ngVLA Antenna Memo # 2

System-level Evaluation of Aperture Size

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Abstract

As part of a broader study of the antenna optical design and the associated down select, we evaluate the optimal aperture size range for the antenna based on the impact to the system design. We use point source sensitivity, survey speed, and imaging fidelity as our performance metrics, while respecting the programmatic limits for construction and operations cost. We conclude that the interesting antenna aperture range spans from approximately 18 m to 20 m, with an 18 m aperture providing a balance of performance on the selected metrics.

1 Introduction

This memo summarizes a brief analysis of the antenna diameter and its relationship to key performance parameters for the array. We constrain the construction and operations cost while varying the antenna diameter and observe the changes in the point source sensitivity, survey speed, and imaging fidelity based on corresponding figures of merit.

This memo draws on the ngVLA Quantitative eXchange Model [2], a parametric cost estimating tool developed for such trade studies, as well as updated information from the Reference Design exercise. All values given are normalized to emphasize relative changes over absolute values.

1.1 Key Performance Parameters (KPPs)

The metrics most relevant to this down select are noted below.

Life Cycle Cost: The project should be optimized based on lifecycle cost analysis, assuming a 20-year operations period. In this analysis, we constrain the construction and operations costs, with the latter limited to 5% of the construction cost per annum.

Sensitivity: The system sensitivity is proportional to the number of apertures in the array times their diameter squared (ND^2). I.e., it is proportional to the total collecting area.

Survey Speed: The system survey speed is proportional to the square of the number of apertures times the square of their diameter (N^2D^2). I.e., sensitivity squared over beam solid angle (which goes as D^{-2}).

Imaging Fidelity: Imaging performance is, to first order, proportional to the number of baselines in the array (N^2). In practice, there is a strong relationship to the array configuration and our ability to use these baselines effectively, but performance will degrade as the array (*u,v*)-coverage becomes more sparse.

2 Performance Comparison

2.1 Construction Cost Constraint

We start by plotting the relationship between the key performance parameters and antenna aperture diameter. All other inputs to the quantitative exchange model remain fixed in this analysis and are representative of the engineering basis in the current cost estimate (±10% of the bottom-up estimates.)

In Figure 1 we hold the construction cost constant and vary the antenna aperture size, changing the number of elements in the array (at that fixed construction cost cap). Point source sensitivity is maximized at an aperture of 22 m, while survey speed is maximized at an aperture diameter of 17 m. Imaging fidelity is maximized at 15 m aperture. Note that the point source sensitivity plot is relatively flat over the range 20 m to 24 m, while survey speed drops at a near linear rate as aperture increases.

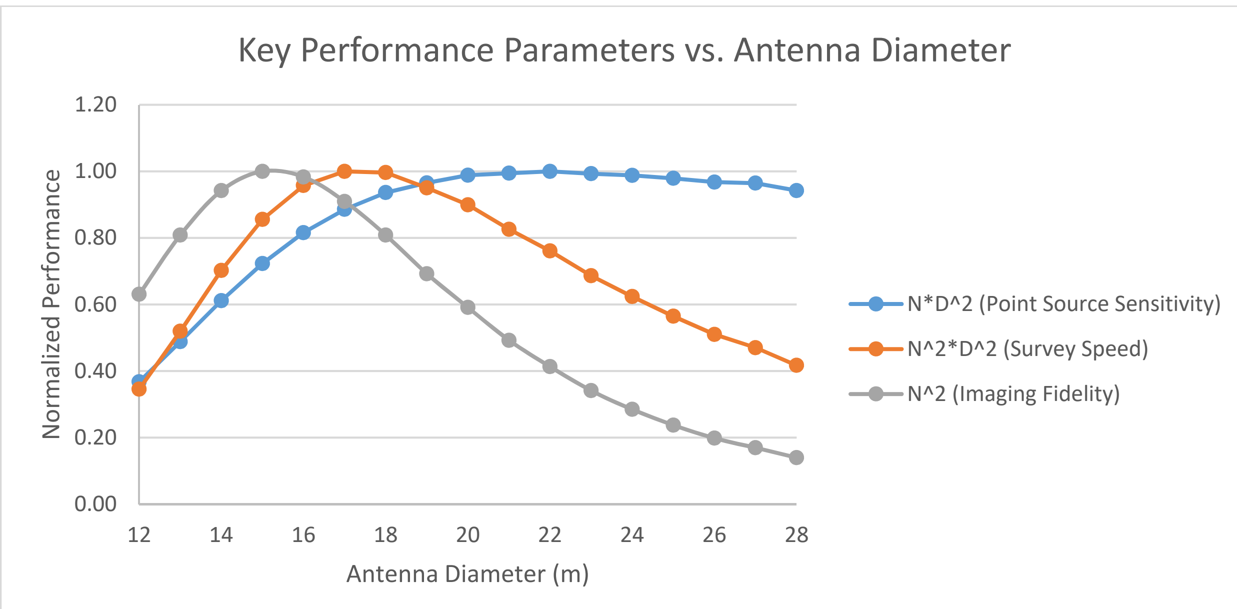

Figure 1 – Normalized KPP performance at fixed construction cost.

