Integrated Receivers and Digitizers: Technical Requirements

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Change Record

Version	Date	Author(s)	Affected Section(s)	Reason
1	2020-01-07	M. Morgan	All	Initial draft, based on preliminary reference design technical requirements.
2	2020-04-23	M. Morgan	10	Changed verification methods (eliminated Design, added Demonstrate, replaced FAT and SAT with T).
3	2020-060-2	M. Morgan	4.1, 9.1	Added IRD0107 for low-frequency support in Band 1.
4	2020-06-17	M. Morgan	All	Reconciliation with updated system requirements, "shall" verbage, final cleanup before requirements review.
5	2021-05-03	M. Morgan	All	Update to reflect new "ngVLA System Electronics Specifications" document.
6	2021-06-01	M. Morgan	All	Revisions after requirements review.
A	2021-06-01	A. Lear	All	Prepared PDF for signatures and approvals.

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1 Introduction

1.1 Purpose

This document presents the technical specifications for the ngVLA Integrated Receiver and Digitizer (IRD) modules.

Many requirements flow down from the ngVLA System Requirements [AD02], which in turn flow down from the ngVLA Science Requirements [AD01].

The IRD subsystem is also subject to the ngVLA System Electronics Specifications [AD04]. Compliance to these requirements shall be verified as specified therein, without reference to an IRD-specific requirement, except in those cases where translation or refinement is needed to apply more directly to IRD.

The integrated receiver packages provide additional amplification to the signals output by the cryogenic stage, down convert them where necessary, digitize them, and deliver the resultant data streams by optical fiber to a moderately remote collection point from the focal plane (but possibly still inside the antenna base).

From there, they are time-stamped and launched onto a conventional network for transmission back to the array correlator and central processing facility. Hooks are needed to provide for synchronization of local oscillators (LOs) and sample clocks, power leveling, command and control, health and performance monitoring, and diagnostics for troubleshooting in the event of component failure.

1.2 Scope

The scope of this document is the set of ngVLA Integrated Receiver and Digitizer modules. This consists of direct-sampled and sideband-separating modules for all telescope bands, which include warm amplification, filtering, power leveling, analog-to-digital conversion, and fiber-optic transmission. Important note: the scope also includes external splitters and combiners as needed to feed them from the cryogenic signal paths.

Cryogenic systems and thermal transitions, as well as front-end cabling, waveguide runs, and fiber-optic signal paths **outside** the IRD modules and splitters themselves are outside the scope of this work package, though interfaces must be considered. This specification establishes the performance, functional, design, and test requirements applicable to the ngVLA IRD modules.

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 conflict between the documents referenced herein and the contents of this Technical Specification, the contents of this Technical Specification shall be considered as a superseding requirement.

Ref. No.	Document Title	Rev/Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	ngVLA System Requirements	020.10.15.10.00-0003-REQ
AD03	ngVLA System Environmental Specifications	020.10.15.10.00-0001-SPE
AD04	ngVLA System Electronics Specifications	020.10.15.10.00-0003-REQ
AD05	ngVLA System Technical Budgets	020.10.25.00.00-0002-DSN
AD06	System EMC and RFI Mitigation Requirements	020.10.15.10.00-0002-REQ

2.2 Interface Control Documents

The following are applicable Interface Control Documents (ICDs):

ICD	Interfacing Subsystem	Rev/Doc. No.
IRD-HIL	Hardware Interface Layer	020.10.40.05.00-0001-ICD
IRD-DBE	Digital Backend/Data Transmission System	020.10.40.05.00-0002-ICD
IRD-EEC	Antenna Electronics Environmental Control System	020.10.40.05.00-0003-ICD
IRD-FED	Front End	020.10.40.05.00-0004-ICD
IRD-ATF	Antenna Time and Frequency	020.10.40.05.00-0005-ICD
IRD-PSU	DC Power Supply	020.10.40.05.00-0006-ICD
IRD-BMR	Bins, Modules, and Racks	020.10.40.05.00-0049-ICD
IRD-AFD	Antenna Fiber Distribution	020.10.40.05.00-0050-ICD
IRD-MCL	Monitor and Control	020.10.40.05.00-0051-ICD

2.3 Reference Documents

The following references provide supporting context:

Ref. No.	Document Title	Rev/Doc. No.
RD01	An Integrated Receiver Concept for the ngVLA	ngVLA Memo #29, Nov. 2017
RD02	Unformatted Digital Fiber-Optic Data Transmission for Radio Astronomy Front-Ends	PASP, vol. 125, no. 928, June 2013
RD03	Downconversion and Digitization Methodology for the ngVLA	ngVLA Electronics Memo No. 1
RD04	Front End Reference Design Description	020.30.03.00.00-0002-DSN-A
RD05	ngVLA Receiver Cascade Analysis	ngVLA_RX_cascade_analysis_Ver9_2019-07-17.pdf
RD06	Headroom, Dynamic Range, and Quantization Considerations	ngVLA Electronics Memo #8

3 Overview of the IRD Technical Requirements

3.1 Document Outline

This document presents the technical requirements of the ngVLA Integrated Receivers and Digitizers. These parameters determine the overall form and performance of the Integrated Receivers and Digitizers.

The functional and performance specifications, along with detailed explanatory notes, are found in Section 4. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirements and should guide the verification procedures.

In many cases the notes contain an explanation or an analysis of how the numeric values of requirements were derived. Where numbers are not well substantiated, this is also documented in the notes. In this way, the required analysis and trade-space available is apparent to scientists and engineers who will guide the evolution of the ngVLA Integrated Receivers and Digitizers concept.

Safety requirements applicable to both the design phase and the functional Integrated Receivers and Digitizers are described in Section 5. Additional requirements for the design phase are described in Section 6. Documentation requirements for both technical design documentation and software are provided in Section 8.

Requirements for the Verification and Test, from the conceptual design through to prototype, are described in Section 10.

Section 11 identifies Key Performance Parameters (KPP) that should be estimated and monitored throughout the design phase. These are metrics to assist in the trade-off analysis of various concepts, and help identify and resolve tensions between requirements as the design progresses.

3.2 Project Background

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a synthesis radio telescope constituted of approximately 244 reflector antennas each of 18 meters diameter operating in a phased or interferometric mode, along with an additional 19 antennas 6 meters in diameter comprising a short-baseline array.

The signal-processing center of the array will be located at the Very Large Array site, on the plains of San Agustin, New Mexico. The array will include stations in other locations throughout the state of New Mexico, west Texas, eastern Arizona, and northern Mexico.

Operations will be conducted from both the VLA Control Building and the Array Operations Center in Socorro, NM.

3.3 General IRD Description

The integrated downconverters will take cryogenically amplified RF inputs over the full frequency range of the telescope in bands and perform all necessary conversions from RF to baseband, from analog to digital, and from copper to fiber in compact, integrated modules. The lower bands may be digitized directly (without down conversion) in the first-, second-, and/or third-Nyquist zones, while the higher bands may be down converted with in-phase and quadrature (I and Q) baseband outputs. Final sideband-separation will be performed numerically by the backend (outside the scope of this work package) with calibrated amplitude and phase coefficients. The initial concept and frequency plan for this subsystem (now somewhat modified, and still evolving) was presented in [RD01].

Due to instantaneous digital bandwidth limitations, more than one downconverter module may be required to service a single RF feed band. Where needed, passive splitters/combiners will be provided within this scope to divide the RF band into more manageable chunks for the integrated modules.

The digitized I and Q or direct-sampled data streams will be transmitted by optical fiber as partially unformatted serial data (there may still be 64b/66b encoding). The mathematical basis of operation and methodology for parsing the bit stream at the receive end is described in detail in [RD02].

Auxiliary inputs to the integrated downconverters will include LOs, sample clocks, power supplies, and the monitor and control (M&C) serial bus. Sufficient on-board monitoring will be provided to isolate most failures to a single module.

The IRD subsystem boundary extends to and includes the input RF splitters, the module connectors to the power supply and MCHIL, the module mechanical/thermal interface surface, and the QSFP fiber-optic transceivers. A SysML representation is shown in Figure 1.

