Central Signal Processor: Preliminary Technical Requirements

020.40.00.00.00-0001-REQ-A-CSP_PRELIM_TECH_REQS

Status: **RELEASED**

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Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2017-11-22	R. Selina	All	Started first draft/outline using ngVLA Antenna Specifications as a template.
02	2017-12-06	O. Ojeda	3.3, 3.4	Elaboration of high-level requirements.
03	2017-12-28	R. Selina	3, Appendix	Added Reference Observing Program (Appendix). Updated N_{chan}, etc. Broadened from correlator to central signal processor. Reorganized specs in section 3 to add clarity.
04	2018-03-19	O. Ojeda	1 thru 4	Revamped to adopt NRC's FSA.
05	2018-03-23	O. Ojeda	All	Further elaboration. Section 4.6 onwards mainly. Ready for discussion and approval.
06	2018-04-20	O. Ojeda	All	Included NRC's feedback. Some requirement numbers have changed.
07	2018-05-25	O. Ojeda	All	Included NRC's revision of previous version. Defined CSP Observing Modes and the document structure adapted.
08	2018-09-10	O. Ojeda	All	Accommodated the Long Baseline Array (LBA) option, as well as new scope from the ngVLA Reference Observing Program and new versions of Science and System Requirements.
09	2018-11-08	O. Ojeda	All	Implemented Internal Review Meeting feedback.
A	2019-07-31	A. Lear	All	Incorporated minor edits by M. McKinnon. Prepared PDF for approvals and release.

Table of Contents

1 Introduction

1.1 Purpose

This document aims to present a *preliminary* set of technical requirements for the ngVLA Central Signal Processor (CSP).

These requirements flow down from the preliminary ngVLA System Requirements [AD01], which in turn flow-down from the preliminary ngVLA Science Requirements [AD02]. The Science goals elaborated by the Science Advisory Council (SAC) and Science Working Groups (SWGs) have been captured in a series of draft use cases described by the Reference Observing Program in the ngVLA Quantitative eXchange Model [AD03]. A preliminary analysis of these use cases, and the flow down recursively to the science, system and sub-system requirements, is reflected in these documents.

NRAO desires a cost-effective and flexible solution for the CSP. The optimization for value requires flexibility in key requirements until the cost and technical impact of the parameters are understood. These requirements are therefore considered *preliminary*, until refined through feedback with the CSP designer.

1.2 Scope

The scope of this document is the ngVLA central signal processor element. This consists of sub-elements, among which there are a correlator and beamformer (CBF) and a Pulsar Engine (PE). The sub-element required to configure, monitor, and control the CSP is not included in this preliminary requirements specification, as it is not deemed to be a cost driver or risk item. Supporting HVAC and electrical infrastructure is outside the scope of this specification, though coarse interface requirements have been defined. RFI shielding of the electronics is also outside the scope of the CSP element.

This specification establishes the ngVLA CSP performance, functional, design, and test requirements.

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 content of this technical specification, the content of this technical specification shall be considered as a superseding requirement.

Ref. No.	Document Title	Rev / Doc. No.
AD01	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ V3, 5/10/2018
AD02	ngVLA Science Requirements	020.10.15.00.00-0001-REQ V13, 4/4/2018
AD03	ngVLA Quantitative eXchange Model	Version 3.13, 8/8/2018.
AD04	Inclusion of the "Long Baseline Major Option" into the ngVLA Baseline Design	020.05.60.01.01-0002-ECO V0.05, 8/2/2018
AD05	ngVLA Time-Domain Correlator Considerations	P. Demorest, S. Ransom, 1/5/2018
AD06	ngVLA Operations Concept	020.10.05.00.00-0002-PLA
AD07	Protection Against Electric Shock – Common Aspects for Installation and Equipment	IEC 61140:2016
AD08	Insulation Coordination for Equipment within Low-Voltage Systems	IEC 60664
AD09	Occupational Safety and Health Standards for General Industry	29 CFR Part 1910
AD10	Military Handbook, Reliability Prediction of Electronic Equipment	MIL-HDBK-217F
AD11	Non-Electronic Parts Reliability Data	NPRD-95
AD12	Electromagnetic Compatibility	IEC 61000-3-5

2.2 Reference Documents

The following references provide supporting context:

Ref. No.	Document Title	Rev / Doc. No.
RD01	TRIDENT Correlator-Beamformer for the ngVLA Preliminary Design Specification	Rev. C, TR-DS-000001
RD02	A Next Generation Very Large Array	Murphy, E. (2017). Proc. IAU, 13(S336), 426-432
RD03	An Integrated Receiver Concept for the ngVLA	ngVLA Memo No. 29
RD04	Initial Imaging Tests of the Spiral Configuration	ngVLA Memo No. 41
RD05	Pulsar Timing Array Requirements for the ngVLA	ngVLA Memo No. 42
RD06	Discovery of Three Pulsars From a Galactic Center Pulsar Population	doi:10.1088/0004-637X/702/2/L177
RD07	Understanding Massive Star Formation through Maser Imaging	Hunter, Todd R., et al. (2018) arXiv:1806.06981
RD08	Interferometry and Synthesis in Radio Astronomy	https://link.springer.com/book/10.1007/978-3-319-44431-4
RD09	USGS Coterminous US Seismic Hazard Map – PGA 2% in 50 Years	ftp://hazards.cr.usgs.gov/web/nshm/conterminous/2014/2014pga2pct.pdf

2.3 Terminology

For a correct interpretation of this document, it is important to provide clear definitions of some terms, which are identified by capital letters. The following table gathers these terms and their definitions.

Term	Definition
Digitized Wideband Signal	The digital signal received from each of the antennas in the (sub-)array that is available at the CSP input.
Function Mode	Each of the modes in which one Frequency Slice Processor can operate. It applies only to the CBF sub-system of the CSP, which is based on NRC's FSA [RD01]. A tentative list of FSP Function Modes is • Correlation • VLBI • Pulsar–TrueDelay–4beam • Pulsar–TrueDelay–10beam • Pulsar–PhaseDelay–100beam
Observation	An instance of the ngVLA operation that involves one sub-array and one Observing Mode.
Observing Mode	Each of the modes in which the CSP can be configured for each Observation independently. The different Observing Modes are • Synthesis Imaging • Sparse Pulsar Timing • Offline Pulsar Search • VLBI
Reference Observing Program (ROP)	A collection of reference use cases which are gathered in [AD03] and in Section 12.
Spectral Window	The band of frequencies extracted from the Digitized Wideband Signal to be processed in one Observation.
Zoom Window	In the Synthesis Imaging Observing Mode, a band of frequencies within a Spectral Window with smaller channel bandwidth.

3 Overview of the Central Signal Processor Technical Requirements

3.1 Document Outline

This document presents the technical specifications of the ngVLA CSP element. These parameters determine the overall form and performance of the CSP. Traceability of these specifications to those specified by [AD01] or [AD02] is indicated when applicable.

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 CSP concept.

Requirements pertinent to interfacing systems are described in Section 5. Initial requirements are noted by interface, along with identified parameters for Interface Control Documents (ICDs) that will fully define the interfaces as the design progresses.

Safety requirements applicable to both the design phase and the functional CSP are described in Section 6. Additional requirements for the design phase are described in Section 7. 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 9.

Section 10 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 General Central Signal Processor Description

The CSP ingests the voltage streams digitized and packetized by the digital backend at the antennas, and transmitted via the data transmission system, and produces a number of low-level data products to be ingested by the archive.

In addition to cross-correlation and auto-correlation capabilities, the CSP will support further capabilities required of modern telescopes to enable VLBI and time-domain science. Specifically, the CSP must operate in at least four different Observing Modes depending on the required data product:

- **Synthesis Imaging**: The CSP computes all spectral auto- and cross-correlation functions, including cross-polarizations within a sub-array.
- **(Dense/Sparse) Pulsar Timing**: The CSP generates an average pulse profile per frequency channel per beam. Timing information must be implicit or explicitly preserved along with the profiles. There are two Pulsar Timing Observing Modes: Sparse and Dense. The difference between them is the number of average pulse profiles that are generated per sub-array. Each of these two Observing Modes finds application for sparse or dense pulsar populations in the sky, which lead to different beamforming requirements.
- **Offline Pulsar Search**: In this Observing Mode the CSP outputs all four Stokes parameters at a given time-frequency resolution. In order to minimize telescope observation time, multiple simultaneous

beams are generated and subsequently stored for offline processing. It is anticipated that an "Online" Pulsar Search Observing Mode might be developed in future for commensal serendipitous searches.

- **VLBI**: Additionally, this VLBI Observing Mode is thought to operate the ngVLA as a single VLBI station within a larger network. Within this mode, several beam-channels can be generated and the resulting voltage stream stored in one of the VLBI standard formats.

These Observing Modes reveal the need for some sub-elements: a correlator, a beamformer, and a pulsar engine (to compute pulsar profiles). The correlator and the beamformer are most efficiently implemented as an integrated sub-element. Therefore, the CSP is composed of a Correlator and Beamformer (CBF) and a Pulsar Engine (PE), besides other ancillary sub-elements that will be dealt with in the future (currently out of the scope of this document). The CSP is not responsible for calibration of the beamformer, and when applicable, supporting visibilities generated with this purpose are processed outside the CSP.

NRC's architecture designated the Frequency Slice Architecture (FSA) is currently under consideration for implementation of the CBF. An ngVLA CBF reference design based on this architecture is described in detail in [RD01]. In the FSA, the CBF splits the wideband input streams into narrower oversampled signals, known as Frequency Slices. These Frequency Slices are processed by independent Frequency Slice Processors (FSPs). Each FSP has the capacity to process any one selectable Frequency Slice, for all antennas in the array, or portion thereof for any sub-array (unless otherwise stated). Additionally, each FSP may be configured to operate in any one FSP Function Mode.

The CSP will support multiple simultaneous sub-arrays. A key requirement for the CSP is the degree of simultaneity supported both within a sub-array and across all sub-arrays. By means of NRC's FSA, an FSP processes one select Frequency Slice in one Function Mode. In general, one Function Mode serves to only one Observing Mode (although this is not mandatory). Therefore, the number of FSPs operating in one Function Mode will determine the maximum bandwidth that any sub-array can devote to the associated Observing Mode.

