Long Baseline Antenna Prototype: Antenna Qualification Electronics Concept

ngVLA Antenna Memo #15

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Abstract

This memo documents the key requirements and concept for the antenna electronics package required to support the verification and validation testing of the long baseline antenna prototype at the GBO. An optional system to support astro-holography is also presented.

1 Introduction

In this memo we consider the conceptual design of the antenna electronics and supporting systems necessary to test the prototype long baseline antenna under development for the US Naval Observatory (USNO).

This electronics concept aims to support both single-dish radiometric testing and interferometric characterization as an element of the VLBA. In particular, a demonstration of performance in Earth Orientation Parameter (EOP) observations such as timekeeping (UT1-UTC corrections) is assumed to be included in the associated verification and validation plan.

Another key assumption is that the prototype will be retrofitted to be an operational element of the "ngVLBA" long baseline array. We will use this term to refer to a future operational array that co-observes with the VLBA and is tailored to geodetic use cases. Given this assumed future, this prototype electronics package considers the growth path to production electronics and attempts to reduce rework when possible or otherwise support long-term development. However, this goal is considered secondary to supporting the verification and validation activities, and significant future development of hardware and software systems is anticipated in the transition from the antenna verification and validation phase to a future operational phase.

2 Key Verification & Validation Requirements

The following are key requirements for the antenna electronics, control software, and supporting test systems to support the verification and validation of the antenna performance:

- Systems must support functional radiometric testing of the antenna (pointing, tracking, beam cuts, tipping curves, etc.) Integration of total power data with the Tpoint package is desirable.
- The outfitted antenna must be interoperable as an element of the VLBA. In particular, it must support both current and emerging UT1-UTC EOP observations. This includes the well-established S-X mode used currently on the VLBA, as well as the proposed (and still under development) X-Ka mode.
- It is a goal that the antenna and software systems support the 'real-time' correlation mode of the VLBA. This will facilitate interferometric verification tests such as pointing model determination and pointing offset measurements.
- Software and test systems must include the capability of performing holography for surface verification from GEO beacons in the 11-12 GHz range and/or water masers at 22 GHz. Interoperability with the GBT in a 'VLBI' mode is desired as a reference antenna for holography measurements.
- It is a goal to advance the design of ngVLA electronics concepts and systems when possible, treating this project as a pre-production "pathfinder".

3 Electronics Modes

The following modes must be supported for the verification and validation tests. The validation tests are the most demanding and constrained in their definition, ensuring interoperability with the VLBA and matching observation parameters to USNO service observations.

3.1 S-X Mode (Validation mode)

The antenna must be integrated as an element of the VLBA in a set of UT1-UTC test observations. These observations are performed using the VLBA S-X dichroic system, but would instead be supported with a wideband receiver as part of the qualification electronics. The following tuning parameters must be supported by the wideband receiver, downconverters, LO system and digitization system:

- Provide 16 discrete 32 MHz subbands; 512 MHz total digitized bandwidth, RHCP only.
- 2-bits per sample, encoded in the VDIF standard.
- Sub-band tunings (MHz):
  - 2188-2220
  - 2220-2252
  - 2252-2284
  - 2284-2316
  - 2380-2412
  - 8460-8492
  - 8492-8524
  - 8524-8556
  - 8556-8588

    - 8620-8652
    - 8684-8716
    - 8748-8780
    - 8812-8844
    - 8844-8876
    - 8876-8908
    - 8908-8940

3.2 X-Ka Mode (Validation mode)

A parallel proposal is under consideration by the USNO to develop X-Ka dual band capabilities on the VLBA. If this proposal is funded, the long baseline prototype antenna must also perform test observations as part of the VLBA using the new X-Ka modes for next-generation UT1-UTC observations. This mode is incorporated into the qualification electronics design as a design requirement, but may be descoped if X-Ka capabilities are not anticipated on the VLBA by the time of testing the long baseline antenna prototype. However, the receiver and downconverters are still required to support higher frequency radiometric and interferometric testing of the antenna.

The subband definition for these modes is still TBC and may change, but center frequencies of 8.4 GHz and 32.0 GHz are anticipated. Current X-Ka testing modes with JPL provide a useful reference for qualification electronics development:

- 16 discrete 32 MHz subbands; 512 MHz total digitized bandwidth, RHCP only. 5 x 32 MHz are in X-band while 11 x 32 MHz are in Ka-band.
- 2-bits per sample, encoded in the VDIF standard.
- Sub-band tunings frequencies (MHz):
    - 8202-8234
    - 8246-8278
    - 8330-8362
    - 8498-8530
    - 8582-8614
    - 31802-31834
    - 31834-31866
    - 31866-31898
    - 31898-31930
    - 31930-31962
    - 32002-32034
    - 32142-32174
    - 32174-32206
    - 32206-32238
    - 32238-32270
    - 32270-32302

3.3 Ku-band and K-band Modes (Verification mode)

The satellite "Ku-band" allocations for America (11.7-12.2 GHz [5,6]) must be accessible with basic tuning options to support stand-alone beam mapping and on-sky holography. Access to the 22.2 GHz water line (K-band) is also highly desirable to enable the use of masers for holography, improving our sampling of elevation ranges during testing. This band may also prove quite useful for interferometric pointing model determination.

