System Electromagnetic Compatibility and Radio Frequency Interference Mitigation Requirements

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R. Selina	Electronics Div., NRAO	2020-11-13

APPROVALS	ORGANIZATION	SIGNATURES
R. Selina, Project Engineer	Electronics Div., NRAO	R Selina Digitally signed by Robert Selina Date: 2020.11.13 13:34:13 -07'00'
T. Kusel, Systems Engineer	PMD, NRAO	Thomas Kusel Digitally signed by Thomas Kusel Date: 2020.11.17 10:14:44 +02'00'
R. Farnsworth, Project Manager	PMD, NRAO	Richard L Farnsworth Digitally signed by Richard L Farnsworth Date: 2020.11.17 14:04:23 -05'00'
M. McKinnon, Project Director	Asst. Director, NM-Operations, NRAO	Mark McKinnon Digitally signed by Mark McKinnon Date: 2020.11.19 14:40:16 -07'00'

RELEASED BY	ORGANIZATION	SIGNATURE
M. McKinnon, Project Director	Asst. Director, NM-Operations, NRAO	Mark McKinnon Digitally signed by Mark McKinnon Date: 2020.11.19 14:40:34 -07'00'

Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2017-10-02	R. Selina	All	Started first draft; used 020.25.00.00.00-0001-SPE-A as a template.
02	2017-10-12	R. Selina	2.1, 3, 4.1	Incorporated feedback from W. Grammer and R. Treacy.
03	2018-05-09	R. Selina	3.1	Updated for consistency with case outlined in SCI0116.
04	2018-09-27	R. Selina	1.3, 2.1, 3.1, 4.	Updated based on review by D. Mertely.
A	2019-07-09	A. Lear	All	Prepared document for approvals & release.
A.01	2019-08-01	R. Selina	Misc.	Minor updates and typographical corrections.
A.02	2020-08-10	R. Selina	1, 1.3, 2, 3.1, 3.2, 4, 5, 6.2	Updated to reflect input from SRR. Struck Section 1.3 from template. Clarified verification considerations. Added EMC refs to MIL-STD-461G. New section on EM immunity requirements, using ALMA-80.05.01.00-001-B-SPE as a template. Language updates to EMC0320, EMC0324, EMC0326, and EMC0327.
A.03	2020-08-12	R. Selina	3.1.1, 3.2	Struck EMC0328, moved associated verification issues to 3.1.1.
A.04	2020-10-15	R. Selina	3.1, 4, 5, 6.1, 6.3, 6.4	Resolving RIDs from SRR. Added EMC0311, 0321, related to emission testing. Updated traceability in Section 4. Updated Verification table with missing requirements. Revised limits in 3.1 to add continuum case (major change). Added comparison to Appendix.
A.05	2020-10-19	R. Selina	2.2, 6.1, 6.3, 6.4	Clarifying emission requirement relationships to total power measurements and the short baseline array. Also clarifying relationship to bandwidth. Added EOP as a reference document.
A.06	2020-10-28	A. Lear	All	Formatting fixes; minor copy edits.
A.07	2020-11-13	R. Selina	3.1, 6	Revised emission thresholds to cover SBA case (about 2dB stricter than rev. A).
B	2020-11-13	A. Lear	All	Prepared PDF for approvals and release.

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1 Introduction

1.1 Purpose

This document presents system-level Electromagnetic Compatibility (EMC) and Radio Frequency Interference (RFI) emission requirements. This specification is a subsection of the Next Generation Very Large Array (ngVLA) System Requirements [AD01], which in turn flow down from the Science Requirements and Stakeholder Requirements.

1.2 Scope

This document is applicable to all equipment, buildings, and infrastructure located at or near the ngVLA antenna sites. All related ngVLA system elements shall be required to comply with this specification.

Off-site buildings, such as the repair center, science center, and data center, are exempted from this specification. This exemption also applies to equipment that reside solely at these off-site operational facilities.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents are applicable to this Technical Specification to the extent specified. In the event of a conflict between the documents referenced herein and the content of this Requirements Specification, the content of the *highest*-level specification (in the requirements flow-down) shall be considered the superseding requirement for design elaboration and verification.

Ref. No.	Document Title	Rev/Doc. No.
AD01	ngVLA System Requirements	020.10.15.10.00-0003-REQ
AD02	Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment	MIL-STD-461G
AD03	International Electrotechnical Commission Standard for Electrostatic Discharge (ESD)	IEC 61000-4-2

2.2 Reference Documents

The following references provide supporting context:

Ref. No.	Document Title	Rev/Doc. No.
RD01	RFI Emission Limits for Equipment at the EVLA Site	EVLA Memo #106. Perley, Brundage, Mertely.
RD02	Attenuation of Radio Frequency Interference by Interferometric Fringe Rotation	EVLA Memo #49. Perley.
RD03	Protection Criteria Used for Radio Astronomical Measurements	ITU-R RA.769-2
RD04	Notes on RFI Emission Levels	VLA/VLBA Interference Memo #34
RD05	A Notional Envelope Observing Program	020.10.15.05.10-0002-REP

3 Emission Requirements

3.1 Radio Frequency Interference Radiated Emission Limits

Parameter	Req. #	Value	Traceability
Spurious Signal Level	EMC0310	Spurious signals generated by the system shall not exceed the equivalent isotropic radiated power limits in Table 1 and Table 2 at a distance of 10m from the nearest receiving element.	SYS2104
Emission Verification Frequencies	EMC0311	Spurious signal emission levels shall be verified by test over a minimum range of 1 GHz up to 12 GHz. Demonstration of EMC above 12 GHz is not required since mitigation at 12 GHz and below is expected to provide a strong indication of performance at higher frequencies. An exception is made for devices that may produce fundamental and harmonic frequencies of LO signals, which shall be tested up to 50 GHz.	SYS2104
Low Frequency Emission	EMC0312	Spurious signal emission levels shall be quantified by test over an extended frequency range of 5 MHz to 1 GHz. While there is no emission threshold within this range, this information shall be collected to inform future system expansion.	SYS2104, SYS5602

The electronics within or near an antenna must be shielded to avoid radio frequency interference (RFI) being received by the Front End electronics, degrading system sensitivity. The tables below are based on the analysis presented in [RD01], updated for the ngVLA use cases and design. The supporting derivations are given in the Appendix, Section 6.3.

