SKA RFI/EMC STANDARD

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LIST OF ABBREVIATIONS

AC .... Alternating Current
ADC .... Analogue-to-Digital Converter
ATP .... Acceptance Test Procedure
BW .... Bandwidth
CISPR .... International Special Committee on Radio Interference
CoC .... Certificate of Compliance
COTS .... Commercial Off-the-Shelf
CPF .... Central Processing Facility
dB.................................. Decibel
dBFS .... Decibel related to Full Scale
DUT............................... Device Under Test
EMC .... Electromagnetic Compatibility
EMCCP .... EMC Control Plan
EMI................................ Electromagnetic Interference
EMISC........................... EMI Shielded Cabinet
EOC .... Engineering Operations Centre
EoR .... Epoch of Re-Ionization
ESD............................... Electrostatic Discharge
EUT............................... Equipment Under Test
IE................................... Induced Emissions
IEC .... International Electrotechnical Commission
IQ .... In-phase Quadrature
IT .... Information Technology
ITU .... International Telecommunications Union
ITE .... Information Technology Equipment
ITF................................. Integration and Testing Facility
JVLA .... Jansky VLA
LISN .... Line Impedance Stabilisation Network
LNA .... Low Noise Amplifier
NCR .... Non-Compliance Report
NRB .... Non-Compliance Review Board
NF .... Noise Figure
PaSD............................. Power and Signal Distribution
PSC............................... Pedestal Shielded Compartment
PSU............................... Power Supply Unit
RAS............................... Radio Astronomy Service

RBW..............................Resolution Bandwidth
RE ....Radiated Emissions
RF ....Radio Frequency
RFI ....Radio Frequency Interference
RPF ....Remote Processing Facility
RQZ ....Radio Quiet Zone
SAT ....Site Acceptance Test
SKA ....Square Kilometre Array
SKAO ....SKA Observatory
SID ....Site Information Document
SPFD ....Spectral Power Flux Density
VLA ....Very Large Array
VNA...............................Vector Network Analyser

1 Executive Summary

The SKAO telescope sites have been specially selected to be as free as possible of external, terrestrially generated radio frequency interference (RFI) over significant bandwidths. The radio quietness of the SKAO sites will be maintained via the establishment of Radio Quiet Zones (RQZs). These are effective in managing the interference generated by equipment or systems outside of the control of the Observatory (external RFI), as well as equipment to be used in SKA telescopes that has to be designed to appropriately limit self-generated RFI that may interfere with nearby telescopes or other sensitive equipment located on the SKA sites. This standard describes the SKA threshold levels of interference harmful for observations (hereafter referred to as "*SKA protection levels"*) as the most important limit to be observed by any equipment that forms part of the telescopes or by activities conducted in the observatory. Furthermore, any electrical equipment that will operate in an environment alongside other equipment will have to prove its Electromagnetic Compatibility (EMC) to internationally accepted generic or product EMC standards.

This standard defines the SKA EMI/EMC requirements, applicable to all equipment within products that constitute the operational 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. For the particular case of radiated emissions, where the *SKA protection levels* will supersede commercial EMC standards, guidance on the derivation of the *emission threshold levels* is provided with the inclusion of SKA-provided software [RD21]. The software derives the *emission threshold levels* without requiring complex calculations on electromagnetic propagation.

Proactive planning is a very important aspect of EMC compliance and, via an EMC control plan (EMCCP), potential risks can be identified and managed. An EMCCP can range from a simple statement of compliance to internationally accepted standards and a plan to provide test results for some commercial off-the-shelf (COTS) equipment, to a description of the EMC program of a bespoke product that will be prototyped, tested and fabricated by a contractor. For more sensitive situations the EMCCP will be a detailed plan including risk analysis, mitigation measures and test plans. A template for an EMCCP is included that shall be completed for any product and will allow consistency in EMC management across the whole project.

Verification of requirements can be achieved by different methods (of which testing is the preferred option for the SKAO). These are described in this document with emphasis on radiated emission testing to comply to the SKA *protection levels*.

Overall, this standard is intended to be the source of the SKA system level requirements on EMC and shall be used as a reference for the derivation of any sub-level EMC requirements.

2 Introduction

2.1 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, it is expected 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 electromagnetic interference (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 [RD1].

This standard describes the SKA threshold levels of interference harmful for observations (hereafter referred to as "*SKA protection levels"*) as the most important limit to be observed by any equipment that forms part of the telescopes or by activities conducted in the observatory. 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. Inevitably this means that for some observations the thresholds may appear to be unnecessarily stringent. Equally, for a number of planned observations, the thresholds will be insufficient for complete protection.

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[1] *Radio Frequency Interference* - degradation of the reception of a wanted signal caused by radio frequency disturbance [RD1].

[2] Since this legislation was introduced, the lower SKA operational frequency range has been extended from 70 to 50 MHz. 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.

For the practical development of the SKA project, limits for radiated emissions from interferers considered harmful to observations are needed to facilitate the engineering design process dealing with EMC issues. The derivation of limits for radiated emissions are detailed in Section 4 of this document. Designers are urged to always try to deliver better performance than the limits provided whenever practicable.

The project's system level requirements are defined in Section 5 and the controls and verification methods to meet this standard are defined in Section 6.

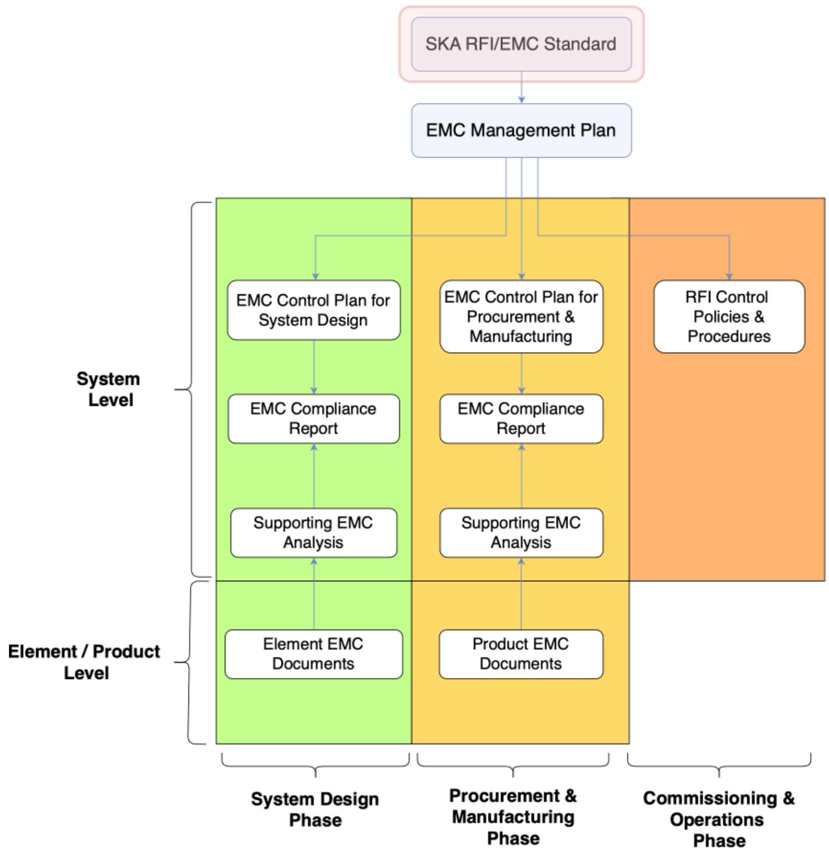

Figure 1: SKA RFI/EMC Standard, highlighted in red, in relation to the EMC document tree.

2.2 Purpose

The purpose of this document is to:

1. Set the SKA *protection levels* at the LNA input of the telescope antennas, assuming a 0 dBi antenna gain, and the associated methods to derive the *emission thresholds* for equipment or systems located on site.
2. Establish procedures for the monitoring and control of EMC matters throughout the entire project.
3. Provide *guidelines* for the interpretation of this document, its associated procedures, measurement, and verification requirements.

2.3 Scope

The equipment covered by the 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 furthermore applies to all ancillary and support equipment 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 6) and the *site access procedures* described in the Site Information Documents (SID) [RD15] and [RD16].

By virtue of their intended function, it is anticipated that application of the strict SKA emission standards thresholds defined in Section 4 will not be necessary for sub-systems housed in formally designated SKA large scale shielded buildings or facilities, as the shielding of these facilities will have been designed to cope with emissions at commercial levels for the equipment expected to be contained therein (e.g., in [RD3] and [RD4]).

