Optics Design for the U.S. SKA Technology Development Project Design Verification Antenna

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***Abstract*— The U.S. design concept for the Square Kilometer Array (SKA) program is based on utilizing a large number of 15 meter dish antennas. The Technology Development Project (TDP) is planning to design and build the first of these antennas to provide a demonstration of the technology and a solid base on which to estimate costs. This paper describes the performance of the selected optics design. It is a dual-shaped offset Gregorian design with a feed indexer that can accommodate corrugated horns, wide band single pixel feeds or phased array feeds.**

Keywords-Wideband Radio Telescope Dual Shaped Optics, Wideband feeds, Corrugated Horns

I. INTRODUCTION

The SKA mid-band array will consist of N reflector antennas outfitted with multiple feeds and LNA's, covering the frequency range of 0.3 to 10 GHz. The performance, capital cost and operating cost of the entire SKA system are all strongly dependent on the antenna design.

The U.S. design concept for the Square Kilometer Array (SKA) program is based on utilizing a large number of 15 meter dish antennas. The Technology Development Project (TDP) is planning to design and build the first of these antennas to provide a demonstration of the technology and a solid base on which to estimate costs. This paper describes the selected optics design.

The optics design utilizes dual, shaped offset reflectors for the SKA / TDP antennas. The offset optics provides a clear optical path and aperture which does not scatter any radiation out of the focused region. Combined with low illumination at the edges of the two reflectors, this leads to very low sidelobes away from the main beam. The optics shape was selected to provide a -21 dB first sidelobe level. The very small wide angle sidelobes from a good offset design reduce the received levels of strong sources out of the field of view, enhancing high dynamic range, a key scientific requirement. They also provide enhanced rejection of RFI, especially from satellites. Dual reflector shaping is also used to provide high aperture efficiency with low edge illuminations thus minimizing the noise temperature contribution.

Whereas one or two wideband feeds can cover the entire SKA mid-frequency band, it takes at least 5 octave band corrugated horns to accomplish the same task. However, it is well known that there is a significant penalty in efficiency, return loss, noise temperature and cross-polarization for using a wideband feed versus a corrugated horn. Thus the baseline plan is to use a series of octave band corrugated horns to cover the required frequency. In this way, the optimum character of the optics design can be demonstrated.

There is also the need for very wide bandwidth feeds. Among the feeds currently under consideration are the QSC feed developed by Cornell, the Log periodic dipole antenna developed for the ATA project, a Quad-ridged Flared Horn developed by Cal Tech and the Eleven feed developed by Chalmers University.

The Design Verification Antenna will be used to quantify the performance of both wideband feeds and corrugated horns. This will enable the SKA project to select the optimum design in terms of total system cost.

II. ANTENNA PERFORMANCE GOALS

An ideal SKA antenna has several optical performance characteristics:

- High aperture efficiency,
- Low system noise temperature,
- Very low wide angle sidelobes
- Low cross polarization
- Good low frequency performance

Efficiency and noise temperature directly affect the number of antennas required. Low wide angle sidelobes imply resistance to undesired signals of all kinds, RFI, satellites, strong sources, etc. Low cross polarization is required for proper calibration of some kinds of observations. Low frequency performance enables the mid-band array to reach down to frequencies difficult to achieve with the SKA low band array.

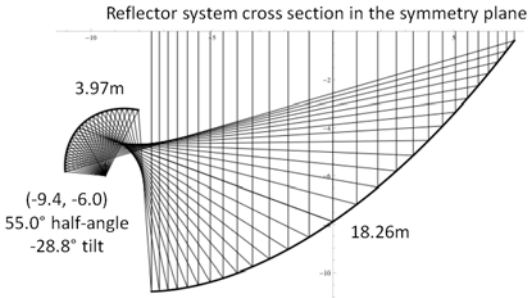

Figure 1. Reflector System Cross Section in the Symmetric Plane

Figure 1 shows a cross section ray trace of the presently selected design. The modelled performance of this design (perfect Gaussian feed) at 1.4 GHz is shown in Figure 2 and has the following characteristics:

- Aperture efficiency: .83
- First sidelobe level: -21 dB.
- Peak crosspolarization: -35 dB. (zero on boresight)
- Wide angle sidelobe envelope: -45 dB (-50 dB. almost everywhere)
- Antenna temperature: <8 Kelvin (includes sky, ground & excludes receiver)

