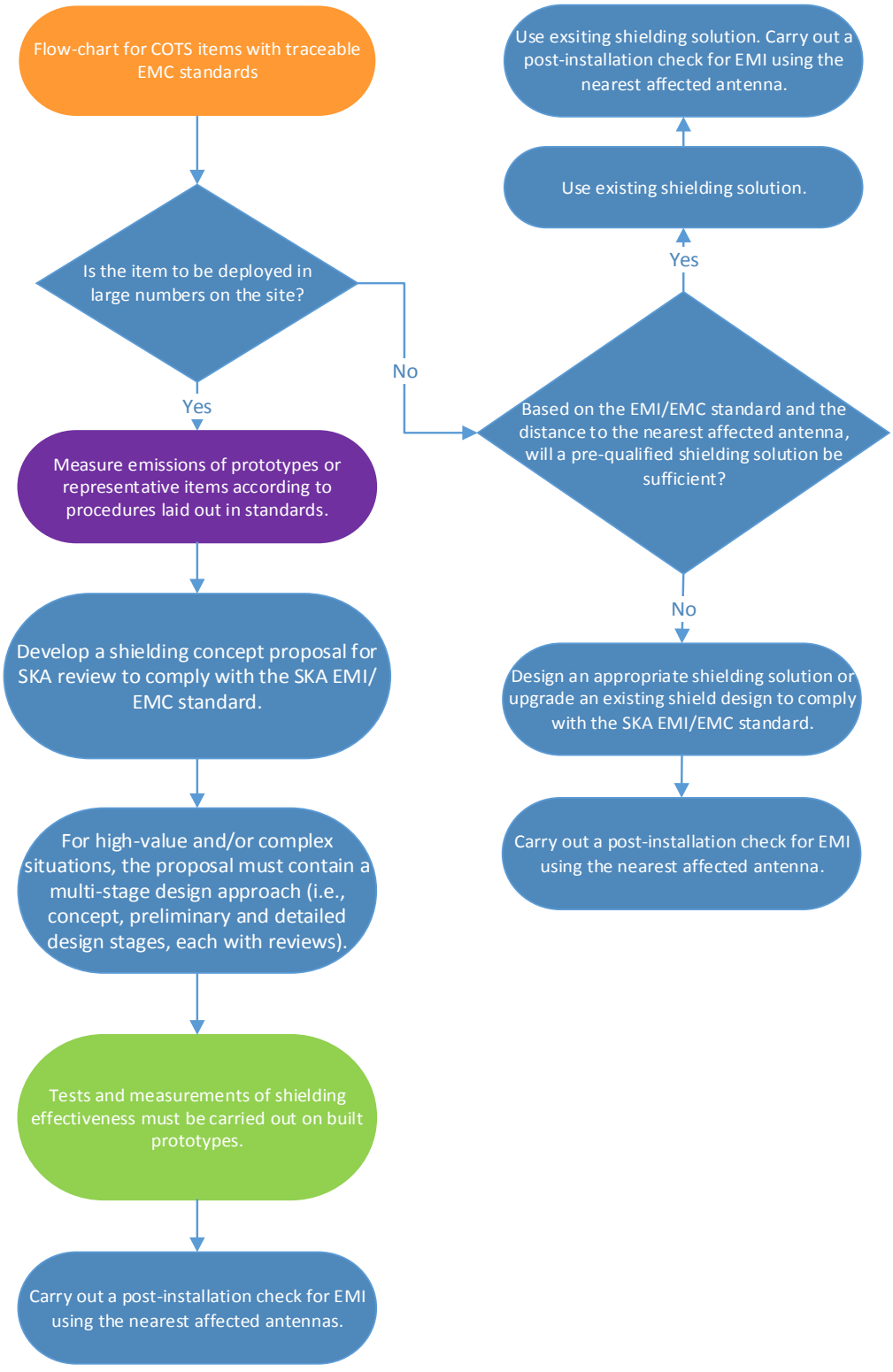


Figure 3: Decision tree for COTS equipment

(A purple box indicates that an emissions measurement is required. A light green box indicates that a shielding effectiveness measurement is required.)

