ngVLA Antenna Memo # 3

Antenna Optical Design Alternatives

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Abstract

For the ngVLA Reference Design, the project has selected an 18m offset Gregorian antenna, with the feed arm on bottom, employing a wide secondary illumination angle. Two-axis linear translation of the feeds is used for focus and band selection. This memo provides a brief summary of the optical geometries, feed and receiver designs, and band selection mechanisms considered for the ngVLA reference design and the basis for selecting the chosen concept. We update the analysis where appropriate based on lessons learned during the reference design stage and provide recommendations for the conceptual design of the antenna optics.

1 Introduction

In preparation for the Astro2020 Decadal Survey, the ngVLA project has prepared a Reference Design as the technical baseline for cost and technical risk assessment. While supporting the key science requirements, the reference design does not represent an optimized design, and a more complete system design will be generated in the coming years as part of the project conceptual and preliminary design phases.

Cost featured prominently in the requirements that informed the antenna optical design. Based largely on expected cost savings over the project lifecycle [1], an offset Gregorian configuration with the feed arm on bottom and a wide secondary angle of illumination was chosen [2].

Here we revisit the alternatives explored in the reference design stage, update the analysis with lessons learned over the last two years of development, and provide recommendations for the conceptual design of the antenna optics.

1.1 Key Performance Parameters

The metrics most relevant to this down select are:

Life Cycle Cost: The project should be optimized based on lifecycle cost analysis, assuming a 20-year operations period. Both the construction and operations phases have cost caps, with the annual operations cost limited to ~5% of construction cost.

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 η the overall 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), assuming a single-pixel feed on all receivers. Or alternatively, it is proportional to sensitivity squared over beam solid angle (which goes as D^{-2}), where D is the diameter of the primary reflector.

Imaging Performance: We will use the term imaging performance as a catch-all for dynamic range and image fidelity. These metrics generally favor lower sidelobe levels, lower spillover, stable and quasi-circular beam patterns, accurate pointing, and more antennas in the array for better u-v plane coverage.

Frequency Coverage: The system must operate over the 1.2 GHz to 116 GHz frequency span, but emphasis is on performance above 10 GHz. The upper bound sets stiffness and surface accuracy requirements, while the lower bound influences the size of the subreflector as well as the size and number of feeds required.

1.2 Design Considerations & Assumptions

Some design considerations and assumptions should be stated up front since these inform the trade-off choices.

Feeds and antenna optics: The feed design and the antenna optics are inextricably linked. Feed size is proportional to the opening angle [3], and the angle subtended by the subreflector is not infinitely variable in any optical design. We will therefore evaluate alternative feed configurations as part of this optics trade study. All receivers are assumed to have a single feed.

Optical shaping: Given the proposal-driven operations model for the ngVLA, and science cases that require sensitivity over relatively small fields (vs. large area surveys), we emphasize performance here with shaped optics that maximize A_{EFF}/T_{SYS} for single pixel receivers.

Motion systems: At a minimum, any ngVLA antenna is expected to have the following degrees of motion: Azimuth, Elevation, Focus (necessary over most ngVLA operating frequencies) and band selection. Depending on the stiffness of the structure and chosen geometry, gravitational deformation may require compensation (focus tracking) in an additional axis. In any case, it is desirable to avoid multiple mechanisms that perform the same function (e.g., multiple focus stages would be undesirable). We will consider the mechanism used for band selection and focus within this study, as well as the feasibility of implementing focus tracking to compensate for gravitational deformation.

Aperture size: Where relevant, we will assume an 18 m aperture in this report, based on the analysis documented in ngVLA Antenna Memo #2 [4].

Operations costs: The majority of the operations cost is labor, and maintenance labor is directly proportional to the number of parts (antennas, receivers, refrigerators, etc.) in the array. Systems that reduce parts count will generally have lower operations cost. Electrical costs make up the second largest operating expense, and these are dominated by cryogenic cooling costs. Reducing the number of cryogenic receivers and combining them in common dewars reduces total radiative surface area, refrigerator parts count, and electrical cost in operations.

2 Feed Concepts & Mechanical Arrangements

Two alternative feed/receiver concepts were developed during the reference design phase: a narrow-angle concept and a wide-angle concept. In this context, 'narrow-angle' refers to feeds with opening angles of 25-40 degrees, suitable for Cassegrain or Gregorian optics; and 'wide-angle' refers to designs with 90-120 degree opening angles, suitable only for offset Gregorian optics.

2.1 Narrow-Angle Concept

The narrow-angle design would employ 3:1 bandwidth smooth-wall conical feeds for operation below 11 GHz. Traditional corrugated horns with waveguide bandwidth would be used to extend up to 116 GHz with a six-band system. Table 1 below summarizes this concept. An opening angle of 30 degrees is assumed in determining the feed horn dimensions [5]. All receivers are cryogenically cooled and are housed in three dewar assemblies (A, B and C).

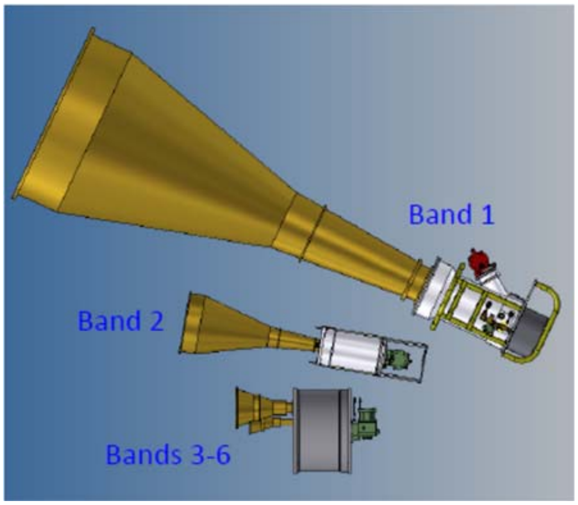
Table 1 - 6-band concept using narrow-angle feed horns. [5]

Bnd. #	Dwr. #	f_L GHz	f_M GHz	f_H GHz	f_H: f_L	BW GHZ	Feed Horn Properties			OMT	Pol. Out
							Temp	L, cm	ID, cm		
1	A	1.2	2.1	3.6	3.00	2.4	300	271.0	112.8	QR	Lin.
2	B	3.6	6.2	10.8	3.00	7.2	300	90.4	37.6	QR	Lin.
3	C	11	14.1	18	1.64	7.0	300	40.9	24.1	WG	Lin.
4	C	18	23.2	30	1.67	12.0	300	25.1	14.7	WG	Lin.
5	C	30	38.7	50	1.67	20.0	20	15.0	8.84	WG	Lin.
6	C	70	90	116	1.66	46.0	20	6.45	3.78	WG	Lin.