Any SKA equipment or sub-systems must be able to deliver its full performance while located in its intended operational environment and not generate high levels of emissions (either radiated or conducted) as to interfere with the operation of other co-located sub-systems or equipment. Established traceable international standards already exist for these situations, and they must be considered for the SKA.

2.3.1 Sub-System Applicability

From the perspective of protecting the SKA telescopes and the sites from radiated interference, 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, 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. The allowable levels in telescope signal chains from conducted interference must be no more than that allowed for its equivalent radiated interference.

3 References

3.1 Applicable Documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

[AD1] Recommendation ITU-R RA.769, "*Protection Criteria Used for Radio Astronomical Measurements*", International Telecommunications Union (ITU), 2003.

3.2 Reference Documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD1] P.E. Dewdney, "*SKA1 System Baseline Design V3*", SKA Document SKA-TEL-SKO-0000002, Rev 03A, SKA Organisation, Jodrell Bank Observatory, UK, Nov 01, 2017.

[RD2] "*IEC International Electrotechnical Vocabulary*", International Electrotechnical Commission (IEC), Electropedia, Available Online, January 2021.

[RD3] CISPR 32, "*Electromagnetic compatibility of multimedia equipment - Emission requirements*", International Special Committee on Radio Interference (CISPR), International Electrotechnical Commission (IEC) Publications, Edition 2.0, 2015.

[RD4] MIL-STD-461G, "*Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment*", Department of Defence Interface Standard, U. S. Department of Defence, 11 December 2015.

[RD5] ACMA, RALI MS 32, "*Coordination of Apparatus Licensed Services within the ARQZWA*", Canberra, December 2014.

[RD6] ACMA, "*Radiocommunications (Mid-West Radio Quiet Zone) Frequency Band Plan 2011*", Canberra, July 2011.

[RD7] "Regulations on Radio Astronomy Protection Levels in Astronomy Advantage Areas Declared for the Purposes of Radio Astronomy", Government Gazette, No. 35007, No. R. 90., 10 February 2012.

[RD8] M. Caiazzo, "*SKA Phase 1 System Requirements Specification*", Document Number SKA-TEL-SKO-0000008, Rev. 12, SKA Organisation, Jodrell Bank Observatory, UK, 2020-06-17.

[RD9] J. Kerr, "*SKA Organisation Health, Safety & Environmental Management Plan*", Document Number SKA-TEL-SKO-0000740, Rev. 03, SKA Organisation, Jodrell Bank Observatory, UK, 2019-10-18.

[RD10] "IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures", IEEE STD 299-2006, IEEE Electromagnetic Compatibility Society, Dec. 29, 2006.

[RD11] "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.

[RD12] A. J. Otto, J. Jonas and F. Di Vruno, "*Applying Telescope Protection Levels to Measurement Data*", Document Number SKA-TEL-SKO-0001796, Rev 01, SKA Organisation, Jodrell Bank Observatory, UK, 2021-02-09.

[RD13] ETSI EN 301 489-1, "*Electromagnetic Compatibility (EMC) Standard for Radio Equipment and Services; Part 1: Common Technical Requirements; Harmonised Standard for Electromagnetic Compatibility*", Harmonised European Standard (EN), Version 2.2.3, ETSI Technical Committee, November 2019.

[RD14] A. J. Otto, F. Di Vruno and T. Nkawu, "*SKA System EMI/EMC Control Plan for Procurement and Manufacturing Phases*", Document Number SKA-TEL-SKO-0001032, SKA Organisation, Jodrell Bank Observatory, UK, 04 January 2021.

[RD15] T. Cheetham, "*South African Site Information & Instructions: SKA1_MID: Site Information*", Document Number SKA-TEL-SKO-0001040, Rev 01, SKA Organisation, Jodrell Bank Observatory, UK, 2020-10-08.

[RD16] K. Adern and A. Schinckel, "*Australian Site Information: SKA1_LOW*", Document Number SKA-TEL-SKO-0001650, Rev 01, SKA Organisation, Jodrell Bank Observatory, UK, 2020-10-24.

[RD17] J. A. Obiebi, "*SKA Product Quality Assurance Plan*", SKA Document Number SKA-TEL-SKO-0000739, Rev 02, SKA Organisation, Jodrell Bank Observatory, UK, 2019-01-31.

[RD18] Recommendation ITU-R P.452-16, "*Prediction Procedure for the Evaluation of Interference Between Stations on the Earth at Frequencies above 0.1 GHz*", International Telecommunications Union (ITU), 2015.

[RD19] R. T. Lord, "*Measuring Weak RFI Signals with a Real-Time Spectrum Analyzer*", Version 2, RFI-WG Memo #23, Radio Frequency Interference Working Group, South African Radio Astronomy Observatory (SARAO), Black River Park, Western Cape, South Africa, 1 October 2013.

[RD20] IEC 61000-4-21, "*Electromagnetic Compatibility (EMC) – Part 4-21: Testing and Measurement Techniques – Reverberation Chamber Test Methods*", EMC Publication, International Electrotechnical Commission (IEC), 2011-01-27.

[RD21] Online: https://emc-standards.skatelescope.org/, Available February 2021.

[RD22] Recommendation ITU-R P.1546-6, "*Method for Point-to-Area Predictions of Terrestrial Services in the Frequency Range 30 MHz to 4 000 MHz*", International Telecommunications Union (ITU), 2018.

4 SKA Protection Levels

RFI can affect the telescope systems in different levels: starting from physical damage of the low noise amplifiers (LNA) in the case of strong emitters located near an antenna or a relatively strong source illuminated by the main beam of a telescope. Below the damage level, saturation (or non-linearities) in the analogue and digital signal chain not only produce data loss in the frequency of the interference but neighbouring channels are also affected. For cases where the RFI is not critically strong it produces data loss according to its time occupancy characteristics. In extreme cases RFI can render a frequency channel unusable to science observations. This section defines limit values for each of these cases to be used in the SKA project.

4.1 Damage Limits

Damage limits refers to the physical damage level of the first stage LNA of the SKA telescope receiver. A received input power of +10 dBm in any SKA band is assumed for the *SKA Damage Limit*. This is to be considered as a dangerous situation for a telescope receiver and should never be reached nor exceeded.

4.2 Saturation Limits

Analogue saturation of a component in the signal chain is when the amplifier behaves non-linear, i.e. when the output power of the amplifier is not equal to the linear input signal power multiplied by the amplifier gain. The output power level that is a result of the LNA not amplifying the input signal with the specified gain is referred to as the saturated output power. During this non-linear process the input signal can be “distorted” by the component adding new frequency components as its output. Digital saturation is likely to occur when the input power to the analogue-to-digital converter (ADC) goes above its specified -3 dBFS to 0 dBFS (full scale) value. For RFI considerations, a conservative limit of -100 dBm at the input to the first stage LNA is assumed as the *SKA Saturation Limit*.

4.3 SKA Protection Levels

The *SKA protection levels* at the LNA input of the telescope antennas were derived from the International Telecommunications Union (ITU) Recommendation ITU-R RA.769 [AD1] (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 radio astronomy community and provides the foundation for many national and international regulations. The national regulations of both Australia and the Republic of South Africa, defining acceptable levels of RFI within both RQZs of the SKA sites [RD5] [RD6] [RD7], 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. The *telescope protection level* 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% (a bandwidth ratio of 1% of the observing frequency is adopted as the average up to 23.8 GHz in the RA.769 recommendation). 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 (a bandwidth ratio corresponding to 0.001% of the observing frequency).

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 a 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 protection levels*.

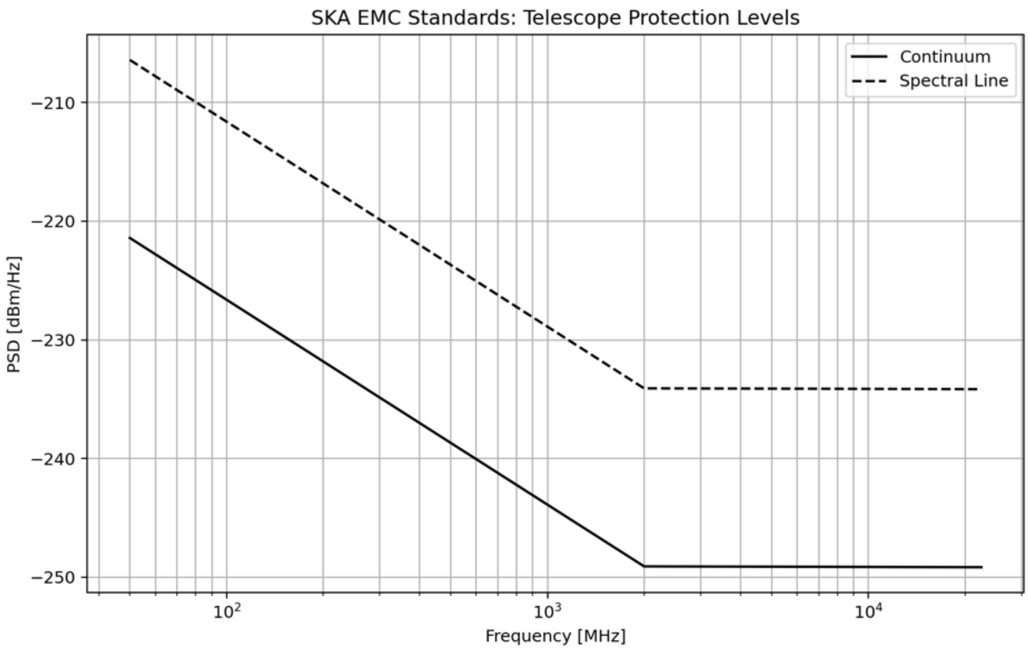

Figure 2: SKA EMC Standards: Telescope protection levels for *Continuum* and *Spectral Line* observations.

