ngVLA Antenna Memo # 1

System-level Cost Comparison of Offset and Symmetric Optics

R. Selina

May 24, 2019, V1.1

Abstract

As part of a broader study of the antenna optical design and the associated down select, here we compare the costs of symmetric Cassegrain and offset Gregorian optics and their impact on the system design. We evaluate the cost in construction and operations, allowing for an estimation of life-cycle costs. We use A_{EFF}/T_{SYS} as our fixed performance metric in this analysis, ensuring that the array has comparable sensitivity, with an emphasis on performance at 30 GHz. We also hold the antenna diameter constant to maintain the system survey speed. In order for system construction costs to be comparable, we conclude that a symmetric Cassegrain antenna would have to cost 38% less than an offset Gregorian of the same aperture diameter. For lifecycle costs to be comparable, the Cassegrain option must cost 76% less than an offset Gregorian antenna.

1 Introduction

This memo summarizes a brief analysis of the impact of the optical geometry on the system cost, with an emphasis on symmetric Cassegrain and offset Gregorian concepts. We hold both the aperture diameter of each antenna element constant, as well the A_{EFF}/T_{SYS} of the array in order to provide comparable sensitivity and survey speed. While performance varies with frequency, we perform our trade analysis at 30 GHz.

This memo draws on the ngVLA Quantitative eXchange Model [1], 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, and minor arithmetic discrepancies are due to rounding in the reported values.

1.1 Key Parameters

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

Life Cycle Cost: Project costs should be optimized based on a lifecycle cost analysis, assuming a 20-year operations period.

Sensitivity: The fundamental metric that relates the antenna performance to system sensitivity is A_{EFF}/T_{SYS}. A_{EFF} is equivalent to $A_{GEOM} * \eta$, where A_{GEOM} is the geometric collecting area and eta is the total aperture efficiency.

Survey Speed: The survey speed is proportional to the system sensitivity squared times the field of view (beam solid angle in this case). By fixing both the antenna diameter (a proxy for field of view) and the array sensitivity in this analysis we retain equivalent performance on this metric.

Frequency Coverage: The system must operate over the 1.2 GHz to 116 GHz span, but emphasis is placed on performance above 10 GHz. 30 GHz is used as a point frequency for analysis when appropriate.

In order to contain the scope of this study to cost impacts, here we will not make any quantitative comparisons of the imaging performance between the two optical concepts. However, it is noted that dynamic range, image fidelity, and other performance metrics generally favor geometries that provide lower sidelobe levels, stable beam patterns, improved pointing accuracy, and more antennas in the array.

2 Optical Concepts

2.1 Offset Gregorian

In this analysis, we will use the Reference Optical Design [2] to represent the offset Gregorian concept. The design has an unblocked aperture with a relatively long focal length to reduce the length of the main reflector in the vertical axis and to reduce interference with a pedestal mount. The subreflector is 3.5 m in aperture, and the main reflector is elliptical with the expected 18 m extent in the horizontal axis and a 20.5 m extent in the vertical axis, as shown in Figure 1.