Pros: This design employs well-understood / low risk technology. The 3:1 bandwidth feeds for Bands 1 – 2 reduce the total number of bands and dewars required, at the expense of illumination efficiency, cross polarization, and noise temperature, compared to octave-bandwidth corrugated horns. The waveguide bandwidth corrugated horns employed for Bands 3 – 6 provide optimum illumination efficiency over the operating bandwidth with low cross polarization. The overall noise temperature with cryogenically cooled LNAs and waveguide polarizers/orthomode transitions (OMTs) would be nearly optimal on Bands 3 – 6.

Cons: The feeds in this design are large - the Band 1 feed is 2.71m (106.7") long, with an aperture over a meter in diameter (see Figure 1). Their size makes it difficult to consolidate receiver bands into a common dewar, and impractical to cool any of the feeds except in the two highest frequency bands. It is also difficult to move the feeds in some mechanical arrangements, due to their size and weight. Because of the wide bandwidths on Bands 1 and 2, each require a cooled quad-ridged OMT with coaxial outputs, which dominates the size of its dewar because of its large size and mass. The quad-ridged OMTs also have a relatively higher noise contribution than an all-waveguide OMT.

Mechanically, the four high frequency bands can be combined in a single dewar with rotation for band selection (see Figure 1, right). This would be an elegant solution for an 11 GHz+ instrument, but once the 6-band concept is considered, the mechanical choices become more limiting. A linear fan or rotation platform arrangement may be feasible (see Figure 2).



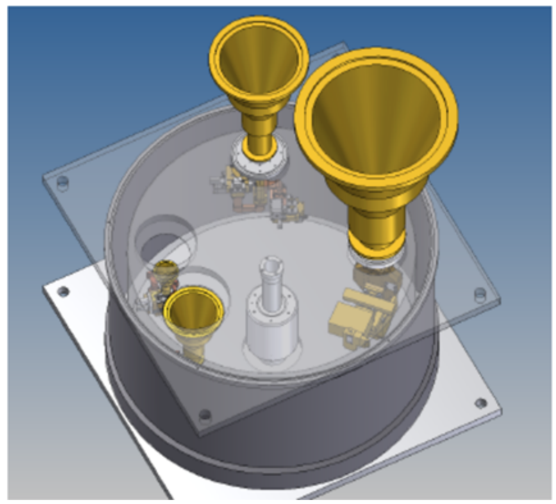


Figure 1 - Left: Fan arrangement of the narrow-angle feed 6-band receiver concept. For scale, note that the Band 1 feed is of order 2.7 meters long. Right: Circular dewar arrangement with Bands 3-6. The feeds on Bands 5 and 6 are cooled to 20K.

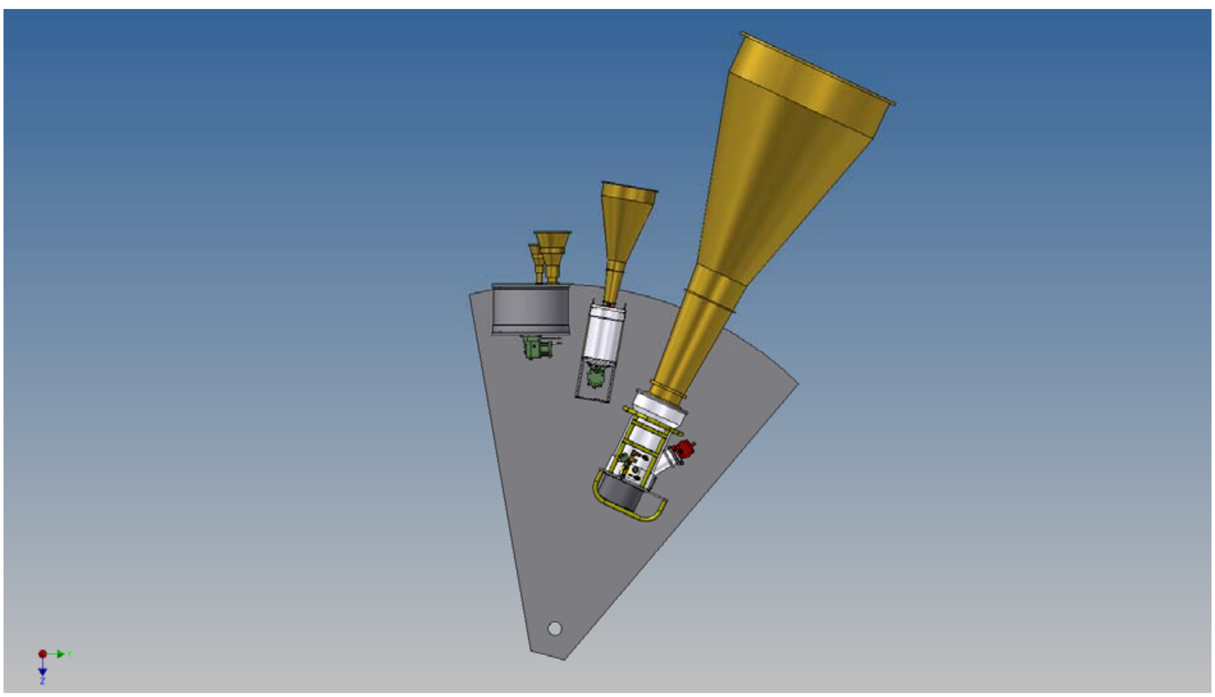


Figure 2 - Band selection concept with the feed phase centers at a fixed radius from a central pivot point.

The round dewar is relatively compact and helps reduce the overall cryogenic loading, but would require an additional band selection mechanism (rotation stage). An alternative mechanical arrangement would be a ring arrangement (applicable to symmetric optical designs) with a semicircular dewar for the high frequencies. These mechanical considerations are discussed in Section 3.

