ngVLA Antenna Memo # 14

Long Baseline Antenna Prototype Test Site Selection

R. Selina (NRAO)
02/28/2024

Abstract

This memo considers the pros and cons of a subset of possible test sites for the ngVLA long baseline antenna prototype. Multiple technical and programmatic criteria are considered, as well as the interrelationship to the broader prototype verification and validation plan. A ranking of the sites on these metrics favors deployment of the prototype for testing at the Green Bank Observatory. In particular, a site near the 'potato patch' (adjacent to the airstrip) is preferred.

1 Introduction

The ngVLA project is working with the US Naval Observatory to develop a long baseline variant of the 18m Main Array antenna for the ngVLA. The long baseline antenna differs in a few key specifications, with an extended lower elevation limit of 7° (vs 12° for the main array antenna) being the most significant change.

A key question in the development of the ngVLA long baseline antenna is the location for deployment for prototype testing. This memo considers criteria that could inform a down-select between sites and then summarizes the ranking of a number of sites given these criteria.

2 Test plan considerations and assumptions

Typically, the primary aim of a prototype is to demonstrate that the proposed design meets its prescribed requirements (i.e., design verification). In this case though, the testing activities may extend to a higher system level, demonstrating the suitability of the design for the identified scientific use cases (design validation). The antenna may also be targeted to transition to the operations phase, so longer-term site value is also a consideration.

The testing scope can be considered progressive and the overall verification and validation plan will be defined over the course of the antenna design phase. We note the possible progressive sets of verification, characterization, and validation goals that could inform the site selection:

1. Testing key performance parameters of the long baseline prototype antenna. (verification)

2. Comparing the performance of the long baseline prototype antenna to the main array antenna. (characterization)
3. Comparing the performance of the long baseline prototype antenna to a VLBA antenna. (characterization)
4. Demonstrating the performance of the long baseline prototype antennas for geodetic use cases. (validation)

2.1 Testing key performance parameters of the long baseline antenna prototype

Site acceptance testing to demonstrate that key performance requirements are met has been well considered for the main array prototype antenna, with a supporting verification plan and analysis [1,2].

Importantly, the supporting analysis concluded that stand-alone radiometric testing would not be sufficiently precise to demonstrate conformance to the reference pointing and surface requirements over a suitable range of Azimuth and Elevation angles and environmental conditions. Interferometric tests would be required, ideally with multiple (5 or more) short baselines. [1]

This verification goal favors testing the new prototype at the VLA site, with the prototype integrated into the VLA for the verification observations. The qualification electronics and software developed for the main array prototype antenna could be reused for this purpose, verifying the performance of the antenna with minimal cost and effort.

Partial verification as a single dish or an element of the VLBA appears feasible, but results would not sample the full operating range of Az/El and may need to have lower temporal and/or spatial resolution. This may be an acceptable compromise given other competing programmatic desires, and the close design connection between the long baseline antenna and main array antenna prototype.

At VLBA sites, surface accuracy may be verified at key elevation angles using brighter calibration sources such as GEO-stationary beacons with a newly developed holography system employing a closely co-located reference antenna. Such a system is envisioned to verify the performance of the ngVLA mid-baseline sites, so development of this test system does have longer-term value. However, such a system would need to be characterized and demonstrated to work at the VLA site prior to use at a remote location, and would entail additional development effort. Assuming such a system is performant, it would demonstrate that the surface meets requirements at key locations in the GEO belt, generally restricting tests to the 20-50 deg elevation range (depending on site latitude). This is ample for ensuring that an antenna has been assembled correctly (as is the case in mid-baseline sites) but is not ideal for design validation as the surface accuracy approaching the upper and lower elevation limits cannot be fully characterized this way, and the long baseline antenna variant is anticipated to have differences in the backup structure that impact its stiffness and deformation at the upper and lower limit of the elevation range. However, so long as GEO targets at 20° or lower in elevation (to the SE and SW) are accessible, this may be sufficient to demonstrate the stiffness of the BUS and allow extrapolation of performance based on the FEA model.

Blind all-sky pointing performance could be determined from single dish radiometric tests with sufficient precision [1]. However, the measurement precision (both time and amplitude resolution) required to verify the 3” reference pointing requirement, combined with the time variability of the environment and pointing performance, precludes robust characterization with less than five reference antennas assuming 100-500mJy sources [1]. Characterization of referenced pointing performance in the GEO belt would be feasible, though this would not fully account for tracking errors over time since these sources have fixed Az-El coordinates on the relevant timescales. However, a limited set of 10+ Jy calibrator sources may permit limited referenced pointing testing in other parts of the sky, with some compromises in the time resolution of the measurement. Referenced pointing performance would therefore be characterizable at a VLBA site with bright sources, at a limited set of Az and El angles, and at lower time resolution.