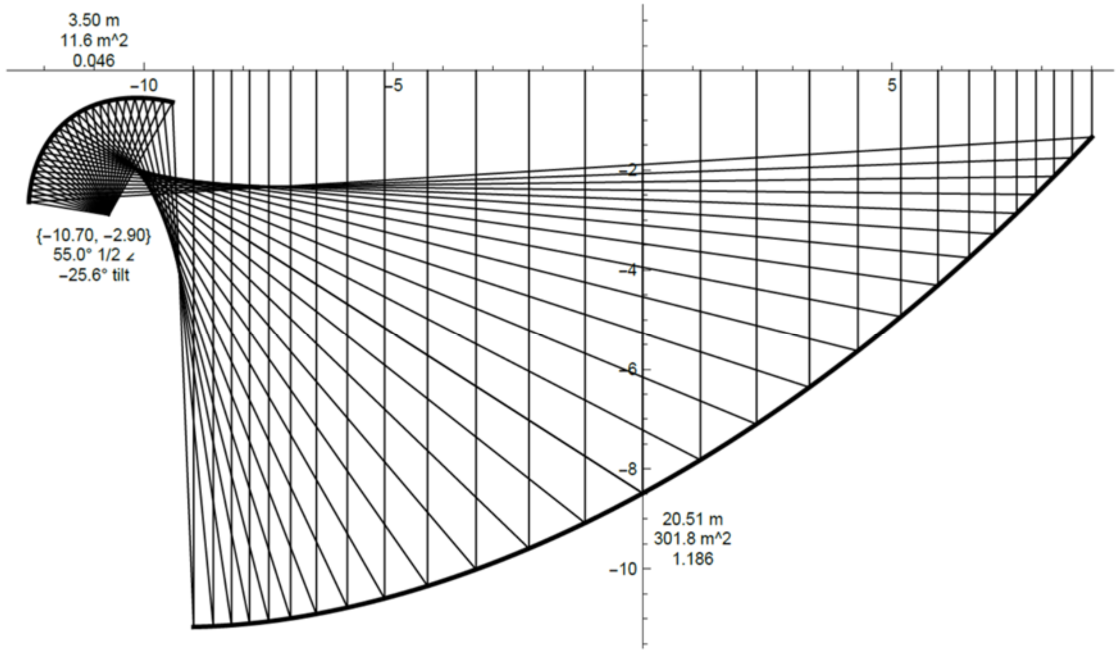

Figure 1 - Shaped offset Gregorian geometry (pointed at zenith). Cross section in the symmetry plan. By Lynn Baker [2].

2.2 Symmetric Cassegrain

For the symmetric Cassegrain concept, we will borrow from the VLBA optical geometry (Figure 2) but will revise the design to an 18 m main reflector aperture and a 3.5 m subreflector, matching the offset Gregorian geometry.

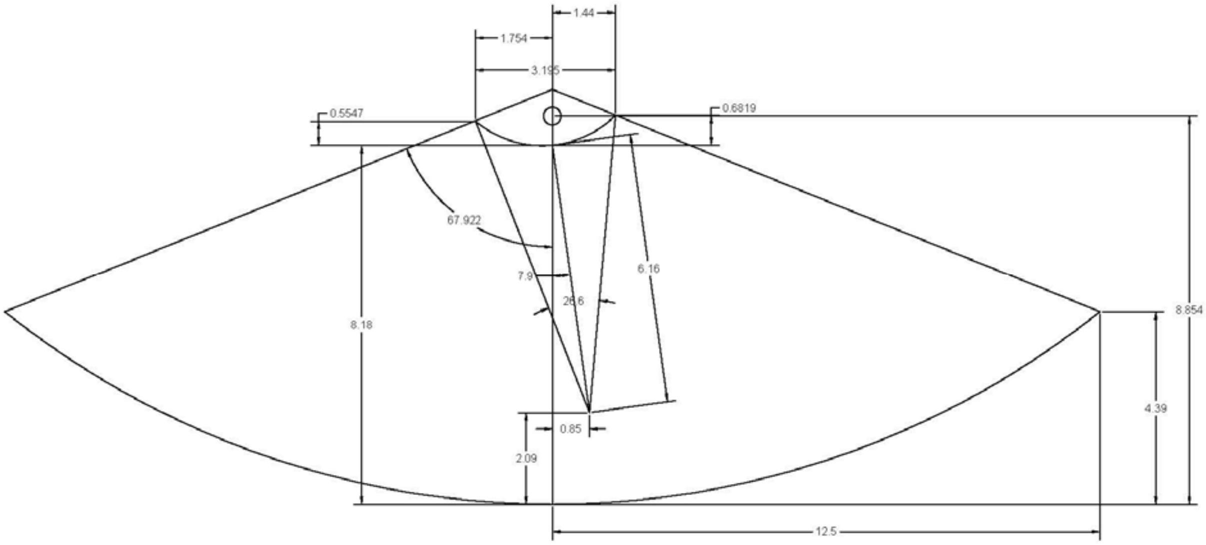

Figure 2 - VLBA Cassegrain optical geometry with a 25m aperture, 3.2m subreflector, and 26.6 degree illumination angle.[3]