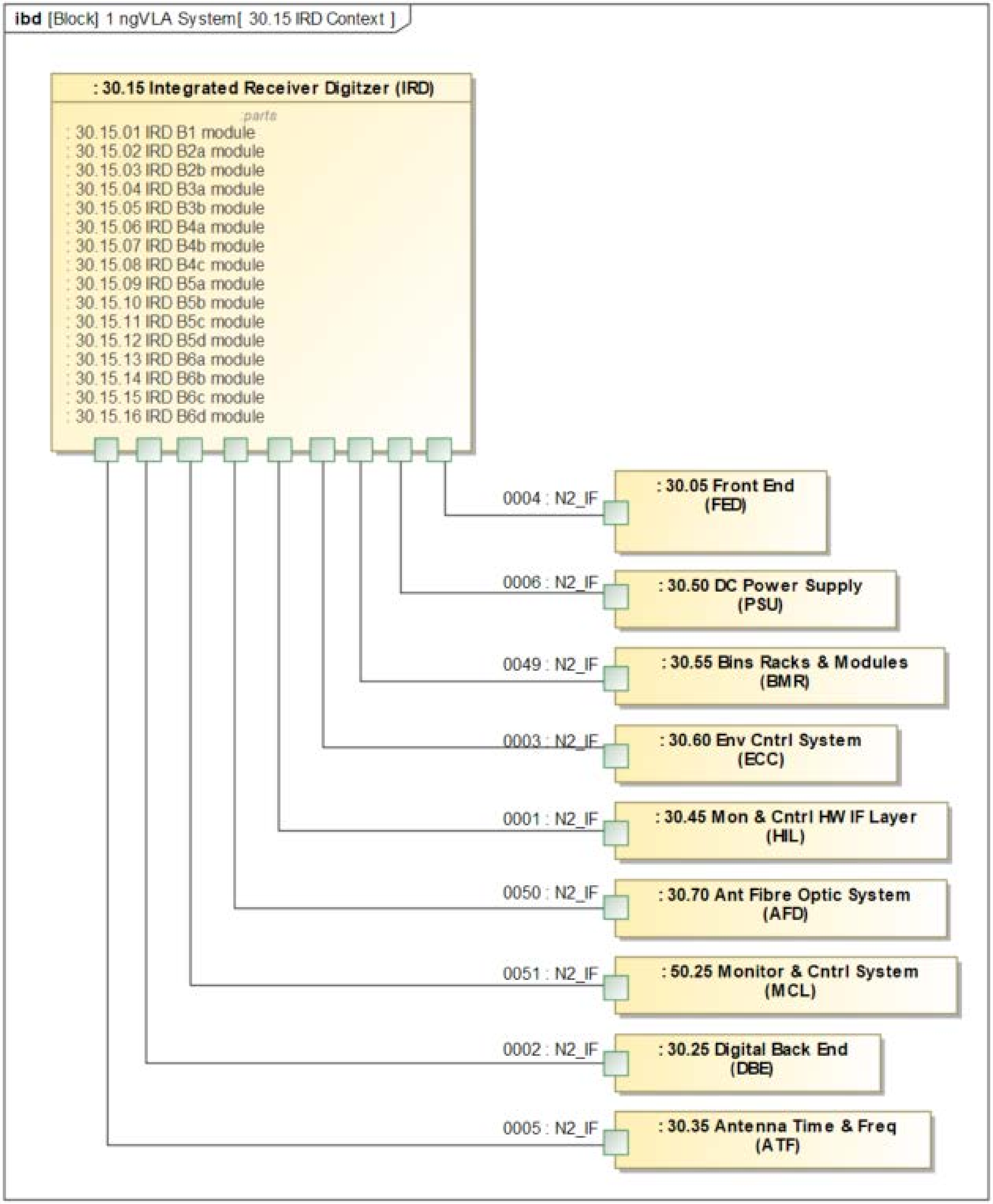

Figure 1. SysML Representation of the IRD subsystem.

3.4 Summary of IRD Requirements

The following table provides a summary of the major requirements in order to provide the reader with a high-level view of the desired system. Should there be a conflict between the requirements listed here and the descriptions in Sections 4 through 10, the latter shall take precedence.

3.4.1 General Functional Specifications

Parameter	Summary of Requirement	Reference Reqs.
RF Input Frequency Bands	1.2–3.5 GHz 3.5–12.3 GHz 12.3–20.5 GHz 20.5–34 GHz 30.5–50.5 GHz 70–116 GHz	IRD0101 IRD0102 IRD0103 IRD0104 IRD0105 IRD0106
IF Bandwidth (after anti-alias filtering)	3.3 GHz (RF ≤ 3.5 GHz) 2.9 GHz per sideband, 2SB (3.5 ≤ RF ≤ 116 GHz)	IRD0301 IRD0302–0306
Image Rejection	≥30 dB (calibrated)	IRD0612–0616
Gain (nominal)	30–40 dB	IRD0411–0416
Gain Flatness	≤5 dB peak-to-peak overall, ≤2.5dB in any 100 MHz	IRD0421–0422
Gain Adjustment Range	–12/+12 dB min. (from nominal)	IRD0431
Noise Temperature	≤1000 K (RF ≤ 50.5 GHz) ≤1500 K (70 ≤ RF ≤ 116 GHz)	IRD0501–0505 IRD0506
Bit Resolution	8 bits	IRD0721–0726

4 IRD Functional and Performance Requirements

All functional and performance requirements apply to a properly functioning system, with nominal inputs and control settings (e.g., attenuator states), under normal operating environmental conditions (temperature, power, etc.), and with normal operational calibrations applied, unless otherwise stated.

4.1 RF Frequency Ranges

Parameter	Req. #	Value	Traceability
Band 1 RF Frequency	IRD0101	The band 1 modules shall process a combined RF frequency range of 1.2–3.5 GHz	SYS0801–0806
Band 2 RF Frequency	IRD0102	The band 2 modules shall process a combined RF frequency range of 3.5–12.3 GHz	SYS0801–0806
Band 3 RF Frequency	IRD0103	The band 3 modules shall process a combined RF frequency range of 12.3–20.5 GHz	SYS0801–0806
Band 4 RF Frequency	IRD0104	The band 4 modules shall process a combined RF frequency range of 20.5–34 GHz	SYS0801–0806
Band 5 RF Frequency	IRD0105	The band 5 modules shall process a combined RF frequency range of 30.5–50.5 GHz	SYS0801–0806
Band 6 RF Frequency	IRD0106	The band 6 modules shall process a combined RF frequency range of 70–116 GHz	SYS0801–0806

Parameter	Req. #	Value	Traceability
Band 1 Low-Frequency Support	IRD0107	It is desirable to provide support for <1 GHz frequency coverage with minimal hardware modification.	SYS5602

The total RF frequency range flows down from the system requirements, and the selection of band edges stem from a combination of engineering feasibility, hardware efficiency, and the system requirement that the band edges do not coincide with important spectral features. These band edges will ultimately be traced back to the FE-IRD interface documentation. Traceability to interface requirements may be added here when the ICDs are completed.

The frequency plan of the IRD subsystem ensures that useable IF bandwidth extends beyond the RF band edges by at least a few hundred MHz. This feature combined with the ability to offset LO frequencies ensures that no redshifted spectral line may straddle two RF bands.

The RF signal path will include a set of passive splitters and combiners to feed the correct bandwidth to each module. Note that the wider RF bands will require more than one module for the desired frequency coverage, which may not encompass the entire tuning range (e.g. Band 6 may only have sufficient modules to process a portion of the Band 6 tuning range represented in IRD0106 at any given time). Although the conceptual design anticipates that all modules within a given RF band will be identical, this is not a requirement.

System requirement SYS5602 states that "it is **desirable** to provide physical interfaces, data transmission and correlator bandwidth for a future commensal low-frequency (<1 GHz) front end." The Band 1 module shall directly digitize a Nyquist band of ~1 MHz to 3.5 GHz. The nominal Band 1 design includes a high-pass filter that attenuates frequencies below 1.2 GHz for the purpose of optimizing dynamic range and interference immunity; however, that filter could be removed providing access to lower frequencies if desired, at some cost to system dynamic range. No specifications on performance below 1.2 GHz (e.g. gain slope, ripple, noise temperature, or spur immunity) are implied, only that basic low-frequency functionality is provided. An additional combiner would be needed ahead of the Band 1 module to couple the input from a low-band antenna.

A subset of antennas (their number as yet undetermined) may require additional Band 4 modules to service the water vapor radiometer (WVR).

4.2 LO Frequencies

Parameter	Req. #	Value	Traceability
Band 2 LO Frequencies	IRD0202	The band 2 modules shall operate with nominal LO frequency inputs of 5.8 and 11.6 GHz	SYS0906
Band 3 LO Frequencies	IRD0203	The band 3 modules shall operate with nominal LO frequency inputs of 14.5 and 20.3 GHz	SYS0906
Band 4 LO Frequencies	IRD0204	The band 4 modules shall operate with nominal LO frequency inputs of 23.2, 29.0, and 34.8 GHz	SYS0906
Band 5 LO Frequencies	IRD0205	The band 5 modules shall operate with nominal LO frequency inputs of 31.9, 37.7, 43.5, and 49.3 GHz	SYS0906
Band 6 LO Frequencies	IRD0206	The band 6 modules shall operate with nominal LO frequency inputs between 72.5 and 113.1 GHz	SYS0905, SYS0906

The LO frequencies above were selected to allow complete coverage of the RF bands in Section 4.1 with overlapping sidebands between adjacent downconverter channels and only minimal gaps at near-DC IF frequencies. LOs were also selected to be harmonically related (multiples of 2.9 GHz) in order to simplify LO generation and sideband calibration while also minimizing the risk of spurious mixing products.

LOs for Bands 1–5 are expected to be fixed-tuned, though small offsets from these frequencies will be supported by the IRD modules in case the system architecture calls for it. It is desirable for the Band 6 LOs to be fixed-tuned as well, however there is an ongoing debate at the system level whether the full complement of Band 6 modules (eight) shall be included on each antenna, or only half that many as a cost-cutting measure. If less than the full complement of modules is included, then the question arises as to the tuning granularity and flexibility of the LOs. At a minimum, LO steps at 5.8 GHz spacing shall be supported, with 2.9 GHz spacing more likely (allowing overlapping "half-steps" to optimize placement of processed bandwidths), or in the extreme case, fully continuous LO tuning. At present, so long as the range specified in IRD0206 is supported, these decisions have little impact on the IRD module design, but they will significantly impact the testing required, as well as the storage, retrieval, and application of calibration coefficients for sideband separation.