2.2 Wide-Angle Feed Concept

The wide-angle feed concept uses a similar band definition to the narrow-angle concept, but a 3.5:1 bandwidth quad-ridge feed horn (QRFH) is used in the lowest two bands, with an axially corrugated feed design used for the high frequency bands. QRFH designs are more easily adapted to wide bandwidth ratios, with some loss in illumination efficiency and cross polarization performance over frequency compared to corrugated horns. The axially corrugated feed horn design chosen in this concept [8] provides a uniformly high illumination efficiency up to ~1.7:1 bandwidth ratios [5,9]. Table 2 below summarizes this concept.

Table 2 - 6-band receiver concept using wide-angle feed horns. [5]

Bnd. #	Dwr. #	f_L GHz	f_M GHz	f_H GHz	f_H: f_L	BW GHZ	Feed Horn Properties				OMT	Pol. Out
							Temp	θ, deg	L, cm	D, cm		
1	A	1.2	2.0	3.5	2.92	2.3	80	58.0	33.0	36.1	--	Lin.
2	B	3.5	6.6	12.3	3.51	8.8	20	58.0	11.3	12.3	--	Lin.
3	B	12.3	15.9	20.5	1.67	8.2	20	55.0	2.90	5.31	WG	Lin.
4	B	20.5	26.4	34.0	1.66	13.5	20	55.0	1.73	3.18	WG	Lin.
5	B	30.5	39.2	50.5	1.66	20.0	20	55.0	1.17	2.14	WG	Lin.
6	B	70	90	116	1.66	46.0	20	55.0	0.51	0.93	WG	Lin.

Pros: This design has numerous advantages over the narrow-angle concept, namely:

- Highly compact feeds, which can be cooled and packaged into combined dewars.
- Only two dewars are needed, compared to a minimum of three for the narrow-angle concept; combining these into a single dewar may also be feasible.
- The QRFH has coaxial outputs for the orthogonal linear polarizations. Therefore a separate OMT is not required on Bands 1 and 2, greatly reducing the volume and mass of these receivers.
- Cooled feeds at all bands will reduce the overall noise temperature (improvement in Bands 1 – 4).
- Allows more flexibility in the mechanical layout, and has a relatively low total mass.

Cons: The wide-angle axially corrugated horns have a slight degradation (~2–5%) in forward gain and pattern stability as a function of frequency, and marginally higher cross polarization, when compared to a traditional corrugated horn over these bandwidths [5,9].

Mechanically, the design lends itself to fan, linear, and circular arrangements with moderately sized dewars. Linear and circular arrangements for the receiver bands are shown in Figure 3. Note that a cylindrical Dewar 'B' would require both rotation and translation stages for selecting a band, while a rectangular, in-line arrangement only needs a linear translation stage.

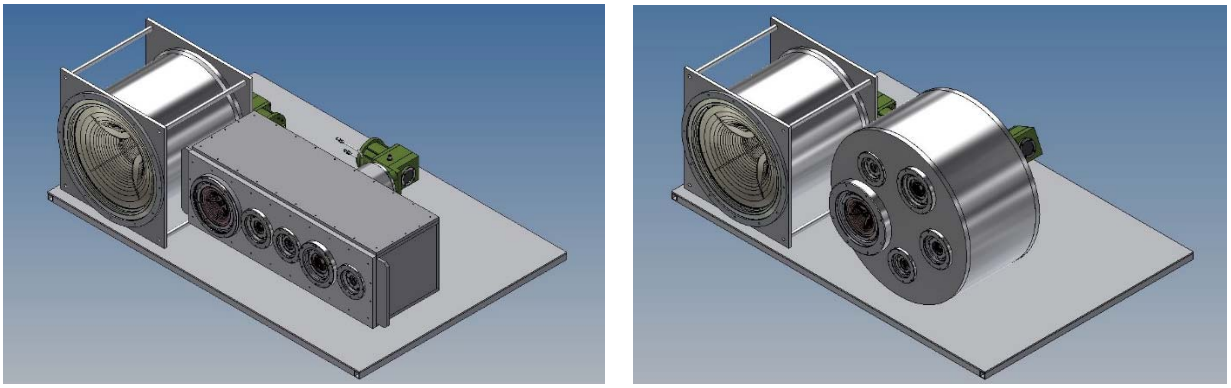


Figure 3 – Left: Linear arrangement of all six bands. As a reference, Band 1 feed diameter is 36cm. Right: Circular arrangement of Bands 2-6. Their feed phase centers are equidistant from the rotation axis. Band 1 is to the side.

2.3 Performance Comparisons

Early design studies suggested that the axially corrugated feeds used in the wide-angle concept may have different (poorer) illumination efficiency, η_{ILLUM}, than the traditional corrugated horns used in the narrow angle concept. However, optical and RF analysis of the reference design optics and feeds [6,7] suggests the difference in η_{ILLUM} becomes less than 2% over 1.65:1 bandwidth ratios with shaping of the optics tailored to the feed pattern. Also, this feed was originally designed for use over octave bandwidths: further optimization for a 1.65:1 range may yield improvement that erases this difference. Therefore, we will consider this parameter to be equivalent for correspondingly well-optimized optical designs.

The wide-angle concept permits all feeds to be cooled, reducing the input noise by 2–3K. This corresponds to a 5–7% improvement in system temperature on Bands 3 and 4. On Bands 1 and 2, the quad-ridged feeds appear to have slightly better illumination efficiency overall than the smooth-wall conical feeds used in the narrow-angle case. Cross polarization performance of the QRFH is slightly worse overall: between 19-25 dB, versus 22-32 dB for the smooth-wall conical feed [12, 13].

For unblocked apertures, the RF performance of the narrow-angle and wide-angle feed concepts will be considered comparable in this analysis. The primary differences will relate to their mechanical implementation, with impact on band selection, focus, cryogenic cooling, and structural implications for the antenna mount.

3 Band Selection & Focus Concepts

There are many viable mechanical concepts for band selection and focus, but we present some of the most relevant options here. Some designs are only applicable to wide or narrow angle feed concepts, as noted.

3.1 Ring Geometry & Focus-Rotation Mechanism

In this geometry the feeds are arranged in a ring with fixed positions, and the subreflector is offset to aim the secondary focus at the feed ring. Ideally, each feed is placed with its phase center at the focal point. Fine focus is with longitudinal adjustment of the subreflector, and band selection by subreflector rotation. The ring geometry is well suited for feeds with narrow illumination angles, because this allows the secondary focus to be placed more conveniently behind the primary mirror. Both the VLA and VLBA symmetric Cassegrain antennas use this geometry, as shown in Figure 4.