2.2 Construction & Operations Cost Constraints

Next we introduce an additional constraint, that the annual operations cost cannot exceed 5% of the construction cost. This is a high-level requirement on the project in order to fit within the NSF AST budget.

Figure 2 shows the collecting area (proportional to ND^2) that can be built within the construction and operations cost limits. The blue construction limit curve is equivalent to the ND^2 curve in Figure 1, while the green curve shows the constraints imposed by the operations cost cap. For apertures 17 m and smaller in diameter, the array that can be built within the construction cap would exceed the available operations budget. The number of apertures in the array (and corresponding total collecting area) would therefore have to be reduced to fit within this operations cost limit. It is the minimum of the two limits that must be respected in this analysis.

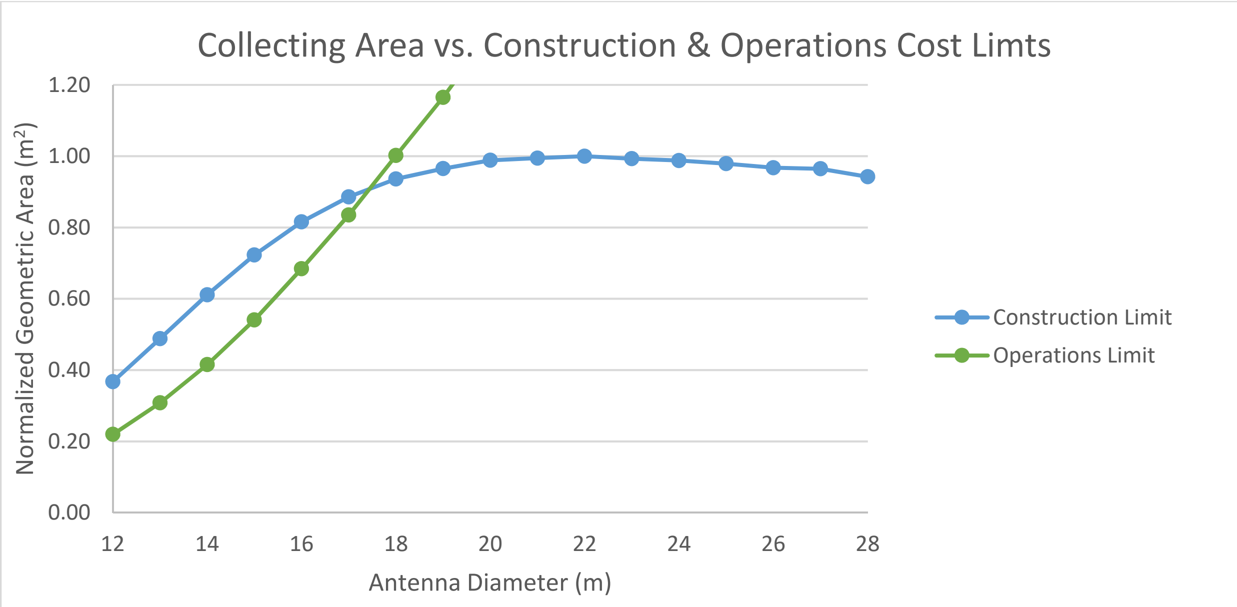

Figure 2 - Collecting area that can be purchased and operated within the construction and operations cost limits. Note that the normalization factors from Figure 1 are used, leading to values above 1.0. Below ~17.5 m aperture the operations cost limits the realizable size of the array.