The sub-band definitions for these satellite holography tests are still TBD and will depend on the center frequency of the associated transmitters. However, 32 MHz subbands spanning up to 512 MHz of bandwidth, as used in the S-X and X-Ka modes, should more than suffice in all scenarios. The 22.2 GHz tunings can be narrow, with a single 32 MHz subband per polarization sufficing to capture all required line features.

Dual polarization recording is desired at 2/4/8-bits per sample, encoded in the VDIF standard.

3.4 Other Modes & Features

When considering other key capabilities that may be supported by the antenna qualification electronics and software the following is assumed:

- A combination of analog and/or digital tuning can be employed to support interoperability with the VLBA and VGOS arrays. Subband center frequencies should be selectable/tunable to kHz-scale resolution. MHz-scale resolution is an acceptable descope, if necessary.
- It would be a goal for digital tuning options to replicate VLBA RDBE functionality in terms of bit-depth, subband bandwidth, subband tunability, number of subbands, and total recorded or transmitted bandwidth.
- Both 'real time' narrow bandwidth and recorded post-processing modes must be supported. A local Mark6 data recorder is required for the post-processed modes, and any real-time modes are constrained by available network bandwidth and the current VLBA real-time correlation mode capabilities.
- Data may be processed using the VLBA DiFX correlator, USNO DiFX correlator and post-processing software, or a customer-supplied digital back end directly connected to the DBE for the testing campaign.
- Integration with the Tpoint software package for pointing data analysis, or the CASA package for holography will be required.

It is a goal that the following set of generic operating modes be supported by the new system, perhaps after a subsequent firmware update to the DBE (providing additional time for development):

- Mode 1: Narrow subbands (32 MHz or less), with dual polarization, at 2 to 4 bits per sample. Total processed bandwidth less than 512 MHz per polarization. Tuning needs to allow an arbitrary band center. Tunability ideally at kHz scale, tolerable at MHz scale.
- Mode 2: Up to 1 GHz of bandwidth per polarization, ideally in one baseband channel (but acceptable to split between a small number of phase-coherent subbands) centered (within a few MHz) on one of a small number of a priori-knowable frequencies. Dual polarization is required. Multi-bit, up to 12 bits per sample, desired.

- Mode 3: As much bandwidth as can be transmitted from the DBE in either band. Dual polarization is desirable. Bit-depth and subband construction is flexible to deliver maximum bandwidth given other practical constraints and available recording capacity.

4 Receiver Band Concepts

Table 1 summarizes the receiver bands must be supported by the qualification electronics. Possible production band concepts for the ngVLBA antenna stations are also provided for context. Note that both the prototype qualification and ngVLBA production band definitions differ from the baseline ngVLA definition, responding to USNO feedback. These 'production' concepts are provided for context only, indicative of performance if single-antenna interoperability with the VGOS array and wideband X-Ka modes are prioritized over alternatives.

Table 1 - Receiver band concepts for LB Antenna prototype qualification and possible ngVLBA deployments.

Receiver Band	Prototype Qualification	Production Concept A	Production Concept B	Production Concept C
ngVLBA B1	2.1 – 9.0 GHz CP (VLBA S-X)	3.3 – 14 GHz LP (VGOS)	2.5 – 14 GHz LP (VGOS)	2.1 – 9.0 GHz CP (VLBA S-X)
ngVLBA B2	8.0 – 34 GHz CP (VLBA X-Ka)	8.0 – 34 GHz LP	8.0 – 48 GHz LP	8.0 – 34 GHz CP (VLBA X-Ka)
ngVLBA B3	N/A	30.5 – 50.5 GHz LP (ngVLA B5)	70 – 116 GHz LP (ngVLA B6)	30.5 – 50.5 GHz LP (ngVLA B5)
ngVLBA B4	N/A	70 – 116 GHz LP (ngVLA B6)	SPARE	70 – 116 GHz LP (ngVLA B6)

The prototype qualification receiver bands must be circularly polarized for interoperability with the VLBA. A cryogenically cooled hybrid coupler is an acceptable approach to producing circularly polarized outputs from a natively linear wideband feed design (likely relying on a quad-ridge architecture). The 8-34 GHz receiver is cooled to 4K to offset some of the losses associated with wideband designs at these frequencies (see Figure 2).

Three production concepts are currently under consideration, in addition to the baseline ngVLA receiver band definition (Figure 1). All new concepts prioritize supporting dual-band / wide-band modes requested by the USNO along with interoperability with the VGOS array or VLBA.

Should the baseline ngVLA receiver concept not meet USNO needs, and interoperability with VGOS be prioritized, Concept A is the preferred of the alternative concepts. It is a four-band design that aims to restrict bandwidth to roughly two octaves, permitting the use of more performant dielectric materials that can improve noise temperature when cryogenically cooled to 4 K (Figure 4). ngVLA receiver bands are used at higher frequencies when waveguide bandwidth is acceptable, for optimal noise performance. Another factor impacting the 34 GHz cutoff for the ngVLBA Band 2 receiver is interoperability with ngVLA Band 4, which shares the same band upper edge. This approach maximizes receiver interoperability with the ngVLA-spec antennas for ngVLA Bands 2-6, while also supporting the wide-band and VGOS interoperating modes. T_{RX} is degraded by roughly a factor of two compared to the ngVLA baseline over the 8-34 GHz range.

Production Concept B employs up to 6:1 bandwidth ratios, providing the widest bandwidth receivers in a 3-band concept, but at the expense of noise temperature and illumination efficiency (Figure 5). Noise performance is degraded an additional 20% compared to concept A below 34 GHz, and approximately 120% above 34GHz. Given this degradation in performance, this concept is not recommended.