Figure 4 - Left: VLA antenna. Focus/rotation mechanism (FRM) is in the apex ring. Right: Close-in view of the feed cone. The large feeds are recessed well into the vertex cabin, to reduce blockage loss. The trade-off is a minor degradation in the phase efficiency and spillover at the low frequencies.

Pros: This geometry is conceptually simple, with only two axes of motion. One big advantage is the feeds remain in fixed locations, making cryogenic and electrical connections simpler. The static geometry also maintains a fixed center of gravity, simplifying the pointing model. Gravitational deformation can be partially corrected for some feed ring positions by adjusting the subreflector rotation (focus tracking).

Cons: Unfortunately, it is difficult to combine multiple feeds and/or receiver bands into a single dewar once the full operating frequency range of the ngVLA is considered, particularly with narrow illumination angles. At low frequencies, the large feed size mandates a correspondingly large ring diameter and feed spacings, in order to keep all beams unobstructed.

A practical solution for a 6-band system would likely require four dewars, with pairs of high frequency receivers sharing dewars, as is shown in Figure 5. The high frequency dewars are placed along an axis roughly parallel to the antenna's elevation axis, to allow focus tracking with these bands. If focus tracking is dispensed with, it is possible to shrink the circle further, as shown in Figure 6. However, this would require a larger range of focus adjustment, and is still not enough to reduce the total number of dewars.

Another inherent downside of this geometry is blockage of the primary mirror by the secondary, and scattering/diffraction off the quadrapod legs. The associated losses would be significant, given the large size of the secondary relative to the primary (3.5m / 18m) on an ngVLA antenna. [1]

Lastly, offsetting the focal point from the axis of symmetry introduces cross-polarized sidelobes for linear polarization, and beam separation (squint) for opposite circular polarizations. This adversely affects the ability to do accurate polarimetry, particularly if the source is offset from the beam center [14, 15].

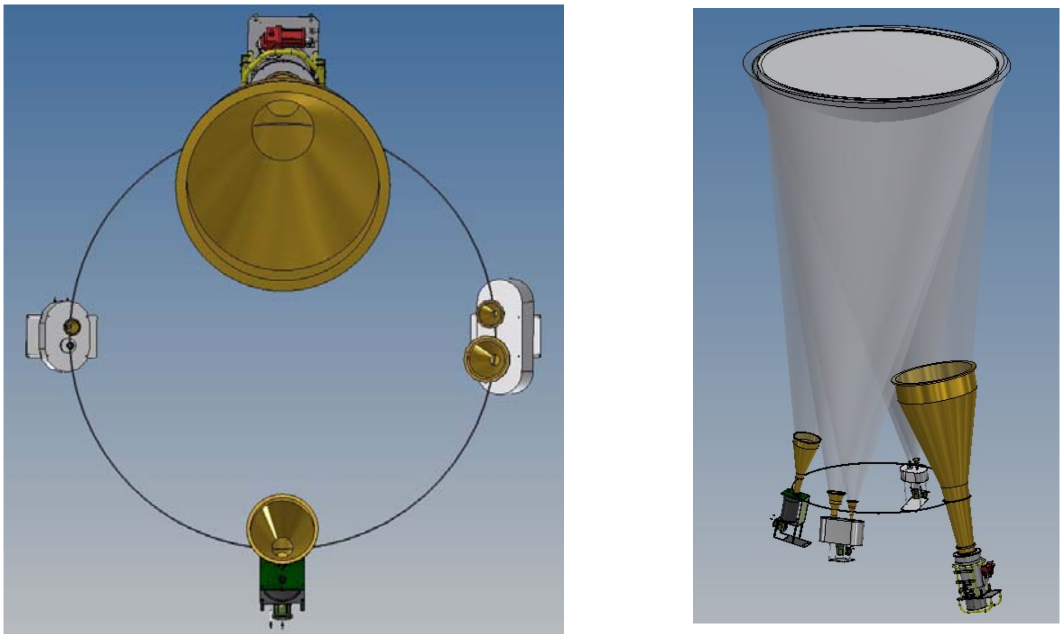


Figure 5 - Receiver/feed arrangement with ***2.5*** *meter diameter ring geometry.*

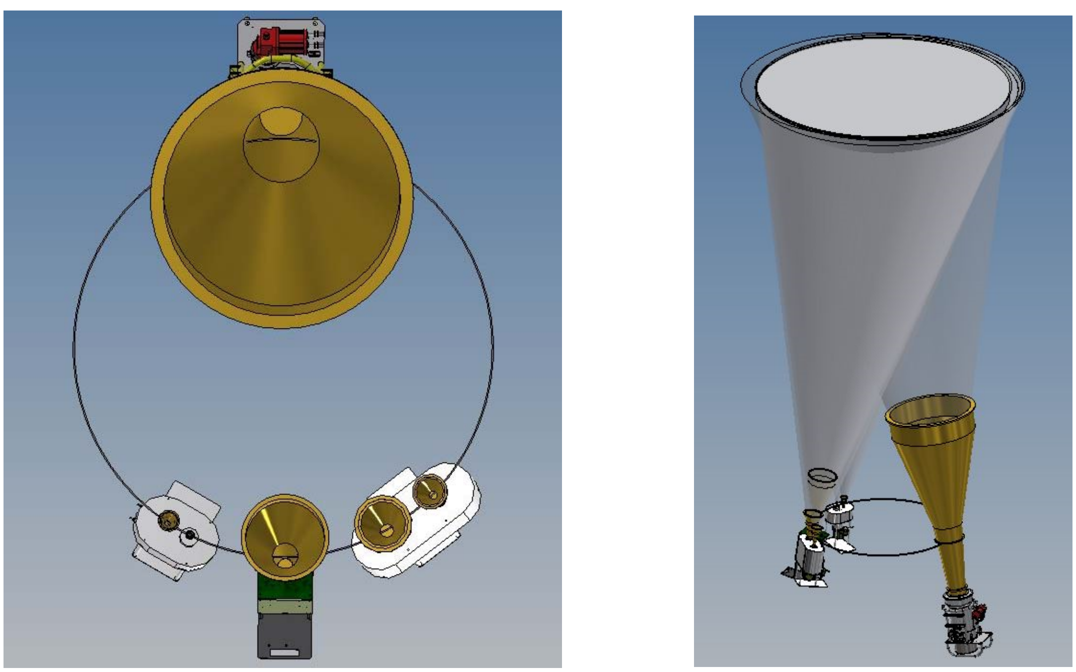


Figure 6 – Receiver/feed arrangement with ***2.0*** *meter diameter ring geometry.*