3 Performance Factors

3.1 Antenna Aperture Efficiency

As noted in Section 1.1, system sensitivity will be held constant in this analysis through a fixed A_{EFF}/T_{SYS}, where A_{EFF} is equivalent to $A_{GEOM} * \eta$, A_{GEOM} is the geometric collecting area, and eta is the total aperture efficiency.

The aperture efficiency is the product of a number of terms including taper, spillover, blockage, cross-polarization, defocus, surface errors, and ohmic losses[1]. We will assume similar illumination and Ruze losses for surface errors in this case, so the difference between the two concepts is limited to the blockage term and the spillover term.

The offset Gregorian has no aperture blockage, and therefore $\eta_{BLOCK} = 1$. The symmetric Cassegrain has blockage from both the subreflector and the quad legs that support it. The 3.5 m subreflector blocks 3.8% of the aperture and we assume that low-profile quad legs and ancillary structural members block an additional 2.8%[2] yielding $\eta_{BLOCK} = 0.87$ for the Cassegrain case[3]. Note that the VLBA blockage is higher, with $\eta_{BLOCK} = 0.86$, even with a smaller subreflector [4].

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[1] We use the convention where $\eta_{TOTAL} = \eta_{ILLUM} * \eta_{SPILL} * \eta_{BLOCK} * \eta_{POL} * \eta_{FOCUS} * \eta_{RUZE} * \eta_{OHM} * \eta_{MISC}$

[2] 2.8% quad leg blockage is equivalent to 0.3 m wide legs that are 6 m long in the aperture plane.

[3] Efficiency figures are in units of power, not field, so $\eta_{BLOCK} = (1-A_{BLOCK}/A_{GEOM})^2$ [9]

The quad legs also reduce the spillover efficiency term by scattering power towards ground. The spillover efficiency of the reference offset Gregorian geometry is approximately $\eta_{SPILL} = 0.97$ [2]. We will assume a well-optimized Cassegrain system with $\eta_{SPILL} = 0.96$. Note that the VLBA scatter term is $\eta_{SPILL} = 0.93$ for frequencies above 10 GHz. [4]

Early design studies suggested that the axially corrugated feed horns (ACFH) used on offset Gregorian geometries may have different (poorer) illumination efficiency, η_{ILLUM}, than traditional corrugated horns used on a Cassegrain geometry. However, optical and RF analysis of the reference design optics and feeds [2,8] suggests this difference in η_{ILLUM} is less than 2% over 1.65:1 bandwidth ratios once shaping is included, and can be further optimized through design, so we will consider this parameter to be equivalent for optimized optical designs.[4]

3.2 Spillover Temperature

Unfortunately, the increased scatter has a double effect on sensitivity, first by reducing the illumination efficiency and effective area in the numerator, and second by increasing the spillover temperature in the denominator.

The Front End Reference Design [5] estimates the system temperature at 30 GHz to be 32 K, inclusive of 4.1 K spillover for the offset Gregorian geometry. We will estimate that the symmetric Cassegrain increases spillover by an additional 2 K through scattering[5], matching the spillover efficiency loss in Section 3.1. The net effect is a 6% reduction in sensitivity (2 K/32 K = 6%). Note that $T_{SCATTER}$ on the VLBA is estimated at 5K at these frequencies. [4]

This result is, of course, frequency dependent. The effect at low frequency is more pronounced where receiver and atmospheric contributions are lower, and the impact is reduced at high frequency where atmospheric contributions dominate. We will use the 30 GHz case in this analysis.