Note 1: *Power levels shall be calculated using bandwidth ratios of 1 % of the centre frequency for continuum and 0.001 % for spectral line.*
Note 2: *The SKA protection levels are defined based on Rec. ITU-R RA.769-2 assuming an integration time of 2000 seconds and typical system temperatures for radio telescope receivers.*

4.3.1 Continuum Protection Level

A bandwidth ratio of 1% of observing frequency is adopted for the *continuum* protection levels (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. The *continuum protection levels* are given in Eq. (1):

$$\text{PSD}\left(\frac{\text{dBm}}{\text{Hz}}\right) = -17\log(f) - 192 \qquad \text{for 50 MHz} \le f < \text{2 GHz}$$

$$\text{PSD}\left(\frac{\text{dBm}}{\text{Hz}}\right) = -249 \qquad \text{for 2 GHz} \le f \le \text{25.5 GHz} \tag{1}$$

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

4.3.2 Spectral Line Protection Level

A bandwidth corresponding to 0.001% of the observing frequency is chosen (equivalent to a Doppler resolution of 3 km/s). The *spectral line protection levels* are given in Eq. (2):

$$\text{PSD}\left(\frac{\text{dBm}}{\text{Hz}}\right) = -17\log(f) - 177 \qquad \text{for 50 MHz} \le f < \text{2 GHz}$$

$$\text{PSD}\left(\frac{\text{dBm}}{\text{Hz}}\right) = -234 \qquad \text{for 2 GHz} \le f \le \text{25.5 GHz} \tag{2}$$

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

Verification procedures must ensure that peak EMI emissions, calculated as received PSD at the nearest affected antenna with the required bandwidths, are lower than the *continuum* and *spectral line* limits over the frequency range **50 MHz to 25.5 GHz**. Note that the measurements are typically made using a fixed channel bandwidth (commonly referred to as the resolution bandwidth or RBW), while the protection levels are specified as PSD in a variable bandwidth.

4.3.3 Bandwidths

The necessity to understand the relationship between the *measured* interference power using an instrument channel bandwidth and the *compliance* PSD defined in the *SKA protection levels* applying a specified threshold bandwidth is detailed in [RD12]. Various combinations of signal bandwidths (Δf_{sig}), instrument bandwidths ($\Delta f_{\text{meas}} = \text{RBW}$) and radio astronomy protection levels bandwidths (Δf_{thresh}) are considered in the derivation of required bandwidth compensation factors.

4.3.4 Limits on Transient or Impulsive Emissions

Transient or impulsive emissions, such as sparks, burst communications, or switching noise, must have an averaged radiated power, in 2000 seconds, that complies to the *Continuum* and *Spectral Line* protection levels. The instantaneous peak power (generated at the antenna receiver) shall be less than the *SKA Saturation Limit* measured with a receiver bandwidth large enough to cover more than 90% of the signal's 3 dB bandwidth.

4.4 Emissions Threshold Levels

The *emission thresholds* for a device, located at a distance R [m] from the telescope receiver, determines the maximum amount of power [dBm] in a resolution bandwidth (RBW) [Hz] channel width that the device is allowed to radiate at that location [RD12]. The process of RFI qualification of such a device and the verification of the *Telescope Protection Levels* are done through measurements against the *Threshold Levels* as depicted in Figure 3.

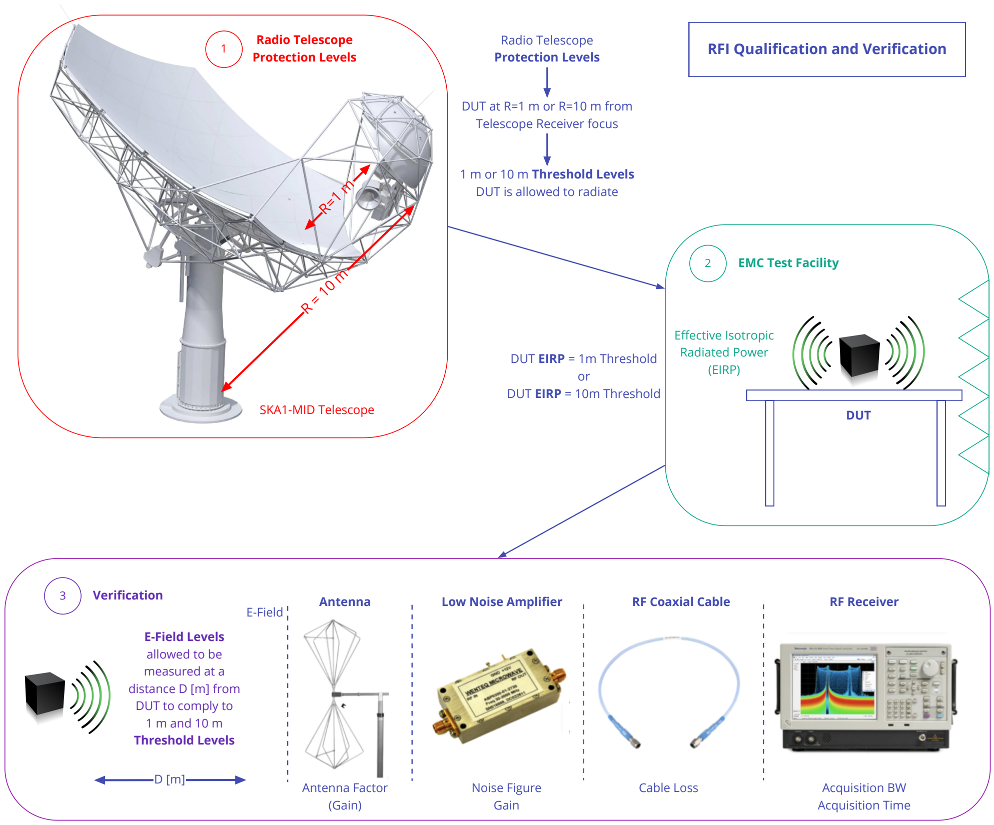

Figure 3: Schematic for the *RFI Qualification and Verification* of the *SKA Protection Levels* through measurements against the *SKA Threshold Levels*. In this example the DUT is located either at R=1 m or R=10 m from the telescope receiver.

The *power emissions threshold level* for a device at a distance R [m] from the telescope receiver is the maximum effective isotropic radiated power (EIRP) level in a RBW channel width [dBm@RBW] that can be radiated as given in Eq. (3). Note that, as in RA.769, this definition considers that the RFI enters the SKA receiver though a 0 dBi sidelobe gain.

$$\mathrm{EIRP_{threshold}[dBm@RBW]} = \mathrm{PSD_{protection\ level}\ [dBm/Hz]} + 10\log_{10}\left(\mathrm{RBW_{protection\ level}}\right) + \mathrm{FSPL\ [dB]} \quad (3)$$

In Eq. (3) $\mathrm{PSD_{protection\ level}}$ is the *SKA protection levels* [dBm/Hz] and FSPL is the Free Space Path Loss in [dB] for R=1 m or R=10 m, or Propagation Modelling and Terrain Loss in [dB] for distances where R > 10 m. The free space path loss (FSPL) equation given by:

$$\mathrm{FSPL} = 10\log_{10}\left(\frac{\lambda}{4\pi R}\right)^2 \quad (4)$$

where λ is the wavelength in [m] and R is the distance between the DUT and telescope receiver in [m]. For cases where the distance R > 10 m, the FSPL is replaced by a Propagation Model that considers terrain blockage, diffraction and atmospheric absorption such as described in Recommendation ITU-R P.452-16 [RD18] and ITU-R P.1546-4 [RD22].