Production Concept C retains the qualification electronics receiver bands below 34 GHz, prioritizing interoperability with the VLBA S-X modes over equivalent VGOS modes. ngVLA-spec bands 5 and 6 are used to extend the high-frequency observing capabilities. This model has higher noise temperature below 34 GHz due to the circular polarization hybrid couplers, and a mixed polarization basis, with linear feeds at high frequency. This concept provides a natural progression from the qualification electronics package to a production package, with a greater degree of reuse.

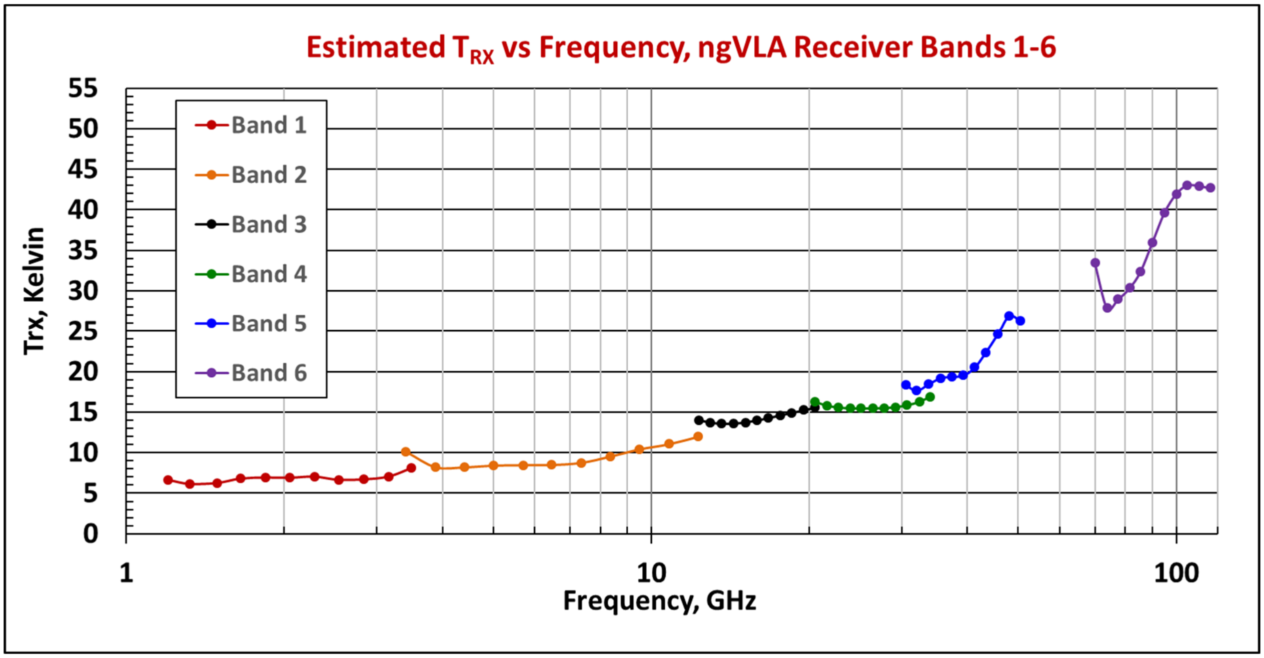

Figure 1 – Estimated T_{RX} vs Frequency for the baseline ngVLA Receiver Configuration. This configuration offers the lowest noise of any of the designs and can be used as a baseline for comparison.