3.2 Fixed Focus & Rotation Mechanisms

In a fixed focus design with a turntable or turret mechanism, the feeds are arranged in an arc on a platform that is rotated for band selection. The turntable configuration has the feeds oriented radially, with their centerlines and the optical axis in the same plane, intersecting the center of rotation: the rotational axis is normal to the plane. In the turret configuration, the feed centerlines, rotational axis and optical axis are all parallel: they are spaced along a circle about the center of rotation.

This mechanical geometry is most applicable to offset optics, and is especially suited to wide angle feed horns (given their smaller size and mass at low frequencies). An indexed feed/receiver turntable is used on the MeerKAT and SKA1-MID dishes, while on the GBT a turret arrangement is used (Figure 7). The subreflector can be in a fixed location, but may require adjustment on very large antennas and/or at high frequencies, to compensate for shifts in the focal point caused by temperature and gravity vector changes.

Pros: This design can maintain a fixed center of gravity during band selection (so long as appropriate counter weights are used), simplifying the antenna mechanical design and ensuring that pointing offsets are not introduced during band switching. The arrangement is more compact, making it easier to integrate receivers together into common dewars.

Cons: A difficulty with this arrangement is focus. As each feed has its own unique focal range, the focus stage must either move the entire feed turntable, or independent focal stages provided on each feed and receiver assembly. Note this is not an issue with low frequency systems, where focal adjustment isn't needed. For example, the MeerKAT antenna has a focus stage only on its X-band system. On the GBT, the subreflector is adjustable longitudinally and transversely relative to the optical axis, to both allow adjustment for focus and to compensate for feed arm sag over elevation.

For ngVLA, Bands 3 through 6 will definitely require focus adjustment, and it is desirable for Band 2 as well. Independent focus mechanisms below each feed are unattractive as they limit our ability to combine receivers into single dewars, and add mechanical complexity that degrades system reliability. Placing a translation stage below the rotating platform is mechanically difficult. Such a design is only attractive to ngVLA if these mechanical deficits can be overcome.

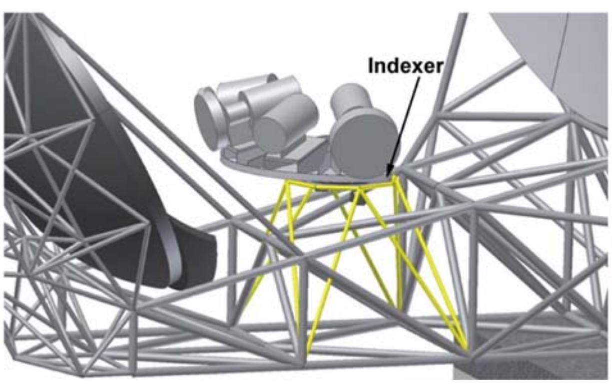


Figure 7 – Left: Early concept sketch of the MeerKAT receiver turntable. Courtesy of General Dynamics and MeerKAT. Right: Receiver/feed turret in the GBT Receiver Room. Photo by Walter Scriptunas II.

3.3 Fixed Focus & Translation Mechanisms

This concept retains the fixed focus as described in Section 3.2, but favors linear translation for band selection and focus (vs. rotation). The feeds are placed with their phase centers in a single plane, and a two-axis linear positioner performs band selection and focus adjustment. This geometry is most applicable to offset geometries with compact (wide angle) feed packages.

Pros: The design is mechanically simple with only two axes of motion. Commercial X-Y stages are robust and affordable, as they are commonly used in milling machines. The arrangement is compact and permits tight integration of the feeds and receivers inside a single dewar.

Cons: The center of gravity moves with focus and band selection adjustments, which may complicate the pointing model and some astrometric calibration strategies. Cryogenic, power, and data lines must all include flexible cable wraps to permit the front end package to move over its full range of motion.

Compensating for gravitational deformation would require adding a third axis of motion.

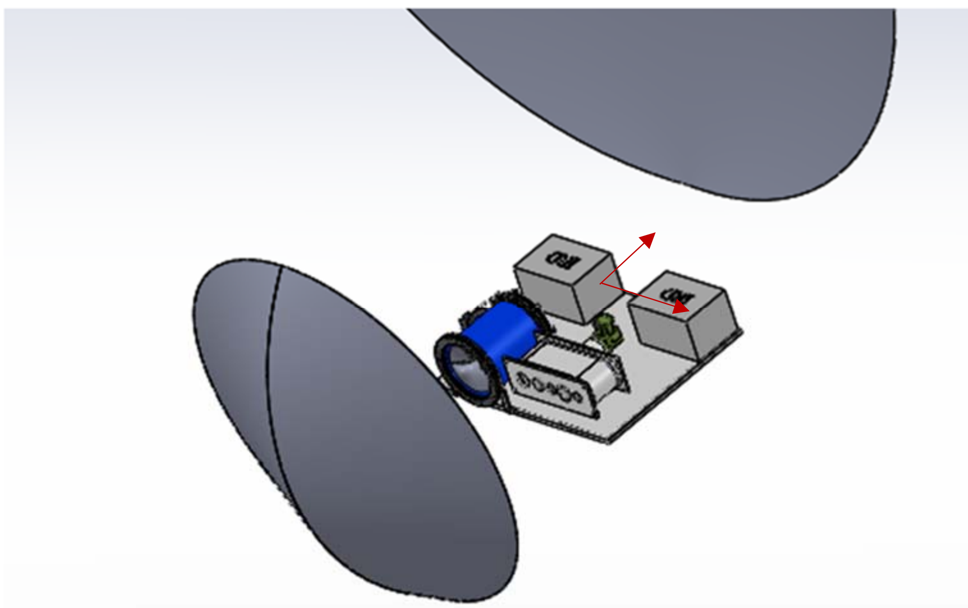


Figure 8 - Offset Gregorian optical geometry with linear translation of the receivers for band selection and focus.