3.3 Summary of CSP Functional Requirements

The following table provides a summary of the major CSP requirements in order to provide the reader with a high-level view of the desired system and for quick reference. Full requirement descriptions can be found in Sections 4 through 8. Should there be a conflict between the requirements listed here and the descriptions in those sections, the latter shall take precedence.

3.3.1 General Functional Specifications

Parameter	**Summary of Requirement**	**Reference Reqs.**
Maximum Number of Antennas	263 antennas	CSP0111
Maximum Bandwidth per Observation	20 GHz per polarization	CSP0121
Spectral Window Bandwidth Selection	200 MHz	CSP0122
Spectral Window Tuning Step	4 MHz	CSP0123
Maximum Aggregate Bandwidth (Simultaneous Observing Modes)	28 GHz, per polarization	CSP0124
Discontinuous Spectral Windows	Supported. Sub-bands narrower than 1 GHz	CSP0125
Minimum Efficiency	98.6%	CSP0131
Maximum Data Transport Delay	250 ms (any antenna to the central facility)	CSP0141
Maximum Array Diameter	10,000 km	CSP0142
Phase-Center Location	Within the smallest circle encompassing the sub-array	CSP0143

Parameter	Summary of Requirement	Reference Reqs.
Packet-Loss Tolerance	Supported	CSP0144
Spectral Leakage	–50 dB (total power, broadband input)	CSP0151
Channel Flatness	0.37 dB (peak to peak)	CSP0152
Channel Gain Correction	Supported	CSP0153
Number of Sub-Arrays	≥10	CSP0181
Sub-Array Independence	Fully supported	CSP0182

3.3.2 Synthesis Imaging Observing Mode Requirements

Parameter	Summary of Requirement	Reference Reqs.
Channel Bandwidth	1 kHz to 7.2 MHz	CSP0221
Number of Channels	750,000	CSP0222
Zoom Capabilities	Supported	CSP0223
Zoom Window Tuning Step	Non-zoomed channel bandwidth	CSP0224
Integration Time	2 ms to 10 s	CSP0225
Number of Simultaneous Phase Reference Positions	≥10	CSP0231
Maximum Slew Rate	2.5 arcmin per second	CSP0232

3.3.3 Pulsar Timing Observing Modes Requirements

Parameter	Summary of Requirement	Reference Reqs.
Number of Beams	10, full array	CSP0321
Number of Sub-Arrays (Outer)	1	CSP0322
Number of Sub-Arrays (Non-Core)	1 to 3	CSP0323
Number of Sub-Arrays (Full Array)	1 to 5	CSP0324
Polarization Calibration	–13 dB (cross-polarization)	CSP0331
Pulsar Timing Accuracy	≤ 2% RMS error increase	CSP0611
Dedispersion Measure Range	0–4,000 pc cm^{-3}	CSP0621
Pulse Period Range	1 ms–30 s	CSP0631
Number of Bins	2,048	CSP0632
Folding Integration Time	1–10 s	CSP0633

3.3.4 Offline Pulsar Search Observing Mode Requirements

Parameter	Summary of Requirement	Reference Reqs.
Number of Beams	10	CSP0421
Maximum Offset from Boresight	0.5”	CSP0422
Number of Antennas	168	CSP0423
Maximum Sub-Array Diameter	30 km	CSP0424
Polarization Calibration	–13 dB (cross-polarization)	CSP0431

3.3.5 VLBI Observing Mode Requirements

Parameter	Summary of Requirement	Reference Reqs.
Number of Beams	3	CSP0521
Number of Sub-Arrays	3, full array	CSP0522
Polarization Calibration	–13 dB (cross-polarization)	CSP0541
Beam-Channel Tuning Resolution	2 kHz	CSP0552
Beam-Channel Sampling Rate	2, 4, 8, …, 256, 448 MS/s	CSP0553
Beam-Channel Format	VDIF	CSP0554

3.3.6 Interface Requirements

Parameter	Summary of Requirement	Reference Reqs.
Interface to DTS	6 inputs at ≥80 Gbps	CSP2101 CSP2102 CSP2103
Interface to the Archive	150 outputs at 40 Gbps	CSP2201 CSP2202
Interface to Time & Frequency Reference Distribution System	100 MHz reference 1 PPS reference	CSP2501 CSP2502

4 Central Signal Processor Functional and Performance Requirements

These requirements apply to a properly functioning system, for an **RFI-free input** and under the normal operating environmental conditions defined in Section 4.6.1, unless otherwise stated.

4.1 General Functional Specifications

The requirements in this Section apply to **all CSP Observing Modes**.

4.1.1 Connected Antennas

Parameter	Req. #	Value	Traceability
Maximum Number of Antennas	CSP0111	The CSP shall support inputs from at least 263 dual-polarization antennas.	

The current array configuration concept clearly defines a 263-antenna ngVLA, arranged as 214 antennas for the main array, 19 antennas for the SBA (Short Baseline Array), and 30 antennas for the LBA (Long Baseline Array). No spare inputs have been required. Rather, a modular scalable design is preferred.

A preliminary configuration for the 214 18m main array can be found in [RD04]. It consists of 94 antennas within a 1-km radius (the "core"), an additional 74 antennas forming a spiral within a 30-km radius (the "spiral"), and an additional 46 antennas extending to distances of hundreds of km from the core.

4.1.2 Processed Bandwidth and Simultaneous Observing Modes

Refer to Section 2.3 for a definition of "Observation" and Spectral Window.

Parameter	Req. #	Value	Traceability
Maximum Bandwidth per Observation	CSP0121	The CSP shall support a maximum bandwidth per Observation of at least 20 GHz per polarization.	SYS0903

This requirement is intended to specify the maximum bandwidth that will be required by a single Observation. If needed, all CSP resources can be devoted to that single Observation. Thus, the CSP designer is free to trade off bandwidth when the CSP operates simultaneously in more than one Observing Mode. Additionally, the maximum number of frequency channels might limit the maximum bandwidth achievable at the finest frequency resolution as well. A bandwidth of at least 20 GHz is only required for the Synthesis Imaging use cases of the ROP. Beamforming Observing Modes will not need this amount of bandwidth (the maximum bandwidth found in the ROP is 8.8 GHz for any beamforming mode) as all use cases operate at the lower frequency bands. However, processing 20 GHz of bandwidth in Pulsar Timing Observing Mode might be desirable in future [AD01], and hence a scalable design as well.

Parameter	Req. #	Value	Traceability
Spectral Window Bandwidth Selection	CSP0122	The CSP shall select the bandwidth of an Observation's Spectral Window in steps less than or equal to 200 MHz and independently from other simultaneous Observations.	SYS0905 SYS0907

The CSP has to adjust the bandwidth of the Spectral Window so that the number of channels can be adjusted according to the Observation needs. This is intended to help controlling the output data rate.

System Requirements [AD01] specify a coarsest sub-band granularity of 1 GHz, with a goal of 200 MHz.

Parameter	Req. #	Value	Traceability
Spectral Window Tuning Step	CSP0123	The CSP shall tune the Spectral Window in steps less than or equal to 4 MHz.	

The goal here is to minimize the number of CSP sub-bands that a frequency band of interest extends across. Note that the receiver LO frequency is slightly tunable and could perform this task. Nonetheless, in some cases it might be preferable doing it digitally. The specified tuning step, 4 MHz, translates to steps of 4,000 channels at their narrowest bandwidth of 1 kHz.

Parameter	Req. #	Value	Traceability
Maximum Aggregate Bandwidth (Simultaneous Observing Modes)	CSP0124	The CSP shall support a maximum aggregate bandwidth of at least 28.8 GHz per polarization across different Observing Modes running simultaneously.	SCI0010

SCI0010 requires all sub-arrays to operate at their full specification. Achieving that goal with NRC's FSA would lead to an FSP part able to process 80-GHz bandwidth (20-GHz of bandwidth in each Observing Mode), or at least 44 GHz (20 GHz in Synthesis Imaging plus 8 GHz for each of the three beamforming Observing Modes). This would result in excessive cost and power dissipation, although it is fundamentally possible.

The justification for the value of 28.8 GHz derives from the relaxation of the requirement to at least support 20-GHz bandwidth in Synthesis Imaging Observing Mode, in addition to 8.8-GHz bandwidth in one of the beamforming Observing Modes (e.g., for simultaneous pulsar timing using full Band 2).

Parameter	Req. #	Value	Traceability
Discontinuous Spectral Windows	CSP0125	The CSP shall support discontinuous Spectral Windows, as far as the maximum aggregate bandwidth is not exceeded. This capability allows selecting which sub-bands are transmitted and/or processed, whose bandwidth cannot be greater than 1 GHz.	SYS0905 SYS0907

The current version of System Requirements [AD01] includes the capability to select any sub-band within the digitized spectral bandwidth, specifically the capability to process the top and bottom of ngVLA Band 6 (70–116 GHz). The required granularity is 1 GHz, with a 200-MHz goal.

4.1.3 Signal to Noise Ratio Efficiency

Parameter	Req. #	Value	Traceability
Minimum Efficiency	CSP0131	The SNR at the output of the CSP shall be at least 98.6% of what could be ideally obtained for the same input signal.	SYS1033

This accounts for sensitivity losses due to diverse non-ideal operations such as quantization, non-ideal filtering and decimation, etc. It also includes any inaccuracies the CSP may incur, such as in delay tracking or phase-delay beamforming. Sensitivity losses not attributable to the CSP are not included, e.g., due to inaccurate beamforming coefficients, which are computed externally to the CSP. As a reference, 4-bit quantization efficiency is better than 98.8%, so this requirement should be feasible.

The required efficiency is obtained by distributing equal weight to the ADC, the Digital Back-End (DBE), and the CSP, in order to satisfy the digital system efficiency required by SYS1033 in [AD01], which is 96%. No significant loss is expected after the CSP. This allows (close to ideal) 4-bit quantization both at the ADC and the DBE.

A detailed SNR efficiency budget should be developed in future versions to guarantee satisfaction of this requirement. This document requires 99.9% efficiency for each individual operation at the CSP that may incur an SNR loss. Up to 14 independent operations can be carried out successively at that efficiency level before violating the overall CSP requirement.

4.1.4 Delay Compensation

Parameter	Req. #	Value	Traceability
Maximum Data Transport Delay	CSP0141	The CSP shall compensate for instrumental delay differences between antennas up to at least 250 ms.	