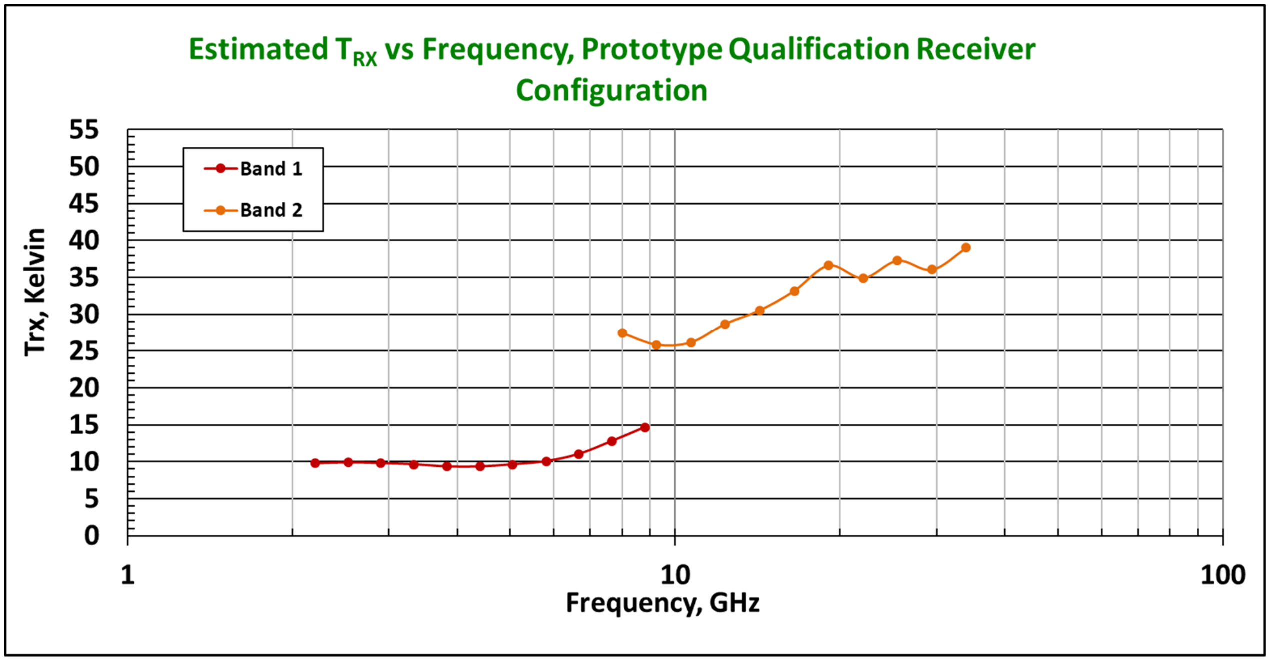

Figure 2 - estimated T_{RX} vs Frequency for the qualification electronics receivers. The losses associated with the hybrid couplers for circular polarization are included, along with the expected offsetting reduction in noise from 4K cryogenics in Band 2.

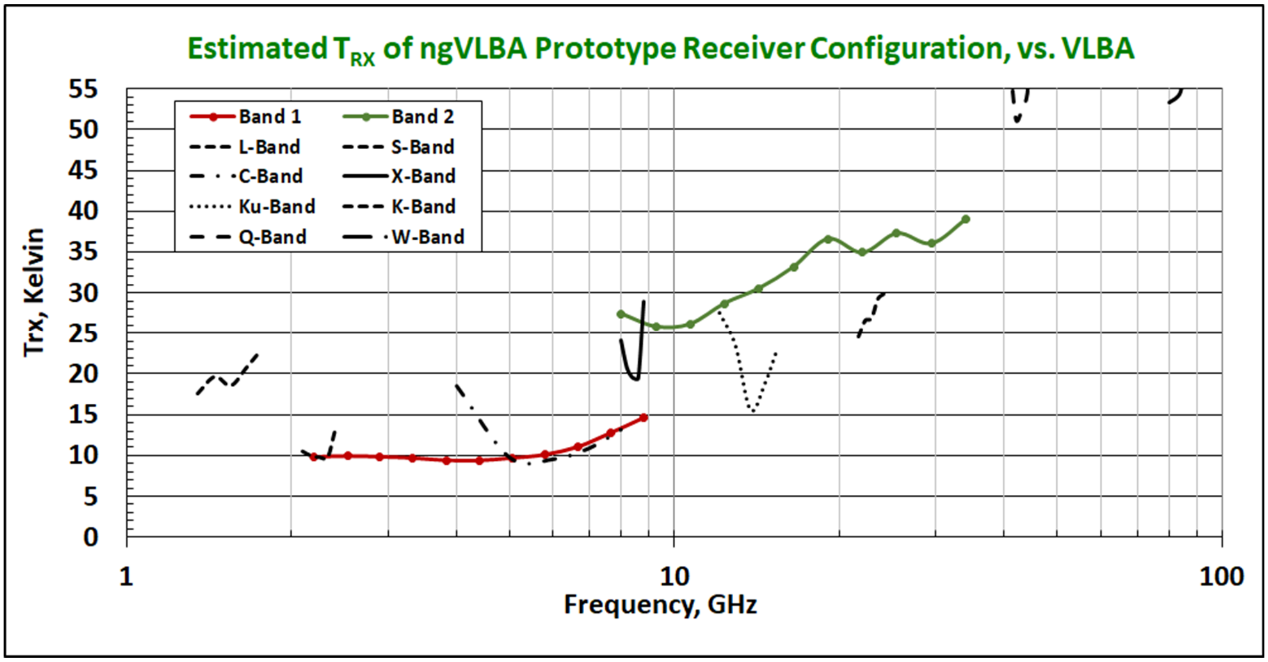

Figure 3 - Comparison of T_{RX} and observable bandwidth with the qualification electronics receivers and the existing VLBA receivers. When considering the performance of dual-band modes vs wide-band modes, we note that VLBA SEFDs degrade by 3% at S-band and 34% at X-band.