3.4 Focal Plane Geometries & Stewart Platforms

In a focal plane geometry, feeds are located, arbitrarily, on a focal plane and band selection and focus is accomplished by tip, tilt, and piston adjustment of the subreflector. All three motions are typically accomplished with a hexapod mount (Stewart platform) adjusting the location and orientation of the subreflector. This concept is most suitable to narrow angle feeds, and is common on millimeter and optical telescopes, including the ALMA 12m antennas and APEX.

Pros: This design provides maximal flexibility in feed placement with a total of 6-degrees of freedom in the placement of the subreflector (lateral, longitudinal, vertical as well as pitch, roll and yaw). The system can also compensate for gravitational and other deformations. Dewar integration can be high, and the feeds can remain in fixed positions, with the attendant advantages mentioned earlier.

Cons: The Stewart platform has a higher degree of mechanical complexity and cost than the alternatives. This approach also assumes the secondary can be pointed off-axis without a significant effect on aperture efficiency, which is not the case with shaped optics. A pure conic system would give a larger field of view but has a penalty in sensitivity of order 15% relative to one that is aggressively shaped. Given ngVLA's proposal-driven operations model and key science goals, sensitivity is a more important metric than field of view.

Figure 9 - Stewart Platform that supports the secondary mirror of the APEX telescope. Courtesy of Physik Instrumente.

3.5 Optical Compatibility

Based on the impact to optical shaping and the resulting loss in sensitivity, Stewart platforms will not be considered further in this analysis.

The optimal choice for the ngVLA antenna then becomes dependent on the requirements of the optical system. A feed ring and focus rotation mechanism is preferred for symmetric Cassegrain geometries, while a fixed focus with a translation stage is preferred for offset Gregorian geometries.

The Cassegrain choice is predicated on practicability – since Cassegrain designs require narrow-angle (and large) feeds, fixed feed locations are a practical necessity, and the two-axis focus-rotation mechanisms are well understood, with many existing designs in use.

For offset Gregorian geometries with wide-angle feeds, our preference for a translation stage versus a turntable is tied to the operating frequency range of the ngVLA. In other arrays with similar optics (e.g., MeerKAT, SKA1-MID), the frequency range is much lower, and a focus adjustment is not required in most of the bands. In this case, the turntable mechanism is attractive for its simplicity and greater compactness. At ngVLA frequencies, where five of the six bands require some focus adjustment and the feeds are also much smaller, a two-axis translation stage meets the requirements and is simpler. A receiver turntable mounted on top of an axial positioner for focus is also possible: however, there are problems with weight and size, and additional mechanical complications with a turntable that also translates.

4 Combined Optical & Feed Concepts

Three optical geometries will be considered in this analysis: symmetric Cassegrain, dual-offset Cassegrain, and offset Gregorian. Here we present the evaluated optical geometries with viable/complementary feed and mechanical arrangements.

4.1 Symmetric Cassegrain Optics with Narrow-Angle Feeds

A symmetric Cassegrain antenna with a narrow opening angle at the secondary focus is a familiar concept, given NRAO experience with the VLA and VLBA. This geometry is only practical for traditional narrow-angle feed horns: widening the illumination angle increases blockage, either from the feed platform or from the larger subreflector that would be required to restore the feed locations close to the vertex.

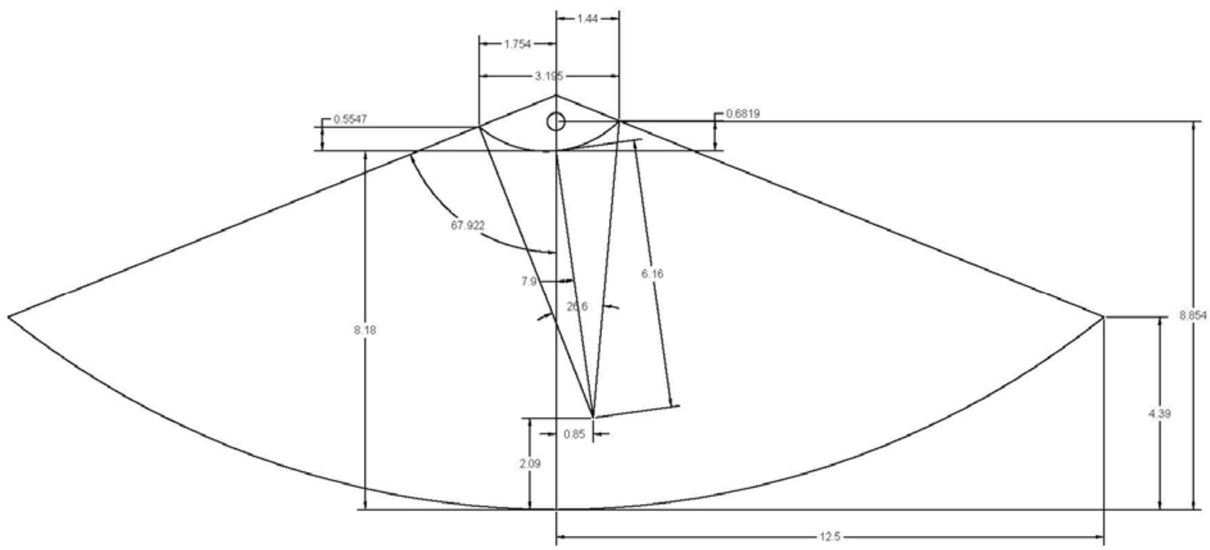


Figure 10 - VLBA Cassegrain Optical Geometry with 26.6 degree illumination angle.

With this geometry, the band selection and focus concept most suitable for ngVLA is the ring geometry with a focus and rotation mechanism, as was done on the VLA and VLBA antennas. Figure 10 shows the VLBA implementation, which is also representative of the VLA. This approach works especially well above 12 GHz, with four feeds consolidated in pairs across two dewars, as shown in Figure 5 and Figure 6. The feed sizes are still relatively compact, permitting an even smaller ring focus diameter than those shown for reduced cross polarization, and also a smaller subreflector for reduced blockage.