This accounts for data transport delays mainly. The value has been taken from [AD04] for up to approximately 5,000-km data links. Once the data transport system is defined, this requirement should be revisited.

Parameter	Req. #	Value	Traceability
Maximum Array Diameter	CSP0142	The CSP shall compensate for geometric and atmospheric delays for pairwise distance between antennas of up to 10,000 km.	

The maximum geometric delay in 10,000-km [RD02] baselines is 3.3 ms, which is small compared to estimated data transport delays.

Parameter	Req. #	Value	Traceability
Phase-Center Location	CSP0143	The CSP shall locate the phase center of each sub-array anywhere within the smallest circle encompassing the sub-array.	SYS0602

SYS0602 requires phase stability regardless of sub-array elements, which can be obtained by providing a phase-center location independent of the sub-array configuration.

Parameter	Req. #	Value	Traceability
Packet-Loss Tolerance	CSP0144	The CSP shall be tolerant of packet loss in communication of data from the antennas.	

This capability is required by [AD04]. By "tolerant" it is understood that the CSP will operate at its full specification (within what would be theoretically feasible) under any kind of packet loss in the data transport system.

4.1.5 Spectral Performance

Parameter	Req. #	Value	Traceability
Spectral Leakage	CSP0151	For a spectrally flat input, the total leaked power from all spectral components spaced more than half the channel spacing away from the center frequency of one channel output, shall be at least 50 dB less than the power from the spectral components within the passband of that same channel output.	SCI0115

This applies to all CSP data products: visibilities, pulse profiles, Stokes parameters and VLBI channels[1]. The channel passband is defined by the half-power points, which must be located at half the channel spacing from the center frequency due to channel flatness requirements when averaging adjacent channels. This requirement is achieved through a combination of both a sharp transition band and high stopband attenuation.

Parameter	Req. #	Value	Traceability
Channel Flatness	CSP0152	The peak-to-peak ripple within the central 80% of the passband of any channel output shall be less than 0.37 dB.	SYS1033 SYS1701 SYS1702 SYS1703

This requirement applies to all CSP data products: visibilities, pulse profiles, Stokes parameters and VLBI channels. It also applies to channels produced by channel averaging or zooming modes. As a result, the channel edge response must be controlled as well. Channels require approximately –3 dB gain at their edges to ensure approximately uniform response across channels.

As the value provided in SYS1702, ±1.5 dB, accounts mainly for analog signal processing, the value in this requirement has been obtained by imposing a 99.9% SNR efficiency due to a non-flat channel for a spectrally flat input signal. The approximate maximum ripple can be computed as:

$$R = 5\log_{10}\left(\frac{1+2\eta\sqrt{1-\eta^2}}{2\eta^2-1}\right)\ \mathrm{dB}$$

where η is the desired SNR efficiency. For $\eta = 0.999$, the maximum ripple becomes ±0.19 dB. This is more stringent than what is obtained by assuming a sinusoidal ripple [RD08]:

$$R = 20\log_{10}\left(1+\sqrt{\frac{2\eta^2-1-\eta\sqrt{3\eta^2-2}}{1-\eta^2}}\right)\ \mathrm{dB}$$

which results in ±0.27 dB.

[1] It would be desirable to develop separate requirements for each Observing Mode, as the spectral dynamic range is only specified for observing emission lines.

Parameter	Req. #	Value	Traceability
Channel Gain Correction	CSP0153	The CSP shall output all overall channel gains for any input.	SYS1701 SYS1702 SYS1703

In practice, the full bandwidth flatness is not critical as long as it is corrected by subsequent processing, which is the motivation for requiring outputting the channel gains. In fact, it is beneficial to allow variable channel gains for processing colored (spectrally non-flat) inputs optimally.

However, channel flatness requirements across spectrally averaged channels impose some constraints on the individual channel gains.

The CSP need not correct its output for the channel gains, but shall provide the means to do it. Future versions shall include the required accuracy.

4.1.6 Sideband Separation

Because of the DBE adapter between the ADC and the CSP, it is not clear at this moment that both sidebands will be made available to the CSP, preventing it from applying any digital sideband separation technique other than in the proximity of the sub-band containing IF zero. Future versions of this document shall specify the required rejection ratio, and which sub-bands must be processed.

4.1.7 RFI Mitigation

RFI detection performance shall be specified through a collection of use cases as a result of an ngVLA RFI study. The RFI detectors generate a flag-bit signal in sync with the data stream. This signal may or may not be used by subsequent signal processing blocks to prevent processing concurrent data.

System requirement SYS0702 specifies that the CSP shall provide the archive of all information necessary to generate flagging tables. These tables should be readily generated from the channel quality measure.

4.1.8 Sub-Array Requirements

Parameter	Req. #	Value	Traceability
Number of Sub-Arrays	CSP0181	The CSP shall support at least 10 sub-arrays operating simultaneously.	SYS0601
Sub-Array Independence	CSP0182	The CSP shall support independent sub-array configuration.	SCI0010

Refer to the discussion under aggregate bandwidth requirement CSP0124 for full compliance with SCI0010.

4.2 Synthesis Imaging Observing Mode

All requirements in this section apply only to the Synthesis Imaging Observing Mode.

4.2.1 Definition

When operating in the Synthesis Imaging Observing Mode, the CSP computes all auto and cross-correlation products (or visibilities) between the antenna inputs within a sub-array.

A sub-array is defined as any arbitrary set of antennas, including the set of all antennas. However, it is not clear yet whether heterogeneous sub-arrays will be required.

4.2.2 Temporal and Spectral Resolutions

Parameter	Req. #	Value	Traceability
Channel Bandwidth	CSP0221	The channel bandwidth shall be selectable within the range from 1 kHz to 7.2 MHz in steps less than or equal to one octave.	SYS1401

Except for Zoom Windows (see CSP0223 and Section 2.3), the channel bandwidth is the same across the entire processed bandwidth. One octave seems a sufficiently fine step to cover the channel bandwidth range.

The maximum channel bandwidth is obtained from the Reference Observing Program in Section 12; while the minimum bandwidth from SYS1401, i.e., 1 kHz/channel. There is a desired goal (SYS1401) of reaching a minimum of 400 Hz/channel.

The ratio between maximum and minimum bandwidths is 7,200. This can be achieved, for instance, through zoom factors up to 128 and channel averaging factors up to 60 channels, with a native channel bandwidth of 128 kHz. Relaxing the required channel averaging factors could lead to prohibitive output data rates.

Parameter	Req. #	Value	Traceability
Number of Channels	CSP0222	The CSP shall compute and output visibilities for up to 750,000 frequency channels at all frequency resolutions.	SYS1402

This is (coarsely) the minimum number of channels needed to comply with the Reference Observing Program in Section 12. This requirement is subject to not exceeding the maximum bandwidth. Considering the maximum bandwidth limit (20 GHz), only channel bandwidths smaller than 26.7 kHz can exceed the maximum number of channels.

Parameter	Req. #	Value	Traceability
Zoom Capabilities	CSP0223	Within each sub-band, the CSP shall be able to generate one or more nonoverlapping Zoom Windows with finer (than non-zoomed) spectral resolution. The bandwidth of each Zoom Window shall be independently selectable in steps of 1,000 channels or less.	KSG3-006

This requirement enables a zoom feature within a more coarsely channelized observation. This capability has been dropped in current Science and System Requirements, but seems still part of ngVLA Key Science Goal 3.

A use case used as a reference for the definition of this requirement is [RD07]. The total number of Zoom Windows is not specified by higher-level requirements. However, it is understood that this number must be limited in practice. As no Zoom Window is included in the Reference Observing Program (see Section 12), [RD07] has been used as a reference instead. This zoom feature is not intended as a way of exceeding the maximum number of channels, which the CSP is required to satisfy across the entire Spectral Window, including any number of Zoom Windows it might contain.

Trading observation bandwidth off in order to satisfy this requirement is deemed an affordable compromise. For example, a sub-band can be processed twice at two different resolution, which forces another sub-band not to be processed.

Parameter	Req. #	Value	Traceability
Zoom Window Tuning Step	CSP0224	The CSP shall tune each Zoom Window with a tuning step less than or equal to the non-zoomed channel bandwidth.	

It is assumed that the CSP correlator will have the capability to select what frequency channels are zoomed, what is the rationale behind the chosen tuning step.

Parameter	Req. #	Value	Traceability
Integration Time	CSP0225	The CSP shall support visibility integration times ranging from 2 ms to 10 s, configurable in steps smaller than or equal to one octave.	SYS2001

There is a trade-off between the maximum integration time and maximum baseline length, which is limited by circumferential smearing. In order to keep the smearing low, a rule of thumb is to keep the integration time well below [RD08]:

$$\left(\omega_e D_\lambda \theta_f\right)^{-1}$$

where ω_e is the Earth's rotation angular velocity, D_λ is the baseline length in wavelength units, and θ_f is the angular size of the sky image. For the 18m main array, the maximum image size is approximately 1,000 km/18 m ≈ 60,000 synthesized beams.

This would lead to a conservative minimum integration time equal to 10% of the above expression, which would result in 20 ms. For the LBA, this value would be 10 times smaller, that is, 2 ms. However, the image sizes in the use cases of the Reference Observing Program are significantly smaller than 60,000 beams, so this requirement needs further revision as the LBA use cases have not been developed yet.

For the maximum integration time, it can be chosen so that the circumferential smearing and radial smearing effects are similar [RD08]. Then, the worst-case radial smearing (2.5-MHz channel bandwidth at 1.2 GHz) allows integration times on the order of 30 s long. However, a maximum integration time of 10 s is deemed long enough to sufficiently decrease the output data rate. Further integration, when needed, can be carried out external to the CSP. Note that the maximum raw visibility data rate at 10 s integration times, for the main array and maximum number of channels, is 55 GB/s at single precision.

Additionally, it can be deduced that shorter integration times will be likely constrained by the archive data rate in practice, and might be only achievable using sub-arrays or a reduced number of channels.

In Section 12, it is shown that the maximum output data rate required by the Reference Observing Program is at least 80 GB/s, which results from use cases with integration times much shorter than 10 s. Thus, increasing the integration time beyond 5 s would not reduce the maximum output data rate that must be supported.

4.2.3 Mosaics and On-the-Fly Mapping

Parameter	Req. #	Value	Traceability
Number of Simultaneous Phase Reference Positions	CSP0231	The CSP shall support up to at least 10 different phase reference positions (in the sky) in Synthesis Imaging Observation Mode.	