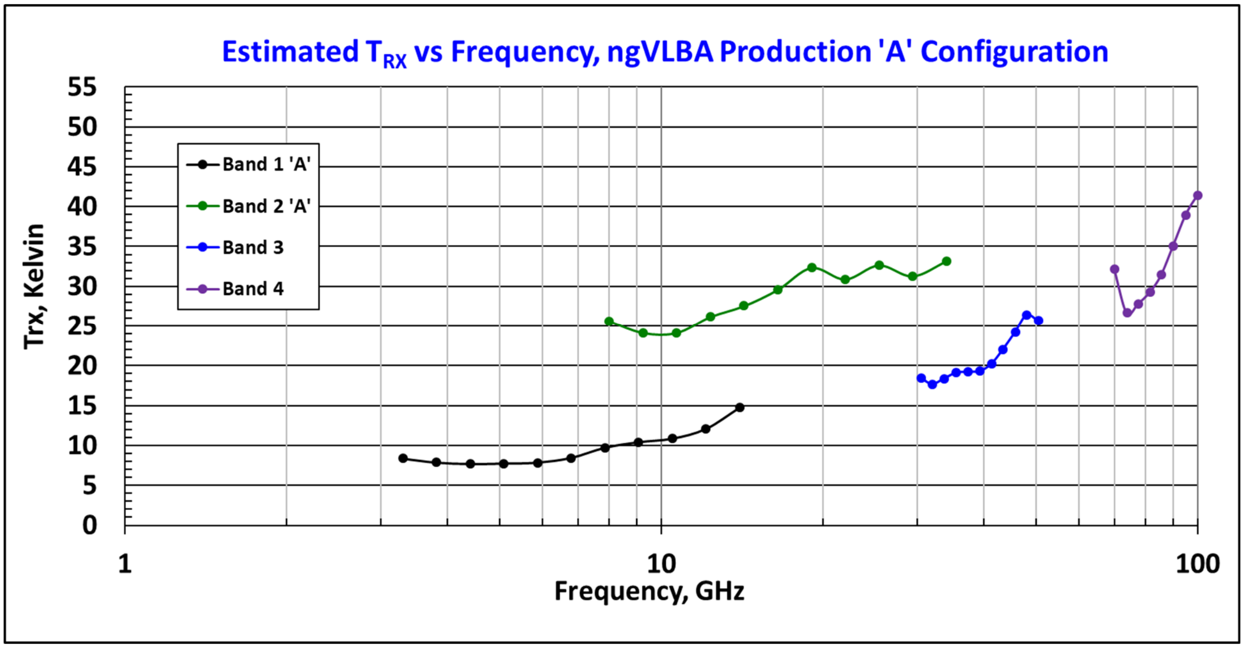

Figure 4 - Estimated T_{RX} vs Frequency for ngVLBA Production concept A. Noise performance of the first two bands is improved compared to the prototype qualification electronics due to the elimination of the hybrid coupler (circular vs linear polarization). The receiver noise in Band 2 is approximately double the baseline ngVLA design, representing the tradeoff in sensitivity vs bandwidth.

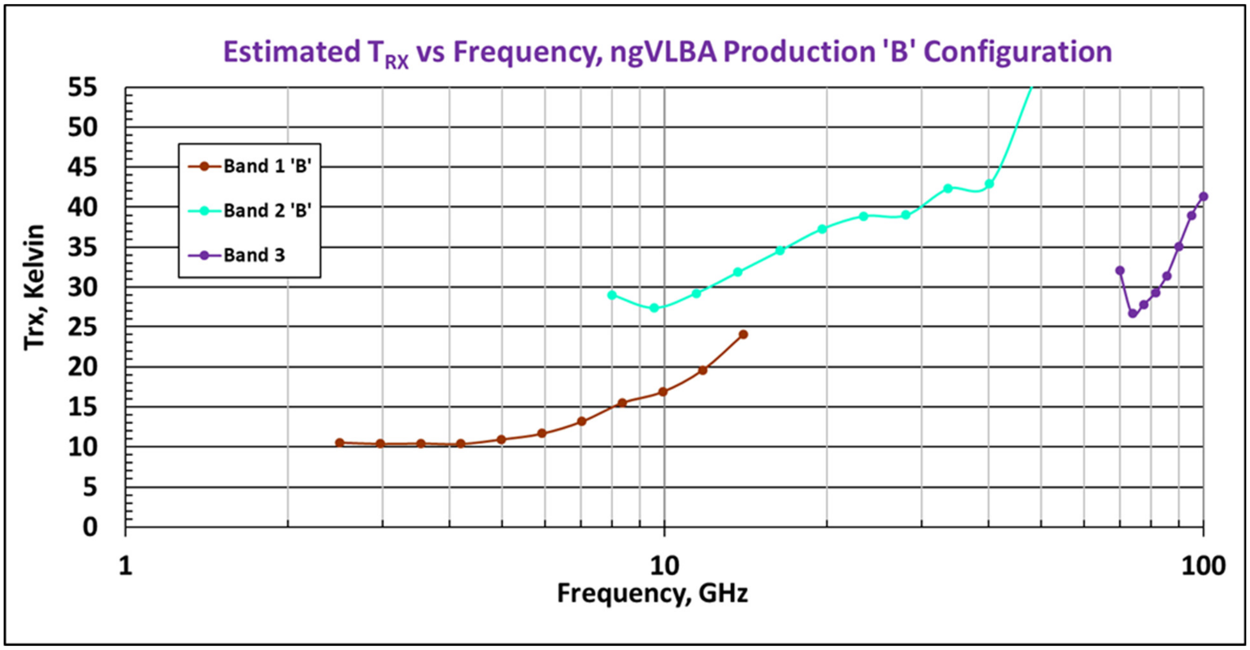

Figure 5 - Estimated T_{RX} vs Frequency for ngVLBA Production Concept B. The receiver noise is degraded an additional 20% in Band 2 compared to production concept A, and the combined losses extend through to the upper 48 GHz band edge. These losses are attributable to the dielectric needed to span the wider band edge ratio, coaxial losses, and degraded LNA noise temperature when spanning this RF bandwidth.

5 Supporting Electronics Concept

The block diagram for the supporting antenna qualification electronics concept is summarized in Figure 6. The wideband receivers are each fed to a set of ngVLA-style integrated receiver downconverter (IRD) modules, sharing the same analog stage design and the ngVLA Band 2, 3 and Band 4 IRDs (for S, X, Ku and Ka tunings respectively). Separate digitizer boards are assumed that will rely on presently available ADC development kits to sample the I-Q basebands at 4.096 Gsps. Bandwidth selection and formatting will take place in a pathfinder digital back end (DBE).