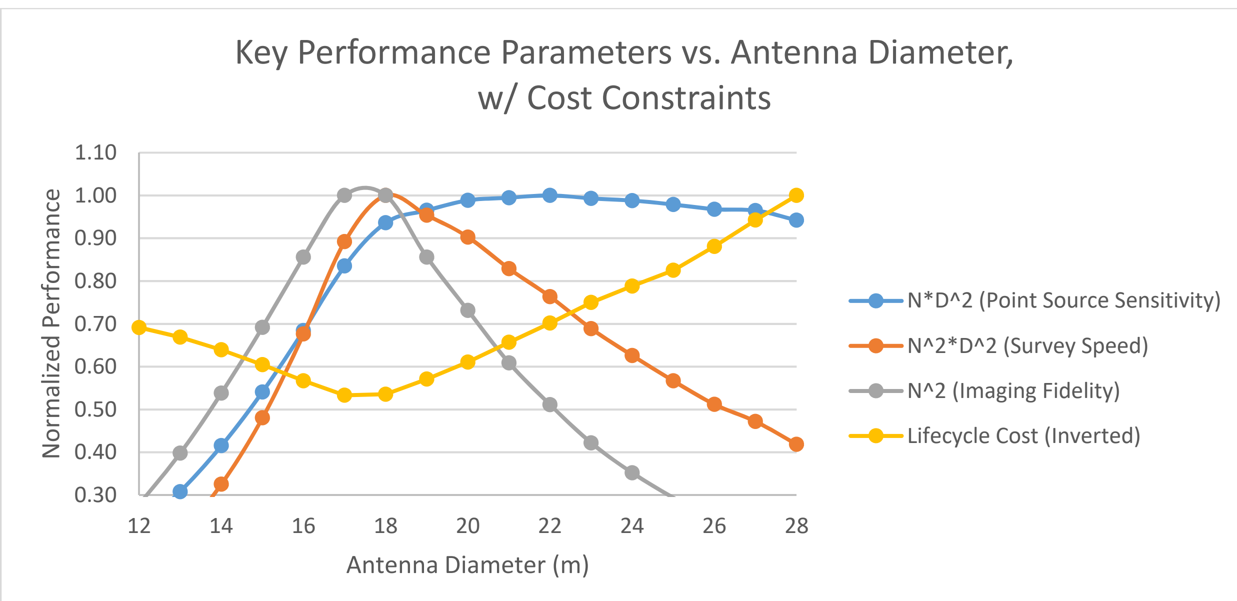

Figure 3 - Performance to KPPs accounting for both the construction and operations cost constraints. Total lifecycle cost is included as an additional independent metric, where 1 is the lowest lifecycle cost.

Array performance, accounting for both the construction and operations cost constraints, is shown in Figure 3. The achievable point source sensitivity is equivalent to the lower of the two curves from Figure 2. Incorporating both constraints, survey speed is now maximized at an antenna aperture of 18 m, imaging fidelity is maximized in the 17 to 18 m range, and point source sensitivity remains maximized at an aperture of 22 m.

We have also added a lifecycle cost metric to this plot. Lifecycle cost is bound in this analysis through the construction and operations cost limits, but it is not equal in all scenarios. In the 17 m to 18 m aperture range, the lifecycle cost is highest since both the construction and operations cost is close to the prescribed limits in Section 1.1. At smaller apertures, the operations cost is limiting and the construction budget is not fully expended. At larger apertures, the construction budget is fully expended but the cost in operation drops with the number of apertures in the array, reducing total lifecycle costs. The curve is inverted so that higher values are better, consistent with the other KPPs in the plot. The key takeaway is that lifecycle costs fall as we go up from 18 m aperture, since arrays with larger aperture sizes have less elements and correspondingly lower operations costs, improving performance on this metric.

2.3 Weighted Key Performance Parameters

In selecting within the 17 m to 22 m range, point source sensitivity, survey speed, imaging fidelity, and life cycle cost may not be equally important. Point source sensitivity contributes to all the key science goals (KSGs) of the ngVLA, while survey speed is only applicable to scenarios where mosaic imaging or on-the-fly mapping is required. There are KSGs where this is necessary, such as LIGO and LISA follow-up searches and imaging of extended emission, but they are a subset of all science cases. An analysis of the science use cases [3] suggests that more than 50% of the analyzed use cases are single pointings with an 18 m to 20 m aperture.

In Figure 4 we show the combined performance of all KPPs with unity weights (weighing all KPPs equally) as well as with weighting factors that prioritize sensitivity and lifecycle cost (weights are shown in Table 1). We see that the equally weighted case favors 18 m apertures, while the weighted scenario B is relatively flat from 18 m to 20 m.