However, for frequencies between 1.2 and 12 GHz, the large apertures and lengths of the feeds make receiver consolidation impractical, and require a larger ring diameter. In the early days of the VLA it was feasible to consolidate bands by locating the polarizers next to the feeds, and having rectangular waveguide connections from them to a single dewar. Modern LNAs have much lower noise, so loss between the feed and LNA has a far greater effect on sensitivity, especially at ambient temperature.

The quadrapod supporting the subreflector is stiff enough over the range of elevation to allow fixed alignment of feeds at all but the highest bands. The feeds for Bands 5 & 6 could be placed at locations where ring focus intersects the elevation axis. Movement of the focal point due to gravitational distortions could then be compensated simply by a slight additional rotation of the subreflector. One downside is that this limits dewar integration to pairs, in order to locate the feeds close to these intersection points.

Pros: Symmetric mounts are expected to be lower cost at a given aperture size. Feed and receiver sizes and weights are mechanically less problematic, since they are fixed on the structure and located toward the center rather than on the edge. Settling time and scanning performance may be better than offset geometries given the added rigidity afforded with the symmetric design, and reaching pointing specifications may prove easier. Finally, the narrow-angle corrugated feed horns have well-optimized illumination patterns and polarization performance over the full bandwidth.

Cons: An integrated dewar design will be difficult with a focus-rotation mechanism, increasing construction and operations cost for the front end and cryogenic system. The blocked aperture reduces effective area, requiring more dishes for a given sensitivity target (increasing cost) or a loss in survey speed (increasing diameter to hold the effective area equal). The blockage also results in higher spillover temperature, and higher sidelobes, than with an unblocked offset geometry. Standing waves are more pronounced on the symmetric geometry, and contribute to more gain ripple across the band. Finally, the offset focus of the secondary suffers from a residual cross polarization that would cancel out in an on-axis Cassegrain or a dual-offset optical system meeting the Mizugutch condition [16].

Conclusion: A symmetric design would be a competitive choice for a 10 GHz + only instrument. Once we extend the operating range down to 1.2 GHz, both the feeds and receivers become large, and operating costs for the cryogenic system dramatically increase. The net loss is sensitivity for the given aperture diameter will require 23% more antennas to compensate. Overall, the total lifecycle cost of this design is predicted to be higher than one based around a dual-offset geometry [1].

The project could revisit this as an alternate choice in the conceptual design, if the offset geometry ends up proving too costly or otherwise impractical.

4.2 Dual-Offset Cassegrain with Narrow-Angle Corrugated Horns

A dual-offset Cassegrain geometry overcomes the problems associated with blockage and scatter on the Symmetric Cassegrain option, while retaining the familiar narrow-angle feed horn concept. Band selection options include a focus-rotation mechanism or a fixed focus with the feeds on an arc (such as the turntable concept).

Pros: This design has excellent A_{EFF}/T_{SYS} performance and a mostly unblocked aperture. Aperture efficiency is high, sidelobes are low, and spillover may be the lowest of any design evaluated [10, 11]. While this may be the most high-performing design on these metrics, the design has practical problems with band selection.

Cons: As with all Cassegrain geometries, this design requires relatively narrow angle feeds which result in large feed packages as described in Section 2.1. At this aperture size, a focus-rotation mechanism for band selection has practical limitations – the feed ring and electronics placement introduces blockage, interferes with the feed arm structure, or requires large offsets in the primary reflector, adding mechanical complexity to the mount and reducing polarization performance. A turntable geometry is also mechanically difficult, considering the location of this equipment on the feed arm, and the limited space and capacity for a very large and heavy low-frequency feed horn.

Conclusion: The design is sub-optimal in this aperture range (16 – 20 m) compared to other alternatives due to the practical difficulties of implementing band selection with the large feeds. Such a design may be attractive with a focus-rotation mechanism in the 25 m or larger class of telescopes, but is not well suited to ngVLA.

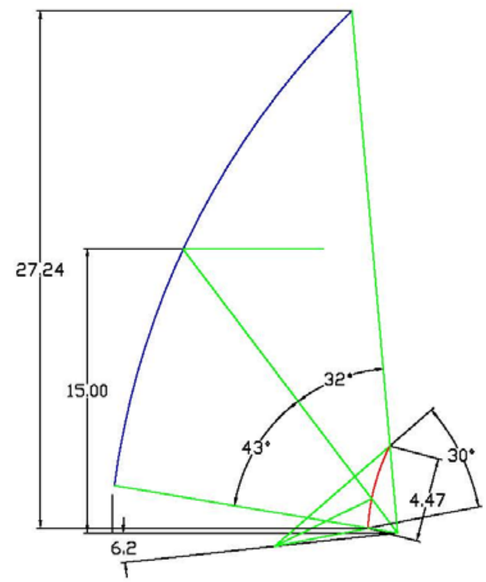


Figure 11 - Early 25m aperture dual offset Cassegrain concept with 30 degree illumination angle. Note the blockage from the subreflecor at the base of the primary mirror. By Sivisankaran Srikanth [10].

4.3 Offset Gregorian with Wide-Angle Feeds

The Offset Gregorian geometry can accommodate both wide and narrow angle feeds. Given the difficulties associated with the offset Cassegrain and narrow-angle feeds, we will focus on a concept with the smaller wide-angle feeds here.

Of the fixed-focus feed geometries, we will explore the translation stage option to maximize the opportunities for feed integration into limited dewars. This concept is the one selected for the reference design exercise.

Pros: The offset Gregorian is the second highest performing design based on A_{EFF}/T_{SYS}, spillover and sidelobe levels (just edged out on spillover by the offset Cassegrain) [10, 11], but the feed mounting and band selection with smaller feeds is more practical. Design optimization with a subreflector shield, combined with the fully unblocked aperture, may result in the most efficient design after further optimization.

The small feed packages permit a high degree of dewar integration, reducing both the construction cost and the operations cost of the front end system. Considering the full impact in aperture efficiency, spillover temperature, and projected mount cost, such a design is projected to be cheaper than a symmetric counterpart [1].

Cons: Offset mounts are inherently a more expensive mechanical arrangement than a symmetric design – the cantilevered feed arm requires additional antenna structure stiffness, as does the increased chord length of the offset main reflector. The linear-translation band select concept shifts the center of gravity during band selection and focus adjustment, which will need to be accounted for in the pointing model.