This requirement has been demanded in [AD04] in support of the LBA.

Parameter	Req. #	Value	Traceability
Maximum Slew Rate	CSP0232	The CSP shall support OTF mapping with full operational capability at slew rates up to 2.5 arcmin per second.	SCI0106

This requirement has been obtained from SCI0106 [AD02].

4.3 Pulsar Timing Observing Modes

All requirements in this section apply only to the CSP operating in both Sparse and Dense Pulsar Timing Observing Modes, unless otherwise stated.

4.3.1 Definition

Through the Pulsar Timing Observing Modes, the CSP computes a given number of "beams" at the CBF, which are further processed by the PE. The standard data products of this Observing Mode are pulsar profiles.

The difference between Sparse and Dense Pulsar Timing Observing Modes resides in the number of beams per sub-array that need to be generated. The purpose of the Dense Mode is to maximize the number of beams per sub-array, even at the cost of other observation parameters. It is intended for telescope time optimization in those cases where multiple pulsars fall within the antenna HPBW. On the contrary, the Sparse Pulsar Timing Observing Mode is aimed at those cases where a single pulsar is within the field of view. Then, the compromises made in the Dense Pulsar Timing Observing Mode to increase the number of beams are no longer required.

Currently, only the Sparse Pulsar Timing Observing Mode is required, although a future implementation of its "Dense" version is anticipated.

The additional processing performed at the PE that shall be supported includes

- Coherent dedispersion: Performed at each beam-channel to correct for propagation through the dispersive medium.
- Channel stitching: Several contiguous beam-channels are combined together to generate a wider beam-channel.
- Conversion to Stokes parameters.
- Folding: Using a time-variant pulse period model, the Stokes parameters are accumulated at each pulse phase bin.

Although the standard result is the pulse profile, certain flexibility in the selection of the CSP data product is desirable.

4.3.2 Sub-Arrays and Number of Beams

Parameter	Req. #	Value	Traceability
Number of Beams	CSP0321	In Dense Pulsar Timing Observing Mode, the CSP shall support at least 10 different beams using the full array. Only one beam per sub-array is required in Sparse Pulsar Timing Observing Mode.	SYS0203

This requirement is in support of timing pulsars located in the Galactic Center (see Section 12). A goal of 50 beams is desired for globular clusters [AD05], but this is not currently required.

According to the Reference Observing Program, the required maximum bandwidth per beam is 8.8 GHz (full bandwidth of Band 2).

Note that at least one additional beam might be desired to facilitate the beamformer calibration while minimizing overheads.

Current FSP Function Modes are limited either in array diameter (phase-delay modes), number of beams, or number of antennas (true-delay) [RD01]. As a result, none of the FSP Function Modes can generate 10 beams for the full array. The decision on which FSP Function Mode is more suitable has to be done on a per Observation basis, depending on the required field of view, number of beams, sub-array configuration and ratio between bandwidth and number of available FSPs.

Although the ngVLA is a flexible sub-array oriented telescope, the following sub-array requirements is a non-exclusive list of explicit use cases that must be supported within Pulsar Timing Observing Mode as a guidance for the CSP designer (only in case general requirement CSP0181 cannot be met).

Parameter	Req. #	Value	Traceability
Number of Sub-Arrays (Outer)	CSP0322	In Pulsar Timing Observing Modes, the CSP shall support 1 sub-array made of the 46 outer antennas.	SYS0203 SYS0601

This capability enables Pulsar Timing Observations using the outer (main-array) antennas, which run simultaneously and independent of other Observation(s) using the spiral and core. More than one sub-array might be useful in low-sensitivity Observations (it is assumed that a 40-antenna sub-array will offer a sensitivity similar to the Robert C. Byrd Green Bank Telescope [RD05]).

Note that both Sparse and Dense Pulsar Timing Observing Modes shall be available for this "outer" sub-array. Thus, maximization of the number of beams in the Dense Pulsar Timing Observing Mode leads to a true-delay beamforming mode constrained in the number of antennas.

Parameter	Req. #	Value	Traceability
Number of Sub-Arrays (Non-Core)	CSP0323	In Pulsar Timing Observing Modes, the CSP shall support up to 3 sub-arrays when only the 120 non-core antennas are used.	SYS0203 SYS0601

The non-core antennas are the antennas located outside the ngVLA core, that is, the outer ones and those located at the 30-km radius spiral. This capability enables pulsar-timing Observations using the non-core antennas, simultaneous with other Observation(s) that use the core antennas only. More than three sub-arrays would be useful in low-sensitivity Observations.

Parameter	Req. #	Value	Traceability
Number of Sub-Arrays (Full Array)	CSP0324	In Pulsar Timing Observing Modes, the CSP shall support up to 5 sub-arrays for the full array.	SYS0203 SYS0601

This capability enables pulsar-timing observations when the 18-m main array is fully devoted to it. Support for more than five sub-arrays might not be required due to the associated sensitivity penalty [AD05]. However, satisfying the general requirement to support ten sub-arrays (CSP0181) might be desirable to optimize telescope time in low-sensitivity Observations. Conversely, a "full-array" true-delay FSP Function Mode could be desirable for high-sensitivity Observations.

4.3.3 Polarization Calibration

Parameter	Req. #	Value	Traceability
Polarization Calibration	CSP0331	The CSP shall apply calibration coefficients such that each cross-polarization beamformed pattern is at least 13 dB lower than its respective co-polarization pattern beam (within the main beam FWHM).	

This requirement is a placeholder for future versions of this document. The polarization calibration level required by [RD05] is at least 5% (–13 dB). This requirement shall be revisited after definition of cross-polarization antenna requirements.

4.3.4 Supporting Visibilities

It is a goal that the CSP shall compute and output ancillary visibilities for one select beam aimed at a calibrator. Such visibilities can be used for real-time calibration of the beamformer. Real-time calibration capabilities have been identified as most likely required by both [AD05] and [RD05]. Calibration based in simultaneous supporting visibilities should contribute towards SYS1061 objective, minimization of calibration overheads.

Computation of the beamforming coefficients shall be carried out externally to the CSP.

This real-time calibration concept is at an early stage. Future studies should define, for instance, the likelihood of finding suitable calibrators within the HPBW of the antenna, the minimum set of correlation products needed for an effective calibration, how fast beamforming coefficients need to be updated, etc. Moreover, visibility channel bandwidths and integration times might need to be restricted with respect to Synthesis Imaging Mode in order to support simultaneity within the same Observing Mode.

4.3.5 Pulsar Timing Accuracy

Parameter	Req. #	Value	Traceability
Pulsar Timing Accuracy	CSP0611	The CSP shall not increase the best achievable timing RMS error by more than 2% with respect to an ideal processor.	

CSP SNR loss, finite time resolution of the overall dedispersed beam-channel response, as well as the folding process incur a loss of pulsar timing accuracy. When computing the error increase, the ideal processor is constrained to the same beam-channel and pulse profile sampling times as the CSP.

4.3.6 Coherent Dedispersion

Parameter	Req. #	Value	Traceability
Dispersion Measure Range	CSP0621	The CSP shall support dispersion measures ranging from 0 to 4,000 pc cm^{-3}.	

Pulsars at the Galactic Center are expected to exhibit DM ≥ 1,500 pc cm^{-3} and even double this value [RD06]. Since these are only estimates, some margin has been added to the maximum value.

In practice, the complexity of implementing a dedispersion filter for a given DM is a function of the radio frequency. In addition, Observations requiring high DM values are more likely to be carried out at high frequencies. Thus, it might be desirable to set an upper DM limit as a function of frequency.

CSP channel flatness requirements apply to the output of the dedispersed beam-channel.

4.3.7 Folding Performance

Parameter	Req. #	Value	Traceability
Pulse Period Range	CSP0631	The CSP shall support pulse periods ranging from 1 ms to 30 s.	

The required pulse period range has been defined in [AD05].

Parameter	Req. #	Value	Traceability
Number of Bins	CSP0632	The CSP shall support up to 2,048 time bins per period.	

The required number of beams has been defined in [AD05].

Parameter	Req. #	Value	Traceability
Folding Integration Time	CSP0633	The CSP shall support folding a variable number of periods such that the integration time can be selected at least within the range from 1 to 10 seconds.	

The upper limit allows dumps every 10 s for millisecond pulsars, as required by [AD05].

4.4 Offline Pulsar Search Observing Mode

All requirements in this Section apply only to the CSP operating in Offline Pulsar Search Observing Mode.

4.4.1 Definition

Through the Offline Pulsar Search Observing Mode, the CSP computes a number of beam-channels, which are then detected (Stokes parameters) and incoherently integrated as required to achieve the selected time-frequency resolution. The CBF generates the beam-channels, which are further processed by the PE. In principle, the minimum frequency resolution is given by the CBF, hence avoiding further channelization at the pulsar engine. This mode is mainly intended for targeted pulsar searches, although it could be used for pulsar timing as well (e.g., globular clusters). The greater number of beams is achieved by phase-delay beamforming, which demands less computational resources per beam. This comes at the cost of maximum baseline length and/or pointing offset, maximum channel bandwidth, and perhaps other desired features such as simultaneous supporting visibilities.

4.4.2 Sub-Arrays and Number of Beams

Parameter	Req. #	Value	Traceability
Number of Beams	CSP0421	The CSP shall generate up to 10 beams, each up to 8.8 GHz wide.	SYS0203

For the Galactic Center search, the goal is to cover a circular area (solid angle) of about 1" diameter at 20 GHz [AD05]. Assuming a circular 0.1" FWHM beam for 30-km baselines at this frequency, at least 91 beams are necessary to cover the targeted area through hexagonal packing. However, the Reference Observing Program (Section 12) explicitly specifies only ten beams for this use case, which is the main driver of CSP0421. The ROP also determines 8.2 GHz of bandwidth for this use case, but the required bandwidth per beam has been increased in anticipation of future use of this Observation Mode in Band 2.

In any case, given the high relative bandwidth under consideration, the number of beams required might vary across the bandwidth depending on the specific frequency band observed and the beamforming strategy. The output data rate of the Galactic Center search (13 GB/s) is smaller than what is required by the Synthesis Imaging Observing Mode.

