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(article starts on next page)

Cryogenic 1.2 to 116 GHz Receiver for Large Arrays

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***Abstract*—Current and future large arrays for radio astronomy are compared and the Next Generation Very Large Array, ngVLA, is introduced. Receiver requirements are described and a 4-feed system covering 1.2 to 116 GHz, in a single vacuum cryogenic enclosure is presented followed by description of the reflector optics, the wide-band feeds, and the expected system performance**

***Index Terms*—radio astronomy, cryogenic, QRFH, low noise amplifiers.**

I. Introduction

During the past 35 years large arrays of telescopes have supplemented large single element telescopes as the primary research tool for radio astronomy [1,2,3] The reasons for this are: 1) Point source sensitivity, proportional to total collecting area, increases as reflector diameter squared while cost tends to increase as a higher power; thus the cost of a single reflector antenna is higher than the cost of an array with the same total collecting area. 2) Arrays can image a given solid angle in the sky with a large number of pixels whereas a single telescope with one feed can only measure the power in one pixel. This principle is being applied at wavelengths from meters to sub-millimeter with the major arrays summarized in Table I. This paper will describe a receiver configuration which is being considered to cover a a wide range of frequencies, 1.2 to 116 GHz, for the next generation Very Large Array (ngVLA) that is in the planning stage for construction in the 2020 decade.[4].

II. Receiver Configuration

The location of the antenna feed and low noise amplifiers (LNAs) is determined by considerations of total efficiency (ratio of effective area to physical area), noise due to spillover and blockage, size of feed (as determined by required illumination angle), and access to the receiver for installation and maintenance.

A. Reflector Optics.

In the past symmetric Cassegrain optics, as in the VLA, has been preferred but current thinking favors shaped Gregorian optics as shown in Fig. 1. Here "shaped" refers to choosing the reflector and sub reflector shapes to optimize the total efficiency for a practical feed pattern. This technique has been developed by JPL and others over many years and typically results in adding 10% to the efficiency. The offset optics results in zero blockage and is more costly for a given reflectors size but this cost increase is much reduced for the multiple reflectors required in an array. Since the sub reflector can be large without blocking the reflector the illumination angle can be large which results in a small feed which can be completely cooled which lowers the system noise. Another choice in the offset optics is whether the access to the feed is high or low and the latter is much preferred for installation and maintenance. This choice also allows a shield to be added to the sub reflector to decrease the spillover noise due to 300K ground radiation. [18].

TABLE I – COMPARISON OF EXISTING AND FUTURE ARRAYS

								Figures of Merit		Comparisons of Figures of Merit				
Array	N	D(m)	Total Area m^2	Tsys(K)	Freq Range, GHz	Comparison Frequency, Fo, GHz	BW (GHz)	Point Source PSFOM	Survey SSFOM at Fo	Point Source Sensitivity Comparison		Survey Speed Comparison		Flux Sens 1 hr uJ
MeerKat	64	13.5	9156.24	18	0.58-14	1.4	1	648	207.4		1.9		12.1	4.92
SKA1-Mid	190	14.5	31358.8	18	0.35-13.8	1.4	1	2219	2108.3		6.4		123.4	1.44
JVLA	27	25	13246.9	49	1-50	1.4	1	344	17.1		1.0		1.0	9.26
ngVLA	256	18	65111	18	1.2-116	1.4	1	4608	5898.2	x JVLA	13.4	x JVLA	345.4	0.7
SKA1-Mid	190	14.5	31358.8	22	0.35-13.8	10	5	4060	7056.8		3.7		41.3	0.79
JVLA	27	25	13246.9	31	1-50	10	4	1089	170.7		1.0		1.0	2.93
ngVLA	256	18	65111	22	1.2-116	10	8	10664	31587.3	x JVLA	9.8	x JVLA	185.1	0.3
ALMA	54	12	6104.16	80	31-950	80	8	275	47.2		1.0		1.0	11.60
ngVLA	256	18	65111	100	1.2-116	80	32	4692	6115.3	xALMA	17.1	xALMA	129.5	0.7

PSFOM = Point Source Figure of Merit = N*D^2/Tsys *BW^0.5

SSFOM = Survey Speed Figure of Merit = (?/D)^2*Nb* (N*D^2/Tsys)^2*BW=((?/D)^2*Nb*(PSFOM)^2