4.3 IF Bandwidth

Parameter	Req. #	Value	Traceability
Band 1 output Bandwidth	IRD0301	Each band 1 module shall provide a digitized output band covering 1.2–3.3 GHz after anti-alias filtering.	SYS0901
Band 2 IF Bandwidth	IRD0302	Each band 2 module shall provide a digitized IF bandwidth of 2.9 GHz after anti-alias filtering.	SYS0903, IRD0202
Band 3 IF Bandwidth	IRD0303	Each band 3 module shall provide a digitized IF bandwidth of 2.9 GHz after anti-alias filtering.	SYS0903, IRD0203
Band 4 IF Bandwidth	IRD0304	Each band 4 module shall provide a digitized IF bandwidth of 2.9 GHz after anti-alias filtering.	SYS0903, IRD0204
Band 5 IF Bandwidth	IRD0305	Each band 5 module shall provide a digitized IF bandwidth of 2.9 GHz after anti-alias filtering.	SYS0903, IRD0205
Band 6 IF Bandwidth	IRD0306	Each band 6 module shall provide a digitized IF bandwidth of 2.9 GHz after anti-alias filtering.	SYS0903, IRD0206

Note that these bandwidths are defined as those for which all other performance requirements apply (e.g. gain flatness, image rejection, anti-aliasing), after filtering and digitization. The LO frequencies ensure that sidebands from adjacent LOs overlap with crossover points corresponding to these IFs. Bands 2 and above are sideband-separating, using compact and inexpensive anti-alias filters with relaxed cutoff requirements. Band 1, in contrast, is direct-sampled in the first Nyquist zone, and will use a more expensive, bulky, and high-performance anti-aliasing filter. Further, all modules are dual polarization. Finally, as noted earlier, some bands will be populated with more than one module. Consequently, the numbers above represent the output/IF bandwidth *per sideband or Nyquist zone*, *per polarization*, and *per module*, as applicable for each band.

4.4 Analog Gain

The net warm electronic gain is required to amplify the weak output spectra of the cryogenic system to a level at the digitizers that balances quantization efficiency and dynamic range. It is specified in terms of nominal (average) value, flatness, and adjustment range. The final values of these specs will depend on the gain specification of the cryogenic amplifiers and the full-scale range of the samplers.

4.4.1 Nominal Gain

Parameter	Req. #	Value	Traceability
Band 1 Nominal Gain	IRD0411	The band 1 module shall have a nominal operating analog gain of 36 dB	SYS1011, SYS1033–1034
Band 2 Nominal Conversion Gain	IRD0412	The band 2 module shall have a nominal operating analog gain of 38 dB	SYS1011–1012, SYS1033–1034
Band 3 Nominal Conversion Gain	IRD0413	The band 3 module shall have a nominal operating analog gain of 36 dB	SYS1012, SYS1033–1034
Band 4 Nominal Conversion Gain	IRD0414	The band 4 module shall have a nominal operating analog gain of 40 dB	SYS1012, SYS1033–1034
Band 5 Nominal Conversion Gain	IRD0415	The band 5 module shall have a nominal operating analog gain of 34 dB	SYS1012, SYS1033–1034
Band 6 Nominal Conversion Gain	IRD0416	The band 6 module shall have a nominal operating analog gain of 27 dB	SYS1013, SYS1033, 1035

Nominal gain is defined as the average analog signal gain between the RF inputs of the IRD modules and the inputs to the samplers over the RF operating frequency for each band defined in Section 4.1. Its value is determined from the expected input signal characteristics and desired rms level at the sampler as follows:

$$G_{nom}(dB) = 10\log\frac{P_{out}}{P_{in}} = 10\log\frac{V_{rms}^2}{R_{out}kG_{FE}T_{FE}BW_{IF}}$$

$$= 10\log\frac{\left(\frac{N_{rms}FSR}{2^n-1}\right)^2}{R_{out}kG_{FE}T_{FE}BW_{IF}}$$

where N_{rms} is the target root-mean-square signal amplitude in sampler threshold levels, FSR is the full-scale range of the sampler, n is the bit resolution, R_{out} is the termination impedance at the sampler, k is Boltzmann's constant, G_{FE} is the cryogenic front-end gain, T_{FE}, is the cryogenic front-end equivalent noise temperature, and BW_{IF} is the 3dB IF bandwidth (not necessarily the alias-free bandwidth). Expected front-end gain and noise temperatures were taken from [RD04] and [RD05]. The target rms signal amplitude is 9 sampler thresholds for 8-bit sampling (~99% quantization efficiency).

The nominal setting of the internal step attenuators are determined post-fabrication as that setting which most closely achieves the desired gain. The modules will further be required to have enough attenuator control range leftover to meet the gain adjustability requirements in Section 4.4.3.

4.4.2 Gain Flatness

Parameter	Req. #	Value	Traceability
Gain Flatness	IRD0421	The analog gain shall vary by no more than 6.7 dB peak-to-peak over that 80% bandwidth defined in Section 4.3 Goal of less than 5 dB.	SYS1703
Gain Ripple	IRD0422	The analog gain shall vary by no more than 2.5 dB peak-to-peak over any 100 MHz range within the 80% bandwidth defined in Section 4.3	SYS1702
Band 1 Return Loss	IRD0423	The input return loss of the Band 1 IRD modules shall exceed 6 dB.	IRD0421, IRD0422

Parameter	Req. #	Value	Traceability
Band 2 Return Loss	IRD0424	The input return loss of the Band 2 IRD modules shall exceed 6 dB.	IRD0421, IRD0422
Band 3 Return Loss	IRD0425	The input return loss of the Band 3 IRD modules shall exceed 6 dB.	IRD0421, IRD0422
Band 4 Return Loss	IRD0426	The input return loss of the Band 4 IRD modules shall exceed 6 dB.	IRD0421, IRD0422
Band 5 Return Loss	IRD0427	The input return loss of the Band 5 IRD modules shall exceed 6 dB.	IRD0421, IRD0422
Band 6 Return Loss	IRD0428	The input return loss of the Band 6 IRD modules shall exceed 6 dB.	IRD0421, IRD0422

Gain flatness is the peak-to-peak variation over 80% of each IF band (defined in Section 4.3). Gain ripple is defined as the peak-to-peak variation over any 100 MHz bandwidth within that range.

The system requirements for gain flatness and ripple are 8 dB and 3 dB, respectively, with a flatness goal of 6 dB. No budget for sharing this allowance across subsystems has been given, but the numbers here are based on the following reasoning. First, note that IRD comprises roughly 60% of the net analog gain (up to 40 dB out of roughly 70 dB). However, several lossy signal-conditioning components such as mixers, filters, variable attenuators, and the solar-mode attenuators must be further compensated by gain stages in the IRD. Thus, the total of all *positive*-gain stages in the IRD is more like 70 dB (out of 100 dB). Thus, IRD assumes 70% of the allowed system gain tolerance in the root-sum-squares sense,

$$Flatness \leq \sqrt{0.7(8dB)^2} = 6.7dB$$

$$Ripple \leq \sqrt{0.7(3dB)^2} = 2.5dB$$

Ripples will also be affected by return loss, both of the IRD subsystem and the front-end. The exact impact will depend on the return loss of both subsystems, and as yet no allocation is provided, but a good place to start is the mismatch loss equivalent to the above allocated ripple of 2.5 dB. Allowing half that amount for return loss (leaving the rest of active components and the FE subsystem),

$$ML = -10\log\left[1 - \left(10^{\frac{-RL}{20}}\right)^2\right] = \frac{ripple}{2} = 1.25dB$$

$$\therefore RL = -10\log\left(1 - 10^{\frac{-ML}{10}}\right) = 6dB$$

Return loss at most frequencies may be significantly better than this, but isolated peaks may occur (especially in Band 6, where the available components are extremely limited) and the return loss requirement should not be made more restrictive than necessary, as achieving it across all frequencies will require input attenuators or isolators, at the cost of sensitivity.

4.4.3 Gain Adjustment

Parameter	Req. #	Value	Traceability
Gain Adjustment Range	IRD0431	The module gain shall be adjustable within a –12/+12 dB range of the nominal values given in Section 4.4.1	SYS1203
Gain Adjustment Step Size	IRD0432	The gain adjustment shall have a maximum step size of 1 dB	SYS1203

Analog gain shall be adjustable in discrete steps via integrated step attenuators or voltage-variable attenuators with discrete voltage control. Gain flatness and ripple requirements (IRD0421–0422) shall be met for all gain-adjustment states. The nominal setting of these attenuators shall be determined on a per module basis to most closely meet the nominal gain targets, with enough range left over to meet the requirements above. These adjustments along with the nominal instantaneous headroom given in Section 4.4.6 combine to provide the operational headroom implied by system requirement SYS1203.

An additional 30 dB attenuation may be available (in a single step) in the lower frequency bands to support solar observations, although the System Requirements do not explicitly necessitate it. No specifications on performance in this operational mode (e.g. noise temperature) are implied.

At present, it is assumed the extra attenuation for solar observation is not needed for the highest frequency band. As described in the system requirements, the source flux of the active sun has a frequency slope that reduces the power at high frequency. The required headroom for solar observation in Band can be estimated as the ratio of the sun at 6000K to the Band 6 mid-band system temperature of 75 K, or 19 dB. This should be within range of the Band 6 receiver implementation without an additional solar attenuator.