Parameter	Req. #	Value	Traceability
Maximum Offset from Boresight	CSP0422	The CSP shall support beam steering offsets up to 0.5" from boresight.	

This requirement arises from KSG4 [AD02] to cover a solid angle up to 0.5" off the Galactic Center [AD05]. The boresight (or phase reference direction) is the only one for which delay is truly compensated, while narrowband phase-delay approximations are used to generate beams towards offset directions.

The following sub-array requirements must be supported within the Offline Pulsar Search Observing Mode as a guidance for the CSP designer (only in case general requirement CSP0181 cannot be met).

Parameter	Req. #	Value	Traceability
Number of Antennas	CSP0423	The CSP shall support one pre-determined sub-array composed of up to 168 antennas.	
Maximum Sub-Array Diameter	CSP0424	The CSP shall support a sub-array diameter up to 30 km long in Offline Pulsar Search Observing Mode.	

Both requirements originate from the need to support the sub-array composed of the core and the spiral. This sub-array provides a good trade-off between sensitivity (78.5%) and covered solid angle for a given number of beams [AD05].

4.4.3 Polarization Calibration

Parameter	Req. #	Value	Traceability
Polarization Calibration	CSP0431	The CSP shall apply calibration coefficients such that each cross-polarization beamformed pattern is at least 13 dB lower than its respective co-polarization pattern beam (within the main beam).	SYS1901

This requirement is a placeholder for future versions of this document. The polarization calibration level required by [RD05] is at least 5% (–13 dB). This requirement shall be revisited after definition of cross-polarization antenna requirements.

Note that the polarization purity requirement SYS1901 demands a post-calibration cross-polarization leakage at least 60 dB smaller than the co-polarization component. However, this requirement does not seem necessary in Pulsar Search Observing Mode and requires further consideration.

4.4.4 Supporting Visibilities

Refer to Section 4.3.4 for an explanation of the role of the CSP in real-time calibration of the beamformer.

Some of the phase-delay beamforming FSP Function Modes developed by NRC allow simultaneous supporting visibilities for a reduced number of beams (16 beams). Those FSP Function Modes might result an interesting option for Observations where real-time calibration is desired.

4.5 Very Long Baseline Interferometry Observing Mode

All requirements in this Section apply only to the CSP operating in VLBI Observing Mode.

4.5.1 Definition

In VBLI Observing Mode, the CSP generates a number of VLBI beam-channels. Each one is a select portion of the spectrum of one wideband beam. In addition, the CSP formats each beam-channel according to a standard VLBI format before outputting the beam-channels voltage stream. Supporting visibilities could be generated from an additional beam pointed at a calibrator.

4.5.2 Sub-Arrays and Number of Beams

Parameter	Req. #	Value	Traceability
Number of Beams	CSP0521	The CSP shall support at least 3 beams in VLBI Observing Mode, each up to 20 GHz wide.	SYS0501

System requirement SYS0501 requires three beams with a goal of five beams. The current VLBI FSP Function Mode of NRC's design allows up to four beams per frequency slice processor. Therefore, five beams can only be obtained by trading bandwidth per beam off. Note that a requirement of 20 GHz bandwidth per beam is much bigger than other VLBI sites' current capabilities. The maximum output data rate, 480 Gbps at 2-bit quantization, is smaller than CSP's output interface limit.

Parameter	Req. #	Value	Traceability
Sub-Arrays	CSP0522	The CSP shall support at least 3 sub-arrays simultaneously operating in VLBI mode, including the full array.	SYS0501

This is understood from VLBI Functional Requirements in the System Requirements document [AD01].

4.5.3 Supporting Visibilities

The considerations made in Section 4.3.4 for Pulsar Timing Observing Modes are equally valid here.

4.5.4 Polarization Calibration

Parameter	Req. #	Value	Traceability
Polarization Calibration	CSP0541	The CSP shall apply calibration coefficients such that each cross-polarization beamformed pattern is at least 13 dB lower than its respective co-polarization pattern beam (within the main beam).	

This requirement follows the same rationale as in Pulsar Timing Observing Mode.

4.5.5 VLBI Channelizer

Parameter	Req. #	Value	Traceability
Number of VLBI Beam-Channels	CSP0551	The CSP shall support at least 4 beam-channels within the same sub-band.	

In some use cases, the band of interest can be narrowband and closely spaced so that they all fit within a single sub-band. This requirement specifies how many of these frequency bands can be individually recorded before having to record the entire sub-band. This requirement assumes a sub-band bandwidth on the order of a few hundreds of MHz.

Parameter	Req. #	Value	Traceability
Beam-Channel Tuning Resolution	CSP0552	The CSP shall independently tune each VLBI beam-channel in steps less than or equal to 2 kHz.	

This resolution guarantees at least 99.9% (SNR) efficiency due to passband mismatch for 1-MHz channel bandwidth.

Parameter	Req. #	Value	Traceability
Beam-Channel Sampling Rate	CSP0553	The CSP shall support all VLBI-standard sampling rates from 2 MS/s to 256 MS/s, and 448 MS/s.	

Standard VLBI sampling rates, expressed in MHz, take values of a power of two. It is not so important the channel bandwidth as the total aggregate bandwidth, so the main driver should be to cover as much aggregate spectrum as possible. The maximum aggregate bandwidth equals the beam bandwidth in CSP0521. However, in current NRC's FSA, the maximum channel bandwidth equals the Frequency Slice bandwidth, which is not a VLBI standard. Thus, all VLBI-standard sampling rates up to twice the Frequency Slice bandwidth, in addition to twice the Frequency Slice bandwidth itself, shall be supported.

Parameter	Req. #	Value	Traceability
Beam-Channel Format	CSP0554	The CSP shall support at least VLBI-standard VDIF format.	

Multiple formats might be added in future.

4.7 Spurious Signals/Radio Frequency Interference Generation

There is no current specification on the spurious signal level of the CSP electronics. Shielding will be provided at the room level by the central electronics building. However, designs that emit less RFI, and therefore require lower levels of shielding, are preferable.

4.8 Environmental Conditions

4.8.1 Normal Operating Conditions

The environmental conditions will comply with the specifications set forth by the infrastructure requirements. It is assumed that the central electronics building HVAC system will maintain such conditions when in normal operation. The adoption of a water cooling system for the CSP is under study. In the event of an HVAC malfunction, the CSP should self-protect and shut down to prevent equipment damage or fire.

4.8.2 Lightning Protection Requirements

Since the CSP electronics will be located within a shielded and grounded room, with only filtered copper connections penetrating that boundary, the shielded room is expected to meet all requirements for lightning protection, for both electronics systems and personnel.

4.8.3 Seismic Protection Requirements

Parameter	Req. #	Value	Traceability
Seismic Protection	CSP0831	The CSP packaging and anchoring to the building shall be designed to withstand a low probability earthquake with up to 0.2g peak acceleration in either the vertical or the horizontal axis.	

Low probability has been defined as a 2% probability of an event exceeding this magnitude over a 50-year period, consistent with data available from the USGS Seismic Hazard Model [RD09].

4.8.4 Site Elevation

Parameter	Req. #	Value	Traceability
Altitude Range	CSP0841	The CSP shall be designed for operation at an altitude of 2200 m.	

This requirement is most applicable to the thermal design of the system.

4.9 Maintenance and Reliability Requirements

Parameter	Req. #	Value	Traceability
Availability	CSP0901	Under Normal Operating Conditions, the CSP shall be available for science operations 95% of the time, excluding scheduled and unscheduled maintenance downtime.	SYS2602

The maintenance and reliability requirements are in support of high-level requirements that limit the total operating cost of the array. Monitor points or sensors should be included in the MTBF/MTTR analysis, but sensors and other components that can be reasonably deemed to be ancillary to operation may be removed from the determination of compliance with the MTBF requirement. “Failure” will be defined as a condition which places the system outside of its performance specifications or into an unsafe state, requiring repair.

4.10 Monitor and Control Requirements

Parameter	Req. #	Value	Traceability
Self-Monitoring	CSP1001	The CSP shall measure, report and monitor a set of parameters that allow for determination of its status and may help predict or respond to failures.	SYS2601

The expectation with self-monitoring is that the CSP control system expose lower level sensors to the monitor and control system when queried. The cadence of access is flexible, and is not expected at high rates (typical access might be on second to minute scales). Any high-cadence monitoring should generally be internal to the CSP control system with a summary output on the interface.

Other features of the M&C interface are to be specified in the Monitor and Control ICD.

4.11 Lifecycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	CSP1101	The CSP shall be designed to be operated and supported for a period of 20 years.	SYS2701
Lifecycle Optimization	CSP1102	The CSP design shall minimize its life-cycle cost for 20 years of operation.	SYS2702

Lifecycle costs include manufacturing, transportation, construction/assembly, operation, and decommissioning.

5 Interface Requirements

This section provides information about the interfaces of the CSP. Interface Control Documents (ICDs) are required between the correlator and all connecting systems. In many cases, specifications for the interfaces are not yet available, but the broad scope of the ICD can be defined.

Some interfaces are highly dependent on architecture, in which case the NRC's FSA has been assumed.

These interfaces shall be developed and documented by the CSP Designer, and approved by the ngVLA Project Office, as part of the correlator conceptual design effort, and updated throughout the design. Post CoDR, the ICD shall only be updated through formal project change control processes.

5.1 Interface to the Data Transmission System

Parameter	Req. #	Value	Traceability
Total Number of Inputs	CSP2101	6 per antenna	
Input Data Rate	CSP2102	Up to 80 Gbps	
Maximum Input Bandwidth and Number of Bits per Sample	CSP2103	10 GHz at 8 (4+4) bits/sample 5 GHz at 16 (8+8) bits/sample	

The CSP will admit six inputs per antenna from the DTS, each at up to 80 Gbps. Polarization pairs from each antenna may be multiplexed through a single input or use independent inputs. It is expected that the CSP is arranged in three equal parts, each part processing two inputs. Then, the input bandwidth per polarization is either 10 GHz with 4-bit quantization or 5 GHz using 8-bit quantization.

Each input consists of a sequence of complex numbers representing the equivalent baseband signal of a 5-GHz bandwidth portion of the radio frequency spectrum, except for the lowest 5-GHz portions, which are directly sampled in one Nyquist zone. Each sample consists of 16 bits, 8 bits for each of the real and imaginary parts. Note that even though the ADC may use 4 bits per sample in some cases, the adapter between the ADC and the CSP might increase the number of bits at the CSP input in order to satisfy efficiency requirements in [AD01]. The total data rate per input is 80 Gbps, and the total input data rate is 480 Gbps per antenna.