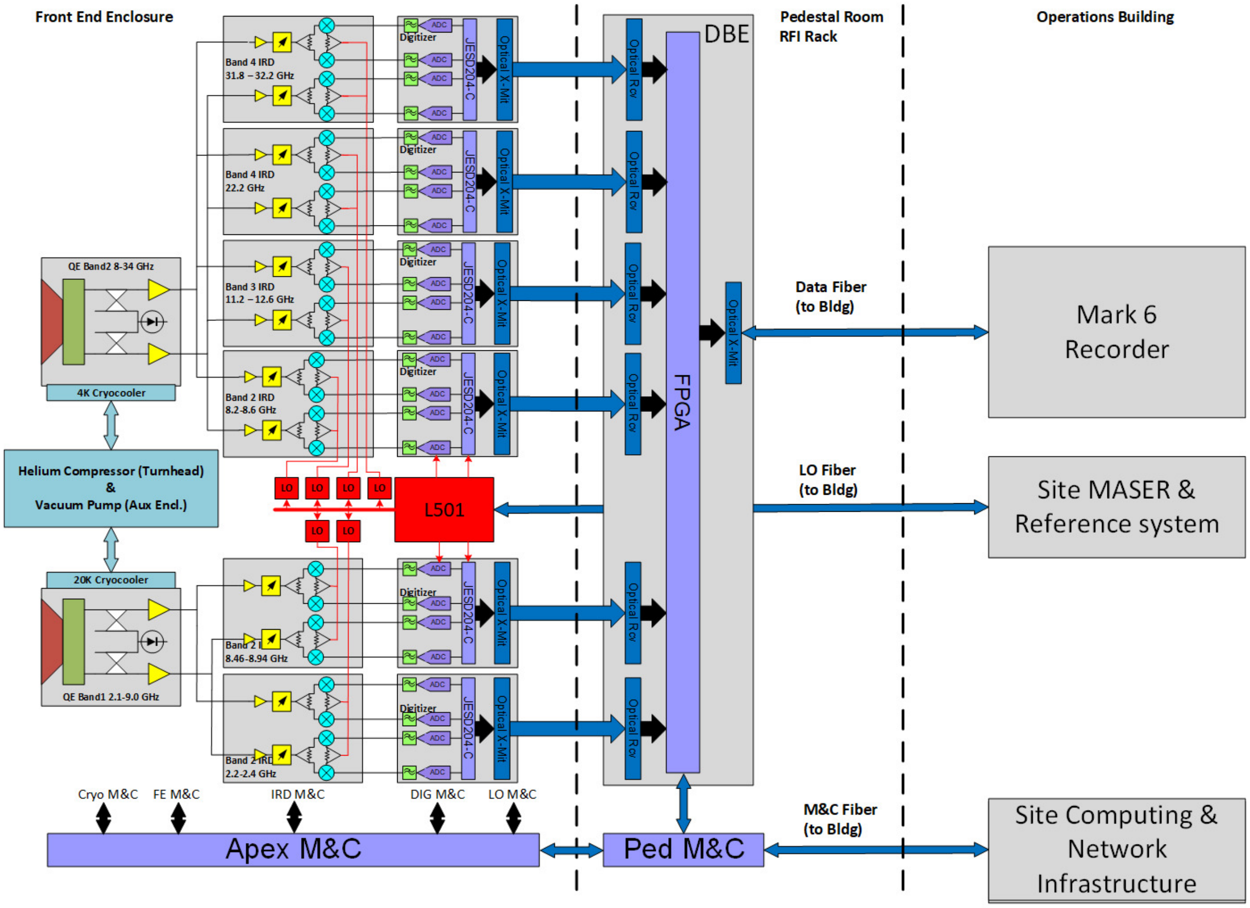

Figure 6 - Simple block diagram for the long baseline antenna qualification electronics.

The LO concept uses fixed LO frequencies at 3.2 GHz, 9.6 GHz, 12.8 GHz, 22.4 GHz and 31.4 GHz. These frequency choices keep the first four LOs harmonically related, minimizing self-generated spurs. No switching is employed in the RF with parallel analog electronic paths preferred, closer to the ngVLA electronics concept for down conversion and digitization. This is anticipated to be the most performant solution (though higher cost) and enables the testing and verification of key architectural design choices in the ngVLA electronics concept.

Ancillary services such as HVAC, DC power distribution, and monitor and control interfaces will rely on ngVLA prototypes tailored for the application. The exception is the cryogenic system, as two receivers will be in separate dewars with the 8-34 GHz feed cooled to 4 K. An ALMA-style refrigerator and compressor may be preferable. However, interfaces from the cryogenics to the M&C software system would all leverage the ngVLA utility module design for the hardware interface layer, providing a common interface standard to the control software. Primary references will rely on a GBO provided maser and GPS-derived time signal that are distributed to the prototype using prototypes of the selected ngVLA time and frequency distribution concept. A dedicated Mark6 recorder provides local data recording of the formatted subbands generated by the digital back end system in the pedestal.