4.4.4 Gain Amplitude Stability

Parameter	**Req. #**	**Value**	**Traceability**
Gain Amplitude Temperature Stability	IRD0441	Gain fluctuations as a function of temperature shall not exceed (0.017 dB)/(0.4 K) under nominal environmental conditions (e.g. temperature regulation).	SYS4902, SYS4904
Gain Amplitude Fluctuations	IRD0442	Gain fluctuations dG/G shall not exceed 1e-3 over a 60 sec period, or 4e-3 over a 200 sec period at 1 MHz bandwidth resolution (TBC).	SYS1601, SYS4601, SYS4604

Gain amplitude stability is required to reach the ngVLA's ultimate sensitivity goals, as well as to enable a low-overhead calibration policy in which bandpass and gain solutions for each antenna and receiver are stored for use in subsequent observations. The temperature stability of gain amplitude shall apply at any point in the pass-band, and shall be met under nominal environmental conditions (especially temperature gradient, 0.4K per 200 seconds) given in Section 4.8.1. Thus, the net gain temperature stability is required to be

$$\Delta G(dB) = 10\log\left(1 + \left[\frac{0.01}{K}\right][0.4K]\right) = 10\log(1.004) = 0.017dB$$

Although temperature is not the only driver of gain changes, it is expected to be the dominant cause for IRD. Power supply fluctuations are another common source of gain changes, but the power supplies will be internally regulated by IRD for the purposes of isolation and EMC immunity, as well as specific bias setting, and this is expected to mitigate that substantially.

There is not currently a system budget allocating overall gain fluctuations to the impacted subsystems. The complete system-level Allan variance requirements are included here as a placeholder.

4.4.5 Gain Phase Stability

Parameter	Req. #	Value	Traceability
Band 1 Phase Stability	IRD0451	The band 1 analog phase shall vary by no more than 15 degrees (absolute) in 300 seconds under nominal environmental conditions (e.g. temperature regulation).	SYS5001
Band 2 Phase Stability	IRD0452	The band 2 analog phase shall vary by no more than 15 degrees (absolute) in 300 seconds under nominal environmental conditions (e.g. temperature regulation).	SYS5001
Band 3 Phase Stability	IRD0453	The band 3 analog phase shall vary by no more than 15 degrees (absolute) in 300 seconds under nominal environmental conditions (e.g. temperature regulation).	SYS5001
Band 4 Phase Stability	IRD0454	The band 4 analog phase shall vary by no more than 15 degrees (absolute) in 300 seconds under nominal environmental conditions (e.g. temperature regulation).	SYS5001
Band 5 Phase Stability	IRD0455	The band 5 analog phase shall vary by no more than 15 degrees (absolute) in 300 seconds under nominal environmental conditions (e.g. temperature regulation).	SYS5001
Band 6 Phase Stability	IRD0456	The band 6 analog phase shall vary by no more than 15 degrees (absolute) in 300 seconds under nominal environmental conditions (e.g. temperature regulation).	SYS5001
Phase Residual	IRD0457	The rms phase delay residual for any band after subtraction of a linear trend over 300s shall be no more than 59 fsec or 0.17 degrees (whichever is greater) under nominal environmental conditions (e.g. temperature regulation).	SYS5001, CAL0314

Gain phase stability is required to reach the ngVLA's ultimate sensitivity goals, as well as to enable a low-overhead calibration policy in which bandpass and gain solutions for each antenna and receiver are stored for use in subsequent observations. The stability of phase shall apply at any point in the pass-band, and shall be met under nominal environmental conditions (especially temperature gradient) given in Section 4.8.1. As described in the system-level requirements [AD02], the phase drift specification has both an absolute part and an rms residual, after subtraction of any linear trend over the specified time period.

The drift to be measured here is inclusive of contributions from the LO and digitizer clocks, and is thus based on the root-sum-square of allocations to the appropriate subsystems in [AD02]:

$$\tau_{absolute} = \sqrt{0.25^2 + 0.25^2} = 0.35\, psec$$

$$\tau_{residual} = \sqrt{42^2 + 42^2} = 59\, fsec$$

Band 1 is direct-sampled and has no LO to contribute to phase drift, but the systems requirements do not make a case for holding the Band 1 integrated module to a higher standard because of this, so the same "combined" drift spec is applied to that band as well.

Finally, although system requirement SYS5001 specify a drift *delay* in fsec, the documentation shows that it was derived from atmospheric effects at the highest RF frequency. For a signal path with frequency translations, from RF to baseband, it is the total phase *angle* that matters, as this equates to a particular delay at the sky frequency. We therefore assume the absolute phase delay spec should be translated to phase using 116 GHz as the equivalent frequency, and that this phase drift angle should apply equally to all receiver bands,

$$\varphi_{abs} \leq 2\pi f\tau = 2\pi(116\ GHz)(0.35\ psec) = 15\ degrees$$

There are other calibration requirements pertaining to the phase residual, however (e.g. CAL0314) that derive from considerations at 8 GHz. We use that frequency translate into phase at or below 8 GHz, and then linear with frequency up to 116 GHz. For example,

$$\varphi_{res} \leq 2\pi f\tau = 2\pi(8\ GHz)(59\ fsec) = 0.17\ degrees$$

4.4.6 Dynamic Range

Parameter	Req. #	Value	Traceability
Band 1 Headroom	IRD0461	The analog band 1 dynamic range shall have a minimum of 26 dB headroom to the 1 dB compression point, and 56 dB headroom to IIP3, with nominal attenuator settings.	SYS1201, SYS1206
Band 2 Headroom	IRD0462	The analog band 2 dynamic range shall have a minimum of 26 dB headroom to the 1 dB compression point, and 52 dB headroom to IIP3, with nominal attenuator settings.	SYS1201, SYS1206
Band 3 Headroom	IRD0463	The analog band 3 dynamic range shall have a minimum of 23 dB headroom to the 1 dB compression point, and 51 dB headroom to IIP3, with nominal attenuator settings.	SYS1201, SYS1206
Band 4 Headroom	IRD0464	The analog band 4 dynamic range shall have a minimum of 22 dB headroom to the 1 dB compression point, and 49 dB headroom to IIP3, with nominal attenuator settings.	SYS1201, SYS1206
Band 5 Headroom	IRD0465	The analog band 5 dynamic range shall have a minimum of 21 dB headroom to the 1 dB compression point, and 47 dB headroom to IIP3, with nominal attenuator settings.	SYS1201, SYS1206
Band 6 Headroom	IRD0466	The analog band 6 dynamic range shall have a minimum of 6 dB headroom (20 dB desired) to the 1 dB compression point, and 41 dB headroom to IIP3, with nominal attenuator settings.	SYS1201, SYS1206

Headroom in this document is defined as the difference between the expected noise power level and the worst-case 1 dB compression point or the IIP3 point in the IRD signal path with nominal attenuator settings (see Section 4.4.3).

4.4.7 Phase Match

Parameter	Req. #	Value	Traceability
Band 1 Phase Match	IRD0471	The differential phase between the signal paths of each Band 1 IRD module shall not drift by more than 0.035 deg rms under nominal environmental conditions (e.g. temperature regulation).	CAL03014

Parameter	Req. #	Value	Traceability
Band 2 Phase Match	IRD0472	The differential phase between the signal paths of each Band 2 IRD module shall not drift by more than 0.1 deg rms under nominal environmental conditions (e.g. temperature regulation).	CAL03014
Band 3 Phase Match	IRD0473	The differential phase between the signal paths of each Band 3 IRD module shall not drift by more than 0.35 deg rms under nominal environmental conditions (e.g. temperature regulation).	CAL03014
Band 4 Phase Match	IRD0474	The differential phase between the signal paths of each Band 4 IRD module shall not drift by more than 0.59 deg rms under nominal environmental conditions (e.g. temperature regulation).	CAL03014
Band 5 Phase Match	IRD0475	The differential phase between the signal paths of each Band 5 IRD module shall not drift by more than 0.88 deg rms under nominal environmental conditions (e.g. temperature regulation).	CAL03014
Band 6 Phase Match	IRD0476	The differential phase between the signal paths of each Band 6 IRD module shall not drift by more than 2 deg rms under nominal environmental conditions (e.g. temperature regulation).	CAL03014

System-level polarization dynamic range requirements demand that the phase delay associated the linear polarization channels are matched to a precision of 80 fsec. This is converted to degrees of phase in the above requirements using the worst-case frequency of each band. For example, in Band 2,

$$\Delta\theta = f\tau = (3.5GHz)(80fs) = 0.1deg$$

4.5 Sensitivity

Parameter	Req. #	Value	Traceability
Band 1 Noise Temperature	IRD0501	The band 1 equivalent noise temperature shall not exceed 1000 K.	SYS1011
Band 2 Noise Temperature	IRD0502	The band 2 equivalent noise temperature shall not exceed 1000 K.	SYS1011, SYS1012
Band 3 Noise Temperature	IRD0503	The band 3 equivalent noise temperature shall not exceed 1000 K.	SYS1012
Band 4 Noise Temperature	IRD0504	The band 4 equivalent noise temperature shall not exceed 1000 K.	SYS1012
Band 5 Noise Temperature	IRD0505	The band 5 equivalent noise temperature shall not exceed 1000 K.	SYS1012
Band 6 Noise Temperature	IRD0506	The band 6 equivalent noise temperature shall not exceed 1500 K.	SYS1013

These noise temperatures ensure that the warm electronics contribute less than 1K to the system noise temperature, assuming the cryogenic input stage has approximately 30 dB gain (an exception is made for Band 6 for which amplifiers meeting the required noise, gain, bandwidth, and dynamic range simultaneously are not available). Noise temperature shall be measured by Y-factor over the integrated noise of the IF bandwidth with the internal step attenuators at nominal setting.