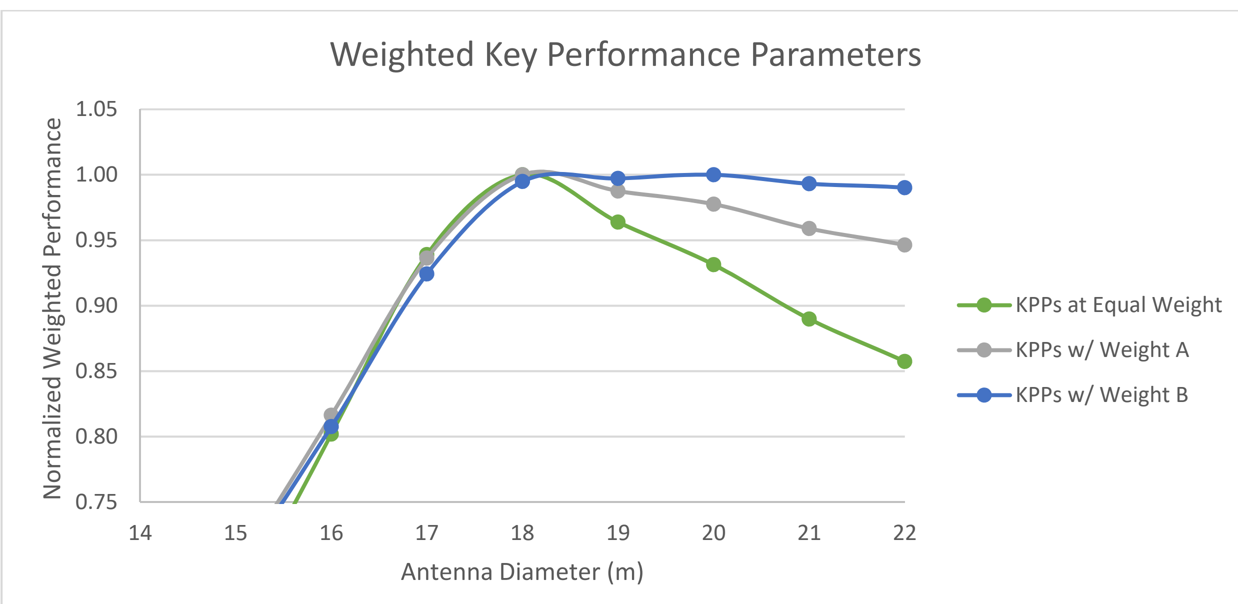

Figure 4 - Combined performance to KPPs using different weights from Table 1.

Table 1 - Weight Factors used for curves in Figure 4. Note that the tabulated values are normalized by their sum before plotting.

WEIGHTS	Equal	A	B
ND^2 (Point Source Sensitivity)	1.0	1.0	1.0
N^2D^2 (Survey Speed)	1.0	0.5	0.5
N^2 (Imaging Fidelity)	1.0	0.5	0.25
Lifecycle Cost (Inverted)	1.0	1.0	1.0

In Weights A and B, survey speed is given lower priority, commensurate with the proportion of expected observations that are larger than a single pointing. Imaging fidelity is also discounted based on the quality of this metric. As noted in Section 1.1, the imaging fidelity is also highly dependent on the configuration design, and extending infrastructure to randomly distributed antennas is expected to be cost prohibitive. We therefore discount the effects of this figure of merit on the achievable imaging performance of the array when focused on this limited range of apertures.

2.4 Sensitivity to Compute Model Scaling

The system cost model is highly sensitive to the science use cases and the time allocation between them. Full band, full beam, full resolution imaging is very demanding and drives the compute model even when used for only a few percent of observing hours. This is true for both the construction and operations cost curves. The construction cost is affected by the proportion of the budget consumed by the construction of the post-processing center, while the operations cost is affected by the cost of data storage.

Most use cases do not push all three boundaries. E.g., protoplanetary disk imaging may be full band and full resolution, but the field of interest is small and does not require full beam imaging. Alternatively, CO mapping may be full beam and high spectral resolution, but it emphasizes surface brightness sensitivity at the expense of angular resolution. Maximizing all three axes can increase the computational intensity by of order 10^3 compared to a typical observation [1]. This effect is further exacerbated at low frequency due to the increased fractional bandwidth of the wide-band receiver designs used for receiver band 1 and band 2.

The input parameters used in this analysis limit these full band, full beam, full resolution cases to a few percent of observing hours, consistent with the current reference observing program [4] and their corresponding technical parameterization. This is appropriate for an array like the ngVLA, with a proposal-driven operations model and science cases that are predominantly small fields. If one were designing a dedicated survey instrument, the computational costs would shift the maxima of the KPPs to the right of these plots.

For context, Figure 5 below shows the same cost model but omitting the full band, full beam, full resolution capability in post processing (i.e., equivalent to Figure 3, but incorporating this difference in capabilities). More of the construction budget is now spent on collecting area (vs. compute capacity) with small aperture arrays, and less of the operations budget expended on data archive costs, shifting all maxima to the left. Such a parameterization may favor 16 m to 18 m apertures, but with notable restrictions on the use of the larger field of view afforded by the 16 m apertures, and increased technical risk in the post processing system design.