It is assumed that the DBE/DTS system will convert from the ADC format to the CSP format, and most likely perform the sub-band selection.

5.2 Interface to the Archive

Parameter	Req. #	Value	Traceability
Total Number of Outputs	CSP2201	150 (one per FSP)	
Data Rate per Output	CSP2202	40 Gbps	

40 Gbps per FSP can allocate the maximum per-FSP data rates required by the ROP (Section 12). An output switch fabric is required as the overall maximum output data rate from the entire CSP is only about 80 GB/s.

5.3 Interface to the Fiber Optic Transmission System

The incoming and outgoing signals are considered part of the interface to the data transmission system and archive respectively. The communications interface to the CSP shall be considered part of the monitor and control system interface.

5.4 Interface to the Central Electronics Building

5.4.1 Electrical Infrastructure

- 3-phase, 208V, 60 Hz power will be provided to the CSP room. Service size is under study.
- Building will provide UPS capability.
- Building will be responsible for protecting CSP from brownout conditions where one or two phases of the distribution system are lost. Any shunt trip device shall be remotely resettable, and shall have a programmable automatic reset sequence.
- Building will provide lightning protection.

The ICD should describe both the mechanical and electrical specifications of the electrical interfaces. Circuit sizing and load estimates should also be described.

5.4.2 HVAC

- Building will provide the HVAC system. Size, plenum temperature, temperature stability, and some other requirements are under study.
- Direct Contact Liquid Cooling is the preferred cooling option for efficiency, lifetime and maturity of COTS supporting technology.

5.4.3 RFI Mitigation

- Building will provide a shielded room, with attenuation dependent on the correlator electronics emissions.

5.4.4 Fire Safety

- Building will provide a fire suppression system.
- Any interlocks or similar devices should be described here.

5.5 Interface to the Time & Frequency Reference Distribution System

Parameter	Req. #	Value	Traceability
Clock reference	CSP2501	100 MHz	
Time reference	CSP2502	1 PPS	

A 100 MHz reference signal will be required to generate clock signals internally. A 1 PPS signal in sync with the 100 MHz reference will be required to solve clock ambiguity within 1-s intervals. Timestamps will be distributed along with data input.

5.6 Interface to the Monitor and Control System

The Local Control System (LCS) will govern the local control of the CSP, processing higher-level commands into lower level commands suitable for configuring the correlator electronics. In all cases, no action or inaction of the monitor and control system can cause incorrect or dangerous conditions in the covered hardware. In addition, the LCS shall provide monitor data defining the current condition of key monitor points that describe the overall health and status of the correlator.

The physical interface between the LCS and M&C system shall be multimode fiber using TCP/IP over Ethernet.

6 Safety

6.1 General

Parameter	Req. #	Value	Traceability
Code Compliance	CSP6001	The design shall comply with all relevant federal and State of New Mexico building codes.	
Safety of Personnel	CSP6002	The design shall allow the Observatory to comply with all relevant federal and state occupational health and safety regulations for personnel servicing the correlator.	

6.2 Safety Design Requirements

6.2.1 Fire Safety

The fire safety requirements of the CSP and its component elements shall comply with their relevant international or US product standard.

6.2.2 Mechanical Safety

The mechanical safety requirements of the CSP shall comply with their relevant international or US product standard.

6.2.3 Electrical Safety

Electrical equipment installed on the CSP 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. Insulation shall be coordinated in conformity with IEC 60664 [AD08] while taking into account the altitude of up to 2500 m above sea level.

6.2.4 Handling, Transport, and Storage Safety

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

6.2.5 Toxic Substances

No use of toxic substance (asbestos, formaldehyde, lead, etc.) and of their derivatives shall be permitted in the CSP. Any insulation materials and paint specifications shall be reviewed by ngVLA.

6.2.6 Confined Space

Considerations of confined space in the sense of [AD09] shall be taken into account in the design where applicable.

7 Requirements for Design

7.1 *Analyses and Design Requirements*

7.1.1 Reliability, Availability, Maintainability, Analysis

A Reliability, Availability, Maintainability analysis shall be performed to locate weak design points and determine whether the design meets the Maintenance and Reliability requirements. ngVLA suggests to apply the Parts Count Method for predicting system reliability as described in [AD10], but the designer may propose to use other methods. For non-electronic parts, the values of [AD11] may be used, or data from manufacturers or other databases may be used. Another, more time consuming (and considered more accurate) method, the Parts Stress Analysis Prediction, is also described in [AD10] and may be used if results of the Parts Count Method do not comply with the Maintenance and Reliability requirements.

The ngVLA CSP will operate at an elevation of 2200m above sea level, where temperature and pressure might decrease the Mean Time Between Failures (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 [AD10]. The analysis shall result in estimates of the MTBF, the Mean Time to Repair (MTTR), assuming that any scheduled preventive maintenance is performed.

7.2 *Electromagnetic Compatibility Requirements*

The ngVLA CSP element shall exhibit complete electromagnetic compatibility (EMC) among components (intra-system electromagnetic compatibility).

7.3 *Materials, Parts and Processes*

7.3.1 Fasteners

All fasteners shall be metric except those that are on off-the-shelf units. The use of standard metric cross-sections for construction materials is preferred but not required.

7.3.2 Paints

Any painted coatings shall be chosen to last at least 20 years without repainting.

7.3.3 Surface Treatment

Any unpainted surfaces shall be treated against corrosion.

7.3.4 Rodent Protection

The correlator room shall be assumed a rodent-free zone, and no specific protection measures will be required.

7.3.5 Name Plates and Product Marking

As a general rule, the main parts and all exchangeable units shall be equipped with nameplates which are visible after installation of the part/unit and which contain the following information:

- Part/unit name
- Drawing number including revision
- Serial number
- Manufacturing month and year
- Name of manufacturer

Alternatively, a system of marking based on barcodes or similar system may be used upon approval by ngVLA.

For Line Replaceable Units (LRU, See Section 11.2), it is highly desirable that the serial number of the LRU be ascertainable over the monitor and control interface (See Section 5.6)

7.3.6 Labels

All cables and switches, junction boxes, sensors, and similar equipment shall be labeled.

8 Documentation Requirements

8.1 Technical Documentation

All documentation related to the CSP 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 the ngVLA Project Office.

8.2 Software and Software Documentation

The CSP software (including so-called firmware) and any other specially developed software, are deliverables. The software shall be delivered in source and object form, together with all procedures and tests necessary for compilation, installation, testing, upgrades and maintenance.

- Software must be tagged with suitable version numbers that allow identification (also on-line remotely) of a Release.
- User manuals of software developed under this specification and of any other commercial software used (controllers embedded software, special tools, etc.) shall be provided.
- Software maintenance and installation upgrade documentation shall be provided.
- Full Test and Acceptance procedures shall be documented.

Software upgrades shall allow deployment and commissioning on a sub-array basis.

9 Verification and Quality Assurance

The design may be verified to meet the requirements by design (D), analysis (A) inspection (I), a factory acceptance test (FAT) or a site acceptance test (SAT). The definitions of each are given below.

Verification by Design: The performance shall be demonstrated by a proper design, which may be checked by the ngVLA project office during the design phase by review of the design documentation.

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 item is determined by a simple inspection or measurement.

Verification by Factory Acceptance Test: The compliance of the developed item / assembly / unit with the specified performance shall be demonstrated by tests. A FAT is performed w/o integration with interfacing systems.

Verification by Site Acceptance Test: The compliance of the developed item / assembly / unit with the specified performance shall be demonstrated by tests. SAT is performed on-site with the equipment as installed.

Multiple verification methods are allowed. The following table summarizes the expected verification method for each requirement.

Req. #	Parameter / Requirement	D	A	I	FAT	SAT
	General					
CSP0111	Maximum Number of Antennas	*				
CSP0121	Maximum Bandwidth per Observation	*				
CSP0122	Spectral Window Bandwidth Selection	*				
CSP0123	Spectral Window Tuning Step	*				
CSP0124	Maximum Aggregate Bandwidth	*				
CSP0125	Discontinuous Spectral Windows	*				
CSP0131	Minimum Efficiency		*		*	
CSP0141	Maximum Data Transport Delay	*				
CSP0142	Maximum Array Diameter	*				
CSP0143	Phase-Center Location	*				
CSP0144	Packet-Loss Tolerance	*			*	
CSP0151	Spectral Leakage		*			
CSP0152	Channel Flatness		*			
CSP0153	Channel Gain Correction	*				
CSP0181	Number of Sub-Arrays	*				
CSP0182	Sub-Array Independence	*			*	*
	Synthesis Imaging					
CSP0221	Channel Bandwidth	*				
CSP0222	Number of Channels	*				
CSP0223	Zoom Capabilities	*				
CSP0224	Zoom Window Tuning Step	*				
CSP0225	Integration Time	*				

Req. #	Parameter / Requirement	D	A	I	FAT	SAT
CSP0231	Number of Simultaneous Phase Reference Positions	*			*	*
CSP0232	Maximum Slew Rate	*			*	*
	Pulsar Timing					
CSP0321	Number of Beams	*				
CSP0322	Number of Sub-Arrays (Outer)	*				
CSP0323	Number of Sub-Arrays (Non-Core)	*				
CSP0324	Number of Sub-Arrays (Full Array)	*				
CSP0331	Polarization Calibration	*			*	*
CSP0611	Pulsar Timing Accuracy	*			*	*
CSP0621	Dispersion Measure Range	*				
CSP0631	Pulse Period Range	*				
CSP0632	Number of Bins	*				
CSP0633	Folding Integration Time	*				
	Offline Pulsar Search					
CSP0421	Number of Beams	*				
CSP0422	Maximum Offset from Boresight	*	*			*
CSP0423	Number of Antennas	*				
CSP0424	Maximum Sub-Array Diameter	*				
CSP0431	Polarization Calibration	*			*	*
	VLBI					
CSP0521	Number of Beams	*				
CSP0522	Sub-Arrays	*				
CSP0541	Polarization Calibration	*			*	*
CSP0551	Number of VLBI Beam-Channels	*			*	*
CSP0552	Beam-Channel Tuning Resolution	*				
CSP0553	Beam-Channel Sampling Rate	*				
CSP0554	Beam-Channel Format					
	Environmental					
CSP0831	Seismic Protection	*				
CSP0841	Altitude Range	*				*
	Maintenance					
CSP0901	Mean Time Between Failures	*				
	M&C					
CSP1001	Self-Monitoring	*			*	*
	Lifecycle					
CSP1101	Design Life	*				
CSP1102	Lifecycle Optimization		*			
	Safety					
CSP6001	Code Compliance	*		*		
CSP6002	Safety of Personnel	*		*		

Table 1 - Expected requirements verification method.