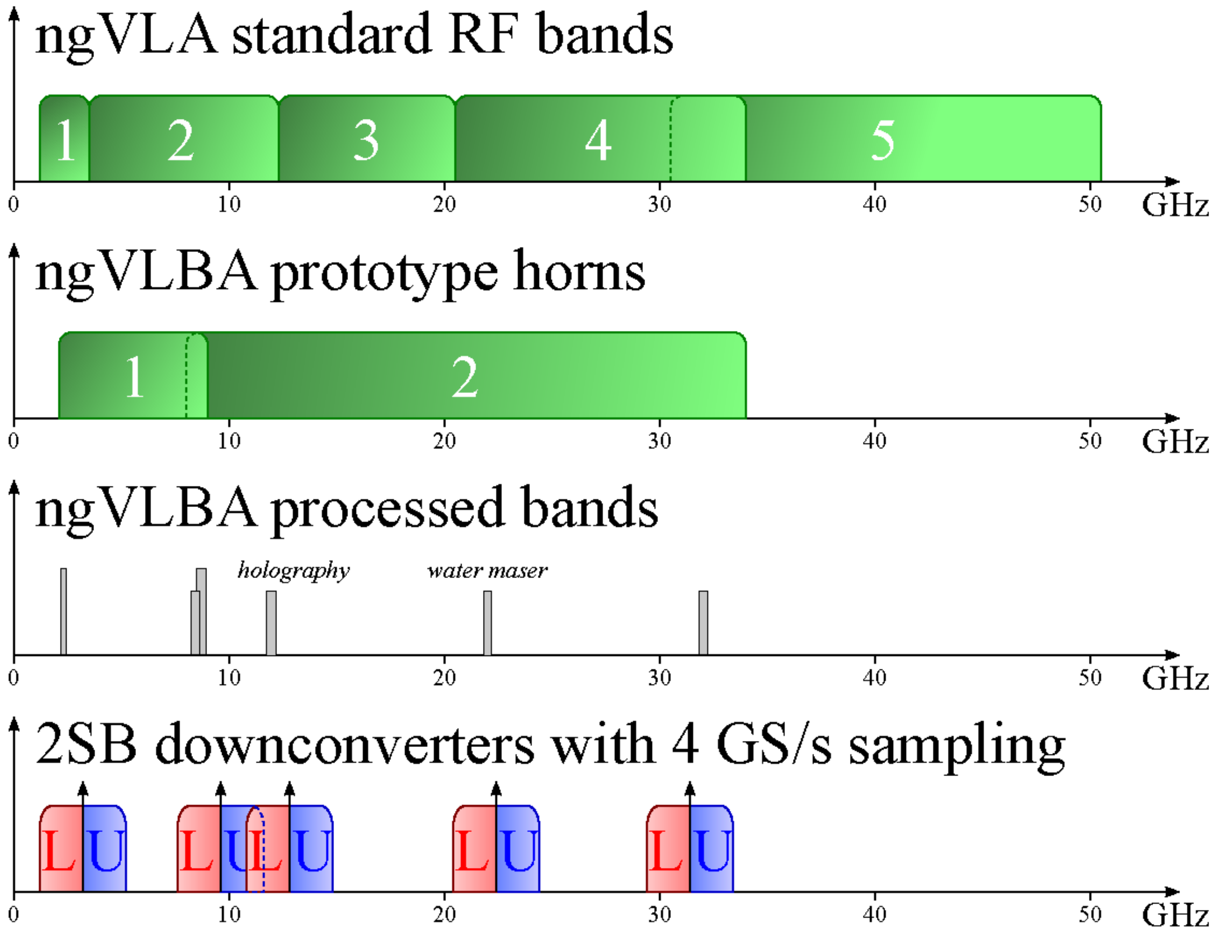

Figure 7 - Comparison of ngVLA RF Band Definition, the prototype wideband horns for antenna qualification, and the associated processed subbands for S-X and X-Ka, Ku-band and K-band modes. The sampled subbands with the 4 GS/s qualification electronics architecture are also shown. Four IRD modules enable the dual band S-X and X-Ka modes (X band is sampled by a parallel pairs of IRDs, one attached to each receiver). Additional IRD modules centered at 12.8 GHz and 22.4 GHz provide access to satellite beacons and water masers used for pointing and surface characterization, inclusive of holography.

The RF bandwidth, tunings required of the qualification electronics, and down-converted and digitized subbands associated with the qualification electronics concept are summarized in Figure 7. The initial deployment of the system will focus on providing the identified processed bands and modes only, but subsequent updates to the DBE firmware should allow tunable access to the spectrum captured by the IRD dual-sideband downconverters and the 4 GSPS ADCs. A production concept would add additional IRD modules, updated 8 GSPS ADCs, and new LO frequencies to fully span the RF bandwidth of each receiver.

More detailed block diagrams of the qualification electronics in the front-end enclosure at the secondary focus, the antenna pedestal room rack, and within the station building are available in ngVLA document 020.02.18.00.00-0001-BLK.

5.1 Stand-Alone Holography System

Characterization of the antenna surface using radiometric techniques may require the development of a standalone holography system. This is envisioned as consisting of a single reference antenna, placed in very close proximity to the antenna under test and pointed at a geostationary beacon or a bright astronomical source such as a water maser. The antenna under test would perform an On-The-Fly (OTF) scan of suitable size to achieve the intended spatial and surface resolution, as described in ngVLA Antenna Memo #12 [1]. The pattern would be 'daisy' shaped to return through the main boresight axis each scan in order to calibrate atmospheric phase.