Table 1 provides an equivalent isotropic radiated power limit over narrow bandwidths, corresponding to a spectral line observation with a resolution of 0.1km/s. Table 2 provides a second equivalent isotropic radiated power limit applicable to wider bandwidths, equivalent to 0.1% of the observing frequency. Both limits must be respected over their respective bandwidth ratios. Limits for frequencies between the table columns shall be linearly interpolated.

Table 1 – Spectral Line Limits. Allowable radiated power for electronic components, at a distance of 10m from the receiving elements, at 100 m/s spectral resolution.

ν_G (GHz)	1	3	6	10	30	45	90
$\Delta\nu$ (Hz)	333	1000	2000	3333	10000	15000	30000
F_H (dB(W/m²)/$\Delta\nu$)	–190	–176	–167	–161	–145	–139	–128
S_H (dB(W/m²/Hz))	–215	–206	–200	–196	–185	–181	–173
$EIRP_H$ ((dBm @ 10m)/$\Delta\nu$)	–129	–115	–106	–100	–84	–78	–67
PSD_H ((dBm @ 10m)/Hz)	–154	–145	–139	–135	–124	–120	–112

Table 2 – Continuum Limits. Allowable radiated power for electronic components, at a distance of 10m from the receiving elements, at 0.1% spectral resolution.

ν_G (GHz)	1	3	6	10	30	45	90
Δν (MHz)	1	3	6	10	30	45	90
F_H (dB(W/m²)/Δν)	–172	–159	–149	–143	–128	–122	–111
S_H (dB(W/m²/Hz))	–232	–223	–217	–213	–203	–198	–190
$EIRP_H$ ((dBm @ 10m)/Δν)	–111	–98	–89	–82	–67	–61	–50
PSD_H ((dBm @ 10m)/Hz)	–171	–162	–156	–152	–142	–137	–129

The tables are based on unity gain, assuming the RFI enters through a sidelobe of the antenna. F_h is the harmful power flux density level, and $EIRP_h$ is the harmful effective isotropic radiated power. The ratio of the emitting device EIRP to the harmful EIRP ($EIRP_h$) is the shielding required. For example, a device with an EIRP of 1nW (–60dBm) at 3GHz would require at least 55dB of shielding to conform to Table 1.

The tables above assume the radiator is 10 m from the antenna feed. For other distances, the $EIRP_h$ can be calculated as follows:

$$EIRP_h = \frac{4\pi r^2 S F_h}{G}$$

where *r* is the distance in meters, *S* is the device shielding ratio, *G* is equal to 1, and F_h is from Table 1.

For Table 1, the radiated power limit is applicable over a bandwidth that corresponds to a spectral resolution of 100 m/s. This can be calculated as 333 Hz * ν_G, where ν_G is the RF frequency in GHz. This resolution bandwidth is inconvenient for testing, so practical test considerations are discussed in the following subsection. For Table 2, the applicable bandwidth can be calculated as 1 MHz * ν_G.

3.1.1 Verification Considerations

A practical test setup will likely sweep at a fixed channel resolution (i.e., at fixed resolution bandwidth). It is preferable that the swept channel width be narrower than the radiated power bandwidth given in the preceding section. Measured EIRP can then be averaged over multiple channels and scaled by the bandwidth ratio, assuming a noise-like distribution of radiated power within each channel.

E.g., at a resolution bandwidth of 1 kHz, evaluating the performance at 10 GHz, the power in four adjacent 1kHz channels could be summed, and then corrected by bandwidth (3.3kHz/4kHz) to produce an $EIRP_h$ for the device to be compared to Table 1. An example of such a test is given in Table 3.

Table 3 – Example of bandwidth scaling for system verification.

Channel (RBW = 1kHz)	Measured Power (dBm)
9.998–9.999 GHz	–106 dBm
9.999–10.000 GHz	–105 dBm
10.000–10.001 GHz	–107 dBm
10.001–10.002 GHz	–105 dBm

Total Power (RBW = 4kHz)	–99.7 dBm
Corrected Power (RBW = 3.3kHz)	–100.5 dBm (i.e., < –100 dBm, Table 1; Pass)

Should the test system noise floor require a wider resolution bandwidth, the assumption of a noise-like distribution of radiated power will need to be substantiated for the device under test.

When shielded enclosures are employed, independent testing of the device emissions without shielding, and the shielding effectiveness of the enclosure, is permitted. In this scenario, the device may be emission tested with an access panel removed to determine the baseline emission level. The shielding of the enclosure can be determined by placing a calibrated higher-power emitter in the shielded enclosure and determining the attenuation over frequency. The effective EIRP, in dBm, is then the sum of the baseline emission level and the attenuation provided by the enclosure.