Occasionally it may be required to obtain the emission threshold level in terms of electric field [dBuV/m@RBW] so that it can be directly compared to radiated emissions measurements in an anechoic chamber or an open test site. The *E-field threshold level* has a dependency with the distance D [m] from the device being measured to the measuring antenna, and is calculated considering the threshold power $EIRP_{threshold}$[dBm@RBW]:

$$E_{threshold}[\text{dBuV/m@RBW}] = EIRP_{threshold}\,[\text{dBm@RBW}] - 20\log_{10}(D\,[\text{m}]) + 104.8\,[\text{dB}] \quad (5)$$

5 RFI/EMC Requirements

As is the case for all commercial products, electrical or electronic equipment that forms part of SKA telescopes must adhere to its applicable EMC regulations set out by national and international governing bodies. These generic or product (family) standards are designed to ensure that equipment will function as designed in its intended environment while not causing interference to other equipment co-located within the same environment. These regulations protect the environment, electromagnetic spectrum and ensure safety of the personnel using the equipment. Section 5.1 presents the general EMC requirements for the SKA with a description of different product and generic standards that can be applicable to SKA products. All SKA equipment must comply with appropriate established international (or national equivalent) standards on electromagnetic susceptibility.

While compliance to international and national standards is the basic EMC requirement for any SKA product, the extreme sensitivity of the SKA receivers to RFI dictates the need for a particular radiated emission and self-induced RFI requirements. These requirements are based on the *SKA protection levels* as defined in Section 4 (derived from the Recommendation ITU-R 769-2). The design of the SKA has considered RFI mitigation as one of its main drivers, providing shielded buildings and areas where equipment adhering to emissions levels dictated by international standards can be located without further mitigation. For equipment outside of those shielded areas, mitigation of the radiated emissions or additional shielding will be needed in most of the cases.

Figure 4 depicts the decision tree to identify the appropriate EMC requirements for an SKA product. All products must meet the international EMC standards irrespective where it is going to be located. In special cases, there might be exceptions which must be agreed with the SKAO and properly documented in the EMC Control Plan (EMCCP) of the product. This standard focuses only on Electromagnetic Compatibility. However, EMC compliance shall not overlook the safety aspects for a product, especially when it comes to electrical installations and metallic enclosures to avoid electric shock. SKA safety requirements and applicable standards are defined in [RD8] and [RD9].

5.1 Product EMC Requirements

ID	Description	Allocation	Verification
EMC-REQ01	All SKA equipment shall be compliant to an applicable EMC product (family) standard for emissions and immunity. If a product (family) standard does not exist for a particular equipment, it shall comply to IEC 61000-6-3 for emissions and IEC 61000-6-2 for immunity (or equivalent). For products in the scope of EN 61000-3-2, EN61000-3-3, EN 61000-3-11 or EN 61000-3-12 the requirements of those standards also apply. For radiated emissions, the *SKA protection levels* in Section 5.2.1 supersedes product or generic requirements.	LFAA, SADT, CSP, SDP, TM, INFRA, DSH	Inspection / Test Reports

Note1: *For radiated emissions, the SKA protection levels in Section 5.2.1 supersedes product or generic requirements.*

Note 2: *The radiated emissions standard applicable to a product is determined by the RFI/EMC Requirements decision tree in Figure 4. Examples of applications of generic or product(family) standards are found in Appendix B.*

Note 3: *Radiated immunity tests are not applicable to SKA products such as receivers or signal chain components up to the digitizer.*

Note 4: *Although the SKAO sites can be considered as industrial, COTS equipment should be qualified to stricter residential emissions levels where possible*

Note 5: *SKA sites will be considered as industrial environments except for radiated emissions requirements.*

Note 6: *A non-exhaustive list of commercial and military EMC standards is provided as guideline in Appendix E.*

Note 7: *With regards to building/structures, where applicable, it is expected that the designer or owner considers lightning strike protection (i.e., IEC 62305-4) and ESD control measures (i.e., EN 61340-5-1) to avoid damage to SKAO equipment within the facility.*

5.2 SKA RFI/EMC Requirements

All SKA equipment located on the telescope sites shall meet the radiated emissions requirements in Section 5.2.1. Equipment or components that forms part of the telescope signal chain shall furthermore comply to the self-induced RFI requirements in Section 5.2.2.

5.2.1 Radiated Emissions

ID	Description	Allocation	Verification
EMC-REQ02	Components of the SKA-LOW and SKA-MID telescope shall generate less RFI at the first LNA input of any SKA telescope receiver than the SKA protection levels defined in Section 4. For equipment located inside SKA provided shielded facilities (see notes) compliance to international EMC standards, as per the decision tree in Figure 3, is deemed sufficient. The verification of equipment located outside SKA provided shielded facilities shall be achieved through a combination of analysis and testing, according to the procedures described in [RD12], to comply to the SKA protection levels. The chosen verification method will depend on the product and its intended installation location, this shall be described in the product EMCCP. To assist in the derivation of the radiated emissions thresholds for a product the SKAO has created the web-based EMC thresholds application tool [RD21] based on the procedure described in [RD12].	LFAA, SADT, CSP, TM, INFRA, DSH	Test

Note 1: *Designers are urged to always try to deliver better performance than the levels given in Section 4.3 wherever practicable.*

Note 2: *The SKA emission thresholds levels, as defined in Section 4.4, can be met in a given situation either by:*

1. *positioning emitting devices at a sufficient distance*
2. *by adding shielding, or*
3. *a combination of both.*

Note 3: *SKA provided shielded facilities include, but are not limited to, the Central Processing Facilities (CPF) and Remote Processing Facilities (RPF). A shielded enclosure not included in a contract is considered an SKA provided shielded facility, i.e. shielded cabinets or DISH shielded pedestal.*

<u>Note 4:</u> Products that have higher clock frequencies than frequency ranges covered by commercial standards shall be tested up to 25.5 GHz for information on the real emissions in those frequencies. In the case where no test information is available, the higher limit in the commercial standards will be extended up to 25.5 GHz for analysis purposes.

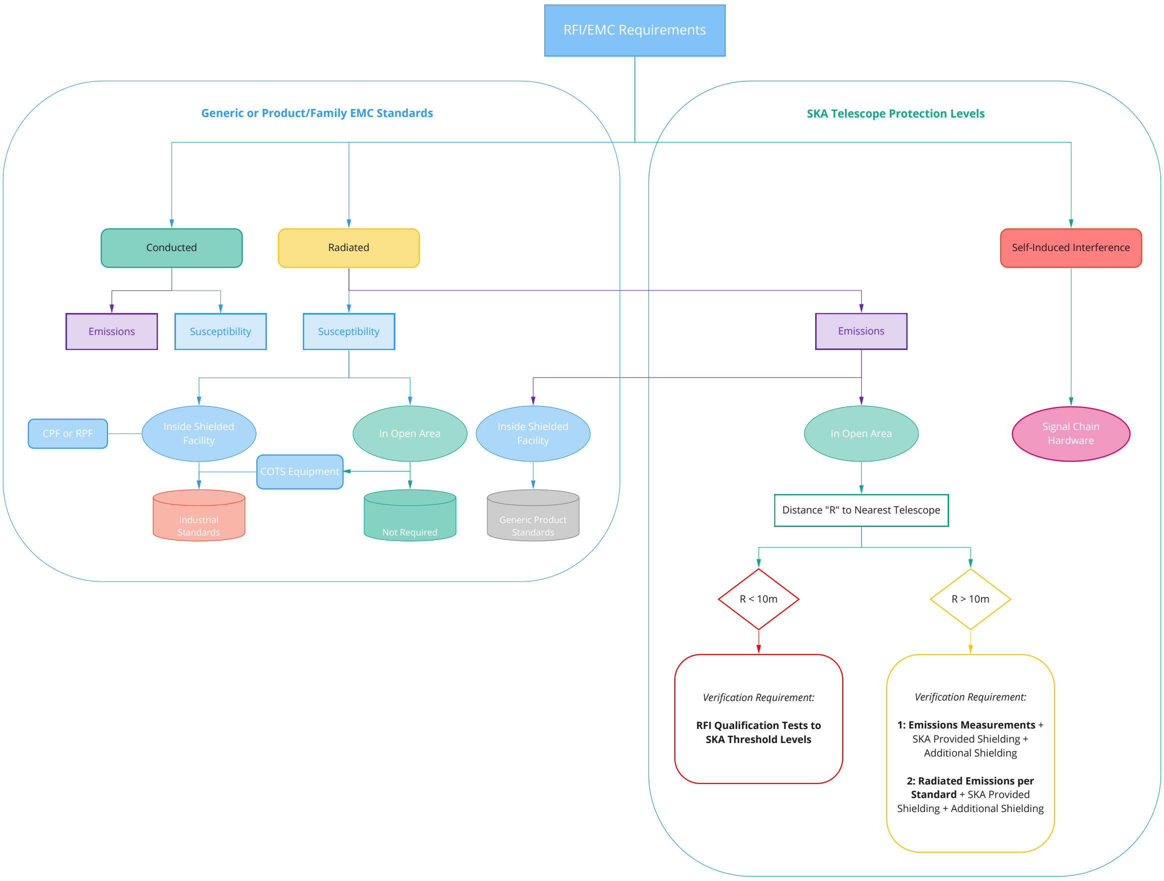

Figure 4: The SKA RFI/EMC Requirements includes (left) Generic or Product EMC Standards; and/or (right) SKA Protection Levels depending on the equipment type and location.