Delay stability and other performance requirements can generally be verified by other means independent of the supporting infrastructure at the prototype site. Some of the deficiencies in the stand-alone radiometric tests could perhaps be overcome with additional supporting instrumentation such as accelerometer characterizations of the structure to infer the pointing errors on shorter timescale (e.g., wind induced buffeting) or the use of an optical pointing telescope. These ancillary tests should only be pursued if demonstrated to be necessary in the detailed test plan analysis.

2.2 Comparing performance to the Main Array antenna

As the long baseline antenna design is a variant of the main array antenna design, understanding how the performance compares between the two designs is quite helpful to the system-level design of the ngVLA. Calibration strategies may be common or need to vary for subarrays using each antenna, and the degree of performance variation could impact observation strategies for full array observations (for example, mandating the use of referenced pointing at different bands). Direct comparisons between the two designs could also inform a trade study to standardize on a single design, or simply be used to assess the cost-performance differences between the two designs as input to the final design phase for antenna production.

Such comparisons are unambiguous when both prototypes are located in the same environment and operated concurrently, as the environmental contribution to performance can be quite significant. The measurement errors should also be low to not significantly influence the results. The most robust solution would be joint observations as antennas 29 and 30 of the VLA, though detailed weather data for each observation could enable comparisons between the antennas when observing at different times, which reduces the need for duplicate antenna electronics.

The main array antenna prototype is outfitted with different electronics (selected for interoperability with the VLA) than would be selected for the long baseline antenna if the latter is observing with the VLBA only. While the main array antenna prototype can be recorded in VLA Y1 mode for cross-correlation with the VLBA, the differences in electronics, the geographical separation, and the higher noise associated with VLBI measurements are expected to make direct comparisons in a VLBI observation infeasible. When not collocated, comparisons of performance will instead need to rely on accurate site weather instrumentation and comparisons of the key performance tests adjusting for differences in environmental conditions.

2.3 Comparing the performance of the long baseline prototype antenna to a VLBA antenna

The VLBA is the gold standard for US-based VLBI observations. Adding the long baseline antenna prototype as an element of the VLBA could enable a more direct comparison to the performance of the VLBA antennas.

The most effective way to make this comparison would be to locate the prototype at a VLBA site, ensuring that the antennas are subject to the same environmental conditions and share the same primary references. Locations remote from a reference VLBA antenna generally make such comparisons harder as the environmental contributions and local conditions can dominate the post-calibration residuals. Remote locations could be instrumented with weather towers to characterize the environmental differences and partially correct for their effects in the analysis, but the added environmental variables will complicate the comparison.

Importantly, this comparison will require that the antennas be restricted to observe in ways that are supported by both designs. E.g., a co-located VLBA antenna could not observe below 7-degrees, and the ngVLA antenna could not slew at a faster rate than the VLBA. This nullifies some of the advantages inherent to each design and limits system-level performance comparisons. The observations still provide a useful validation check in overlapping parameter space, but the inherent limits of such joint tests must be kept in mind when assessing the design's suitability to the primary use cases.

2.4 Demonstrating the performance of the long baseline prototype antennas to the VLBA for geodetic use cases

Demonstrating the unique capabilities of the long baseline prototype antenna would likely require a pair of antennas at a minimum, forming a long baseline equivalent to a VLBA baseline. This would then allow direct comparison of the results generated by the ngVLA and VLBA antennas as sub-arrayed pairs, while leveraging the capability differences of the two arrays. Ideally the baselines would be in close proximity (the prototypes installed on two VLBA sites) to eliminate environmental influences between the antennas under test and the reference baseline.

However, while the observations are performed concurrently, observing strategies could be developed unique to each array. VLBA solutions could leverage the full elevation range at the site, and ngVLA solutions could leverage higher slew rates and perhaps bandwidth. Variations of a UT1-UTC observation would form a natural test. This suggests a wide-band receiver is needed on the ngVLA prototype antennas (with associated supporting electronics and software), to observe the same dual band frequencies used in UT1-UTC observations at the time of prototyping (VLBA S-X today, but possibly X-Ka by the time the new prototype is constructed).

Full capability demonstration of the ngVLA long baseline design for this use case would require four or more prototypes deployed as long baseline clusters, allowing concurrent multi-subarray observations to demonstrate long baseline cluster functionality. However, we assume that such a significant expense is not feasible as part of the next phase of the project.

A more minimum implementation would require a single baseline with a length and orientation that can be considered comparable to a VLBA baseline, with weather instrumentation at each site to account for the environmental differences. While the resources required are more modest, such a test is still anticipated to be outside the available fiscal envelope and will not be used as a metric for site selection for the prototype.

2.5 Long Term Site Value

As the second ngVLA prototype antenna, the prototype long baseline antenna may be targeted to transition to the operations phase, so longer-term site value is an important consideration in the section of the site for deployment and testing.