3.1.2 Off-Antenna Equipment & Site Building Requirements

Electronics equipment outside the antenna, or located in buildings near the site, are subject to the same emission requirements listed in Section 3, but the distance should be updated to reflect the distance from the building or equipment perimeter to the nearest antenna in the array. E.g., equipment located 1 km from the nearest antenna would have an $EIRP_h$ threshold that is 40dB higher than Table 1 and Table 2 ($10*\log((1000m/10m)^2)= 40dB$).

Shielding requirements for buildings and enclosures shall be based on measured emissions of the housed equipment, or representative analogs for that equipment.

3.2 Electrically Coupled Coherent Signal Limits

Local oscillator signals and harmonics which are coherently distributed across the array, and therefore common amongst array elements, are subject to thresholds on coupled or directly-injected signal strength. These thresholds are set relative to the system power level on cold sky, based on SYS2104.

Compliance with SYS2104 is to be determined over the full operating range of the system. Care should also be exercised where signals could couple into any intermediate frequency bands used as part of the down-conversion and digitization architecture.

As this requirement is given at the system level, it is not discussed further in this technical specification.

3.3 Electromagnetic Emission Design Requirements

The following requirements shall be fulfilled *as a minimum* to support the emission requirements for the design, but the designer may propose alternatives if quantitative evidence is provided that the alternatives are at least as effective as the specification. Shielding requirements may be computed as described in Section 3.

Parameter	Req. #	Value	Traceability
Drive System Shielding	EMC0320	Drive motors shall be shielded and all motor leads, both power and control, shall be filtered.	SYS2104
Relay Contact Arcing	EMC0321	All relay contacts and actuators shall be properly bypassed with snubber circuits, shielded, and/or filtered.	SYS2104

Parameter	Req. #	Value	Traceability
Amplifiers & Oscillators	EMC0322	All amplifiers and oscillators shall be mounted in shielded enclosures that will provide effective shielding of radio frequency energy.	SYS2104
Silicone Controlled Rectifiers	EMC0323	Silicon-controlled rectifier switching devices shall not be used unless phase controlled and zero current crossing switching techniques are used.	SYS2104
Gaseous Discharge Devices	EMC0324	No gaseous discharge devices shall be employed in active circuits, except as noise sources for test and calibration. Use of such devices for lightning and ESD protection is permitted.	SYS2104
Static Discharge Mitigation	EMC0325	Means shall be employed to reduce static electricity and the consequent radio frequency noise generated in any rotating machinery.	SYS2104
Display Shielding	EMC0326	All displays (LCD, plasma, LED, CRT) shall have fully enclosed RFI shields, including an RFI shield in front of the display. This requirement may be waived if the screen is powered off during typical operation and is used for maintenance purposes only. It must be possible to monitor and turn off such emitting devices remotely (via the M&C System).	SYS2104
Digital Equipment Shielding	EMC0327	All digital equipment, whether a simple logic circuit, embedded CPU, or rack mounted PC shall be shielded and have its AC or DC power line and communication line(s) filtered at the chassis.	SYS2104

The goal of these requirements is to limit the use of devices that are likely to cause harmful emission levels, and shield the remaining necessary emitters. This list is not comprehensive, and the designer should exercise due diligence in limiting the harmful emissions generated by his/her design. Design for RFI emission mitigation is expected to be a significant effort in most electronic components of the ngVLA.

4 Immunity Requirements

All ngVLA equipment shall exhibit complete electromagnetic compatibility (EMC) among components (intra-system electromagnetic compatibility). Prevention of electromagnetic interference (EMI) between subsystems (inter-system electromagnetic compatibility) is also critical.

The following requirements establish the required robustness of the system to perform without degradation in the presence of defined electromagnetic disturbances. Thresholds where a defined degradation in performance is permitted are also listed.

4.1 Commercial Off-The-Shelf Equipment

Parameter	Req. #	Value	Traceability
COTS Immunity Standards	EMC0401	Commercial off-the-shelf (COTS) equipment shall conform to IEC product family standards for immunity standards, or to the generic standard IEC 61000 – Part 6: Generic Standards if no product family standard is given.	SYS2107
COTS Certification	EMC0402	All commercial equipment shall have a CE mark or FCC compliance identification.	SYS2107

Commercial-off-the-shelf equipment will be accepted in the system where it does not degrade the overall system functionality and ensures that the performance criteria established later in this section is maintained at the subsystem and system level.

The requirements listed in this section aim to ensure that otherwise acceptable COTS components are not made ineligible due to testing compliance with ngVLA EMC standards. These COTS standards are applicable to electromagnetic immunity only, with emission requirements applicable to all equipment present during observations at the ngVLA antenna sites.

4.2 Performance Criteria

The following performance criteria will be applied in subsequent sections of this specification.

Performance Standard	Description
A	Normal performance within specifications.
B	Temporary loss of function, or degradation of performance, which ceases after the disturbance ceases. The equipment recovers to normal performance, without Operator intervention.
C	Temporary loss of function, or degradation of performance, the correction of which requires Operator or software supervisory system intervention.
D	Loss of function, or degradation of performance, which is not recoverable. Examples include damaged hardware or loss of firmware or software images.