The holography system is anticipated to use either (a) the Ku-band frequencies most frequently supported by satellites accessible from North America, primarily in the 11.7 to 12.2 GHz range [5,6], or (b) The water maser line at 22.2 GHz, concurrent with the Ku-band or K-band mode of the electronics on the prototype antenna.

The A/T required of the reference antenna is set by the required holography map precision and the source flux of the K-band water masers, and first-order calculations suggest a 4 m-class deployable antenna with warm receiving electronics ($T_{sys} \approx 200K$) and two-axis drives will be performant. Such antenna systems are commercially available, along with feeds and LNAs (see Figure 8). A solution from mtex that would provide interfaces matching the ngVLA ACU would minimize total development effort and is under discussion. In either scenario, the antenna should be rapidly deployable and transportable. Designs leveraging a flat rack (skid) ISO container may facilitate logistics.

Figure 8 - Representative deployable Ku-band reference antenna package. DataPath DKET 3400 Series 4.0m system.

The signals from the reference antenna must be down-converted, digitized, filtered, and formatted with subband characteristics matching the antenna under test. The simplest way to achieve this will be to duplicate the qualification electronics path from the IRD through the DBE at Ku-band and K-band, reducing total development effort. A coaxial feed could be employed to eliminate any mechanical band switching.

Data from the reference antenna and antenna under test could be recorded on Mark6 recorders for post processing. Alternatives could include sending the data to the VLBA DiFX correlator in the real-time mode as the bandwidths processed are narrow, or deploying a local two-antenna software DiFX correlator at the GBO to enable real-time correlation without the need for data transmission over the internet. These options should be assessed for feasibility, but the recorded mode can be adopted as the baseline solution.

Developing this system presents a significant expense, but has long-term value as the reference antennas and associated electronics could be used for ngVLA mid-baseline antenna surface characterization and setting where no nearby ngVLA antennas are available to function as a reference.

Should developing this system prove too costly within the envelope of this proposal, single-baseline OTF holography using the GBT as the reference antenna may be pursued as a viable alternative. This would enable testing the long baseline antenna prototype, while leaving the characterization of the ngVLA mid-baseline antennas as an unresolved challenge.

6 Conclusions

The proposed antenna qualification electronics package should support the key observing modes and associated requirements for the long baseline antenna verification and validation tests. The conceptual design leverages ngVLA concepts and can function as a "pathfinder" prototype for multiple system components, while also supporting future development paths that are of interest to the USNO and other geodetic users.

The stand-alone holography reference antenna is an optional piece of test instrumentation that will enable astro-holography for future remote antennas. For the prototype at the GBO, the GBT would function effectively as a reference antenna if the associated test time can be secured, providing a possible descope path while still ensuring that the surface of the prototype is well characterized.

7 References

[1] J. Mangum "Verification Testing for the ngVLA 18 m Prototype Antenna" ngVLA Antenna Memo #12, 2021.

[2] R. Selina. "18m Antenna Customer Verification Plan" ngVLA Doc. 020.25.00.00.00-0011-PLA, 2021.

[3] J. Jackson. "Potential ngVLA Sites at the Green Bank Observatory" ngVLA Doc. 020.10.25.00.00-0008 REP, 2023.

[4] R. Selina "Long Baseline Antenna Prototype Test Site Selection" ngVLA Antenna Memo #14, 2024

[5] Satellite Signals "Satellite Beacon Frequencies" Accessed from https://www.satsig.net/eut2beac.htm, 1/25/2024.

[6] Wikipedia "Ku band" Accessed from https://en.wikipedia.org/wiki/Ku_band#America 5/23/2024.

8 Appendix

8.1 Aperture and Tsys Calculations for Holography Reference Antenna

In order to calculate the necessary aperture size of the holography reference antenna, we adopt Equation 12 from Memo 12:

$$\begin{aligned}\delta z &= \left(\frac{c}{4\pi\nu\cos\phi}\right)\left(\frac{1}{2S}\sqrt{\frac{N_{grid}}{N_{ref}Bt_{grid}}}\right)\left(\frac{2kT_{sys}}{\eta_i\eta_b A_p}\right)\\ &= \frac{c\sqrt{N_{grid}}kT_{sys}}{\nu\pi^2 D^2 S\eta_i\eta_b\cos\phi\sqrt{N_{ref}Bt_{grid}}}\\ &\simeq \frac{6\times10^4\sqrt{N_{grid}}T_{sys}(K)}{\nu(GHz)D^2(m)S(Jy)\eta_i\eta_b\sqrt{N_{ref}B(MHz)t_{grid}(sec)}}\,\mu m \qquad (12)\end{aligned}$$

Assuming:

$\eta_i = 0.7$

$\eta_b = 1.0$

B = 10 MHz

S = 1000 Jy

$N_{grid} = 661$

$N_{ref} = 1$

ν = 22 GHz

T_{sys} = 200 K (Warm Receiver)

δz = 35 micron

Solving for D^2:

$D^2(m) \approx 181/\mathrm{sqrt}(t_{grid}(sec))\ m^2$

For t_{grid} = 10 seconds, $D \approx 7.6$m.

Water masers vary in flux density by a few orders of magnitude. For S = 4000 Jy, the required aperture size decreases by sqrt(4) and D ≈ 3.8m.

We will adopt T_{sys} = 200 K and D = 3.8m as working values for the initial holography reference antenna concept, but these values can be refined in the preliminary design phase depending on component availability, feasibility and a refined source selection.