10 Key Performance Parameters

This section provides key performance parameters that the designer should estimate and that NRAO should monitor NRAO throughout the project design phase. These parameters strongly influence 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 discussed in Section 4.

The technical requirements are generally specified as *minimum* values. This gives the designer some latitude in optimization for a balanced design. Understanding the CSP's anticipated performance (not just its specified minimum) on these parameters is valuable 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 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. #
Maximum bandwidth per Observation	CSP0121
Maximum aggregate bandwidth	CSP0124
Sub-array independence	CSP0182
Zoom capabilities	CSP0223
Number of simultaneous phase reference positions	CSP0231
Number of beams	CSP0321 CSP0421 CSP0521
Mean Time Between Failures	CSP0901
Interface to the archive	CSP2201 CSP2202

Table 2 - Key performance parameters for monitoring during design.

11 Appendix

11.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ADC	Analog to Digital Converter
CBF	Correlator and Beamformer
CCU	Correlator Control Unit
CDR	Critical Design Review
CoDR	Conceptual Design Review
CPC	Cross-Polarization Correction
CSP	Central Signal Processor
CW	Continuous Wave (Sine wave of fixed frequency and amplitude)
DBE	Digital Back End
DFT	Digital Fourier Transform
DTS	Data Transmission System
EIRP	Equivalent Isotropic Radiated Power
EM	Electro-Magnetic
EMC	Electro-Magnetic Compatibility
EMP	Electro-Magnetic Pulse
FAT	Factory Acceptance Test
FDR	Final Design Review
FEA	Finite Element Analysis
FOV	Field of View
FSA	Frequency Slice Architecture
FSP	Frequency Slice Processor
FWHM	Full Width Half Max
HPBW	Half Power Beam Width
HVAC	Heating, Ventilation & Air Conditioning
ICD	Interface Control Document
IF	Intermediate Frequency
KPP	Key Performance Parameters
KSG	Key Science Goal
LBA	Long Baseline Array
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
NRC	National Research Council Canada
OTF	On-The-Fly
PDB	Phase-Delay Beamforming
PE	Pulsar Engine

Acronym	Description
PPS	Pulse Per Second
PTB	Pulsar Timing Beamforming
RD	Reference Document
RFI	Radio Frequency Interference
RMS	Root Mean Square
ROP	Reference Observing Program
RSS	Root of Sum of Squares
RTP	Round Trip Phase
SAC	Science Advisory Council
SAT	Site Acceptance Test
SBA	Short Baseline Array
SCFO	Sample Clock Frequency Offset
SNR	Signal to Noise Ratio
SRSS	Square Root Sum of the Square
SWG	Science Working Group
TAC	Technical Advisory Council
VCC	Very Coarse Channelizer
VDIF	VLBI Data Interchange Format
VLA	Jansky Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry

11.2 Maintenance Definitions

11.2.1 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 easiness of handling, etc.) by maintenance staff of technician level.

LRU exchange shall be possible by 2 trained people within 4 working hours. It is desirable that LRU replacement be possible using only standard tools identified in a CSP maintenance manual.

A systematic procedure for safe exchange of every LRU shall be provided in the Maintenance Manual.

LRUs shall be defined by the CSP designer, depending on the design. The LRUs will be maintained by the ngVLA project (with or without industrial support).

11.2.2 Periodic Preventive Maintenance

Preventive maintenance may be performed at planned intervals in order to maintain the correlator operational and within its specified performance. Any required preventive maintenance should be documented in the Maintenance Manual.

11.3 Reference Observing Program

		Science Use Cases						
Name	Science Use Fraction	Field of View (arcsec)	PSF FWHM (mas)	Dynamic Range	Center Frequency	Bandwidth	Science Channel Width	Maximum Dump Time
KSG1 Driving Cont Band 6 eg Taurus disk	0.03	5.0	10	1.00E+03	100.0 GHz	FULL	120.0 MHz	1
KSG1 Driving Cont Band 4 eg Taurus disk	0.03	5.0	10	1.00E+03	27.3 GHz	FULL	120.0 MHz	2
KSG2 Driving Line Band 5 eg Sgr B2(N)	0.03	60.0	100	1.00E+03	40.5 GHz	4.0 GHz	13.5 kHz	1
KSG2 Driving Line Band 4 eg Sgr B2(N)	0.03	60.0	100	1.00E+03	27.3 GHz	4.0 GHz	9.1 kHz	2
KSG2 Driving Line Band 3 eg Sgr B2(N)	0.03	60.0	100	1.00E+03	16.4 GHz	4.0 GHz	5.5 kHz	2
KSG3 Driving Line Band 5 eg COSMOS	0.03	FULL	1000	1.00E+02	40.5 GHz	FULL	675.0 kHz	1
KSG3 Driving Line Band 4 eg COSMOS	0.03	FULL	1000	1.00E+02	27.3 GHz	FULL	455.0 kHz	2
KSG3 Driving Line Band 3 eg COSMOS	0.03	FULL	1000	1.00E+02	16.4 GHz	FULL	273.3 kHz	2
KSG3 Driving Line Band 6 eg Spiderweb galaxy	0.03	5.0	100	1.00E+03	72.0 GHz	240.0 MHz	7.2 MHz	1
KSG3 Driving Line Band 5 eg Spiderweb galaxy	0.03	5.0	100	1.00E+03	36.0 GHz	120.0 MHz	3.6 MHz	1
KSG3 Driving Line Band 4 eg Spiderweb galaxy	0.03	5.0	100	1.00E+03	27.7 GHz	92.3 MHz	2.8 MHz	2
KSG3 Driving Line Band 6 eg Virgo Cluster	0.03	FULL	100	1.00E+03	112.5 GHz	6.0 GHz	375.0 kHz	1
KSG3 Driving Line Band 6 eg Virgo Cluster	0.03	FULL	100	1.00E+03	89.0 GHz	6.0 GHz	296.7 kHz	1
KSG3 Driving Line Band 1 eg M81 Group	0.03	FULL	1000	1.00E+03	1.4 GHz	7.0 MHz	4.7 kHz	2
KSG3 Driving Line Band 1 eg M81 Group	0.03	FULL	60000	1.00E+03	1.4 GHz	7.0 MHz	4.7 kHz	2
KSG5 Driving Cont Band 1 OTF Find LIGO event	0.03	FULL	1000	5.00E+03	2.4 GHz	FULL	2.0 MHz	0.5
KSG5 Driving Cont Band 4 OTF Find LISA event	0.03	FULL	1000	5.00E+03	27.3 GHz	FULL	5.0 MHz	0.5
KSG5+4 Driving Cont Band 2 OTF Find BHs+Possibl	0.03	FULL	1000	5.00E+03	7.9 GHz	FULL	5.0 MHz	0.5
KSG5 Driving Cont eg Band 2 Followup from OTF	0.03	1.0	10	5.00E+03	7.9 GHz	FULL	120.0 MHz	2
KSG5 Driving Cont Band 2 Find SMBH binaries in \	0.03	2.5	10	5.00E+03	7.9 GHz	FULL	120.0 MHz	2
KSG3 Supporting Cont Band 6 eg Virgo Cluster	0.03	FULL	1000	5.00E+03	93.0 GHz	FULL	5.0 MHz	1
KSG3 Supporting Cont Band 5 eg Virgo Cluster	0.03	FULL	1000	5.00E+03	40.5 GHz	FULL	5.0 MHz	1
KSG3 Supporting Cont Band 4 eg Virgo Cluster	0.03	FULL	1000	5.00E+03	27.3 GHz	FULL	5.0 MHz	2
KSG3 Supporting Cont Band 3 eg Virgo Cluster	0.03	FULL	1000	5.00E+03	16.4 GHz	FULL	5.0 MHz	2
KSG3 Supporting Cont Band 2 eg Virgo Cluster	0.03	FULL	1000	5.00E+03	7.9 GHz	FULL	5.0 MHz	2
KSG5 Driving Cont Band 1 PTA timing 5 subs 1 PSF	0.03	0.1	10	1.00E+02	2.4 GHz	FULL	500.0 kHz	2
KSG4 Driving Cont Band 3 GalCen search 1 sub 10	0.03	0.1	10	1.00E+02	16.4 GHz	FULL	1.0 MHz	0.0001
KSG4 Driving Cont Band 3 GalCen timing 1 sub 10	0.03	0.1	10	1.00E+02	16.4 GHz	FULL	1.0 MHz	2
KSG5 Driving Cont Band 2 PTA timing 5 subs 1 PSF	0.03	0.1	10	1.00E+02	7.9 GHz	FULL	500.0 kHz	2