Fo is the frequency for evaluation of FOM's. which is proportional to Fo^-2

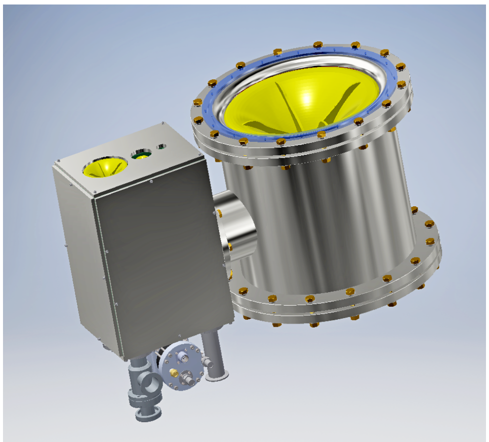
Ratio's to JVLA are for the same center frequency, Fo, at 1.4 and 10 GHz; ratio's to ALMA are at 80 GHz

Fig. 1 Offset Gregorian shaped optics antenna proposed for SKA and ngVLA and used on the Meerkat array (unshaped, but as shown above. Note the large, easy access, platform for access to receivers.

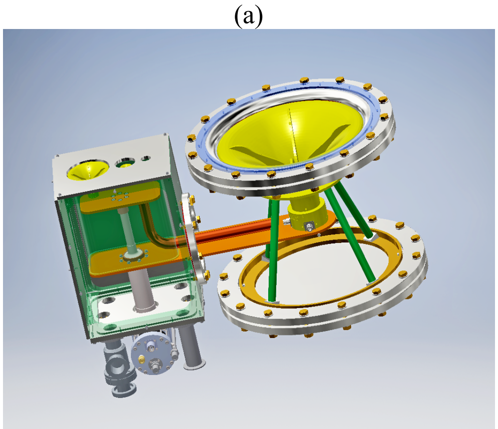
B. *Cryogenic Receiver Layout*

For a given desired frequency range of the array the breakdown of the receiving system into frequency ranges, number of dewars, number of cryocoolers, and AC power required need to be considered. For the ngVLA the science requirements are to cover 1.2 to 116 GHz with a gap of 50 to 70 GHz due to atmospheric oxygen attenuation and noise emission. The AC power required is an important consideration for operating cost. For example, with a 200 element array and 15kW of AC power per element the annual power bill is $5.2M at 0.2$ per kWhr, We have a goal to cut this by a factor of 10 with 1.5kW of cooling power per element. This requires much attention to the thermal design of the receiver in terms of thermal radiation, conductive heat paths, and the feed input infra-red filter.

For a given frequency range the key parameter for both feed and LNA design is the ratio of highest frequency to lowest frequency. For typical waveguides the single mode range is 1.45:1 and many components, including feeds, have been designed for this range. However, much development has been carried out by several groups in the past 10 years and 3.5:1 feeds and LNAs are being considered for the ngVLA. The ngVLA configuration that is being considered, shown in Fig. 2, utilizes feeds and LNAs for 1.2 to 4.2, 4.2 to 15, 15 to 50 GHz, and 70 to 116 GHz. These four feeds are housed in two dewars which share the same vacuum system and a cryocooler which can provide 5W on a 62K first stage and 1.5W at 11K on a second stage while drawing only 1.5 kW of AC power.



(a)



(b)

Fig. 2 – (a) Exterior view of 4-feed, 1.2-116 GHz receiver package. (b) Inteior view showing 1.2 to 4.2 GHz feed at right in cylinger and at left rectangular dewar with three high frequency feeds and closed-cycler cryocooler.