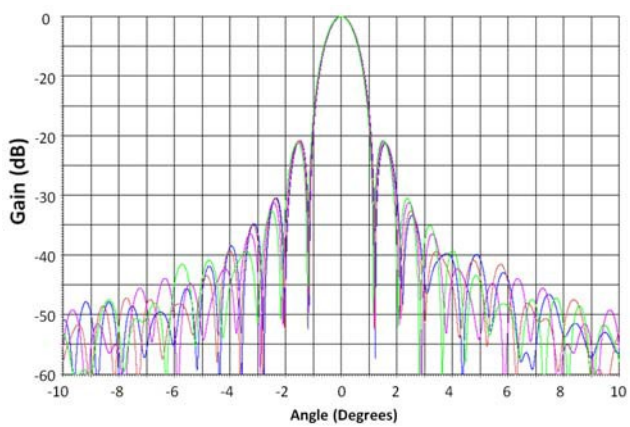

Figure 2. Radiation Pattern at 1.4 GHz (φ = 0, 45, 90, 135°)

The shaping has been tailored to give high aperture efficiency, resulting in the -21 dB first sidelobe. The shaping can be adjusted to provide progressively lower sidelobe levels at a penalty of decreasing efficiency. A typical radiation pattern is shown in Fig. 2 for -21 dB first sidelobe..

An ideal SKA antenna has several mechanical performance characteristics:

- Gain stability with elevation angle, wind and temperature
- Sufficiently accurate initial pointing in all conditions
- High pointing repeatability in all conditions
- Very high reliability
- Long maintenance intervals

High dynamic range imaging requires stable gain and very accurate pointing capability (post correction). Reliability and long maintenance intervals are required to keep operating costs at a minimum. These goals are achieved with careful structural design and analysis. Figure 3 shows a drawing of the selected design, a dual shaped offset Gregorian design with a feed indexer.

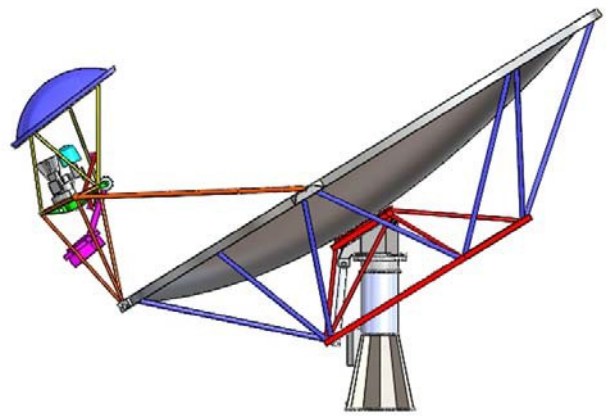

Figure 3. 15 Meter Offset Gregorian Antenna Single Piece Reflectors

III. Dual Reflector Shaping

Dual reflector shaping is utilized to both increase the aperture efficiency and reduce the noise temperature. The aperture efficiency is increased by making the aperture illumination more uniform. Noise temperature is decreased by capturing more of the feed energy in the subreflector and thus by reducing the amount of energy that is spilled past the subreflector.

The reflectors are designed with a shaping method that controls the how the energy from the feed is distributed across the aperture plane. In particular, a deeply tapered feed illumination can be redistributed to a more uniform aperture illumination with a steep roll off near the aperture edge. This raises the spillover efficiency of the system by capturing more of the energy from the feed and keeps the aperture efficiency high by controlling the aperture distribution without raising the spillover past the primary edge.

Fig. 1 shows a cross section of a the offset system with a 15 meter aperture in the plane of symmetry. The shaping is evident in the ray distribution in the aperture. The plotted rays emanate from the focus with equal steps in elevation angle and map to the aperture plane with large increments in radius in the center and small increments in radius near the edge. This gives the desired energy redistribution. One side effect of the shaping is obvious; the rays do not cross at an intermediate focus but are spread out in a caustic region.

Various parameters of this optical system are shown on the plot. The location of the focus, the half angle subtended by the edge of the secondary and the tilt angle of the boresite ray are shown under the focal point. The rim to rim dimension, total reflector area and the area as a fraction of the aperture disk are shown close to each of the reflectors. Although the secondary looms large in this view, it is less than 1/12 of the size of the primary in area. A 3-dimensional drawing of the antenna is shown in Fig. 3. The critical parameter in the design is the half-angle subtended by the secondary. Since, as will be shown, each feed has a different gain and half-power beamwidth a different subreflector half-angle is required for maximum efficiency over the frequency band.