In this context, a deployment at a long baseline subarray site is strongly favored to an installation within the extent of the main array. The VLA site ranks poorly on this metric, and nearby VLBA sites like Pie Town are envisioned to transition to main array installations which also reduces their value for long baseline antenna prototype deployment. Within the current set of candidate long baseline subarray sites [9], existing observatory sites with supporting infrastructure and staff such as Green Bank or Owens Valley are the most attractive given the logistics involved with deployment and testing. Green Bank may be the most practical of these sites given the joint management by AUI and proximity to key ngVLA personnel in Charlottesville.

3 Site Selection Criteria

Table 1 summarizes the criteria used to inform site selection.

Criteria	Weight	Description
Feasibility of testing key performance parameters of the prototype	0.90	Site impact on the precision of testing referenced pointing, delay stability and surface accuracy over a range of elevation and Azimuth angles.
Feasibility of testing low elevation performance	0.90	Site horizon level and any obstructions that restrict observations to 7-degrees in elevation as a function of Azimuth. Informed by Beasley & Medcalf, 1992 [3].
Feasibility of comparison to the Main Array Antenna 18m design	0.10	Ability to directly compare the as-tested performance to the main array antenna to characterize any differences in performance between the two 18m antenna designs.
Feasibility of demonstrating VLBI performance with the VLBA	0.50	Site impact on the characterization of VLBI performance and comparison to existing UT1-UTC and ICRF observations. Proximity to a VLBA site used for UT1-UTC observations (MK, PT, LA, SC) for direct comparison.
(Lack of) Programmatic dependencies on other initiatives	0.10	Programmatic dependencies for site selection on other initiatives such as the VNDA project, site infrastructure upgrades, etc.
Site & Electronics Costs	0.10	Availability of infrastructure and electronics systems to support the testing phase. Development work required, proximity of key staff, travel time and costs, etc.

Criteria	Weight	Description
NEPA and Site Acquisition	0.50	Availability of an observatory site with both space and regulatory clearances to permit the installation of the antenna. Perceived difficulty in regulatory compliance.
Long-Term Site Value	0.90	Value of the antenna installation as a possible Antenna #1 in the long baseline subarray, tailored to USNO use cases.
Programmatic Value	0.90	Value of the antenna installation in meeting other stakeholder needs that help advance the project or secure future funding.
Other Considerations	0.10	Any other considerations that influence the site selection.

The weights associated with each metric were agreed upon within the ngVLA project office and aim to balance the relative value of the verification and validation activities with the long-term and programmatic value of the sites given the intention that the prototype be the first production article of the ngVLA long baseline subarray.

4 Candidate Sites

The following sites have been proposed as candidates for the long baseline antenna prototype testing:

- The VLA site on the plains of San Agustin, New Mexico (VL)
- The Pie Town site of the VLBA in New Mexico (PT)
- Green Bank Observatory in West Virginia (GB)

These sites are compared and rated on the previously established criteria in the table below. A 1-10 scale is used, where 10 is best and 1 is worst. A final composite score inclusive of the criteria weights is also provided.

Criteria	Weight	VL	PT	GB
Feasibility of testing key performance parameters of the prototype	0.9	10	7	7
Feasibility of testing low elevation performance	0.9	10	7	7
Feasibility of comparison to the Main Array Antenna 18m design	0.1	10	5	5
Feasibility of demonstrating VLBI performance	0.5	7	10	7
(Lack of) Programmatic dependencies on other initiatives	0.1	10	6	6
Site & Electronics Costs	0.1	10	5	5
NEPA and Site Acquisition	0.5	10	7	10
Long-Term Site Value	0.9	5	7	10
Programmatic Value	0.9	2	4	10
Other Considerations	0.1	-	-	-
Total Score		**35.80**	**32.60**	**40.70**

Overall, the VLA site ranks well on its ability to support the verification of the prototype antenna, but ranks poorly in terms of long-term site value and programmatic value. Pie Town scores highest on validation metrics. Greenbank ranks adequately on both verification and validation metrics, and highest on long-term site value and programmatic value, leading to the highest composite score amongst the three candidate sites.

5 GBO Sites

A more detailed assessment of candidate sites for ngVLA antenna deployment at the Green Bank Observatory has also been conducted [4]. In addition to the site logistics and available supporting infrastructure, this local site evaluation considers the accessible horizon in support of the long baseline antenna prototype testing and long-term performance. Four candidate sites are subsequently identified as viable:

- Beard House
- West End of the Air Strip
- Middle of the Air Strip (Potato Patch)
- Deer Stand

Additional criteria that should be considered in the final site selection includes RFI protection for the existing facilities. The ngVLA Antenna has been designed with shielding and emission levels suitable for use at the VLA site as part of a connected element array. These specifications are relaxed relative to the ITU 769-2 requirements for single dish radiometry by approximately 17dB at 1 GHz. [5] The permissible emission levels are in line with the NRQZ specification [6] and ITU 769-2 when placed approximately 500m from the GBT or any low-frequency (<1 GHz) instrument. Given the other instruments on the site, this makes this Middle of the Air Strip (a.k.a, the Potato Patch) the most attractive site that would not lead to the need for a redesign of the antenna servo system filters. Conformance to GBO site RFI requirements should be carried as a risk until the 18m Main Array Antenna prototype is installed and its emissions characterized at the VLA site.