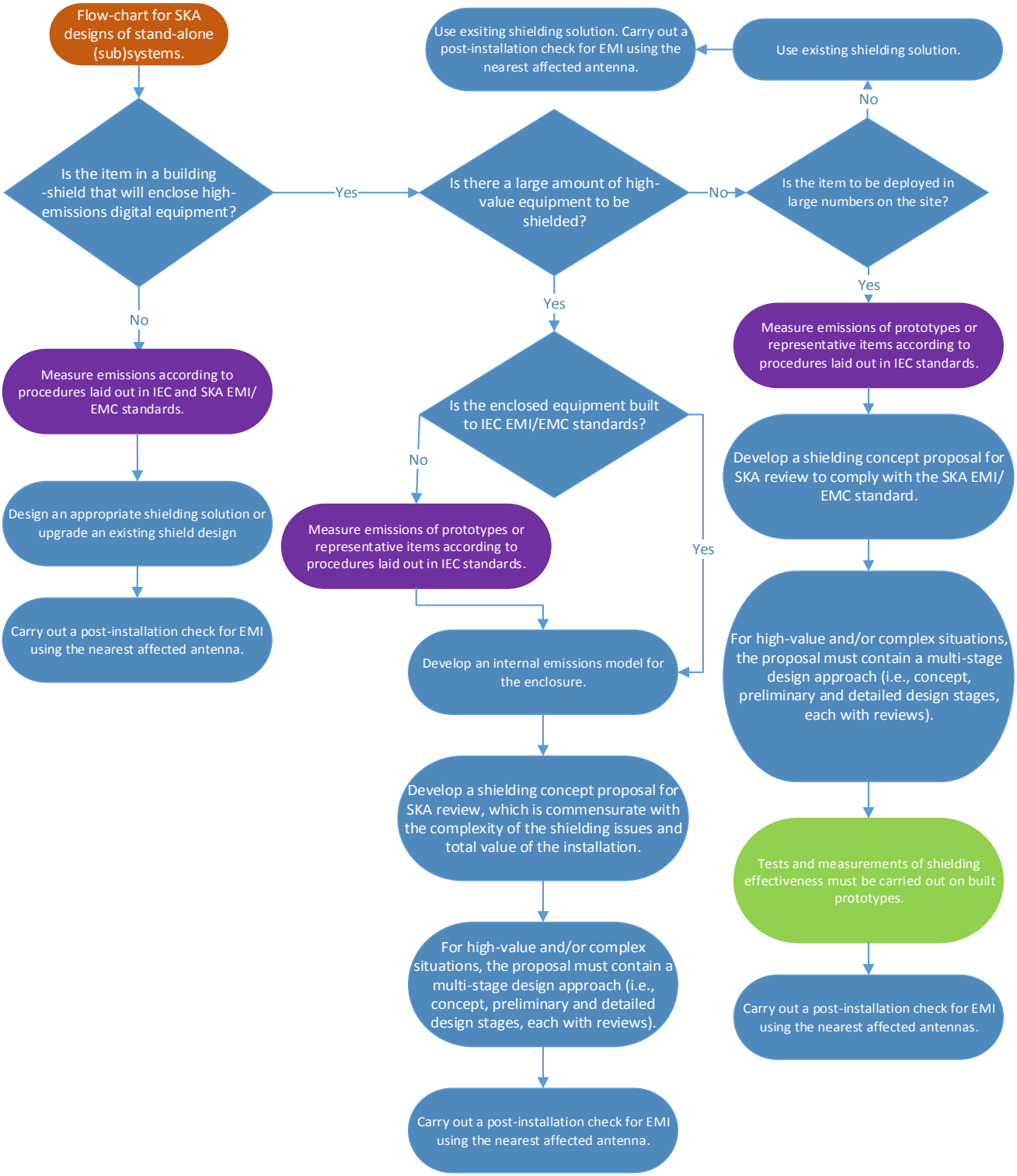


Figure 4: Third stage decision tree

(A purple box indicates that an emissions measurement is required. A light green box indicates that a shielding effectiveness measurement is required.)

8.1 Best Practices in EMI-Robust Electrical and Electronics Design

The decision trees described in this section are designed to be as general as possible. However, they do not explicitly note that an initial inspection of supplied equipment (especially COTS equipment) will likely save time. Inspection should determine whether best practice has been used to avoid both conducted and radiated interference.[6] If not, then either a different selection should be made, a re-design considered on how the unit would be incorporated into the sub-system, or if considered viable, negotiations with the supplier undertaken to modify the design of the offending part.

8.2 Test and Verification Measurements

The measurements required for the SKA standard are of two basic types, field-strength measurements from potential emitters of EMI and shielding effectiveness. The methods used are either directly from widely accepted standards or are adapted minimally to meet SKA requirements.

In some situations it may be desirable to make emission measurements of COTS equipment that already meets recognised standards, even though the procedures described herein do not require it. For example, a device that meets CISPR-22 standards may be believed to emit much less than the standard requires. If it is measured, such a device would require less shielding than would be indicated by using the CISPR standard levels alone.