Name	Use Fraction	FOV Imaged	Image Linear	Validation Band	Actual Bandwidth	Maximum Channel	N Chan	Visibility Dump Time (s)	Core	Mid	Stations	N Antenna	Nbaseline	N Facets
KSG1 Driving Cont Band 6 eg Taurus disk	0.03	5.0	1500	Band 6	20.0 GHz	2.5 MHz	7902	0.39	Yes	Yes	Yes	215	23,005	1
KSG1 Driving Cont Band 4 eg Taurus disk	0.03	5.0	1500	Band 4	13.5 GHz	576.6 kHz	23415	0.39	Yes	Yes	Yes	215	23,005	1
KSG2 Driving Line Band 5 eg Sgr B2(N)	0.03	60.0	1800	Band 5	4.0 GHz	13.5 kHz	296297	1.00	Yes	Yes	No	155	11,935	1
KSG2 Driving Line Band 4 eg Sgr B2(N)	0.03	60.0	1800	Band 4	4.0 GHz	9.1 kHz	439561	2.00	Yes	Yes	No	155	11,935	1
KSG2 Driving Line Band 3 eg Sgr B2(N)	0.03	60.0	1800	Band 3	4.0 GHz	5.5 kHz	727273	2.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 5 eg COSMOS	0.03	114.9	345	Band 5*	20.0 GHz	675.0 kHz	29630	1.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 4 eg COSMOS	0.03	170.5	512	Band 4*	13.5 GHz	455.0 kHz	29671	2.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 3 eg COSMOS	0.03	284.9	855	Band 3	8.2 GHz	273.3 kHz	30004	2.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 6 eg Spiderweb galaxy	0.03	5.0	150	Band 6	240.0 MHz	7.2 MHz	34	1.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 5 eg Spiderweb galaxy	0.03	5.0	150	Band 5	120.0 MHz	3.6 MHz	34	1.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 4 eg Spiderweb galaxy	0.03	5.0	150	Band 4	92.3 MHz	2.8 MHz	34	2.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 6 eg Virgo Cluster	0.03	32.0	960	Band 6	6.0 GHz	375.0 kHz	16000	1.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 6 eg Virgo Cluster	0.03	40.7	1222	Band 6	6.0 GHz	296.7 kHz	20223	1.00	Yes	Yes	No	155	11,935	1
KSG3 Driving Line Band 1 eg M81 Group	0.03	2473.8	7421	Band 1	7.0 MHz	4.7 kHz	1480	2.00	Yes	Yes	No	155	11,935	30
KSG3 Driving Line Band 1 eg M81 Group	0.03	2473.8	124	Band 1	7.0 MHz	4.7 kHz	1480	2.00	Yes	No	No	77	2,926	1
KSG5 Driving Cont Band 1 OTF Find LIGO event	0.03	2920.1	8760	Band 1	2.3 GHz	216.0 kHz	10649	0.50	Yes	Yes	No	155	11,935	42
KSG5 Driving Cont Band 4 OTF Find LISA event	0.03	170.5	512	Band 4*	13.5 GHz	3.7 MHz	3650	0.50	Yes	Yes	No	155	11,935	1
KSG5+4 Driving Cont Band 2 OTF Find BHs+Possib	0.03	1001.2	3003	Band 2	8.8 GHz	630.0 kHz	13969	0.50	Yes	Yes	No	155	11,935	5
KSG5 Driving Cont eg Band 2 Followup from OTF	0.03	1.0	300	Band 2	8.8 GHz	98.4 kHz	89397	0.39	Yes	Yes	Yes	215	23,005	1
KSG5 Driving Cont Band 2 Find SMBH binaries in \	0.03	2.5	750	Band 2	8.8 GHz	98.4 kHz	89397	0.39	Yes	Yes	Yes	215	23,005	1
KSG3 Supporting Cont Band 6 eg Virgo Cluster	0.03	42.2	127	Band 6	20.0 GHz	5.0 MHz	4000	1.00	Yes	No	No	77	2,926	1
KSG3 Supporting Cont Band 5 eg Virgo Cluster	0.03	114.9	345	Band 5*	20.0 GHz	5.0 MHz	4000	1.00	Yes	Yes	No	155	11,935	1
KSG3 Supporting Cont Band 4 eg Virgo Cluster	0.03	170.5	512	Band 4*	13.5 GHz	3.7 MHz	3650	2.00	Yes	Yes	No	155	11,935	1
KSG3 Supporting Cont Band 3 eg Virgo Cluster	0.03	284.9	855	Band 3	8.2 GHz	2.2 MHz	3704	2.00	Yes	Yes	No	155	11,935	1
KSG3 Supporting Cont Band 2 eg Virgo Cluster	0.03	1001.2	3003	Band 2	8.8 GHz	630.0 kHz	13969	2.00	Yes	Yes	No	155	11,935	5
KSG5 Driving Cont Band 1 PTA timing 5 subs 1 PSF	0.03	0.1	30	Band 1*	2.3 GHz	35.2 kHz	65423	0.39	Yes	Yes	Yes	215	23,005	1
KSG4 Driving Cont Band 3 GalCen search 1 sub 10	0.03	0.1	30	Band 3	8.2 GHz	345.9 kHz	23704	0.00	Yes	Yes	Yes	215	23,005	1
KSG4 Driving Cont Band 3 GalCen timing 1 sub 10	0.03	0.1	30	Band 3	8.2 GHz	345.9 kHz	23704	0.39	Yes	Yes	Yes	215	23,005	1
KSG5 Driving Cont Band 2 PTA timing 5 subs 1 PSF	0.03	0.1	30	Band 2	8.8 GHz	98.4 kHz	89397	0.39	Yes	Yes	Yes	215	23,005	1

Correlation Use Cases

Name	Criterion 1: Number of Channels	Criterion 1: Visibility Dump Time (s)	Criterion 1: Number of Baselines	Criterion 1: CSP Data Rate (GB/s)	Criterion 1: FSP Number of Channels	Criterion 1: FSP Data Rate (GB/s)	Criterion 2: Number of Channels	Criterion 2: Visibility Dump Time (s)	Criterion 2: Number of Baselines	Criterion 2: CSP Data Rate (GB/s)	Criterion 2: FSP Number of Channels	Criterion 2: FSP Data Rate (GB/s)
KSG1 Driving Cont Band 6 eg Taurus disk	7,902	0.386	23,005	7.54	80	0.08	8,507	1.000	23,005	3.13	80	0.03
KSG1 Driving Cont Band 4 eg Taurus disk	23,415	0.386	23,005	22.35	347	0.33	5,742	2.000	23,005	1.06	347	0.06
KSG2 Driving Line Band 5 eg Sgr B2(N)	296,297	1.000	11,935	56.58	14,815	2.83	296,297	1.000	14,196	67.30	14,815	3.37
KSG2 Driving Line Band 4 eg Sgr B2(N)	439,561	2.000	11,935	41.97	16,384	1.56	439,561	2.000	14,196	49.92	16,384	1.86
KSG2 Driving Line Band 3 eg Sgr B2(N)	727,273	2.000	11,935	69.44	16,384	1.56	727,273	2.000	14,196	82.59	16,384	1.86
KSG3 Driving Line Band 5 eg COSMOS	29,630	1.000	11,935	5.66	297	0.06	29,630	1.000	14,196	6.73	297	0.07
KSG3 Driving Line Band 4 eg COSMOS	29,671	2.000	11,935	2.83	440	0.04	29,671	2.000	14,196	3.37	440	0.05
KSG3 Driving Line Band 3 eg COSMOS	30,004	2.000	11,935	2.86	732	0.07	30,004	2.000	14,196	3.41	732	0.08
KSG3 Driving Line Band 6 eg Spiderweb galaxy	34	1.000	11,935	0.01	28	0.01	34	1.000	14,196	0.01	28	0.01
KSG3 Driving Line Band 5 eg Spiderweb galaxy	34	1.000	11,935	0.01	56	0.01	34	1.000	14,196	0.01	56	0.01
KSG3 Driving Line Band 4 eg Spiderweb galaxy	34	2.000	11,935	0.00	72	0.01	33	2.000	14,196	0.00	72	0.01
KSG3 Driving Line Band 6 eg Virgo Cluster	16,000	1.000	11,935	3.06	534	0.10	16,000	1.000	14,196	3.63	534	0.12
KSG3 Driving Line Band 6 eg Virgo Cluster	20,223	1.000	11,935	3.86	675	0.13	20,223	1.000	14,196	4.59	675	0.15
KSG3 Driving Line Band 1 eg Virgo Cluster	1,480	2.000	11,935	0.14	16,384	1.56	1,490	1.162	14,196	0.29	16,384	3.20
KSG3 Driving Line Band 1 eg M81 Group	1,480	2.000	2,926	0.03	16,384	0.38	1,490	2.000	4,465	0.05	16,384	0.59
KSG5 Driving Cont Band 1 OTF Find LIGO event	10,649	2.000	11,935	1.02	926	0.09	15,581	0.984	14,196	3.60	926	0.21
KSG5 Driving Cont Band 4 OTF Find LISA event	3,650	2.000	11,935	0.35	55	0.01	5,340	2.000	14,196	0.61	55	0.01
KSG5 Driving Cont Band 2 OTF Find BHs for Tom	13,969	2.000	11,935	1.33	318	0.03	20,439	2.000	14,196	2.32	318	0.04
KSG5 Driving Cont eg Band 2 Followup from OTF	89,397	0.386	23,005	85.32	2,033	1.94	749	2.000	23,005	0.14	2,033	0.37
KSG5 Driving Cont Band 2 Find SMBH binaries in VLASS	89,397	0.386	23,005	85.32	2,033	1.94	1,872	2.000	23,005	0.34	2,033	0.37
KSG3 Supporting Cont Band 6 eg Virgo Cluster	4,000	1.000	2,926	0.19	40	0.00	4,000	1.000	4,465	0.29	40	0.00
KSG3 Supporting Cont Band 5 eg Virgo Cluster	4,000	1.000	11,935	0.76	40	0.01	5,332	1.000	14,196	1.21	40	0.01
KSG3 Supporting Cont Band 4 eg Virgo Cluster	3,650	2.000	11,935	0.35	55	0.01	5,340	2.000	14,196	0.61	55	0.01
KSG3 Supporting Cont Band 3 eg Virgo Cluster	3,704	2.000	11,935	0.35	91	0.01	5,420	2.000	14,196	0.62	91	0.01
KSG3 Supporting Cont Band 2 eg Virgo Cluster	13,969	2.000	11,935	1.33	318	0.03	20,439	2.000	14,196	2.32	318	0.04

Bytes per visibility	**4**	(16b+16b)
Polarization products	**4**	

Beamforming Use Cases

Name	Number of Channels	Visibility Dump Time (s)	Beam-Phase bin Product	CSP Data Rate (GB/s)	FSP Number of Channels	FSP Data Rate (GB/s)
KSG5 Driving Cont Band 1 PTA timing 5 subs 1 PSF each	4,600	2.00	10,240	0.38	400.00	0.03
KSG4 Driving Cont Band 3 GC search 1 sub 10 PSFs	8,200	0.00010	10	13.12	200.00	0.32
KSG4 Driving Cont Band 3 GC timing 1 sub 10 PSFs	8,200	2.00	20,480	1.34	200.00	0.03
KSG5 Driving Cont Band 2 PTA timing 5 subs 1 PSF each	17,600	2.00	10,240	1.44	400.00	0.03

Bytes per polarization product	**4**	32
Polarization products	**4**	