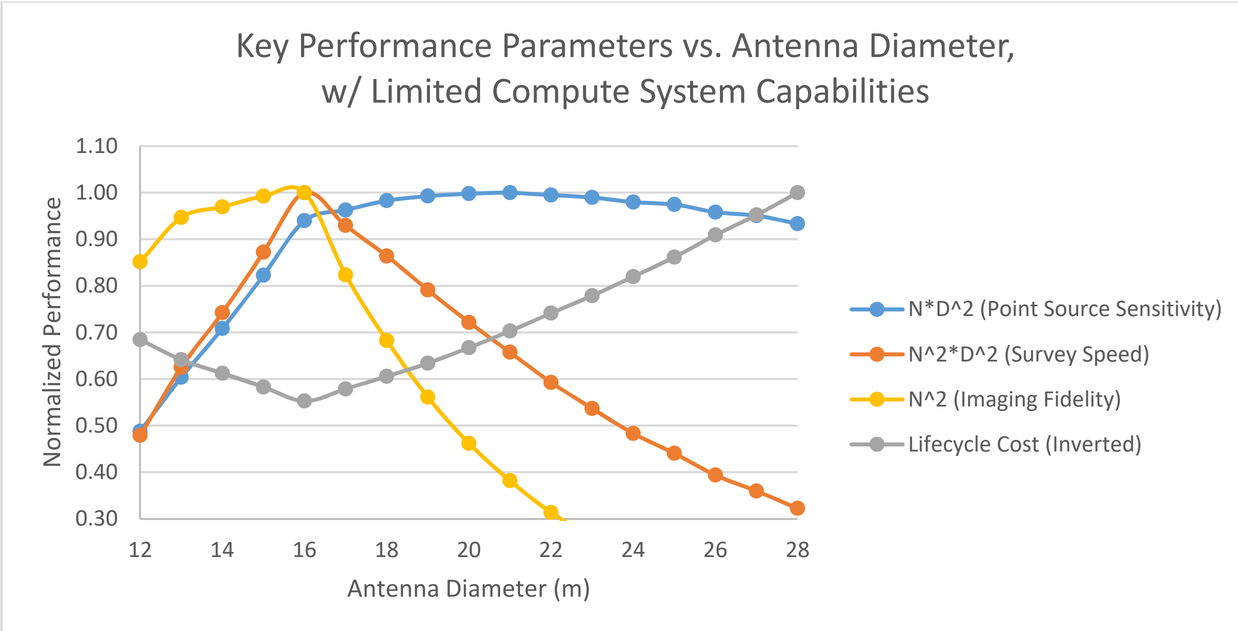

Figure 5 – Performance to each KPP respecting construction and operations cost constraints and no support for full band, full beam, full resolution observing.

3 Conclusions & Discussion of Other Factors

Respecting the cost and operations constraints, while providing limited full band, full beam, full resolution imaging capabilities, and using a coarse weighting between our key performance parameters, leads us to prefer designs in the 18 m to 20 m range as shown in Figure 4.

Apertures smaller than 18 m present a significant technical risk to the post processing system, by increasing the number of apertures in the array (data and compute scale with N^2) as well as the field of view. Any design changes favoring smaller apertures must consider the effects on the post processing and archive systems, or restrict the capabilities deployed in the post processing system as was done in Section 2.4. We do not advocate for pushing lower than 18 m given the uncertainty inherent in this parametric analysis and the fragility of such a solution. Solutions in the 18 m to 20 m range are more flexible to system design changes in this respect.

The 18 m aperture of the reference design is an appropriate starting point based on this analysis, but should be reconsidered depending on the technical solution preferred for the mount, backup structure, and reflectors. E.g., 18 m may be a practical upper limit for single piece rim supported composite reflectors, which are expected to be cheaper than traditional designs. If a more traditional steel backup structure and aluminum panel design were used, which is more likely to scale to larger apertures, a design with 20 m apertures would reduce the technical risk in the post processing system while offering lower lifecycle cost through operations savings.

Looking at the balance of performance, technical risk, and the total lifecycle cost of the instrument leads us to favor continuing with an 18 m aperture for further design development through the conceptual design down select.

4 References

[1] Hiriart, Rafael. ngVLA Memo in prep.

[2] Kern, Jeff et al. “ngVLA Quantitative eXchange Model” V3.0 (2017)

[3] Selina, Rob et al. “Summary of the Science Use Case Analysis” ngVLA Memo #18 (2007)

[4] Wrobel, Joan. “ngVLA Reference Observing Program” ngVLA Doc. No. 020.10.15.05.10-0001-REP (2019)