4.3 Conducted Immunity

4.3.1 Step Voltage Fluctuations

Parameter	Req. #	Value	Traceability
AC Supply Step Fluctuation	EMC0411	The immunity limit for rectangular (step) voltage changes on the AC supply lines shall be a ±12% change in supply voltage, for a duration of up to 3 sec, while meeting Performance Standard A.	SYS2107
DC Supply Step Fluctuation	EMC0412	The immunity limit for rectangular (step) voltage changes on the DC supply lines shall be a ±12% change in supply voltage, for a duration of up to 3 sec, while meeting Performance Standard A.	SYS2107

Verification of step voltage fluctuation immunity shall be based on test results whenever possible. Exceptions may be made for systems drawing over 30A (e.g., antenna drives), where tests become impractical. Verification in such cases may be based on inspection of manufacturer certifications (in the event of COTS equipment) or by analysis.

For polyphase systems, the voltage fluctuation should be applied to a single phase and to all three phases as separate tests.

4.3.2 Voltage Dips

Parameter	Req. #	Value	Traceability
AC Supply Short Voltage Dip	EMC0421	The immunity limit for voltage dips on the AC supply lines shall be –30% change in supply for a period of 10 msec, while meeting Performance Standard B.	SYS2107
AC Supply Long Voltage Dip	EMC0422	The immunity limit for voltage dips on the AC supply lines shall be –50% change in supply for a period of 100 msec, while meeting Performance Standard C.	SYS2107
DC Supply Short Voltage Dip	EMC0423	The immunity limit for voltage dips on the DC supply lines shall be –30% change in supply for a period of 10 msec, while meeting Performance Standard B.	SYS2107
DC Supply Long Voltage Dip	EMC0424	The immunity limit for voltage dips on the DC supply lines shall be –50% change in supply for a period of 100 msec, while meeting Performance Standard C.	SYS2107

Verification of long and short voltage dip immunity shall be based on test results whenever possible. Exceptions may be made for systems drawing over 30A (e.g., antenna drives), where tests become impractical. Verification in such cases may be based on inspection of manufacturer certifications (in the event of COTS equipment) or by analysis.

For polyphase systems, the voltage dips should be applied to a single phase and to all three phases as separate tests.

4.3.3 Voltage Interruptions

Parameter	Req. #	Value	Traceability
AC Supply Voltage Interruptions	EMC0431	The immunity limit for voltage interruptions on the AC supply lines shall be a voltage drop of 95% or more for a period of 5 seconds, while meeting Performance Standard C. This applies to both UPS and non-UPS supplied equipment.	SYS2107
DC Supply Voltage Interruptions	EMC0432	The immunity limit for voltage interruptions on the DC supply lines shall be a voltage drop of 95% or more for a period of 5 seconds, while meeting Performance Standard C.	SYS2107

Verification of voltage interruption immunity shall be based on test results. No exceptions are anticipated, given that the experimental test setup is expected to be practical for all ngVLA electronics systems. The supply lines may be grounded or float in the test setup. For polyphase systems, the voltage interruptions should be applied to a single phase and to all three phases as separate tests.

4.3.4 Voltage Surges and Bursts

Parameter	Req. #	Value	Traceability
AC Supply Burst Immunity	EMC0451	The system shall conform to MIL-STD-461G CS117 for transients and burst immunity for AC powered systems, while meeting Performance Standard C. Safety critical systems (as defined by the Hazard Analysis) shall meet or exceed Performance Standard B.	SYS2107
DC Supply Burst Immunity	EMC0452	The system shall conform to MIL-STD-461G CS117 for transients and burst immunity for DC powered systems, while meeting Performance Standard C. Safety critical systems (as defined by the Hazard Analysis) shall meet or exceed Performance Standard B.	SYS2107

The purpose of these requirements is to ensure equipment safety and reliable operation when subjected to high-energy disturbances on power and signal interconnects caused by overvoltage from switching and lightning transients.

Verification of burst immunity shall be based on test results whenever possible. Exceptions may be made for systems drawing over 30A (e.g., antenna drives), where tests become impractical. Verification in such cases may be based on inspection of manufacturer certifications (in the event of COTS equipment) or by analysis.

UPS-protected COTS devices may be exempted from this requirement if mitigation of the conducted burst risk can be demonstrated by inspection or analysis.

4.3.5 Conducted Noise

Parameter	Req. #	Value	Traceability
AC Supply Conducted Noise Immunity	EMC0461	The system shall conform to MIL-STD-461G CS101 conducted susceptibility for all AC powered systems, while meeting Performance Standard A.	SYS2107
DC Supply Conducted Noise Immunity	EMC0462	The system shall conform to MIL-STD-461G CS101 conducted susceptibility for all DC powered systems, while meeting Performance Standard A.	SYS2107

The conducted noise immunity requirements confirm that system performance is not impacted by noise on AC and DC mains supply conductors over the span of frequencies from 30 Hz to 150 kHz. Verification of conducted noise immunity shall be based on test results whenever possible.

4.4 Electrostatic Discharge (ESD) Requirements

Parameter	Req. #	Value	Traceability
ESD Low Air Discharge	EMC0471	Enclosed systems shall conform to MIL-STD-461G CS118 with an air discharge level up to 8kV while meeting performance criteria A. Testing to this discharge level at ESD Compliance Level 4 per IEC 61000-4-2 will also be accepted.	SYS2107
ESD High Air Discharge	EMC0472	Enclosed systems shall conform to MIL-STD-461G CS118 with an air discharge level up to 15kV while meeting performance criteria B. Testing to this discharge level at ESD Compliance Level 4 per IEC 61000-4-2 will also be accepted.	SYS2107
ESD Direct Contact Discharge	EMC0473	Enclosed systems shall conform to MIL-STD-461G CS118 with a direct contact discharge level up to 8kV while meeting performance criteria A. Testing to this discharge level at ESD Compliance Level 4 per IEC 61000-4-2 will also be accepted.	SYS2107

The ESD air-discharge and direct contact thresholds assume the devices are enclosed in any provided enclosures, as they would be found in the operational environment. Test locations are any accessible point outside of a closed cabinet (e.g., door handles or panels).