3.3 Combined Impacts

The combined aperture efficiency and spillover impacts on system sensitivity are summarized in

Table 1. Values are normalized to emphasize the relative differences between the two optical geometries.

Table 1 - Normalized Efficiency Factors.

Geometry	η_{BLOCK}	η_{SPILL}	T_{SYS}	η_{TOTAL}
Offset Gregorian	1.0	1.0	1.0	1.0
Symm. Cassegrain	0.87	0.99	0.94	0.81

Using the values from Table 1 we see that the effective sensitivity of a symmetric Cassegrain antenna is approximately 81% that of an offset Gregorian of the same aperture. In other words, 23% (1/0.81) more

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[4] Even if this delta remained, the ACFH are sufficiently small to be cooled, yielding a ~3K improvement in T_{REC} that more than offsets the illumination difference (and this T_{SYS} difference is not included in Section 3.2)

[5] Assume a simple noise model with sky temperature of 15 K and ground temperature of 300 K, for an average temperature of 158 K over the full 4π sr. A 1.2% difference in η_{SPILL} equals a 2K noise contribution.

antennas are required with a Symmetric Cassegrain to achieve the same system-level point source sensitivity and survey speed.

3.4 Expected Cost Differences

Symmetric designs are generally expected to be cheaper than offset geometries of the same aperture. This can help offset some of the performance differences described in Section 3.3. The three primary reasons for this are:

1) The geometric area of the main reflector is larger in an offset geometry, requiring additional backup structure and supporting mount stiffness.
2) The subreflector support structure is cantilevered and therefore must also be stiffer.
3) The offset main reflector increases the interference between the backup structure and the pedestal structure at low elevation, requiring an offset in the elevation axis relative to the azimuth axis. (Note: true only for feed low designs with pedestal mounts.)

The impact of the first factor can be approximated with a simple scaling law. Studies by D'Addario [6] and others have found that antenna costs approximately scale with $D^{2.7}$. This conclusion is relatively intuitive, since the size of the structure scales with its volume (proportional to D^3).

For our reference optical geometry, the main reflector has a chord length of 20.5 m in the vertical axis and the nominal width of 18 m in the horizontal axis. Scaling by the average diameter of 19.25 m suggests a cost premium of order 20% compared to a symmetric Cassegrain design ($(19.25/18)^{2.7} = 1.2$). This conclusion assumes that the underlying technology of the backup structure is constant across the size range in question. Breakpoints that require more exotic materials or structural designs can introduce step functions into any cost curve.

For the cost penalty associated with the cantilevered subreflector support structure we add of order 5% to the cost[6], since this this heavier feed arm structure is located on the elevation assembly and therefore impacts the structural design of both the backup structure and supporting mount.

Finally, resolving the interference with a pedestal mount requires an offset between the elevation axis and azimuth axis, which in turn requires longer yoke arms. These cantilevered yoke arms can contribute significantly to the pointing error, so the added stiffness required may be substantial. We will assume a 10% impact in total cost for this change[7]. Note that this factor is only applicable to feed low configurations with pedestal mounts, but since we are presently leaning towards such a mount after factoring in the operational costs, we will include this factor in the analysis.

We will assume, conservatively, that the effects described may be multiplicative. Therefore, the estimated premium is up to 39% for an offset Gregorian (feed low, pedestal) design compared to a symmetric

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[6] We note that the feed arm structure accounts for ~5% of the NRC cost estimate for their 18m ngVLA antenna concept. GDMS figures look similar, suggesting this cost penalty is conservative.

[7] We note that the yoke arms make up 21% of the NRC cost estimate for their 18m ngVLA antenna concept. The pedestal, bearings and yoke combined add up to 41%. A 10% cost reduction is roughly equivalent to a 25% reduction in the mass of these elements for a symmetric design, so the 10% factor is likely conservative (41% * 0.25 = 10.25%).