5.2.2 Self-Induced RFI

ID	Description	Allocation	Verification
EMC-REQ03	Self-induced RFI of components included in the signal chain of the telescopes, which is within the telescope's operating frequency bands, shall be below the SKA protection levels defined at the input of the receiver. This requirement is applicable to equipment directly involved in the signal chain of the telescopes (receiver, digitizer and correlator). The applicable threshold shall be derived according to the equipment under test and specified in the EMCCP. Verification of the requirement shall be through connection of equipment to necessary simulators/emulators (simulating normal operating conditions) and be allowed to run for at least 2000 seconds. The analogue or digital output shall be recorded and post processed to show compliance with the requirement at the receiver point.	LFAA, CSP, DSH	Test

6 EMC Control and Verification Methods

EMC and RFI control must be approached as an integral part of the equipment/product development and production cycle. This section describes the *EMC Control Plan* and *EMC Compliance Report* as the main EMC deliverables for any SKA product for which this standard applies. It also describes the *EMC Controls* to be used by SKAO regarding site access and the non-compliances reporting and resolving process.

6.1 EMC Control Plan

Formal consideration of EMC is required within the SKA project to ensure that all equipment is electromagnetically compatible with itself and with all other systems in operation in the observatory (receivers and observing systems, power, data transfer, communications, etc.). The system level EMC Control Plan for the SKA telescope is described in [RD14] where more detail about the EMC control process can be found also applicable to product level. A product EMC Control Plan (EMCCP) shall be submitted by the contractor responsible for the product design and/or manufacture to be approved by the SKAO [RD14]. The EMCCP shall contain the appropriate level of detail and complexity to communicate all EMC issues as well as the plan on how these issues will be addressed and mitigated.

The EMCCP is intended to control and monitor the EMC aspects of the development, manufacturing and installation of the product. The SKAO expects a preliminary version of the EMCCP during a tender evaluation process that will be further developed through the life of the product. The EMCCP identifies the entity(s) responsible for accomplishing and documenting the EMC programme, the applicable EMC requirements, the EMC verification programme (including verification methods) and the conditions for EMC compliance of the product. It shall furthermore cover all relevant issues including scope, purpose, and requirements; EMC design; RFI risk analysis; EMC safety analysis; emission limits; verification and 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.

An EMCCP template is provided in Appendix A to assist the manufacturer or contractor in generating their own. Some sections in the template have a short description of what is expected, and other sections are given as titles only. It is understood that a contractor shall decide which sections are applicable depending on the product.

6.2 EMC Compliance Report

The EMC compliance report describes all activities conducted to achieve compliance to the applicable EMC requirements for the product. It shall contain an executive summary with an *EMC compliance matrix* listing the requirements, the level of compliance achieved (fully, partial or non-compliant), the list of non-compliance reports and references to any decisions such as waivers or deviations. It also contains all the information about the tests performed to verify the requirements (test procedures, setup, detailed test results, etc.). Content required to be provided in the EMC test report(s) is discussed in Appendix D.

6.3 EMC Controls

To protect the RFI quietness of the SKA sites, site access processes are implemented by SARAO and CSIRO on the respective sites and are provided in [RD15] and [RD16]. The RFI team of SKAO will follow the same approach for consistency and will act as the communication channel between the site entity and the product responsible in EMC/RFI matters.

Any equipment to be installed outside of an SKA shielded facility shall have an RFI permit or Certificate of Compliance (CoC) to be allowed on the SKA sites. An RFI permit will typically be issued by SKAO (or site entities) after an *EMC Compliance Report* is accepted (including laboratory acceptance and/or factory acceptance tests for production lines have been concluded). RFI Permits can be issued by SKAO (in coordination with site entities) for equipment that do not fully comply to the SKA EMC/EMI Standards, especially where the equipment will only be used on the site for a limited period. The RFI Permit will have a fixed duration of validity. Equipment required to be installed permanently on site will be issued with a CoC on successful completion of site acceptance tests (SAT) performed by SKAO. An RFI Permit or CoC will indicate which areas of site the RFI Permit or CoC has been issued for. Contractors must comply with the terms and conditions defined in these Permits and CoCs. If during the usage of the product/equipment, or during post-installation tests, the requirements for a Permit or CoC were not met, a Non-Compliance Notice or Non-Compliance Report (NCR) will be issued and corrective actions will have to be conducted to obtain a valid Permit or CoC.

6.4 Non-Compliance Treatment

After approval of the initial EMCCP, it is anticipated that the programme defined in it will be managed and operated by the product responsible, with routine SKAO oversight via scheduled reviews. However, the design and development and manufacturing process will occasionally result in issues with equipment or systems that exhibit some level of non-compliance with the applicable requirements, such events will be classified as a Non-Compliance Report (NCR) and will follow the resolution process defined in [RD17].

NCRs are considered of major importance for EMC management. The NCRs process allows for early detection of issues and the appropriate treatment for their correction. As described in [RD17], NCRs will be assessed for criticality (minor/major) and major NCRs will be analysed by a Non-compliance Review Board (NRB) where SKAO will participate with the contractor. In NRBs, SKAO will have the final decision on the disposition of the issue. The resolution of NCRs will feedback information for necessary modifications and corrective actions to the production process. Each contractor will maintain a NCR logbook with all the minor/major NCRs that will be included in the final compliance report of the product.

As part of the normal process of NCRs resolution, waivers or deviations can be granted by SKAO.

7 Qualifying Telescope Protection Levels

The qualification of equipment to the *SKA protection levels* is not a trivial exercise. Not only due to the extremely low *emission thresholds levels* resulting from the *SKA protection levels*, but also because the *SKA protection levels* are defined with variable RBWs as a function of the observing frequency. Commercial and military standards have measurement RBWs that are defined as a few step values in all test frequencies.

This section provides a summary of the detail considerations needed to verify *SKA protection levels* (Section 4.3) by applying *SKA threshold levels* (Section 4.4) to RFI measurement data is given in [RD12]. The schematic for the *RFI Qualification and Verification* of the *SKA protection levels* through measurements against the *SKA threshold levels* are given in Figure 3. The radiated emissions limits defined by these *SKA threshold levels*, especially for equipment that will be located at distances in the order of R=1 m (equipment on the receiver indexer or RI in the case of SKA-MID; or smart-box in the case of SKA-LOW) or R=10 m (equipment in the pedestal shielded compartment or PSC for SKA-MID) from the SKA receiver, are much more strict than limits defined in commercial or military EMC standards. An example of how the *SKA protection levels* compare to commercial/military EMC standards are given in Appendix C.

To be able to verify the very stringent *SKA protection levels*, specific requirements with regard to the testing facility and instrumentation should be considered (Section 7.1.1). Two approaches, as depicted in Figure 5 and discussed in detail in [RD12], can be considered when applying telescope protection levels to measurement data:

1. Translate and propagate the SKA EMC Standards *protection levels* from $PSD_{telescope}$ to an equivalent power ($EIRP_{thresh}$) or E-field$_{thresh}$ [dBuV/m] *threshold level* for a device located at a distance R [m] from the telescope, as measured at a distance D [m] from the DUT. The channel integrated power or E-field$_{meas}$ (to equivalent *Continuum* bandwidths of 1% of f_c) is compared to the bandwidth compensated *Continuum* threshold, while the measured power or E-field$_{meas}$ is compared original *Spectral Line* threshold level in either [dBm] or [dBuV/m].

2. Propagate the measured PSD_{meas} to the LNA input of the telescope receiver and compare the measured levels directly to the bandwidth compensated *Spectral Line* protection levels in PSD_{thresh} [dBm/Hz]. The channel integrated measurements (to equivalent *Continuum* bandwidths of 1% of f_c) is compared to the original *Continuum* protection levels in PSD_{thresh} [dBm/Hz].