Service personnel will be provided with wrist bands at site service points and at all repair locations to prevent the occurrence of ESD to equipment within racks or enclosures during service.

5 Verification

The design may be verified to meet the requirements by analysis (A), inspection (I), a demonstration (D), or a test (T), each defined below.

Verification by Analysis: The fulfillment of the specified performance shall be demonstrated by appropriate analysis (hand calculations, finite element analysis, thermal modeling, etc.), which will be checked by the ngVLA project office during the design phase.

Verification by Inspection: The compliance of the developed system is determined by a simple inspection or measurement.

Verification by Demonstration: The compliance of the developed feature is determined by a demonstration.

Verification by Test: The compliance of the developed system with the specified performance shall be demonstrated by site acceptance tests.

Multiple verification methods are allowed. The primary (final) verification method is identified below. Subsystems or individual components may have alternate methods of verification, depending on the risk presented by the given parameter to that subsystem or component.

Req. #	Parameter/Requirement	A	I	D	T
EMC0310	Spurious Signal Level				*
EMC0311	Emission Verification Frequencies		*		
EMC0312	Low Frequency Emission		*		
EMC0320	Drive System Shielding		*		
EMC0321	Relay Contact Arcing		*		
EMC0322	Amplifiers and Oscillators		*		
EMC0324	Gaseous Discharge Devices		*		
EMC0325	Static Discharge Mitigation		*		
EMC0326	Display Shielding		*		
EMC0327	Digital Equipment Shielding		*		
EMC0328	EMC Test Frequencies		*		
EMC0401	COTS Immunity Standards		*		
EMC0402	COTS Certification		*		
EMC0411	AC Supply Step Fluctuation				*
EMC0412	DC Supply Step Fluctuation				*
EMC0421	AC Supply Short Voltage Dip				*
EMC0422	AC Supply Long Voltage Dip				*
EMC0423	DC Supply Short Voltage Dip				*
EMC0424	DC Supply Long Voltage Dip				*
EMC0431	AC Supply Voltage Interruptions				*
EMC0432	DC Supply Voltage Interruptions				*
EMC0451	AC Supply Burst Immunity				*
EMC0452	DC Supply Burst Immunity				*
EMC0461	AC Supply Conducted Noise Immunity				*
EMC0462	DC Supply Conducted Noise Immunity				*
EMC0471	ESD Low Air Discharge				*
EMC0472	ESD High Air Discharge				*
EMC0473	ESD Direct Contact Discharge				*

6 Appendix

6.1 Abbreviations & Acronyms

Acronym	Description
AC	Alternating Current
AD	Applicable Document
CDR	Critical Design Review
CE	Conformité Européenne
CoDR	Conceptual Design Review
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
DC	Direct Current
EIRP	Effective Isotropic Radiated Power
EMC	Electro-Magnetic Compatibility
EMI	Electro-Magnetic Interference
ESD	Electro-Static Discharge
FCC	Federal Communications Commission
FDR	Final Design Review
HVAC	Heating, Ventilation & Air Conditioning
ICD	Interface Control Document
IEC	International Electrotechnical Commission
IPT	Integrated Product Team
ITU	International Telecommunication Union
LO	Local Oscillator
LRU	Line Replaceable Unit
ngVLA	Next Generation Very Large Array
PC	Personal Computer
PSD	Power Spectral Density
RBW	Resolution Bandwidth
RD	Reference Document
RFI	Radio Frequency Interference
rms	Root Mean Square
RSS	Root of Sum of Squares
SAC	Science Advisory Council
SBA	Short Baseline Array
SPFD	Spectral Power Flux Density
SRSS	Square Root Sum of the Square
SWG	Science Working Group
TAC	Technical Advisory Council
TBD	To Be Determined
TPA	Total Power Array
UPS	Uninterruptible Power Supply
VLA	(Jansky) Very Large Array
VLBA	Very Long Baseline Array

6.2 Definitions

Burst: A sequence of a limited number of pulses, or an oscillation of limited duration.

Electromagnetic Compatibility (EMC): The ability of a device to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to the environment and nearby devices.

Electromagnetic Compatibility Level: A specified maximum electromagnetic disturbance level that may be impressed on the device.

Electromagnetic Disturbance: Any electromagnetic phenomena which may degrade the performance of a device. An electromagnetic disturbance may be noise, an unwanted signal, or a change in the propagation medium.

Electromagnetic Interference (EMI): The degradation of the performance of a device caused by an electromagnetic disturbance. Disturbance is the cause, while interference is the effect.

Harmonic: A frequency that is a multiple of a Fourier component of a periodic signal.

(Total) Harmonic Factor: The ratio of the rms value of harmonic content to the rms value of an alternating signal.

Immunity: The ability of a device to perform without degradation in the presence of an electromagnetic disturbance.

Interharmonics: A discrete or wideband frequency signal which is not an integer multiple of a Fourier component of a periodic signal.

Susceptibility: The inability of a device to perform without degradation in the presence of an electromagnetic disturbance.

Voltage Dip: A sudden reduction in the voltage at a point in an electrical network, followed by a recovery, on timescales of msec to sec.

Voltage Imbalance: In a polyphase system, a condition in which the rms values of the phase voltages, or the phase angles between consecutive phases, are not equal.