Cassegrain design of the same aperture, i.e., a comparable Cassegrain may cost 72% (1/1.39) of a Gregorian implementation.

4 System Cost Impact

4.1 Construction

In order to establish the cost impact on construction, the relative costs of the symmetric Cassegrain and offset Gregorian antennas must be known, as well as the cost to outfit them with electronics and turn them into functional array elements.

Investigations with the ngVLA Quantitative eXchange Model [1], using historical actuals and other references as inputs, found that system sensitivity is optimized with an antenna element that costs approximately half of the total array cost, i.e., that the cost to outfit an antenna into a functional array element is approximately equivalent to the cost of the antenna. This ratio can also be seen in the current bottom-up construction estimate, where 46% of the construction cost is in the antennas (Figure 3).

Using the values from the model, we will assume that the optimal cost of the antenna element is 50% of the array cost. For simplicity, we will also ignore any cost differences in implementation of the antenna electronics and foundation.

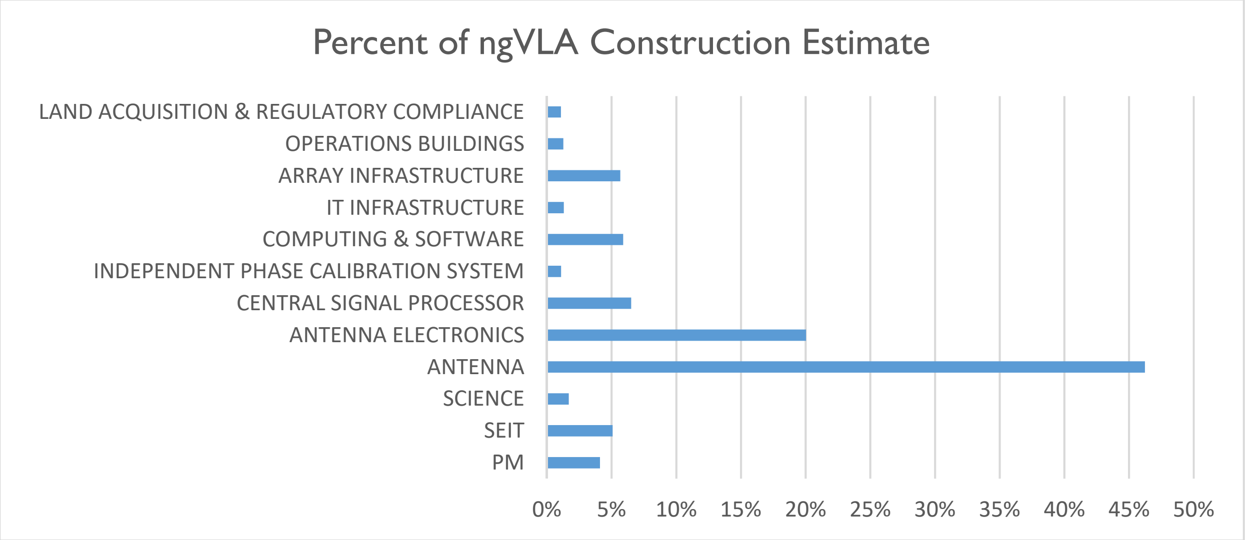

Figure 3 - Current composition of the ngVLA Construction Cost Estimate (A. Walter)

Based on these assumptions we build a simple construction cost model using Gregorian antennas and normalized construction cost and quantities (Table 2).

Table 2 - Simple construction cost model for a Gregorian array (baseline).

Gregorian Baseline	**$/EA**	**QTY**	**Sub-Total**
Antenna	$ 1.00	1.00	$ 1.00
Everything Else	$ 1.00	1.00	$ 1.00
Total			**$ 2.00**

Should the Cassegrain and Gregorian mounts have equal cost, the Cassegrain implementation would require 20% more antennas to have matching point source sensitivity and survey speed (Section 3.3). Costs scale almost linearly with the number of antennas, so the total project construction cost would be of order 23% higher (Table 3).