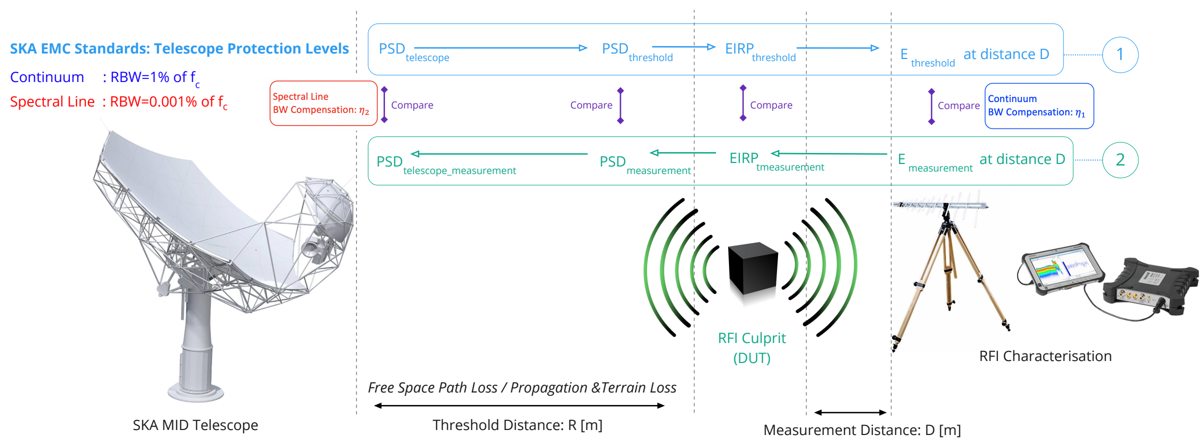

Figure 5: Two approaches to applying telescope protection levels to measurement data of a DUT located at a distance R [m] from the telescope and characterised at a distance D [m] from the DUT.

7.1.1 Testing Facilities Requirements

The radiated emission limits defined by *SKA protection levels* are much more strict than limits defined in commercial or military EMC standards (example is given in Appendix C). This implies that commercial EMC test facilities might not be suitably equipped to successfully qualify equipment to the *SKA protection levels*. To determine the suitability of commercial EMC measurement and test facilities for SKA RFI Qualification, the following are the minimum requirements that need to be considered:

7.1.1.1 Anechoic Chamber Requirements

The following are required when considering a commercial EMC facility for SKA RFI qualification:

1. Chamber should be sufficiently shielded from environmental RFI between the frequency range 50 MHz and 25.5 GHz.
2. Chamber size should be sufficient to house equipment under test (EUT) with a 2 m buffer between antennas and the RF absorbers. Antennas will be located 1 m from EUT to ensure sensitivity to verify *SKA threshold levels*.
3. Line Impedance Stabilisation Network (LISN) required for isolated chamber power. Single and three phase power if required.
4. Ground plane big enough to support all equipment with representative cable lengths is required.
5. Separate shielded room for instrument shielding is a requirement.

7.1.1.2 Reverberation Chamber Requirements

The following are required when considering a reverberation chamber test method:

1. The reverberation chamber is calibrated according to IEC 61000-4-21 [RD20].
2. The E-field variation in the working volume is below the IEC sigma limit for chamber field uniformity validation.
3. Calibrated chamber loss, antenna validation factor and chamber calibration factor should be available and in the correct format to be used in the post processing scripts and to include in reports.
4. Equipment should be tested in the reverberation chamber working volume which is defined as the region that is $\lambda/4$ from the walls and any metallic structures such as stirrers at the lowest usable frequency.

7.1.1.3 Instrument Requirements

The following are required for instruments used during SKA RFI qualification:

1. Calibrated RF receiver that can capture and store raw voltage IQ (in-phase quadrature) data, to be post processed (in real time or post processed at any future stage) in various resolution bandwidths (RBWs). This includes a personal computer (PC) that will support automated instrument control software and post processing scripts, as well as be equipped with sufficient external storage. Time and frequency domain data should be reconstructed from the IQ data. Algorithms to use in the post processing of the data shall be agrees with SKAO and documented in the test procedure / report.
2. Pulsed RFI thresholds up to 2 GHz should be verified using an instrument with sufficient dynamic range, and a real time acquisition bandwidth no less than 500 MHz.
3. A suite of RF antennas (with manufacturer supplied 1 m antenna factor and gain calibration files) that will cover the frequency range between 50 MHz and 25.5 GHz.

4. Low Noise Amplifiers (LNAs) - with noise figures less than NF < 1.4 dB - that will cover the frequency range between 50 MHz and 25.5 GHz.
5. All calibration files (including antenna gain, antenna factor, LNA gain, all cable losses or external attenuators) should be available and in the correct format to be used in the post processing scripts and to include in reports.
6. Vector Network Analyser (VNA) measurements to determine the loss of the exact radio frequency (RF) cables planned to be used outside and inside the anechoic chamber should be made before the RFI Qualification campaign. This should make provision for cables connecting LNAs as well. Cables should be labelled accordingly.
7. LNA gains should be measured, with the same power sources (linear supplies) that will be used in the final test configuration, using a VNA before the RFI Qualification campaign. Temperature stability should be characterised.
8. Antenna gains and antenna factors for the suite of antennas that will be used in the final configuration should, if not available from the manufacturer, be measured for a distance of 1 m.
9. Common mode measurements on cables should be available and done to compare to site installation acceptance test procedure (ATP).

7.1.1.4 Average Noise Subtraction

To increase the sensitivity of the setup as much as possible, the average noise power of the measurement in frequency domain shall be estimated and subtracted from the measurement. This methodology is based on the radiometer equation and is described in detail in [RD19].

Background RFI measurements of the facility, with sufficient sensitivity and acquisition time, should be made to verify a clean spectrum from 50 MHz to 18 GHz with a 7σ confidence (where σ is the standard deviation of the noise) compared to *SKA Spectral Line threshold levels*. These measurements should be done using the same RF receiver, cables, LNAs and antenna suites, as specified above.

7.2 Shielding Measurements

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. 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.

Two standards for verifying shielding effectiveness, IEEE 299-2006 [RD10] and IEEE 299.1-2013 [RD11], forms the basis for the SKA shielding effectiveness standard. The first applies to enclosures greater than 2 m in smallest dimension, as would apply for Central Processing Facilities (CPFs) or Remote Processing Facilities (RPFs) shielding, and the second applies to enclosures with the smallest dimension between 0.1 and 2 m.

Standardised enclosures, used to enclose items whose emissions exceed the SKA protection levels, 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 during these qualification tests. 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 protection levels* 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.

7.2.1 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 shielding 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 large SKA shielded facilities or site buildings should be designed conservatively. These 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.

7.2.2 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).

Appendix A EMC Control Plan Template

A.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.

A.2 Example EMCCP Structure

A.2.1 Overview

A.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.

A.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.

A.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.

A.2.1.4 Terminology

List acronyms, glossary explanations, etc.

A.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.

A.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.

A.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.

A.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.

A.2.3.3 Documentation to be Provided
List and describe.

A.2.3.4 Sub-Contractor & Supplier Coordination
Discuss plans for defining responsibilities and coordinating the EMC program with sub-contractors & suppliers.

A.2.4 Technical Program
A.2.4.1 EMC Requirements
Identify specific EMC requirements.

A.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.

A.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.

A.2.4.4 Reviews
Detail on EMC design reviews and proposed scheduling.

A.2.4.5 EMI Safety Analysis
Address appropriate provisions for review of safety related issues.

A.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.

A.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 their EMC Program, establishing requirements, participating in reviews, verification, and approval requirements for documents such as Control Plans, Test Procedure and Test Reports, etc.

A.2.5 Control Plan Revisions
Statement concerning criteria for revising the EMCCP in phases of ongoing development.

Appendix B Applications of Generic or Product EMC Standards

B.1 Example 1: IT Equipment

To demonstrate the process of applying generic or product EMC standards, IT equipment is used as an example. In this scenario, the equipment is intended to be used inside an SKA *shielded facility* and the contractor is expected to identify the applicable EMC standards.