Voltage Interruption: The disappearance of a supply voltage. In this specification, defined to be for a period not exceeding 1 minute.

Voltage Surge: A transient voltage wave characterized by a rapid increase and a slower decrease.

6.3 Derivation of RFI Emission Limits

The EIRP limits listed in Section 3 are based on the analysis performed for the VLA [RD01], refining the values in ITU RA.769-2 [RD03] for a connected element interferometer. The allowable emission limits are computed for an interferometer with attenuation of a stationary RFI source provided by phase winding. The specifications in Section 3 rely on this attenuation, and may not be suitable for total power radiometry. The analysis in [RD01] uses an expression for the attenuation factor from [RD02]:

$$R = N_a + 12\sqrt{\tau \nu_G B_K \cos\delta}$$

Where N_a is the number of antennas in the array, τ is the integration time in seconds, ν_G is the RF frequency in GHz, B_K is the maximum baseline in km, and δ is the source declination. The coefficient 12 is unique to the VLA, and must be recomputed for ngVLA. This coefficient was derived from equation 16 in [RD02]:

$$C = \frac{\sqrt{1000}}{1.34\sqrt{f}} = 12$$

The square root of 1000 accounts for the fact that RD02 Equation 16 is in MHz rather than GHz. f is the ratio of B_{MAX}/B_{MEAN} which, for VLA, is approximately 4. The factor 1.34 subsumes a number of constants, including $1/N_a$, so must be corrected by $27/N_a$ for the ngVLA. The resultant formula suitable for the ngVLA is:

$$R = N_a + \frac{0.87N_a}{\sqrt{f}}\sqrt{\tau \nu_G B_K \cos\delta}$$

The computation for ngVLA is complicated by the routine use of sub-arrays. The attenuation is minimized when the array is compact and the source is high in the sky. Standalone use of the short baseline array (SBA) presents a limiting conservative case, and the following input parameters (Table 4) were used to determine the attenuation factor:

Table 4 – Input parameters to fringe rotation attenuation computation.

Parameter	Value	Units	Notes
N_a	19		SBA rev. C
$B_{Max,K}$	0.060	km	SBA rev. C
δ	85	degrees	Gets worse at high declination.
$B_{Mean,K}$	0.029	km	SBA rev. C
f	2.1		Ratio of max to mean baseline, in core.

The remainder of the analysis follows the process outlined in [RD01]. An integration period of 2,000 seconds was used, and the emitter was placed at a distance of 10m from the receiver. The resolution bandwidth for Table 1 is consistent with SCI0116, while Table 2 uses a resolution bandwidth more appropriate for a continuum observation with less channelization. The detailed derivations in support of Table 1 are shown in Table 5.

Table 5 – Detailed derivations for Spectral Line limits.

ν_G (GHz)	1	3	6	10	30	45	90
T_{SYS} (K)	25	25	27	25	34	45	68
Δν (Hz)	333	1000	2000	3333	10000	15000	30000
σ_P (W) – *Single Dish*	1.41E-22	2.44E-22	3.73E-22	4.45E-22	1.05E-21	1.70E-21	3.63E-21
$P_{HARM-SD}$ (W) – *Single Dish*	1.41E-23	2.44E-23	3.73E-23	4.45E-23	1.05E-22	1.70E-22	3.63E-22
R [Attenuation Factor]	56	83	110	136	221	267	370
R (dB)	17	19	20	21	23	24	26
$P_{HARM-INT}$ (W) – *Interferometer*	7.88E-22	2.03E-21	4.08E-21	6.05E-21	2.32E-20	4.54E-20	1.34E-19
A_e (m^2)	7.16E-03	7.96E-04	1.99E-04	7.16E-05	7.96E-06	3.54E-06	8.84E-07
F_{HARM} (watt/m^2) – *Interferometer*	1.10E-19	2.54E-18	2.05E-17	8.45E-17	2.92E-15	1.28E-14	1.52E-13
F_{HARM} (dB(watt/m^2))	–190	–176	–167	–161	–145	–139	–128
S_{HARM} (W/m^2/Hz)	3.30E-22	2.54E-21	1.03E-20	2.53E-20	2.92E-19	8.56E-19	5.06E-18
S_{HARM} (dB(W/m^2/Hz))	–215	–206	–200	–196	–185	–181	–173
EIRP limit (W) – *Interferometer*	1.38E-16	3.20E-15	2.58E-14	1.06E-13	3.67E-12	1.61E-11	1.91E-10
EIRP (dBm) – *Interferometer*	–129	–115	–106	–100	–84	–78	–67
PSD (W @ 10m)/Hz	4.15E-19	3.20E-18	1.29E-17	3.19E-17	3.67E-16	1.08E-15	6.36E-15
PSD (dBW @ 10m)/Hz	–184	–175	–169	–165	–154	–150	–142
PSD (dBm @ 10m)/Hz	–154	–145	–139	–135	–124	–120	–112

The parameters in Table 5 are described below, along with any constants used in their computation.

Parameter	Description
ν_G (GHz)	The point frequency applicable to this analysis.
T_{SYS} (K)	The assumed system temperature.
Δν (Hz)	The bandwidth over which the emission limit applies.
σ_P (W)	The power detection threshold (noise limit) of the system, at the specified T_{SYS} and bandwidth, over a period of 2000 seconds.
$P_{HARM-SD}$ (W)	The harmful emission threshold applicable to single-dish total power radiometry, assuming an acceptable interference to noise ratio of 0.1.
R	The interferometric attenuation factor, as described in EVLA Memo #49 [RD02].