8.3 Facilities

Although the verification methods are those prescribed by international standards, the actual emission levels to be measured for the SKA thresholds will often be many dBs lower. A certain degree of rigour will be needed to obtain consistent results. This will be time consuming, and this is why the guidelines outlined in this appendix have been devised to minimise the number of different measurements actually needed. This is also why a conservative shielding solution may be more effective overall than trying to characterise emissions with a high degree of precision.

Access to equipment and facilities that can provide reproducible tests results is critical to any measurement programme. Open-air test sites must be sufficiently free of RFI that valid repeatable measurements can be conducted in the required frequency ranges. Alternatives are large absorber-lined shielded rooms. A reverberation chamber may be needed for some tests.

8.4 Field-Strength Emissions Measurements

The purple boxes in Figure 3 and Figure 4 indicate that emission measurements are required. Under the SKA standard, the CISPR-22 [8] methods as defined in chapters 8 and 10 of that document (not the actual standards) for measuring radiated “disturbances” form the basis for these measurements. Note that this is quite distinct from adopting the actual radiated limits contained in the CISPR-22 document. The method can be adapted to measurements for much lower limits of emission, which will hopefully be the case for much of the equipment to be used on the SKA site.

[6] Best practices include especially the physical layout of circuitry and wiring so as not to create incidental antennas or current loops. There is abundant literature on this topic, but such practices are not necessarily followed in COTS electronics or in custom-built hardware.

8.5 Shielding Measurements

The light green boxes in figures 3 and 4 indicate that shielding effectiveness measurements are required. For SKA, the IEEE 299-2006 and IEEE 299.1-2013 standards have been adopted for measuring shielding effectiveness. If necessary, such as when the shields are incorporated into buildings, these must be carried out on site. By preference they should be carried out off site.

9 Notes on Some Established Traceable Standards

9.1 Emissions

9.1.1 IEC 61000 Series on EMC

The International Electrotechnical Commission (IEC) is an international organisation that publishes widely recognised standards for all electrical, electronic and related technologies. The 61000 series covers EMC and EMI. A small number of these standards are specifically applicable to EMI on SKA sites, but many others will be applicable in a more general sense and may be referenced in the procurement of SKA equipment and facilities. IEC 61000-4 standards contain standards on testing and measurement techniques. IEC 61000-5 standards are guidelines for installation and mitigation of EMI. EN61000-6-3 is a widely used emission standard, identical to CISPR-22 at frequencies up to 1 GHz, but 6 dB lower for 1 to 6 GHz.

9.1.2 Other Relevant Established Standards

Although there appears to be no fully accepted overarching international standard for EMI, this section contains brief descriptions of widely recognised standards. Equipment purchased for the SKA will have a high likelihood of having passed compliance testing for some of these standards. This can provide a starting point for determining the potential for EMI and in many cases proceeding directly to a shielding or positioning solution without extensive measurements.

These established standards also contain measurement techniques and methods for verification of the standard. Methods used for SKA verification should adhere as closely as possible to these methods so that potential suppliers of equipment can adapt their methods as easily as possible to SKA standards.

9.1.2.1 IEC CISPR-22

The International Special Committee on Radio Interference goes by the acronym, CISPR, originating from Comité International Spécial Des Perturbations Radioélectriques. CISPR-22 [8] is the standard on RFI of interest to the SKA, covering Electromagnetic Compatibility (EMC) of information technology equipment (ITE), multimedia equipment and receivers, including measurement techniques.

The electric field emission limits are given in [8] for Class B equipment, which would be most appropriate for equipment considered for siting on an SKA site. The standard also contains descriptions of verification methods. Equipment that is certified as Class A will meet a lower standard. If such equipment is considered for the SKA, it must be shielded or positioned accordingly to meet the SKA standard.

Table 1: CISPR-22 Class B Electric Field Emission Limits

Frequency Range	Electric Field Maximum Levels (dB ($\mu V \cdot m^{-1}$))	Measurement Distance (m)	Measurement Bandwidth (kHz)
30 – 230 MHz	30	10	120
230 MHz – 1 GHz	37	10	120
1 – 3 GHz	50	3	1000
3 – 6 GHz	54	3	1000

At frequencies less than 1 GHz, CISPR 16-1-1, on which CISPR-22 measurements are based, specifies quasi-peak detection, whose response is dependent on the repetition frequency of pulses of equivalent total area. This is calibrated in such a way that the output response of a 100 Hz repetition frequency is the same as an unmodulated sine wave input. Thus a much higher disturbance input is allowed if the repetition frequency is lower. Table 3 of [9] (Pulse response of quasi-peak receivers) provides factors to account for repetition rate.