4.6 *Spurious Signals/Radio Frequency Interference Generation*

Spurious signals in this document may include any unwanted signal power (aside from in-band noise) that leak into the signal path. These may include image bands, alias bands, and spurious CW or narrowband tones.

4.6.1 Image Rejection

Parameter	Req. #	Value	Traceability
Uncalibrated Image Rejection	IRD0611	The downconverting IRD modules as-built shall achieve uncalibrated image rejection greater than 7 dB.	ICD with DBE
Band 2 Image Rejection	IRD0612	Band 2 calibration measurements shall provide coefficients sufficient to achieve calibrated image rejection greater than 30 dB.	SYS1704
Band 3 Image Rejection	IRD0613	Band 3 calibration measurements shall provide coefficients sufficient to achieve calibrated image rejection greater than 30 dB.	SYS1704
Band 4 Image Rejection	IRD0614	Band 4 calibration measurements shall provide coefficients sufficient to achieve calibrated image rejection greater than 30 dB.	SYS1704
Band 5 Image Rejection	IRD0615	Band 5 calibration measurements shall provide coefficients sufficient to achieve calibrated image rejection greater than 30 dB.	SYS1704
Band 6 Image Rejection	IRD0616	Band 6 calibration measurements shall provide coefficients sufficient to achieve calibrated image rejection greater than 30 dB.	SYS1704

Image rejection shall be measured with calibrated corrections applied, over the full gain adjustment range. Although sideband separation will ultimately be performed in the digital backend, the level of image rejection achieved will depend on the accuracy of the calibration measurements performed by IRD, which will as a byproduct test the compliance with these metrics. It is likely, however, that the corrective implementation in the DBE (a FIR filter in the time-domain) will differ from that used in IRD measurements (frequency-domain). A mathematical translation of the measured calibration coefficients into those needed by the DBE shall be required. The uncalibrated image rejection level (IRD0611) is included to support the design of the DBE functionality. Assuming both implementations are mathematically correct, the same level of performance represented in IRD0612–0616 should be achievable.

4.6.2 Alias Rejection

Parameter	Req. #	Value	Traceability
Band 1 Alias Rejection	IRD0621	Band 1 alias rejection shall exceed 40 dB	SYS1704, SYS6106
Band 2 Alias Rejection	IRD0622	Band 2 alias rejection shall exceed 40 dB	SYS1704, SYS6106
Band 3 Alias Rejection	IRD0623	Band 3 alias rejection shall exceed 40 dB	SYS1704, SYS6106
Band 4 Alias Rejection	IRD0624	Band 4 alias rejection shall exceed 40 dB	SYS1704, SYS6106
Band 5 Alias Rejection	IRD0625	Band 5 alias rejection shall exceed 40 dB	SYS1704, SYS6106
Band 6 Alias Rejection	IRD0626	Band 6 alias rejection shall exceed 40 dB	SYS1704, SYS6106

At present, no system-level requirement specific to aliasing has been given. The most phenomenologically similar spectral purity metric which is called out specifically is sideband separation, SYS1704, which has a minimum rejection requirement of 30 dB, and a goal of 40 dB. Alternatively, SYS6106 specifies minimum emissive spectral dynamic range as 50 dB, but this does not directly translate into spectral purity (the presence of a spurious signal does not necessarily effect the dynamic range of nearby frequency channels). The relative value of the sideband-separation requirement (30 dB) supports this interpretation.

Also, as noted in [AD02], fringe washing (which applies to aliasing in most cases as effectively as it does to sideband separation) will provide ~20 dB attenuation, and another ~20 dB may be obtained via LO and sampler clock offsets. We therefore believe it is safe to adopt an alias-rejection level of 40 dB (equivalent to the sideband separation goal).

These rejection levels apply to the anti-aliasing-filtered IF bandwidths defined in Section 4.3. The rejection, in turn, is measured relative to the corresponding in-band gain.

4.6.3 Spurious Narrowband Tones

Parameter	Req. #	Value	Traceability
Spurious Tone Power	IRD0631	Self-generated signals shall not exceed –43 dB/MHz relative to the system noise level.	SYS2104

Spurious tones in this context refers to any narrowband spurious signal, regardless of its source (e.g., mixing products, clock harmonics, switching transients, oscillations). The relative "spurious power" in a given spectral bin will be calculated as $(P–N)/N$, where P is the total power in the bin and N is the average power in the adjacent two bins. The bin size will be chosen as large as possible to include broad spurs, while narrow enough to exclude microscale baseband ripples to >10 dB below the spec limit.

4.6.4 Radiated Emission Limits

Parameter	Req. #	Value	Traceability
Spurious Emission	IRD0641	Spurious signals emitted by the IRD modules shall not exceed the equivalent isotropic radiated power limits specified in EMC0310.	EMC0310
Emission Verification	IRD0642	Spurious signals emitted by the IRD modules shall be verified by test in the range specified by EMC0311.	EMC0311
Low Frequency Emission	IRD0643	Spurious signals emitted by the IRD modules below the verification frequency range shall nevertheless be measured for informational purposes.	EMC0312

4.7 Digitization

4.7.1 Sample Rate

Although the system requirements do not directly imply any particular sample rate from the IRD modules, the requirements for bit resolution (SYS1034–SYS1035), along with the requirement to minimize life cycle costs (SYS2802), and the IRD team's estimation of the technological readiness of fiber optic transceiver technologies, all combine to drive the sample rate as a design decision. Specifically, 56 Gbps transceivers are now sufficiently mature and fit well with feasible sample rates. Faster serial streams (e.g. 112 Gbps) are less mature and would imply ADC sample rates that are probably impractical at this stage, while slower serial streams, say 28 Gbps, would roughly double the number of modules required per antenna. Thus, we elect to sample at 7 GS/s for 8-bit sampling (7 GS/s*8 bits/sample = 56 Gbps).

We are not listing this as a requirement, as other solutions are possible, but we leave the discussion here as the design decision does ultimately trace from the system-level requirements for bit resolution and cost optimization.

4.7.2 Bit Resolution

Parameter	Req. #	Value	Traceability
Band 1 Bit Resolution	IRD0721	Band 1 shall be sampled to a depth of 8 bits	SYS1034
Band 2 Bit Resolution	IRD0722	Band 2 shall be sampled to a depth of 8 bits	SYS1034
Band 3 Bit Resolution	IRD0723	Band 3 shall be sampled to a depth of 8 bits	SYS1034
Band 4 Bit Resolution	IRD0724	Band 4 shall be sampled to a depth of 8 bits	SYS1034
Band 5 Bit Resolution	IRD0725	Band 5 shall be sampled to a depth of 8 bits	SYS1034
Band 6 Bit Resolution	IRD0726	Band 6 shall be sampled to a depth of 8 bits	SYS1035

Note that these represent the bit resolution format at the front-end exclusive of nonlinearity and distortion, not the effective number of bits (ENOB). The correlator may requantize these data streams at lower or higher resolution levels (with appropriate care for sensitivity and dynamic range).

As described in [RD06], ENOB and the related Signal-to-Noise and Distortion ratio (SINAD) are empirically derived performance metrics that assume a particular input signal (usually, in commercial datasheets, a strong injected tone at a specified frequency, with wideband noise far below the 9 rms sampler thresholds we are targeting as described in Section 4.4.1). One must be careful, then, in applying these metrics to radio astronomy, where the input spectra are typically quite different. Nevertheless, careful consideration in [RD06] of dynamic range requirements and typical digitizer behaviors (as in how performance with a tone relates to performance with wideband noise) have led to the following *guidelines*:

$$ENOB^* \geq \begin{cases} 7.35 & Bands\ 1-5 \\ 5.2 & Band\ 6 \end{cases}$$

where ENOB* is a modified form of the effective number of bits which applies to traditional SNR instead of SINAD (thus neglecting distortion). As described in [RD06], these guidelines are based on the experiences of previous telescopes (including, esp., the EVLA) as well as anticipated changes in the future RFI environment. The most significant of those changes is the expected proliferation of low-orbiting satellite constellations, effecting Bands 2–5, and the prevalence of vehicular radar in Band 6. Differences in the headroom required to deal with those two sources of interference are what led to the differing required ENOB numbers quoted above.

We have thus selected 8 bits as the common sampling depth for all six bands, for which the above performance measures should be readily achievable. These and other specific requirements for the Serial Analog-to-Digital Converter (SADC) which is integral to the IRD work package shall be included as part of the development contract for that component.

4.8 Environmental Conditions

All functional and performance specifications given herein are to be met at nominal operating conditions, while basic functionality is required over the limiting operational conditions.

4.8.1 Normal Operating Conditions

Parameter	Req. #	Value	Traceability
Nominal Temperature	IRD0811	IRD performance requirements shall be met for ambient temperatures within –15 C ≤ T ≤ 35 C	ENV0323
Nominal Temperature Gradient	IRD0812	IRD performance requirements shall be met for ambient temperature gradients (as measured on the temperature controlled surface on the outside of the IRD module housing) not exceeding 0.4K in 200 seconds	SYS4904

Verification tests shall be considered successful if the measurement passes while environmental conditions are within the ranges of the nominal operating conditions, unless otherwise explicitly stated. No extraordinary measures will be taken "exercise" the system over all corners of the environmental parameter space (nor will any be taken to meet more stringent environmental conditions than these).