Parameter	Description
$P_{HARM-INT}$ (W)	The harmful emission threshold applicable to interferometric measurements.
A_e (m^2)	An isotropic antenna's effective cross-section area as a function of frequency.
F_{HARM} (W/m^2)	The harmful threshold in power flux density units.
S_{HARM} ($W/m^2/Hz$)	The harmful threshold in spectral power flux density units.
EIRP (watts)	The limit in effective isotropic radiated power, expressed in watts, 10m from the receiver, for the given bandwidth.
EIRP (dBm)	The limit in effective isotropic radiated power, expressed in dBm, 10m from the receiver, for the given bandwidth.
PSD (W @ 10m)/Hz	The detrimental threshold in power spectral density units.

6.3.1 Total Power Array Considerations

The computations in Table 5 assume an interferometric attenuation factor specific to the short baseline array. The factor is larger for all other interferometric subarrays presently envisioned, so this limit will suffice for all interferometric use cases.

The total power array (TPA) would not benefit from the attenuation factors used in computing the detrimental threshold levels. A strict interpretation and flow down of the requirements, inclusive of a total power array, would require us to adopt the ITU RA.769-2 standards directly, which are approximately 17dB to 26dB stricter than the specification provided in this document.

We will assess the value of such a requirement in the context of the Notional Envelope Observing Program (EOP) [RD05]. While the distribution of the main array and SBA use cases is broadly distributed over frequency, the TPA use cases are highly skewed towards the upper frequency bands. Fully 94% of the identified TPA use cases would employ Band 6 (70–116 GHz), with the remaining 6% using Band 1 (1.2–3.5 GHz).

The emission requirements are expected to drive the design at low frequency (<10 GHz). Mitigation of emission for wavelengths comparable to the enclosure size is appreciably harder than for short wavelengths. Short wavelength emission tends to be more directional, and more easily absorbed. Any mitigation strategy that meets the emission requirements at low frequency is expected to provide attenuation at high frequency well in excess of the specification. This assumption is captured in requirement EMC0311. We therefore expect that the emission thresholds specified will prove ample to protect TPA observations in Band 6, and deem discarding a limited number of channels in Band 1 an acceptable compromise given the external RFI environment at low frequency.

As the TPA design and use cases are further developed, this assumption should be revisited. Mitigation unique to the TPA antennas could be considered to reduce local emissions to the ITU standards, if necessary.

6.4 Comparison to ITU RA.769-2 and Other Facilities

A comparison to the known ITU RA.769-2 standard, and other facilities, may provide useful context to these requirements.

The ngVLA detrimental emission thresholds given in Section 3.1 differ from the ITU standards in some key ways:

- The T_{SYS} values are based on the ngVLA reference design and differ from the T_{ANT} and T_{REC} values used in the ITU standard.
- The spectral resolution in the ITU standard is tied to the width of the bandwidth allocations to radio astronomy. This leads to some structure in the ITU standard over frequency. The ngVLA specification is given at a fixed spectral resolution applicable for spectral line and continuum mode channelization (100 m/s and 0.1% of the center frequency, respectively.)
- ITU Tables 1 and 2 are applicable to single dish total power radiometry. This is in excess of what is required for an imaging interferometer, so the ngVLA requirement includes an interferometric attenuation factor, following the methodology used to determine the VLA emission thresholds [RD01, RD02]. The resultant values are very close to those given in ITU Table 3 for VLBI observations.

The last item is the most significant, and the derivation of this attenuation factor is described in Section 6.3. We note that this derivation is in conflict with the desired inclusion of total power capability on the ngVLA, but we deem this risk minor for two reasons:

- The majority of the total power use cases are high frequency. The self-interference risk is minimal above 10 GHz due to the directionality of such RFI and the efficacy of shielding and absorber materials at high frequencies.
- Alternative design solutions may be explored for the total power dishes, so they may adopt a stricter standard and can be placed at an appropriate distance from neighboring antennas.

These considerations are described further in Section 6.3.1.

The spectral power flux density limits given in the ITU Tables 1, 2, and 3 are contrasted with the ngVLA requirements in Figure 1. The VLA emission requirements are also given for context. As part of the model verification process the ITU values were recomputed at desired point frequencies. This required some assumed or interpolated inputs, so the values in this figure may differ from the ITU tables by ±2 dB. Note that the derivation of these limits is independent of the array collecting area, since it is assumed to enter through a feed receiver sidelobe. Hence, the VLA limits are very close to the ngVLA limits. The primary differences between the VLA and ngVLA cases are due to different spectral resolution (bandwidth) assumptions, and the number of antennas in each array which influences the interferometric attenuation factor.

Figure 2 converts these values to a power spectral density at 10m. The corresponding limits for the MeerKAT telescope are added for context. MeerKAT has effectively adopted the ITU standard, but smoothed over frequency by adopting a standard spectral resolution that scales with frequency.