9.1.2.2 MIL-STD-461F

This US Department of Defence standard establishes interface and verification requirements for the control of the EMI and susceptibility of electronic, electrical, and electromechanical equipment. It is a widely used standard for industrial equipment, and some items procured for the SKA may already meet this standard.

MIL-STD-461F [10] is written for a large variety of purposes – the section, RE-102 (radiated emissions, electric field, 10 kHz to 18 GHz) is relevant to the SKA, in particular the part for ground applications, Navy Mobile and Army. The limits are contained [10] as a function of frequency as they are stated in units of dB(μV-m^{-1}) of electric field. Detection is based on peak detection in terms of a receiver calibrated in terms of an equivalent rms value of a sine wave the produces the same peak value, as described in Section 4.3.10.1 of [10].

The standard also contains descriptions of verification methods.

Table 2: MIL-STD-461F Electric Field Emission Limits

Frequency Range	Electric Field Maximum Levels (dB (μV-m^{-1}))	Measurement Distance (m)	Measurement Bandwidth (kHz)
10 - 100 MHz	24	1	100
100 MHz – 1 GHz	20 log(f GHz) + 44	1	100
1 GHz – 18 GHz	20 log(f GHz) + 44	1	1000
>18 GHz	69	1	1000

9.1.2.3 Other potential Standards

Equipment that may be used for the SKA may meet standards from other national or regional organisations. In making a case for utilising such standards without making a full set of measurements, it will be important that the standard is complete and designed for purposes of setting limits on EMI that are applicable to the SKA. Approval for use of an alternative standard other than those listed in [14] will be required.

9.2 Shielding

The SKA thresholds for EMI can be met in a given situation either by positioning emitting devices at a sufficient distance, by adding shielding, or a combination of both. In many situations shielding will be required.

There are two standards for verifying shielding effectiveness, IEEE 299-2006 [11] and IEEE 299.1-2013 [12], which form the basis for the SKA shielding effectiveness standard. The first applies to enclosures greater than 2 m in smallest dimension and the second applies to enclosures with the smallest dimension between 0.1 and 2 m.

Standardised enclosures that are used for multiple applications will require thorough testing and qualification, and should be equipped with as many penetrations as needed for all foreseen applications.

It is likely that standard shielded enclosures will be qualified and used to enclose items whose emissions exceed the SKA standard. These enclosures may be used without individual qualification if no modifications to penetrations have occurred from the test conditions. Optical fibre penetrations installed through a waveguide-beyond-cut off that was present when the shield was tested will stand as exceptions. No metallic material may be inserted in a waveguide-beyond-cut off. Designs should favour fluid-based heat transfer rather than air-based heat transfer, both from a volume perspective and from the size of penetrations required.

It is likely that meeting the SKA standard will require levels of shielding effectiveness that are higher than those required for industrial applications. This also implies that testing methods may be pushed to the limit as well. It is important that test equipment is fully qualified for the task, especially for non-linear and dynamic range effects.

It is likely that a conservative design for shielding, such as welded steel construction, will be less expensive in the long run than a shielding system that requires constant checking and maintenance.

9.2.1 IEEE 299-2006

This standard should be applied as written with particular attention being paid to the following:

- The shielding requirements must be well documented and understood by the testing authority.
- The shields shall be tested over the entire SKA frequency range:
    - Resonant frequencies should be avoided (as described in the standards document).
    - The frequency coverage shall be contained in the approved test plan.
    - The final test shall rule out, with a high degree of confidence, leakage above design emission levels over the SKA frequency range.
- The test plan shall be approved by the relevant SKA authority:
    - A preliminary assessment of the shield should be made before completing the test plan, to check for the likelihood of shielding defects (gaps, cracks, and penetrations) that are likely to cause failure of the final test.
- The shields must be equipped with the full set of penetrations at the time that the tests are carried out. Shields should be designed with the minimum number of penetrations possible, especially metallic penetrations. In many cases only well-filtered power need penetrate the walls.
- High-value shielding situations, such as in large SKA site buildings should be designed conservatively. This favours welded steel enclosures on all sides. Buildings should be tested before occupancy, and preferably before interior finishing, if any, is installed. For enclosures that have joints in the shielding walls, the joints must remain accessible during operations.
- The cursory checks recommended in the standards document are particularly important for the SKA, which will typically require high values of shielding effectiveness.
- Since the purpose of the shields is to keep EMI confined, an inside-out approach may be more effective than an outside in approach. In principle they should be equivalent.
- The shielding report should make the case that that the shield meets specifications. In the case of high-value shields extensive detail is expected. In particular any risks and/or shortcomings in the testing should be noted.