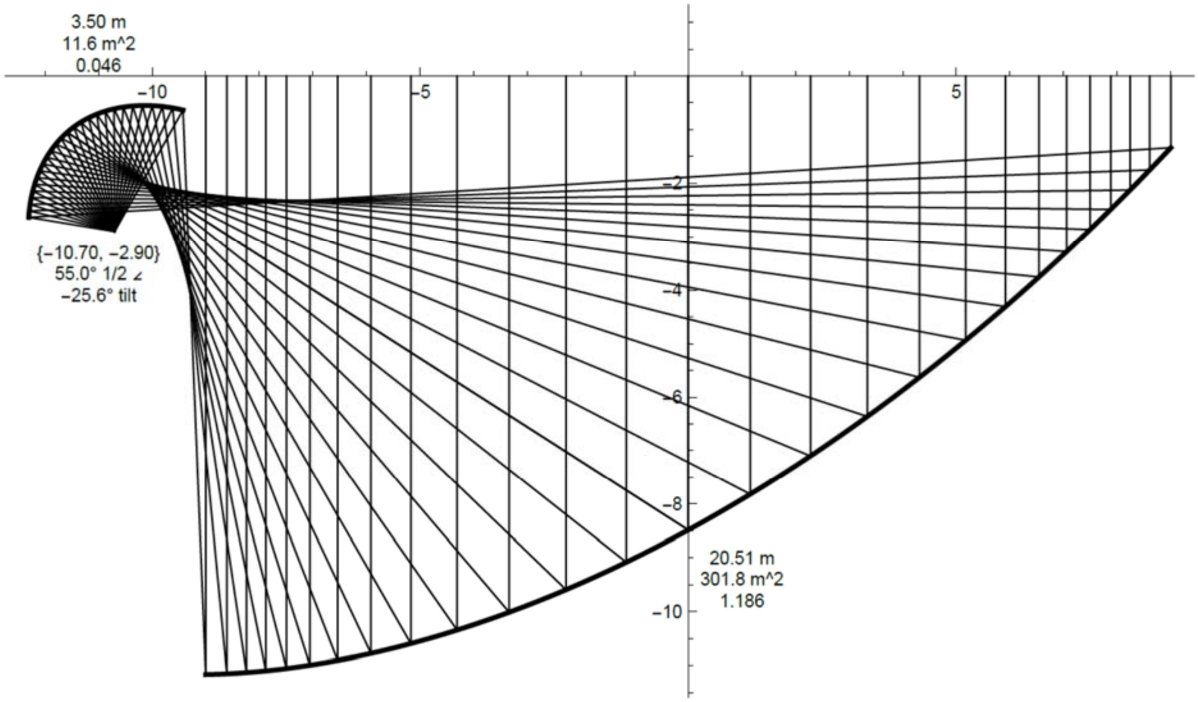


Figure 12 - Shaped Offset Gregorian Geometry (pointed at zenith) of the ngVLA reference optical design. Cross section in the symmetry plan. By Lynn Baker [4].

5 Conclusions & Discussion of Other Factors

The dual-offset Cassegrain, given ngVLA's choice of 18m aperture [4] has practical limitations and is not considered further in this analysis. The choice is therefore restricted to symmetric Cassegrain or offset Gregorian geometries, with their respective feed concepts, focus mechanisms and band selection mechanisms. A qualitative summary of the performance of each on these metrics is available in Table 3.

Table 3 - Performance Summary of Offset Gregorian and Symmetric Cassegrain optics on selected metrics.

Concept	Offset Gregorian Wide-angle feeds, fixed focus, linear translation mechanism	Symmetric Cassegrain Narrow-angle feeds, feed ring, focus-rotation mechanism
Life-Cycle Cost	Lowest projected lifecycle costs, per analysis in [1].	Lower construction cost for the mount, but savings must be large (38% - 76%) to offset the lifecycle advantage of an offset Gregorian.
Sensitivity	Highest A_{EFF}/T_{SYS} of selected options.	Blockage and scattering reduce A_{EFF}/T_{SYS}. Requires 20% additional apertures at 18m [1], or 20m apertures (which would reduce survey speed).
Survey Speed	Highest sensitivity at a given aperture size means fastest possible survey speed (since choice maximizes FoV and sensitivity)	

Concept	Offset Gregorian Wide-angle feeds, fixed focus, linear translation mechanism	Symmetric Cassegrain Narrow-angle feeds, feed ring, focus-rotation mechanism
Imaging Performance	Excellent sidelobe, spillover, and cross-polarization performance.	Sidelobe level may be 3-6 dB higher, spillover also higher by a few K, but some choices could increase the number of apertures in the array, which has a positive influence on imaging performance.
Frequency Coverage	Excellent performance over full 1.2 GHz to 116 GHz range, due to an unblocked aperture.	The low frequency limit mandates a subreflector size that is large relative to the 18m primary aperture. The resulting blockage loss is applied to all frequencies.
Other Pros	Design continuity from the reference design, including feed, front-end and cryogenic system concepts.	Most mechanically available concept, more designers and manufacturers, lower tooling costs for prototype.
Other Cons	Prototype and development costs are expected to be higher. Also, uncertainty in final production cost: no industry experience building comparable antennas on the scale envisioned.	Ring focus geometry adds inherent cross polarization. Required FRM on apex is a high-maintenance item. Major redesign on front end and cryogenic system concepts.
Final Ranking	Preferred option.	Should only be considered if the construction cost deltas exceed the projections in [1], or the frequency coverage requirements change at the system level.

Based on the available information, the offset Gregorian optics, with wide-angle feeds, fixed focus, and linear translation mechanisms for focal adjustment and band selection is preferred. Should the cost differences in construction be larger than projected in [1], this conclusion could be re-evaluated, but the potential for additional cost reduction afforded by the small feed/receiver packages, dewar integration and reduced operating cost, and sensitivity improvements through cooled feeds all suggest that the design optimization of an offset Gregorian option is likely to yield additional performance benefits and value through detailed engineering.

6 Future Work

In order to keep this analysis brief, we have not considered (1) the mount concept to support the preferred optics, or (2) the trade-offs associated with offset feed-high vs feed-low configurations. These two questions are inherently intertwined, but can be explored independently of this downselect. Earlier studies into various mounts have confirmed their feasibility in either the offset or symmetric designs, the structural impacts, and likely cost differences, which were taken into account in this analysis.

7 References

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