4.8.2 Limiting Operational Conditions

Parameter	Req. #	Value	Traceability
Limiting Temperature	IRD0821	The IRD modules shall remain basically functional for ambient temperatures within –20 C ≤ T ≤ 45 C	ENV0332
Limiting Temperature Gradient	IRD0822	The IRD modules shall remain basically functional for ambient temperature gradients not exceeding 3.6°C/Hr.	ENV0324

The limiting operational conditions define the ranges over which basic functionality is assured without necessarily meeting specifications. They are not intended to define safe storage or working limits beyond which permanent damage may occur (these will be described in Sections 4.8.3–4.8.5).

4.8.3 Survival Conditions

Parameter	Req. #	Value	Traceability
Survival Temperature	IRD0831	The IRD modules shall survive exposure, when installed on the antenna, to ambient temperatures in the range –30C ≤ T ≤ 50C	ENV0342
Thermal Shutdown	IRD0832	The IRD modules will shut down when temperatures exceeding a safe level have been detected.	IRD0831

Temperatures of critical components inside the IRD modules may be significantly higher than ambient conditions. The exact tripping point for thermal shutdown implied in IRD0832 may therefore be different from the range specified in IRD0831.

4.8.4 Transportation Conditions

Parameter	Req. #	Value	Traceability
Transportation Temperature	IRD0841	The IRD modules shall survive exposure during transportation to ambient temperatures in the range –30C ≤ T ≤ 60C	ENV0382
Vibration	IRD0842	The IRD modules shall be designed to withstand vibrations when installed in the Antenna Electronics LRU consistent with ENV0531.	ENV0531

4.8.5 Storage Conditions

Parameter	Req. #	Value	Traceability
Storage Temperature	IRD0851	The IRD modules shall survive storage at ambient temperatures in the range 0C ≤ T ≤ 30C	ENV0372
Storage Humidity	IRD0852	The IRD modules shall survive storage at relative humidity in the range 10% ≤ RH ≤ 90%	ENV0373

4.8.6 Mechanical Shock

Parameter	Req. #	Value	Traceability
Mechanical Shock	IRD0861	The IRD modules shall survive mechanical shock levels, while installed in the Antenna Electronics LRU, as defined in ENV0582.	ENV0582

4.8.7 Electrostatic Discharge (ESD) Requirements

Parameter	Req. #	Value	Traceability
ESD Immunity	IRD0871	The IRD modules shall survive ESD testing, while installed in the Antenna Electronics LRU, as defined in EMC0473.	EMC0473

The ESD Direct Contact Discharge requirement EMC0473 specifies that the devices are assumed to be enclosed in any provided enclosures, as they would be found in the operational environment. For IRD, this means that they are mounted within the appropriate bins in the Antenna Electronics LRU. Most importantly, connectors to the IRD modules are not exposed, but connected to the appropriate interfacing systems (unused test point connectors are capped with shorting plugs).

4.8.8 Power Supply Quality

Parameter	Req. #	Value	Traceability
Line Regulation	IRD0881	IRD Performance requirements shall be met when the power supply inputs to the modules are externally regulated (level TBD).	IRD0442
Power Supply Tolerance	IRD0882	The IRD modules shall tolerate power supply variations ±10% from nominal while fully functional.	ETR0823
Overvoltage Limit	IRD0883	The IRD modules shall survive power supply excursions up to 20% above nominal.	ETR0818

Power supply line regulation is required to meet gain stability requirements.

4.9 Monitor & Control Requirements

Parameter	Req. #	Value	Traceability
IF Signal Monitors	IRD0902	The integrated modules shall measure and report total IF signal power entering each digitizer channel.	SYS3101

Parameter	Req. #	Value	Traceability
Remote Identification	IRD0903	The integrated modules shall report the following information to the M&C system, to the extent applicable, upon request: 1. Module/Model Number (e.g. "Band 3") 2. Serial Number 3. CID Number 4. Hardware Revision Level 5. Software Revision Level 6. Firmware Revision Level	ETR0403
Standby Mode	IRD0904	The integrated modules shall be capable of entering a low-power standby mode on command. M&C communications shall still be functional in this mode.	ETR0810
Automatic Initialization	IRD0905	The integrated modules shall automatically boot into a nominal operational mode on power-up, absent any command from M&C.	ETR0811
Fast Read-Out	IRD0906	The M&C interface shall be fast enough to support streaming of diagnostic data.	SYS3105
Temperature Sensor	IRD0907	The IRD modules shall measure and report internal temperature.	IRD0821

The monitor points (IRD0902) may comprise raw voltages or digital values in arbitrary units, subject to appropriate scaling and translation to recover meaningful values. No specific precision or accuracy is implied in these requirements. The anticipated implementation of these monitors are logarithmic amplifiers, which provide superior readout range greater than 40 dB, and fast readout on the order of 100 ns. They may be used in early commissioning for pointing and tracking tests of the first antennas prior to a working (auto)correlator.

It should be noted that a number of system requirements exist which describe the desired functionality of line-replaceable units (LRU) — for example SYS3012 for the generation of alerts, SYS3110 for the generation of support tickets, and SYS3111 to enable hot-swapping. The IRD subsystem is not considered an LRU in the ngVLA, so no direct flowdown is given for these requirements except when some particular functionality is needed in the IRD modules to support the LRU requirement (such as IRD0906, discussed below).

No onboard memory is provided in the IRD modules for monitor and control outputs, but the fast read-out requirement (IRD0906) is intended to enable diagnostic "oscilloscope" functionality (SYS3105) orchestrated by the M&C subsystem. The system requirement applies to an LRU, which in this case is the complete Antenna Electronics package. It is expected that the monitor and control interface board (MIB) will poll the IRD modules at a rate necessary to deliver the functionality required in SYS3105.

Remote identification information (IRD0903) shall be provide to the extent applicable. In addition to those items listed, ETR0403 additionally calls for the "UID and IUID from Physical tracking tag or device," but such devices are only required at the LRU level (which the IRD modules are not) as stated in ETR0402.

4.10 Mass and Physical Dimensions

Parameter	Req. #	Value	Traceability
Physical Dimensions	IRD1001	Each integrated module shall fit within a physical envelope measuring 40 x 80 x 160 mm in size.	SYS2403

Parameter	Req. #	Value	Traceability
Mass	IRD1002	Each integrated module shall weigh less than 1.5 kg.	SYS2403
Connector Orientation	IRD1003	RF input connectors/flanges shall be located at one end of the physical envelope above, while the outputs and LO, clock, bias, and M&C inputs shall be located at the opposite end.	SYS2403
Mounting Holes	IRD1004	Each integrated module shall include at least four clear holes (sized for M2.5 metric screws) oriented to mount against a temperature-controlled surface in contact with the largest face of the above physical envelope.	IRD0441, IRD0451–0456

SYS2403 calls for the modularization of antenna systems into Line Replaceable Units (LRUs) to facilitate site maintenance. The small physical size (IRD1001) and mass (IRD1002) of the IRD modules, along with the ease of their integration with connected subsystems through direct-line signal paths (IRD1003) are considered enabling factors in allowing the fully integrated antenna electronics package to be a practical LRU.

The availability of a large mating surface to the temperature control system (IRD1004) is essential to achieving the amplitude (IRD0441) and phase (IRD0451–IRD0456) stability requirements.

4.11 Maintenance and Reliability Requirements

Parameter	Req. #	Value	Traceability
Mean Time Between Maintenance	IRD1101	MTBM ≥ 18,519 hrs. (TBC)	SYS2610

The maintenance and reliability requirements are in support of high-level requirements that limit the total operating cost of the array. SYS2610 places a limit upon the antenna electronics of 1500 hours between maintenance activities. The ngVLA System Technical Budget spreadsheet [AD05] further provides an allocation to the IRD subsystem of 18,519 hours.

The number of hours indicated refers to operational hours, independent of operating mode.

4.12 Lifecycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	IRD1201	The integrated modules shall be designed to be operated and supported for a period of 30 years.	SYS2801
Cost Optimization	IRD1202	The IRD design shall minimize its lifecycle cost for 20 years of operation.	SYS2802
Sustainability	IRD1203	Sustainability and long-term environmental impact shall be considered in any material or design trade-study.	SYS2803
Part Selection for Maintainability	IRD1204	Individual component selection criteria shall include the projected continuity of support for the component or interchangeable equivalents over the system design life.	SYS2805

Parameter	Req. #	Value	Traceability
Critical Spares	IRD1205	Critical spares shall be identified and provided with sufficient inventory to support the facility for its operational life.	SYS2812

Lifecycle costs include manufacturing, transportation, construction/assembly, operation, and decommissioning. Critical spares are defined as parts that are likely to be obsoleted over the operating life, are unlikely to have market substitutes, and cannot be produced/ordered in small volumes.

5 Safety

5.1 General

Parameter	Req. #	Value	Traceability
Safety Specification	IRD5101	The integrated module designs shall comply with the System Safety Specification.	SYS2700

5.2 Safety Design Requirements

5.2.1 Electrical Safety

Electrical equipment installed on the antenna shall comply with their relevant international or US product standard.

Electrical installations and equipment shall be specifically built and/or derated in order to safely perform their intended functions under the applicable environmental conditions.

5.2.2 Handling, Transport, and Storage Safety

The design of the Integrated Receivers and Digitizers shall incorporate all means necessary to preclude or limit hazards to personnel and equipment during assembly, disassembly, test, and operation.