Table 3 - Simple construction cost model for a Cassegrain array at equal unit cost.

Cassegrain @ Equal Cost	**$/EA**	**QTY**	**Sub-Total**
Antenna	$ 1.00	1.23	$ 1.23
Everything Else	$ 1.00	1.23	$ 1.23
Total			**$ 2.47**
Cost Relative to Gregorian Baseline			**123 %**

The full impact may be slightly worse than this, since the central signal processing and computing system scaling has a strong relationship to the number of visibilities processed, which scales by the number of apertures in the array squared. However, this cost is not dominant at this array size and the effect will be ignored in this analysis.

Conversely, for the Cassegrain option to match the sensitivity of the Gregorian for the same nominal system cost, the antenna would have to cost 38% less. Recall that the performance of a Cassegrain is 0.81 of a Gregorian (19% penalty), and the cost of the antenna is only half the cost of the outfitted element, requiring double those savings in the antenna, a 38% cost reduction, to provide equal performance and total construction cost. (Table 4) Put another way, a Gregorian antenna can cost 61% more (1/0.62 - 1 = 0.61) than its Cassegrain equivalent and still be cost neutral in construction.

Table 4 - Simple construction cost model for a Cassegrain array at equal construction cost.

Cassegrain @ Equal Cost	**$/EA**	**QTY**	**Sub-Total**
Antenna	$ 0.62	1.23	$ 0.77
Everything Else	$ 1.00	1.23	$ 1.23
Total			**$ 2.00**
Cost Relative to Gregorian Baseline			**100 %**

With the expected cost savings for a Cassegrain option of 28% (see Section 3.4), we see that the Cassegrain system is project to increase total construction cost by of order 6% (Table 5).

Table 5 - Simple construction cost model for a Cassegrain array at projected unit cost.

Cassegrain @ Equal Cost	**$/EA**	**QTY**	**Sub-Total**
Antenna	$ 0.72	1.23	$ 0.89
Everything Else	$ 1.00	1.23	$ 1.23
Total			**$ 2.12**
Cost Relative to Gregorian Baseline			**106 %**

4.2 Operations

The operations cost scale with the number of system elements in the array (be they antennas, receivers, cryogenic refrigerators, etc.) Since the Cassegrain implementation will have 23% more antennas, it will increase the annual operations cost by of order 23% from this factor alone.

This number may underestimate the total impact since we do not consider the impact on the post processing system and storage, which as noted above scale with the number of apertures in the array squared. Since this is approximately 3% of the operations cost, it could increase annual operations by 1.5% ($3\% * (1.23)^2 = 4.5\%$).

Differences in the implementation of the cryogenic system may also impact the cost in operations. We note that the electrical power cost is estimated to be of order 5% of the operations cost, with the antenna cryogenics as a dominant factor. A design that doubled the number of refrigerators (dewar integration will be much more difficult with Cassegrain optics) could add another 3-4% to the annual operations cost.

Since these deficits could perhaps be improved with detailed engineering effort, we will ignore them for now and focus solely on the 23% factor from the increase in the size of the array.

4.3 Lifecycle Cost

For simplicity, we will consider the lifecycle to be the construction and operations phases only, as the design phase costs should be comparable and the disposal cost is a one-time expense that is not as significant.

The operations cost per year are approximately 5% of the construction cost, and the array design life is 20 years. Therefore, the operations cost over 20 years is comparable to the initial cost of construction. Even if the Cassegrain mounts were sufficiently cheaper to offset the system cost impact in construction, they would still raise the operations cost by 23% per year, and the total lifecycle cost by 12% (Table 6).

Table 6 - Simple lifecycle cost model for Gregorian and Cassegrain arrays with the same construction cost.