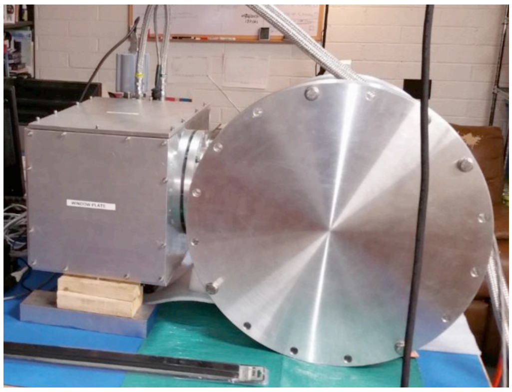


Fig. 3 - Front view of dewar system with blank front plates as used for initial vacuum and cooling tests. The 40.6cm diameter cylinder with side port was purchased as semi-standard vacuum tee and the rectangular side dewar was machined from a solid block of aluminum

The thermal requirements are strongly dependent upon cooling of the 1.2 to 4.2 GHz feed to a temperature of under 100K to reduce its thermal noise contribution to <1K. Experiments are now in process to determine the required thermal straps and insulating material. A small second cooler, a single-stage Stirling type requiring just 200W of AC power is also being considered just to cool the large feed. We expect to report further thermal design details and test results at the EUCAP 1018 meeting.

II. Wideband Feed

The feed selected for the 3.5:1 frequency ranges is the quad-ridge flared horn, QRFH, introduced in the Caltech Ph.D. thesis of A. Akgiray [5,6] The feed performance is mainly governed by the shape of the inside surface of the horn and inside edge of the ridges. The fields in the front aperture plane of the feed as a function of frequency can be calculated from a transform of the desired feed pattern and multiple ridged-circular-waveguide modes are required I to produce this aperture plane pattern. No direct synthesis technique for the shapes of the ridges and horn has been found. Electromagnetic computer aided design programs are available to calculate the field patterns given a trial shape and optimization methods are then used to maximize a figure of merit involving key parameters such as total efficiency and return loss at a coaxial connector port. The initial shapes were mathematical functions such as exponentials but later a spline fit to as many as 20 discrete points was found to give the highest efficiency. The field patterns for a given geometry can be calculated in several minutese with the CST Studio software utilizing a graphics array processor speed-up board in a multi-core computer.

The results after several months of optimization by co-authors of this paper resulted the feed shown in Fig. 4 with total efficiency averaging 77% and reflection coefficient averaging -16dB as shown in Fig. 5. The feed can be scaled in size by 3.5:1 to provide designs for 4.2 to 15 and 15 to 50 GHz with near the same modeled performance. The 1.2 to 4.2 GHz is now being machined with the horn in two circular portions turned on a lathe and connected with a threaded joint. The ridges will be milled and bolted to the horn. For the higher frequency QRFH feeds the ridge is too thin to be bolted to the horn and an 8 to 50 GHz feed has been milled in four quadrants with each quadrant including a center ridge [7]

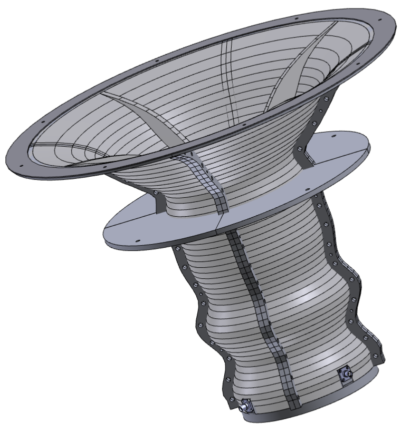
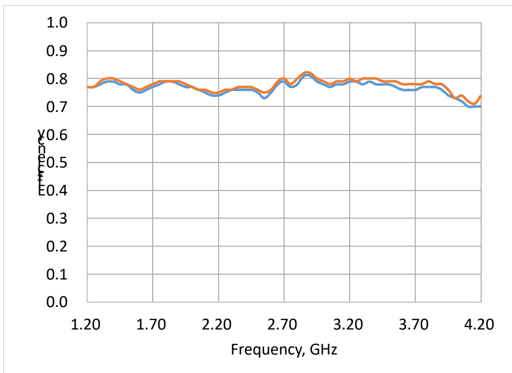
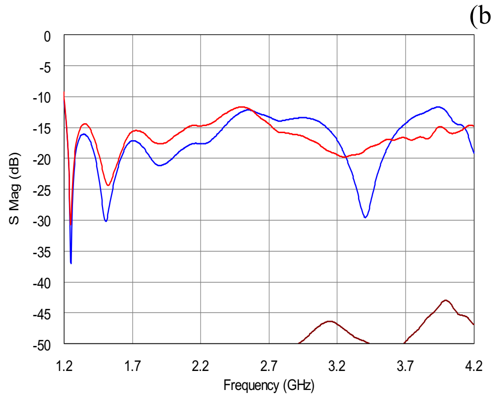


Fig. 4 - Isometric view of 1.2 to 4.2 GHz QRF H feed with diameter 38.8cm and length 31m. The feed will be constructed of 7 parts consisting of 2 cylinder sections turned on a lathe, 4 milled ridges, and a back plate.