Parameter	Req. #	Value	Traceability
ESD Packaging and Storage	IRD5221	The IRD modules shall be packaged, shipped, and stored in ESD protective packaging and/or equipped with shorting plugs and conductive caps on all external connections. These items shall only be sealed and opened at ESD safe workstations.	ETR0503

6 Requirements for Design

6.1 Analyses and Design Requirements

6.1.1 Reliability, Availability, Maintainability Analysis

A Reliability, Availability, Maintainability analysis shall be performed in order to locate weak design points and to determine whether the design meets the Maintenance and Reliability requirements. ngVLA suggests to apply the Parts Count Method for predicting the reliability of the system as described in the MIL-HDBK-217F, but the designer may propose to use other methods.

Another, but more time consuming (and considered more accurate) method, the Parts Stress Analysis Prediction, is also described in MIL-HDBK-217F. This may be used if the result of the Parts Count Method does not comply with the Maintenance and Reliability requirements.

The ngVLA equipment will typically operate at an elevation of 2200m above sea level, where temperature and pressure might decrease the MTBF relative to that at low elevations. These conditions shall be taken into specific account in the reliability prediction by using the environmental factor given in MIL-HDBK-217F.

The analysis shall result in estimates of the Mean Time Between Failures (MTBF), the Mean Time To Repair (MTTR), assuming that any scheduled preventive maintenance is performed.

6.2 Electromagnetic Compatibility Requirements

The IRD modules shall be designed to minimize self-generated RFI. This is integral to the design of the housing, which isolates the analog and digital functions to the maximum extent possible, and shall be demonstrated by the long-integration tests necessary to verify the restrictive requirement on spurious tone power (IRD0631). High-frequency PCBs, especially those incorporating high-speed digital circuitry, shall also be subject to signal-integrity analysis to minimize emissions, leakage, and cross-talk.

Parameter	Req. #	Value	Traceability
EMC/RFI Design Considerations	IRD6201	The IRD modules shall be designed to minimize self-generated RFI and to ensure electromagnetic compatibility (EMC) with ngVLA systems. High-speed digital PCBs shall undergo rigorous signal integrity analysis.	ETR0714

6.3 Materials, Parts, and Processes

6.3.1 Fasteners

Parameter	Req. #	Value	Traceability
Metric Fasteners	IRD6311	All external fasteners, such as mounting holes for the integrated modules, shall be metric. Industry standard interfaces, such as coaxial connector threads and hex nut sizes, and waveguide flange screws, as well as fasteners internal to the integrated modules, may use non-metric units.	ETR1161

6.3.2 Housings and Connectors

Parameter	Req. #	Value	Traceability
Housing Labels	IRD6321	The IRD module housings shall be labelled with the band designation and housing serial number. These may be cross-referenced with the unique identification numbers provided over the M&C interface in accordance with IRD0903.	ETR0403
RF Connector Labels	IRD6322	Each RF connector shall be labeled on the outside of the IRD module.	ETR1185
M&C Pinouts	IRD6323	M&C connectors that are common to multiple IRD modules shall have a standardized pinout.	ETR1142

Parameter	Req. #	Value	Traceability
Power Pinout	IRD6324	Power connectors that are common to multiple IRD modules shall have a standardized pinout.	ETR1142

It is anticipated that power and M&C connections to the IRD modules will be ganged on a common multipin cable and connector. Whether or not this is the case, these connectors shall have standard pinouts (IRD6323, IRD6324) to prevent incorrect mating and allow for use of shared test cabling.

6.3.3 Electrical Wiring

The ngVLA Systems Electronics Specifications [AD04] restrict the colors of wire used to carry specific signals and power supply voltages [ETR1103–1124], but exempts multi-conductor cables from these requirements. All connections to the IRD modules shall be either RF coaxial, waveguide, fiber-optic, or multi-conductor, and are thus exempted from these coloring requirements.

7 Printed Circuit Boards (PCBs)

7.1 Substrate Materials

Parameter	Req. #	Value	Traceability
Standard PCB Substrate Material	IRD7101	Default material for printed circuit boards in the IRD modules that do not require high-frequency or low-loss operation shall be FR-4.	ETR0702
High-Performance PCB Substrate Material	IRD7102	In cases where high-frequency and or low-loss performance is required, a so-called "soft substrate" or microwave laminate such Rogers RO4350B, Duroid 6006, Cuflon, Megtron-6, or other similar material may be used.	ETR0702

7.2 Plating/Surface Finish

Parameter	Req. #	Value	Traceability
Standard PCB Plating/Surface Finish	IRD7201	Default plating/surface finish for PCBs in the IRD modules that do not require wire bondability or extremely low loss shall be Electroless Nickel/Immersion Gold (ENIG).	ETR0704
Bondable / low-loss PCB Plating / Surface Finish	IRD7202	In cases where wire bondability is required, or where high-frequency loss is critical, PCBs shall use Electroless Nickel/Electroless Palladium/Immersion Gold (ENEPIG) or immersion silver surface finish/plating.	ETR0704

7.3 Soldermask and Silkscreen

The ngVLA System Electronics Specifications [AD04] restrict the types and colors of solder masks used (depending on revision level) as well as the content of silkscreen labels and alignment marks. However, exceptions are permitted where high-frequency analog performance may preclude the use of a solder mask (e.g. in a mm-wave soft substrate bonded to a MMIC chip), or where the board may be too small or dense to permit the use of silkscreen markings. Many small substrates are used in the IRD modules that fit within these exempted categories, while others are more conventional in design and can follow the stricter guidelines.

Parameter	Req. #	Value	Traceability
Solder Mask Color	IRD7301	PCBs in IRD modules that utilize a solder mask shall conform to the revision-dependent color sequence described in the ngVLA System Electronics Specifications [AD04].	ETR0707
PCB Markings/ Silkscreen	IRD7302	PCBs in IRD modules that utilize a silkscreen shall conform to the marking and fiducial requirements described in the ngVLA System Electronics Specifications [AD04].	ETR0706, ETR0716, ETR0708, ETR0713

8 Programmable Devices

8.1 Firmware Upgradeability

Parameter	Req. #	Value	Traceability
Firmware Updates	IRD8101	Firmware for each IRD module shall be upgradeable remotely through the M&C interface.	ETR0907

Firmware within the IRD module shall be updated through an external SPI bus from the monitor and control interface board (MIB).

8.2 Self-Test

Parameter	Req. #	Value	Traceability
Self-Test	IRD8201	The IRD modules shall perform self-tests and/or advanced diagnostics upon request of the M&C system.	ETR0910, ETR0911

The ngVLA Systems Electronics Specifications [AD04] call for electronic devices with M&C capability to perform self-tests at an appropriate time period left to the designer (ETR0910). Due to the sensitive nature of the signal path running through the IRD subsystem, it makes little sense for the IRD modules to have the autonomy to perform self-tests at its own discretion, even potentially during an observation. (While the analog and digital segments of the IRD modules are designed with isolation and stability of performance in mind, it is still an integral part of the design concept that any transient, intermittent, or irregular digital activity, not directly associated with digitizing streaming data, should be kept to a minimum, or avoided altogether.) A more logical approach is to perform such tests at a time when one can be confident they will not interfere with telescope operation, say immediately before and immediately after an observation, which can only be commanded through the M&C interface.

9 Documentation Requirements

9.1 Technical Documentation

All documentation related to the Integrated Receivers and Digitizers shall meet the following requirements.

- The language used for written documentation shall be English.
- Drawings shall be generated according to ISO standards and use metric units.
- Layouts of electronic circuits and printed circuit boards shall also be provided in electronically readable form. The ngVLA preferred formats are Altium Designer files for electronic circuit diagrams and printed circuit board layouts.
- The electronic document formats are Microsoft Word and Adobe PDF.
- The preferred CAD system used is AutoDesk Inventor and/or AutoCAD.

Any deviation from the above shall be agreed to by ngVLA.

10 Verification and Quality Assurance

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, although the primary (final) verification method is identified below.