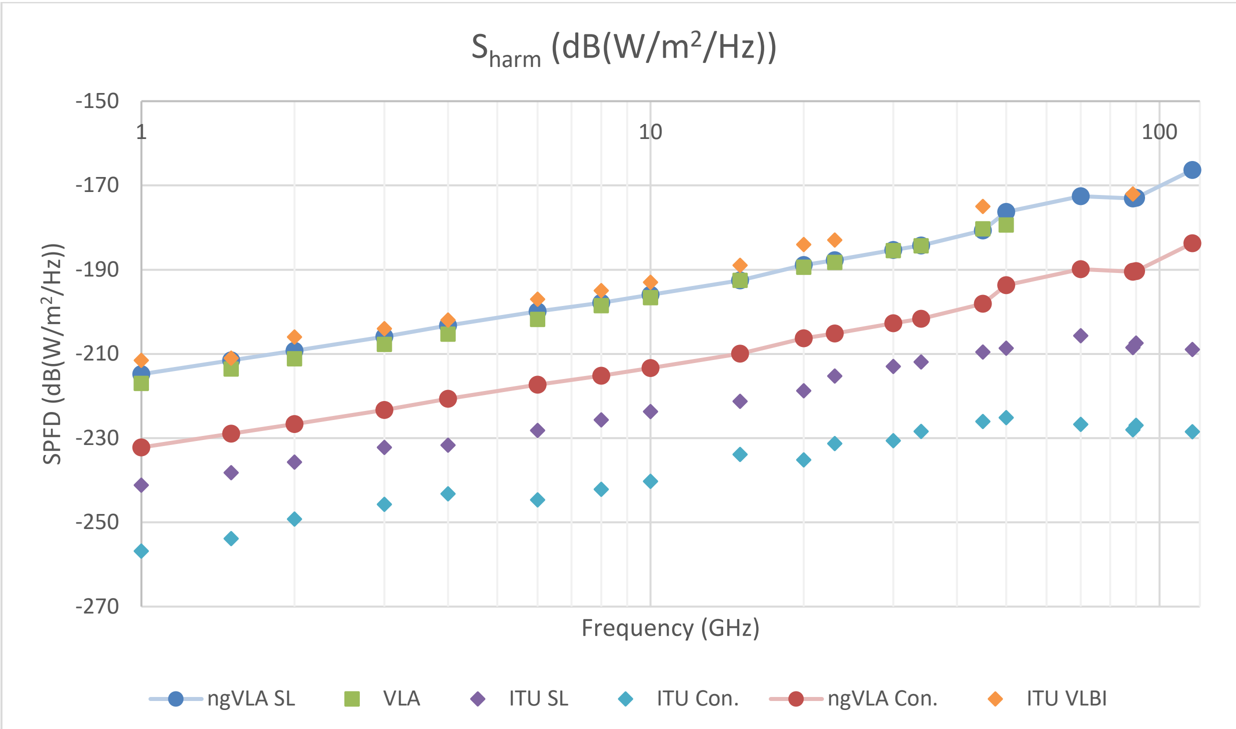

Figure 1 – Spectral Power Flux Density Limits for the ngVLA, VLA and ITU-R RA.769-2.

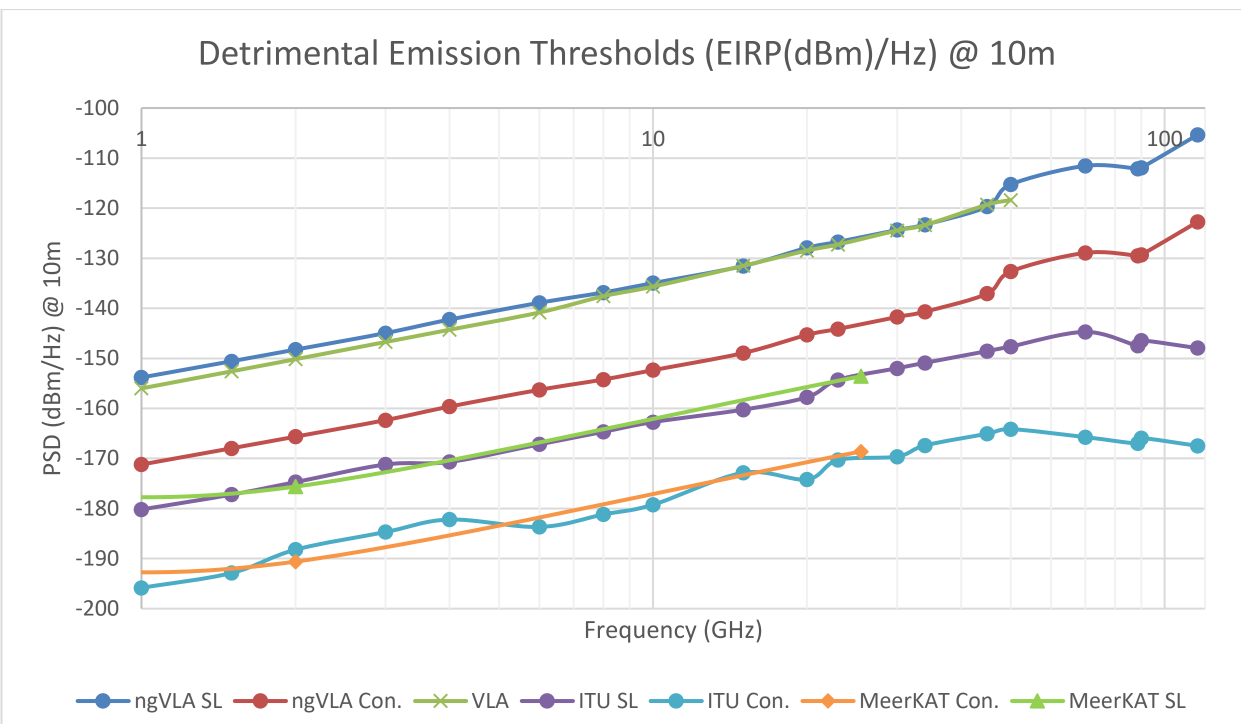

Figure 2 – Power Spectral Density Limits for the ngVLA, VLA, MeerKAT, and ITU-R RA.769-2.