	Gregorian	**Cassegrain**
Construction	$ 1.00	$ 1.00
Operations	$ 1.00	$ 1.23
Lifecycle	**$ 2.00**	**$ 2.23**
Relative Cost		**112 %**

In order to have a cost neutral impact over the full lifecycle, the Cassegrain array must generate sufficient cost savings in construction to offset the higher operations cost. The Cassegrain mounts would need to cost 76% less than their Gregorian equivalent to match the lifecycle cost of the Gregorian baseline (Table 7, Table 8)

Table 7 - Simple lifecycle cost model for Gregorian and Cassegrain arrays with the same lifecycle cost.

	Gregorian	**Cassegrain**
Construction	$ 1.00	$ 0.77
Operations	$ 1.00	$ 1.23
Lifecycle	**$ 2.00**	**$ 2.00**
Relative Cost		**100 %**

Table 8 - Simple construction cost model for a Cassegrain array to achieve matching lifecycle cost.

Cassegrain @ 77% Baseline Cost	**$/EA**	**QTY**	**Sub-Total**
Antenna	$ 0.24	1.23	$ 0.30
Everything Else	$ 1.00	1.23	$ 1.23
Total			**$ 1.53**
Construction Cost Relative to Gregorian Baseline			**77 %**

5 Conclusions & Discussion of Other Factors

As noted above, we estimate that the Cassegrain option would need to cost 38% less than its Gregorian equivalent to match the system construction cost, when holding point source sensitivity and survey speed constant. Over a 20-year life, the Cassegrain antenna would have to cost 76% less to match the lifecycle cost of its Gregorian equivalent.

We estimate that structural factors could explain a 28% cost savings for Cassegrain mounts of equivalent diameter, so an achievable Gregorian implementation is expected to be cheaper in both total construction cost and lifecycle cost. System construction costs with a Gregorian implementation are estimated to be 6% less, annual operations costs 23% less, and total lifecycle cost 15% less.

In this analysis, we have assumed a highly optimized Cassegrain optical system that has lower losses than NRAO has achieved with similar systems such as the VLBA antennas. Achievable savings with a Gregorian system may be higher than reported, and we have neglected other important factors that would bolster this conclusion. The Gregorian concept permits very compact cooled feeds in integrated dewars with a simplified cryogenic refrigeration system. A Cassegrain system would have significantly larger feeds on a feed ring (r ~ 2 m), and achieving the same level of cryogenic refrigeration integration is unlikely. This will increase the construction costs of the front end and cryogenic systems, and the latter is a significant input to the electrical load of the antenna and recurring electrical cost in operations, so the lifecycle deficit of a Cassegrain system is likely worse when accounting for these factors. The cooled feeds can also reduce the total system temperature by of order 3K compared to their narrow-angle Cassegrain equivalents, further bolstering this analysis.

The construction cost premium for a Gregorian is also highly dependent on the concept for the reflector and backup structure. The factors in Section 3.4 assume a traditional implementation with a steel tubular backup structure and aluminum panels. Other technical concepts, such as rim-supported composite reflectors [7], may have lower cost differences between the two optical configurations.

6 References

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

[2] Baker, Lynn. “Analysis of ngVLA Design #6 with Ideal and Actual Feed” ngVLA Doc 020.25.01.00.00-0001-REP (2018)

[3] Srikanth, Sivasankaran. “Towards Optics Design for the ngVLA” URSI/NRSM Boulder, CO. (2017)

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[5] Grammer, Wes. “Front End Reference Design Description” ngVLA Doc 020.30.03.00.00-0003-DSN (2019)

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[8] Lehmensiek, Robert. “Final Report: ngVLA Project PO Number: 362812” Doc No. EA-NGV-DR-01.

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The National Radio Astronomy Observatory and Green Bank Observatory are facilities of the U.S. National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work was supported by awards AST-2034328 (MSIP Prototype Antenna) and AST-2334267 (ngVLA Design Activities); NRAO related activities are funded under award AST-1647378 (NRAO Operations/Development).