Req. #	Parameter / Requirement	A	I	D	T
IRD0101	Band 1 RF Frequency			*	
IRD0102	Band 2 RF Frequency			*	
IRD0103	Band 3 RF Frequency			*	
IRD0104	Band 4 RF Frequency			*	
IRD0105	Band 5 RF Frequency			*	
IRD0106	Band 6 RF Frequency			*	
IRD0107	Band 1 Low-Frequency Support		*		
IRD0202	Band 2 LO Frequencies			*	
IRD0203	Band 3 LO Frequencies			*	
IRD0204	Band 4 LO Frequency			*	
IRD0205	Band 5 LO Frequencies			*	
IRD0206	Band 6 LO Frequencies			*	
IRD0301	Band 1 output Bandwidth				*
IRD0302	Band 2 IF Bandwidth				*
IRD0303	Band 3 IF Bandwidth				*
IRD0304	Band 4 IF Bandwidth				*
IRD0305	Band 5 IF Bandwidth				*
IRD0306	Band 6 IF Bandwidth				*
IRD0411	Band 1 Nominal Gain				*

Req. #	Parameter / Requirement	A	I	D	T
IRD0412	Band 2 Nominal Conversion Gain				*
IRD0413	Band 3 Nominal Conversion Gain				*
IRD0414	Band 4 Nominal Conversion Gain				*
IRD0415	Band 5 Nominal Conversion Gain				*
IRD0416	Band 6 Nominal Conversion Gain				*
IRD0421	Gain Flatness				*
IRD0422	Gain Ripple				*
IRD0423	Band 1 Return Loss				*
IRD0424	Band 2 Return Loss				*
IRD0425	Band 3 Return Loss				*
IRD0426	Band 4 Return Loss				*
IRD0427	Band 5 Return Loss				*
IRD0428	Band 6 Return Loss				*
IRD0431	Gain Adjustment Range				*
IRD0432	Gain Adjustment Step Size			*	
IRD0441	Gain Amplitude Temperature Stability				*
IRD0442	Gain Amplitude Fluctuations				*
IRD0451	Band 1 Phase Stability				*
IRD0452	Band 2 Phase Stability				*
IRD0453	Band 3 Phase Stability				*
IRD0454	Band 4 Phase Stability				*
IRD0455	Band 5 Phase Stability				*
IRD0456	Band 6 Phase Stability				*
IRD0457	Phase Residual				*
IRD0461	Band 1 Headroom			*	
IRD0462	Band 2 Headroom			*	
IRD0463	Band 3 Headroom			*	
IRD0464	Band 4 Headroom			*	
IRD0465	Band 5 Headroom			*	
IRD0466	Band 6 Headroom			*	
IRD0471	Band 1 Phase Match				*
IRD0472	Band 2 Phase Match				*
IRD0473	Band 3 Phase Match				*
IRD0474	Band 4 Phase Match				*
IRD0475	Band 5 Phase Match				*
IRD0476	Band 6 Phase Match				*
IRD0501	Band 1 Noise Temperature				*
IRD0502	Band 2 Noise Temperature				*
IRD0503	Band 3 Noise Temperature				*
IRD0504	Band 4 Noise Temperature				*
IRD0505	Band 5 Noise Temperature				*
IRD0506	Band 6 Noise Temperature				*
IRD0611	Uncalibrated Image Rejection				*
IRD0612	Band 2 Image Rejection				*
IRD0613	Band 3 Image Rejection				*
IRD0614	Band 4 Image Rejection				*

Req. #	Parameter / Requirement	A	I	D	T
IRD0615	Band 5 Image Rejection				*
IRD0616	Band 6 Image Rejection				*
IRD0621	Band 1 Alias Rejection			*	
IRD0622	Band 2 Alias Rejection			*	
IRD0623	Band 3 Alias Rejection			*	
IRD0624	Band 4 Alias Rejection			*	
IRD0625	Band 5 Alias Rejection			*	
IRD0626	Band 6 Alias Rejection			*	
IRD0631	Spurious Tone Power				*
IRD0641	Spurious Emission				*
IRD0642	Emission Verification				*
IRD0643	Low Frequency Emission				*
IRD0721	Band 1 Bit Resolution			*	
IRD0722	Band 2 Bit Resolution			*	
IRD0723	Band 3 Bit Resolution			*	
IRD0724	Band 4 Bit Resolution			*	
IRD0725	Band 5 Bit Resolution			*	
IRD0726	Band 6 Bit Resolution			*	
IRD0811	Nominal Temperature				*
IRD0812	Nominal Temperature Gradient				*
IRD0821	Limiting Temperature				*
IRD0822	Limiting Temperature Gradient				*
IRD0831	Survival Temperature				*
IRD0832	Thermal Shutdown				*
IRD0841	Transportation Temperature				*
IRD0842	Vibration				*
IRD0851	Storage Temperature				*
IRD0852	Storage Humidity				*
IRD0861	Mechanical Shock				*
IRD0871	ESD Immunity				*
IRD0881	Line Regulation				*
IRD0882	Power Supply Tolerance				*
IRD0883	Overvoltage Limit				*
IRD0902	IF Signal Monitors			*	
IRD0903	Remote Identification			*	
IRD0904	Standby Mode			*	
IRD0905	Automatic Initialization			*	
IRD0906	Fast Read-Out			*	
IRD0907	Temperature Sensor			*	
IRD1001	Physical Dimensions		*		
IRD1002	Mass			*	
IRD1003	Connector Orientation		*		
IRD1004	Mounting Holes		*		
IRD1101	Mean Time Between Maintenance	*			
IRD1201	Design Life	*			
IRD1202	Cost Optimization	*			

Req. #	Parameter / Requirement	A	I	D	T
IRD1203	Sustainability	*			
IRD1204	Part Selection for Maintainability	*			
IRD1205	Critical Spares	*			
IRD5101	Safety Specification	*			
IRD5221	ESD Packaging and Storage		*		
IRD6201	EMC/RFI Design Considerations	*			
IRD6311	Metric Fasteners		*		
IRD6321	Housing Labels		*		
IRD6322	RF Connector Labels		*		
IRD6323	M&C Pinouts		*		
IRD6324	Power Pinout		*		
IRD7101	Standard PCB Substrate Material		*		
IRD7102	High-Performance PCB Substrate Material		*		
IRD7201	Standard PCB Plating/Surface Finish		*		
IRD7202	Bondable / low-loss PCB Plating / Surface Finish		*		
IRD7301	Solder Mask Color		*		
IRD7302	PCB Markings/ Silkscreen		*		
IRD8101	Firmware Updates			*	

Table 1 - Expected requirements verification method.

11 Key Performance Parameters

This section provides Key Performance Parameters that should be estimated by the designer and monitored by NRAO throughout the design phase of the project. These are parameters that have a large influence on the eventual effectiveness of the facility, and are useful high-level metrics for trade-off decisions.

These parameters are of higher importance to NRAO. Improved performance above the requirement is desirable on these parameters. The impact on system-level performance is often discussed in the narrative in Section 4.

The technical requirements are generally specified as *minimum* values. The goal is to give the designer some latitude in optimization for a balanced design. Understanding the anticipated performance of the Integrated Receivers and Digitizers (not just its specified minimum) on these parameters is of value for system-level analysis and performance estimation.

These parameters may also be useful for determining the relative priority of the requirements documented in Section 4 and can assist in the required analysis should tensions be identified between requirements, or reductions in capability be required to fit within cost constraints.

The Key Performance Parameters that have been identified for monitoring are described in Table 2. Note that the order in the table reflects the order in the document, and is not indicative of relative importance or priority.

Key Performance Parameter	Req. #
Bands 1–6 output/IF Bandwidth	IRD0301–0306
Gain Flatness	IRD0421
Gain Ripple	IRD0422
Gain Adjustment Range	IRD0431

Key Performance Parameter	Req. #
Gain Amplitude Stability	IRD0441
Bands 1–6 Phase Stability	IRD0451–0456
Bands 1–6 Headroom	IRD0461–0466
Bands 1–6 Noise Temperature	IRD0501–0506
Bands 2–6 Image Rejection	IRD0612–0616
Bands 1–6 Bit Resolution	IRD0721–0726
Physical Dimensions	IRD1001
Mass	IRD1002

Table 2 - Key Performance Parameters for monitoring during design.

12 Appendix

12.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CDR	Critical Design Review
CoDR	Conceptual Design Review
CW	Continuous Wave (Sine wave of fixed frequency and amplitude)
EIRP	Equivalent Isotropic Radiated Power
EM	Electro-Magnetic
EMC	Electro-Magnetic Compatibility
EMP	Electro-Magnetic Pulse
ENOB	Effective Number of Bits
FDR	Final Design Review
FEA	Finite Element Analysis
FOV	Field of View
FWHM	Full Width Half Max (of Primary Beam Power)
HVAC	Heating, Ventilation & Air Conditioning
ICD	Interface Control Document
IF	Intermediate Frequency
IRD	Integrated Receivers and Digitizers, a.k.a. Integrated Downconverters and Digitizers, etc.
KPP	Key Performance Parameters
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LO	Local Oscillator
LRU	Line Replaceable Unit
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
ngVLA	Next Generation VLA
RD	Reference Document
RFI	Radio Frequency Interference
RMS	Root Mean Square
RSS	Root of Sum of Squares

Acronym	Description
RTP	Round Trip Phase
SAC	Science Advisory Council
SADC	Serial Analog-to-Digital Converter
SINAD	Signal-to-Noise and Distortion ratio
SNR	Signal to Noise Ratio
SRSS	Square Root Sum of the Square
SWG	Science Working Group
TAC	Technical Advisory Council
TBD	To Be Determined
VLA	Jansky Very Large Array

12.2 Maintenance Definitions

12.2.1 Maintenance Approach

Required maintenance tasks shall be minimized.

Maintenance shall be mainly performed at assembly and subassembly level by exchange of Line Replaceable Units (LRUs). LRUs are defined as units which can be easily exchanged (without extensive calibration, of sufficient low mass and dimension for ease of handling, etc.) by maintenance staff of technician level.

LRU exchange shall be possible by two trained people within four working hours. It is desirable that LRU replacement be possible using only standard tools identified in a maintenance manual for the appropriate subsystem. A step-by-step procedure for safe exchange of every LRU shall be provided in the Maintenance Manual.

LRUs shall be defined by the Integrated Project Team, depending on the design. It is anticipated that the IRD modules shall be components within the larger front-end electronics LRU specific to the Antenna Electronics IPT. The LRUs will be maintained by the ngVLA project (with or without industrial support).

12.2.2 Periodic Preventive Maintenance

Preventive maintenance may be performed at planned intervals in order to keep the Integrated Receivers and Digitizers operational and within their specified performance. Any required preventive maintenance should be documented in the Maintenance Manual.