(a)

(b



(b)

Fig. 5 – Feed modeled performance: (a) total feed efficiency in shaped Gregorian system for ports 1 (blue) and 2 (red) showing average of 77% from 1.2 to 4.2 GHz; **(Spillover efficiency to be added)** (b) S parameters of the feed which average -16dB with peak of -12dB. The cross coupling of the two ports due to capacitance between the probes is < -43 dB

The system sensitivity is proportional to the total feed efficiency divided by the system noise temperature, Tsys. A key question for the receiver system design is the number of receivers and their frequency range. For the 1.2 to 50 GHz range we have selected three 3.5:1 receivers with one cryocooler (perhaps aided by a small 60K Stirling cooler) as an alternative to five receivers with two 20K coolers being considered as the baseline approach for ngVLA. The resolution of this question will depend upon: 1) whether narrower bandwidth feeds have significant superior performance to the feed described in this paper, 2) whether more narrow band LNA's have significantly lower noise, and 3) whether a non-directional coupler noise calibration system, to be described below, is acceptable. It also should be noted that the single-crycooler system described in this paper could accommodate more high frequency feeds as they are small. The rational for using two cryocoolers instead of one for the six reeiver approach needs further consideration.

The noise calibration system enters into the system design because the directional couplers that are usually used either have waveguide or octave bandwidth or are lossy and add to the system noise even when cooled. For example, the Krytar 101004020 1 to 4 GHz coupler is specified [8] as <0.8dB loss at 300K and is quite large. This would add 3.5K if cooled to 20K or 10.5k for cooling to 60K unless the cooled loss was much less. So, even for cooling to 20K the system noise is likely to be increased by ~20% by the directional coupler. At higher frequencies with waveguide directional couplers the loss is much less and are most suitable for the bands above 30 GHz. For the lowest frequency band a non-directional 40dB coupler (NDC) is being designed and will also provide the thermal isolation between the 60K feed and 20K LNAs The NDC has the disadvantage that the noise calibration temperature will depend upon the feed reflection coefficient.   However this frequency variation can be calibrated by a hot and cold absorber system noise measurement and the non-directional calibration signal will be very stable and can be used as a quick monitor of system noise. The absolute calibration of the array including antenna efficiency will be accomplished by observations of radio sources with known flux and the noise calibration signal can be specified in terms of flux density, Janskys.

Total system noise temperature is dependent on the five parameters shown in the left column of Table II. It is notable that the LNA which has dominated system noise in the past is likely to be only about 25% of the system noise. Much attention must be given to the contributions of spillover, feed loss, windows, infra-red filter, and feed to LNA coupling.

The LNA noise temperature used in the table are based upon measured data of LNAs now in use in radio astronomy or commercially available [9,10]. Improvements should be expected in the many years before a 2025 anticiapation of ngVLA construction start.

TABLE II – System Noise Temperature

Noise, K, due to component	**Remarks**	**Tsys 1.4 GHz**	**Tsys 8 GHz**	**Tsys 15 GHz**	**Tsys 35 GHz**	**Tsys 80 GHz**
Sky	Background + atmosphere, 45deg, 13mm	4	6	8	15	43
Spillover & Blockage	Reduce with offset antenna And ground shield	3	3	3	3	3
Feed loss	Computed 0.1 dB @60K for 1.4 GHz @20K for 8-116 GHz	1	1	1	2	4
Window and IR Filter	Mylar window; multilayer polymer blanket	2	3	3	3	3
Feed to LNA No Coupler	0.1 dB	1	1	2	2	2
LNA	Robust LNA measured at connector	4	5	8	12	25
Total	**Estimate, +/- 5K**	**15**	**19**	**25**	**37**	**80**

Acknowledgment

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