The contractor shall go through the following process:

1. Search for the applicable standard on the national standards body website. In case the applicable standard is not found, search for the generic or product family standard. The national standards usually refer to international standards with a slightly different title and different publication date. In this example the product family standard for IT equipment is EN 55032 for emissions and refers to the international standard CISPR 32. The immunity tests for IT equipment are specified in EN 55035 / CISPR 35 (product conformity to EN 55XXX implies compliance to equivalent CISPR XX).
2. EN 55032 (*generic*) refers to basic EMC publications which define test methods. This is similar to IEC 61000-4-2 for electrostatic discharge (ESD) and IEC 61000-4-3 for radiated immunity, etc. The contractor must ensure that an accredited laboratory tests the equipment to the correct limits and levels. The SKA recommends IT equipment to be tested for Class B emissions where possible. To obtain more detail about the product, the contractor may request the EMC facility to test to industrial levels.
3. The contractor must request an EMC compliance report from the test laboratory when the equipment has been assessed and passed all the tests.

The CISPR 32 emission requirements are sufficient in the case where the equipment will be in the *SKA provided shielded facility* that provides additional shielding to reduce the emissions to meet the *SKA telescope protection levels*. The contractor is responsible to identify the applicable safety standards and ensure that the product complies. For the IT equipment in this example, it is the IEC 62368-1: “Audio/video, information and communication technology equipment –Part 1: Safety requirements”.

Appendix C SKA Threshold Levels vs. Commercial/Military EMC Standards

A non-exhaustive list of commercial and military EMC standards are given in Appendix E. Consider the example of radiated emission limits from a commercial (in this case industrial) EMC standard, CISPR 22 Class A, as well as a military EMC standard MIL-STD-461G (Air Force) given in Table 1 and Table 2, compared at a frequency of 850 MHz to the requirements of the SKA EMC Standards in Figure 6.

Table 1: MIL-STD-461G radiated emission limits in E-Field [dBuV/m] for Army and Air Force

MIL-STD-461G Radiated Emission Limits				
Frequency Range [MHz]	**Army: E-Field Max. Levels [dBuV/m]**	**Air Force: E-Field Max. Levels [dBuV/m]**	**Measurement Distance [m]**	**Measurement Bandwidth [kHz]**
10 – 100 MHz	24	44	1 m	100 kHz
100 MHz – 1 GHz	$20\log_{10}$(f [GHz]) + 44	$20\log_{10}$(f [GHz]) + 64	1 m	100 kHz
1 GHz – 18 GHz	$20\log_{10}$(f [GHz]) + 44	$20\log_{10}$(f [GHz]) + 64	1 m	1000 kHz
>18 GHz	69	89	1 m	1000 kHz

Table 2: CISPR 22 Class A and Class B radiated emission limits in E-Field [dBuV/m]

CISPR 22 Class A and Class B Radiated Emission Limits				
Frequency Range [MHz]	**Class A: E-Field Max. Levels [dBuV/m]**	**Class B: E-Field Max. Levels [dBuV/m]**	**Measurement Distance [m]**	**Measurement Bandwidth [kHz]**
30 – 230 MHz	40	30	10 m	120 kHz
230 MHz – 1 GHz	47	37	10 m	120 kHz
1 – 3 GHz	76	70	3 m	1000 kHz
3 – 6 GHz	80	74	3 m	1000 kHz

SKA EMC Standard Telescope Protection Levels: E-Field Thresholds
CISPR 22 Class A:

Table 3: Example details for Commercial/Military EMC Standards.

	CISPR 22 Class A		**MIL-STD-461G**	
Example Frequency	f_c = 850 MHz		f_c = 850 MHz	
DUT Distance from Telescope	R = 10 m		R = 10 m	
Standard Measurement Distance	d_{std} = 10 m	f < 1 GHz	d_{std} = 1 m	f < 1 GHz
Standard Resolution Bandwidth	RBW_{std} = 120 kHz	f < 1 GHz	RBW_{std} = 100 kHz	f < 1 GHz
Standard Radiated Emissions Limit	E_{std} = 47 dBuV/m		E_{std} = 62.6 dBuV/m	

The wavelength at 850 MHz is equal to $\lambda = \frac{c}{f_c} = \frac{2.99796\times10^8}{850\times10^6} = 0.3527$ [m].

In this example, the threshold levels are compared to a measurement distance D=1 m from the DUT. The adjusted standards limit that will be measured at the distance D is therefore:

$$\mathrm{E_{adj}} = \mathrm{E_{std}} + 20\log_{10}\left(\frac{\mathrm{d_{std}}}{\mathrm{D}}\right) = 67\ [\frac{\mathrm{dBuV}}{\mathrm{m}}].$$

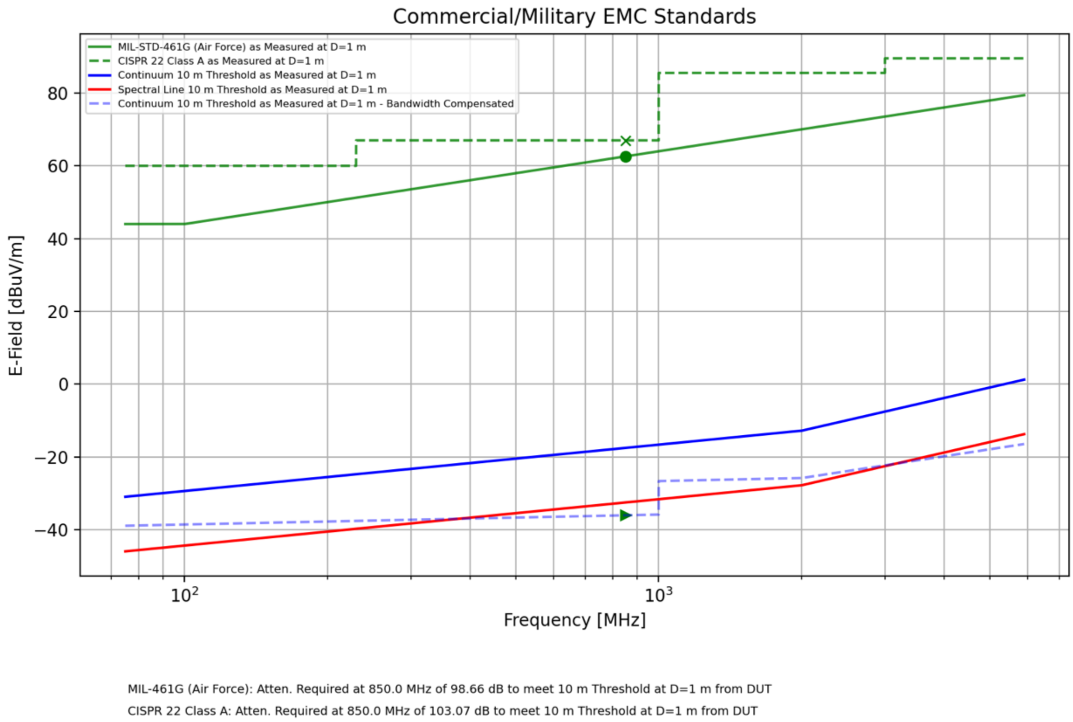

Figure 6: Example of commercial/industrial (CISPR 22 Class A) and military (MIL-461G Air Force) EMC radiated emission limits compared to the SKA EMC Standards *10 m threshold* as measured at a distance D=1 m from DUT.

The *Continuum* telescope protection level at 850 MHz is given by:

$$\text{PSD}_{\text{tel\_cont}} = -17.2708\ \log_{10}(850) - 192.0714 = -242.7\ [\frac{\text{dBm}}{\text{Hz}}]$$

The *Spectral Line* telescope protection level at 850 MHz is therefore:

$$\text{PSD}_{\text{tel\_spec}}[\text{dBm/Hz}] = \text{PSD}_{\text{tel\_cont}}\ [\text{dBm/Hz}] + 15\ \text{dB} = -227.7\ [\frac{\text{dBm}}{\text{Hz}}]$$

The FSPL over R=10 m at 850 MHz is given by:

$$\text{FSPL} = 10\log_{10}\left(\frac{\lambda}{4\pi R}\right)^2 = -51\ \text{dB}$$

The SKA EMC Standards 10 m *thresholds* at 850 MHz is therefore $\text{PSD}_{\text{thresh\_cont}}$ = -191.7 [dBm/Hz] and $\text{PSD}_{\text{thresh\_spec}}$ = -176.7 [dBm/Hz].