Should an issue be identified with the preferred site, the west end of the airstrip appears to be a viable backup, but presents a slightly higher risk of RFI emission compliance due to the increased proximity to the GBT. The Beard House has unique historical preservation requirements and associated risks. Both the Beard House and the site opposite the deer stand are in close proximity to the under-construction CHIME outriggers. A more detailed analysis of the RFI sensitivity of this telescope should be performed before considering these two sites.

Figure 1 - Approximate site of the preferred ngVLA Site (in orange) near the middle of the air strip (the potato patch). [5] The site is approximately 1.2km from the GBT and 500m from the CHIME outrigger site. The main utility corridor (electrical and fiber service) is also approximately 500m to the north of this site.

6 Site Specific Considerations

With the identified preference for the site adjacent to the airstrip at the GBO, we consider possible site-specific considerations to be studied in the preparation of a detailed plan for prototype deployment and testing:

- A decision should be made to retain or update the RFI emission limits for the long baseline antenna design prior to releasing the design contract. Given the minimal risk at the preferred airstrip site, and the projected performance of the main array antenna [7,8], minimizing design differences between the long baseline antenna and main array antenna is the preferred approach from the ngVLA perspective.
- A full suite of antenna test electronics will be required spanning from receiver to data recorder, and must be interoperable with the VLBA. If such a system is based on the ngVLA electronics architecture, which is strongly preferred given interface constraints, that precludes reuse of any VLBA backends (VNDA and the RDBE are not compatible), and the development of these systems will need to be prioritized.
- A new software integration layer will need to be developed to interface the long baseline antenna prototype and test electronics with the VLBA executor.
- The distribution of time and frequency references from the GBO Jansky Lab is sufficiently far that round-trip phase correction will likely be required on these reference signals. ngVLA pre-production prototypes may be the most effective solution.

- The stand-alone holography system described in Section 2.1 will need to be developed and tested. This includes the development of a 2-3m class reference antenna and X or Ku-band signal path to a VDIF-encoded data stream. These may be variants of the antenna test electronics. A software back-end will be needed to function as a square law detector and data formatter, and a new conversion tool may be required in CASA to ingest the data set for analysis.
- A weather station and webcam will be required in the vicinity of the ngVLA antenna site (within ~100m). This can likely be based on an existing design.
- Regulatory requirements should be reviewed for permissible proximity to the airstrip and should inform the final site design.
- Geotechnical studies should be conducted at the preferred site to inform a final foundation design.

These considerations will be further explored in subsequent memoranda or technical documentation as the test plan is further elaborated.

7 Conclusions

The three sites considered (GB, PT and VLA) all appear viable at a high level and differ primarily in their ranking in support of design verification, design validation, or long-term operational site value. The associated weights in the trade study therefore largely inform the selection between them.

Given a resulting preference for installation and test of the long baseline antenna prototype at Green Bank, the preferred sites within the Observatory appear to be adjacent to the airstrip as these sites are both relatively practical and should avoid the need for additional RFI protection measures beyond those already incorporated into the ngVLA antenna designs.

Key supporting test infrastructure and site-specific considerations should be further considered as the prototype deployment and test plan is developed during the preliminary design phase of the project.

8 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] A. Beasley. & D. Medcalf "VLBA Antenna Horizons" VLBA Test Memo #37, 1992.

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

[5] R. Selina "System Electromagnetic Compatibility and Radio Frequency Interference Mitigation Requirements" ngVLA Doc. 020.10.15.10.00-0002-REQ, 2020.

[6] NRAO Spectrum Management "National Radio Quiet Zone (NRQZ)" Accessed from https://info.nrao.edu/do/spectrum-management/national-radio-quiet-zone-nrqz-1, 2/27/2024.

[7] mtex antenna technology "DRD-32: EMC Control Plan: Measurements of ngVLA servo culprits" 1021006-REP-26-40400-002 Revision 2, 2023.

[8] mtex antenna technology "DRD-32: EMC Control Plan: Measurements of ngVLA servo culprits below 1 GHz" 1021006-REP-26-40400-003 Revision 1, 2023.

[9] C. Walker "Suggested Changes to ngVLA LONG" ngVLA Memo #105, 2022.