9.2.2 IEEE 299.1-2013

This standard is for small shielded enclosures, from 0.1 to 2 m in size. Although from an EMI perspective, consolidation of electrical equipment in a few large enclosures is better than many small ones, it is likely that small shielded enclosures will nevertheless be needed for the SKA.

The measurement methods depend on whether the enclosure is physically small (i.e., too small for probes to actually sample the fields properly) and/or electrically small (maximum dimensions much smaller than a wavelength at the highest frequency).

10 Sample Electromagnetic Compatibility Control Plan (EMCCP)

10.1 Minimum requirements of an EMCCP

The EMCCP should specify the objectives, scope, EMC program activities, schedule and reporting, EMC program deliverables, key participants, and methods and techniques by which the EMC program objectives will be met. The EMCCP should contain the items in the outline given below. Consortia may add to or expand the framework to meet their individual needs to reflect significant complexity in some cases. It is also anticipated that as the SKA project develops, individual EMCCPs may grow to become collections of documents at various stages of maturity.

10.2 Example EMCCP Structure

10.2.1 OVERVIEW

10.2.1.1 Scope

Brief discussion covering the scope of the EMC program for the equipment or system under consideration with respect to SKA EMC requirements.

10.2.1.2 Purpose

Objectives of the EMC program. Identify the originator of the plan and the SKA organisational context to which the plan is to be submitted.

10.2.1.3 Reference & Applicable support documentation

In addition to the usual SKA listing of applicable & reference document practice, include all EMC specifications applicable to the program, industry specifications, special requirements, any other documents that may justify modification of the basic guidelines, etc.

10.2.1.4 Terminology

List acronyms, glossary explanations, etc.

10.2.2 DESCRIPTION OF EQUIPMENT OR SYSTEM

Give a brief description including a block diagram of the equipment or subsystem. Briefly discuss the intended function, physical size, operational environment, and any relevant specific operating characteristics, interfaces, etc.

10.2.3 PROGRAMME ORGANISATION & RESPONSIBILITIES

The organisation and management of the proposed EMC control plan should be described in appropriate detail and may need the following sections as required.

10.2.3.1 Management

Describe the control & management support required of the effective implementation of the programme and identify how potential non-compliance issues will be handled. Responsible management and project personnel should be identified. As a minimum a responsible person should be nominated as a focal point. Define the EMC responsibility of all subcontractors. If the EMC engineering is to be subcontracted to a consulting firm, identify the firm and the individual who will be the EMC engineering contact or consultant.

10.2.3.2 Milestones

Identify the EMC program schedule milestones. Pertinent events may be used as milestones including scheduled reviews driven by other systems engineering requirements of the SKA project.

10.2.3.3 Documentation to be provided

List and describe.

10.2.3.4 Sub-contractor & Supplier Coordination

Discuss plans for defining responsibilities and coordinating the EMC program with sub-contractors & suppliers.

10.2.4 TECHNICAL PROGRAM

10.2.4.1 EMC Requirements

Identify specific EMC requirements.

10.2.4.2 EMC Concepts

EMC concepts to be used to attain electromagnetic compatibility. For systems, this discussion should include allocation of the requirements and the EMC program to equipment suppliers, design reviews including resolution of problems, and verification of the plan.

10.2.4.3 Specific Design Considerations

Identify and characterize interference sources (both internal and external to the system) and describe EMI reduction techniques and susceptibility control procedures.

10.2.4.4 Reviews

Detail on EMC design reviews and proposed scheduling.

10.2.4.5 EMI Safety Analysis

Address appropriate provisions for review of safety related issues.

10.2.4.6 Verification

Describe the verification process in detail. Verification within the EMCCP includes inspection, demonstration, analysis and testing. Individual equipment may be verified using any of the four or a combination of the four as a valid verification method. The overall system itself can usually be verified only by testing.

10.2.4.7 Sub-Contractor & Supplier EMC Programme

Sub-contractors & suppliers shall meet the EMC requirements of the SKA and follow the same guidelines for the EMCCP necessary for the scale of their contribution, which may include identifying engineers responsible for the their EMC Program, establishing requirements, participating in reviews, verification, and approval requirements for documents such as Control Plans, Test Procedure and Test Reports, etc.

10.2.5 CONTROL PLAN REVISIONS

Statement concerning criteria for revising the EMCCP in phases of ongoing development.