The maximum allowed EIRP to be emitted in [dBm] by the culprit:

$$\text{EIRP}_{\text{thresh\_cont}} = \text{PSD}_{\text{thresh\_cont}} + 10\log_{10}(1\% \cdot f_c) = -191.7 + 10\log_{10}(10^{-2} \cdot 850 \times 10^6) = -122.4\ [\text{dBm}]$$

$$\text{EIRP}_{\text{thresh\_spec}} = \text{PSD}_{\text{thresh\_spec}} + 10\log_{10}(0.001\% \cdot f_c) = -176.7 + 10\log_{10}(10^{-5} \cdot 850 \times 10^6) = -137.4\ [\text{dBm}]$$

Finally, the maximum allowed E-field that can be measured in [dBuV/m] at a distance D=1 [m] from the DUT is given by:

$$\text{E-Field}_{\text{thresh\_cont}} = -122.4 - 20\log_{10}(1) + 104.8 = -17.6\ [\text{dBuV/m}]$$

$$\text{E-Field}_{\text{thresh\_spec}} = -137.4 - 20\log_{10}(1) + 104.8 = -32.6\ [\text{dBuV/m}]$$

The *Continuum* threshold level is bandwidth compensated η_1:

$$\text{E-Field}_{\text{BW comp thresh\_cont}} = \text{E-Field}_{\text{thresh\_cont}} \times \left(\frac{\Delta f_{\text{meas}}}{\Delta f_{\text{thresh}}}\right) = -17.6 + 10\log_{10}\left(\frac{120\times10^{3}}{10^{-2}\cdot850\times10^{6}}\right) = -36.1 \text{ [dBuV/m]}$$

The attenuation required for the CISPR 22 Class A DUT located R=10 m from the telescope receiver and emitting at 850 MHz is 67 – (– 36.1) = **103.1 dB**. A similar process can be followed for a MIL-STD-461G (Air Force) DUT located R=10 m from the telescope receiver and emitting at 850 MHz. The attenuation required for the MIL-STD-461G DUT will be **98.7 dB**.

Appendix D EMC Test Reports

An EMC test/compliance report is expected to state the EMC specification to which the equipment is tested to and encompass the following sections information listed in Table 4 (similar approach to the guidelines given in CISPR 32).

Table 4: SKA minimum requirements for EMC test reports

No.	Information	Remarks
1	Name and address of the test facility	
2	Names and titles of persons authorizing the report	
3	EUT description and information	e.g., 230 VAC/50Hz, EUT highest clock frequency, 1.6 GHz, etc. In addition, include the COTS equipment name, model number, serial number, and manufacturer. EUT power input voltages and frequencies must be recorded for each test.
4	EUT software / firmware version	
5	Prototype or production version of the EUT	
6	Function of the EUT and its intended environment	
7	State the applicable product and basic EMC standards	The standards must include publication dates and emissions limits and/or immunity test levels
8	Deviations from the Basic EMC standards	Provide the rational for the deviation
9	Applicability of the test / tests not performed	The decision and justification not to perform a measurement or test shall be documented.
10	EUT settings and operating test modes must be defined.	Test modes can be implemented to maximise EM emissions. This may be different from normal operation.
11	Document immunity test level for each immunity test and emissions compliance class and group	For instance, equipment certified to CISPR 11 / EN 55011 are separated into groups. For emissions, Class A/B
12	State immunity pass/fail criteria	
13	Record environmental conditions as required by the relevant Basic EMC standards	e.g., ESD test must be performed under specific conditions.
14	Compliance summary statement	Compliance of the EUT or system with each test. D
15	Test data that support the compliance determination for each test performed	Include correct units of measurement
16	EUT configuration or test setup during the test, including a block diagram Block diagram of the EUT or system and all peripherals and auxiliary equipment used.	Documentation shall clearly show connections of all support equipment to exercise the EUT.
17	Test equipment used, including calibration or maintenance dates	
18	System check/verification tests must be performed prior to testing.	e.g., ESD, surge, radiated immunity uniform field area, etc.
19	Test parameters used	e.g., frequencies, phase angles, type of modulation, dwell time, etc.
20	ESD test points	Photograph or drawing showing the exact ESD test points with discharge method (air or contact) identified.
21	Measured conducted and radiated emissions	Tabular data of at least the six highest emissions for each test shall be included. Add a column for *margin* with respect to the specified limit.
22	The methods used to reduce the impact of ambients	Especially when testing in an Open Area Test Site (OATS)
23	Measured harmonics and flicker emissions	
24	EUT or system modifications	Describe EUT or system modifications needed to pass any of the emissions or immunity tests. A statement that they will all be incorporated into production units.
25	The order in which tests were performed	
26	Effects on the EUT or system that were observed during or after the application of the test disturbances, and the duration for which these effects persisted	A comment can be added after each test, i.e., “EUT operated as intended, no malfunction observed.”
27	Photographs of each test setup including the EUT or system and all peripherals and auxiliary equipment used.	
28	Measurement uncertainty of each test, where applicable.	This is very important for radiated emissions, i.e., ± 4.9 dB.
29	State the port under test and which line.	e.g., AC power line, neutral, live or PE.

30	For emissions, state the type of detector used, e.g. Average, Quasi-Peak	
31	The compliance report must have a statement of conformity or non-compliance	

Appendix E Commercial/Military EMC Standards (Non-Exhaustive)

Type of standard	Publication / EN	Title
Basic standards (Test methods)	IEC 61000-4-2	Electromagnetic compatibility (EMC) - Part 4-2: Testing and measurement techniques - Electrostatic discharge immunity test
	IEC 61000-4-3	Electromagnetic compatibility (EMC) - Part 4-3: Testing and measurement techniques - Radiated, radio-frequency, electromagnetic field immunity test
	IEC 61000-4-4	Electromagnetic compatibility (EMC) - Part 4-4: Testing and measurement techniques - Electrical fast transient/burst immunity test
	IEC 61000-4-5	Electromagnetic compatibility (EMC) - Part 4-5: Testing and measurement techniques - Surge immunity test
	IEC 61000-4-6	Electromagnetic compatibility (EMC) - Part 4-6: Testing and measurement techniques - Immunity to conducted disturbances, induced by radio-frequency fields
	IEC 61000-4-8	Electromagnetic compatibility (EMC) - Part 4-8: Testing and measurement techniques - Power frequency
	IEC 61000-4-11	Electromagnetic compatibility (EMC) - Part 4-11: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests
	IEC 61000-4-16	Electromagnetic compatibility (EMC) - Part 4-16: Testing and measurement techniques - Test for immunity to conducted, common mode disturbances in the frequency range 0 Hz to 150 kHz
Generic standards	IEC 61000-6-1	Electromagnetic compatibility (EMC) - Part 6-1: Generic standards - Immunity for residential, commercial, and light-industrial environments
	IEC 61000-6-2	Electromagnetic compatibility (EMC) - Part 6-2: Generic standards - Immunity for industrial environments
	IEC 61000-6-3	Electromagnetic compatibility (EMC) - Part 6-3: Generic standards - Emission standard for residential, commercial and light-industrial environments
	IEC 61000-6-4	Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments
	IEC 61000-6-5	Electromagnetic compatibility (EMC) - Part 6-5: Generic standards - Immunity for power station and substation environments
Product standards	CISPR 11 /EN55011	Industrial, scientific and medical equipment - Radio-frequency disturbance characteristics - Limits and methods of measurement
	CISPR 12 / EN 55012	Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of off-board receivers
	CISPR 14-1 / EN 55014-1	Electromagnetic compatibility - Requirements for household appliances, electric tools and similar apparatus - Part 1: Emission
	CISPR 14-2 / EN 55014-2	Electromagnetic compatibility - Requirements for household appliances, electric tools and similar apparatus - Part 2: Immunity - Product family standard
	CISPR 15 / EN 55015	Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment
	CISPR 32 / EN 55032	Electromagnetic compatibility of multimedia equipment – Emission Requirements
	CISPR 35 / EN 55035	Electromagnetic compatibility of multimedia equipment - Immunity requirements
	CISPR 25 / EN 55025	Vehicles, boats and internal combustion engines - Radio disturbance characteristics - Limits and methods of measurement for the protection of on-board receivers
	IEC 60945	Maritime navigation and radiocommunication equipment and systems - General requirements - Methods of testing and required test results
	IEC 61326-1	Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 1: General requirements
	IEC 62041	Safety of transformers, reactors, power supply units and combinations thereof - EMC requirements

Military / Defence EMC	MIL-STD-461G	DEPARTMENT OF DEFENSE INTERFACE STANDARD REQUIREMENTS FOR THE CONTROL OF ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS OF SUBSYSTEMS AND EQUIPMENT
	Defence Standard 59-411 Part 3	Electromagnetic Compatibility Part 3 Test Methods and Limits for Equipment and Sub Systems
Recommended-Best Practices	NRS 083-2	ELECTROMAGNETIC COMPATIBILITY (EMC) IN ELECTRICITY UTILITY NETWORKS
Radio equipment	ETSI 301 489-1	ElectroMagnetic Compatibility (EMC) standard for radio equipment and services; Part 1: Common technical requirements; Harmonised Standard for ElectroMagnetic Compatibility