IV. Variable Shaping to Create New Subreflectors

The choice of feed for the optics is not yet obvious, which makes it difficult to proceed with the final reflector design. It is possible to create new shaped subreflectors matched to a previously designed primary reflector, providing a different opening half angle than the original design. This concept provides a way to move forward with the main optical design and still have options for the opening half angle

The construction method is simple and is illustrated in Fig. 4. The given primary reflector is shown and is from the 50 degree half angle design. A ray from the aperture point A is reflected from the known primary at point P and propagates toward a set of possible secondary points, S. The ray then reflects at the point S to the new focus F. The choice of point S is calculated by requiring a constant path length along the ray, APSF. The location of the new focus and the choice of constant path length are selectable parameters for the calculation. The procedure is repeated for a complete set of rays from aperture, yielding a locus of points defining the new subreflector surface. This construction method ensures that the reflection law is satisfied at the new subreflector.

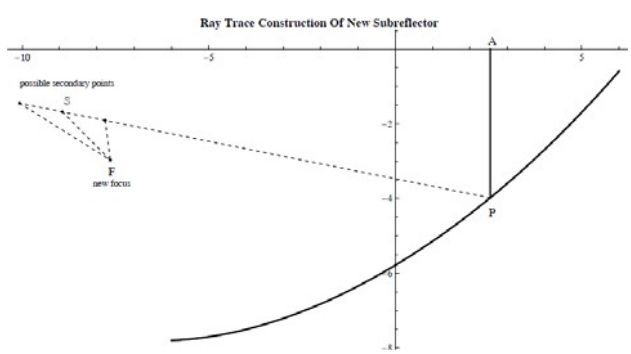

Figure 4. Ray Trace method to construct new subreflector

Figure 2.3.18 shows a cross section of a reflector system calculated with this method and Fig. 2.3.19 shows a close up of the new subreflector. The original design had an opening angle of 50 degrees and the new design has an opening angle of 55 degrees. The old subreflector is shown as a dashed line and the old focus is the isolated dot. The new and old subreflectors have the boresight point in common, indirectly selecting the constant path length. Under this choice the only remaining free parameter is the location of the new focus. It is moved in x,z to give the desired new opening half angle with minimum variation in half angle around the rim. Figure 2.3.20 shows the opening half angle around the rim for the 32 azimuth values. The variation is very small, yielding an effective design.

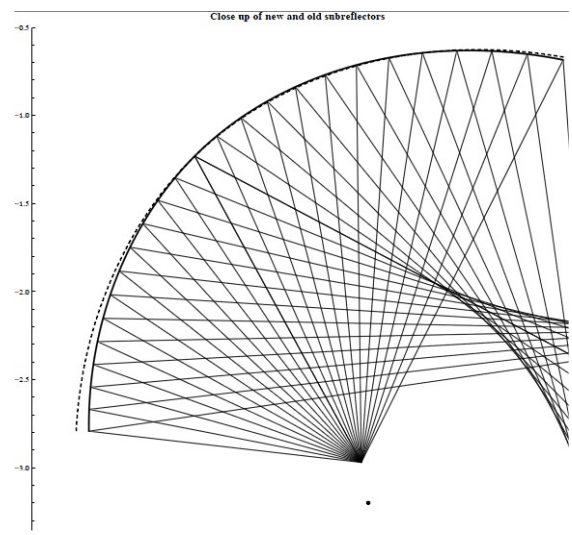

Figure 5. Close up of new and old subreflector

Analysis of four new subreflectors drawn from the 55 degree baseline case at 35, 45, 55, and 65 degrees half angle shows a very small loss in performance. Figures 6 and 7 show the radiation patterns at 1.4 GHz for the φ = 0 and 90 degree cases with the 4 patterns overlapped. This technique provides a way to adapt a given primary to different feeds, allowing progress on designing and building the optics while still retaining a wide range of possibilities for the final selection of the feed.

At this stage of the project the feeds are not mature enough to make a final choice. However the schedule for building the TDP Design Verification Antenna (DVA1) requires that a decision on the optics design be made before the feed development is completed. A shaped dual reflector optics design is presented that provides a wide range of subreflector opening angles so the fabrication of the antenna can proceed.

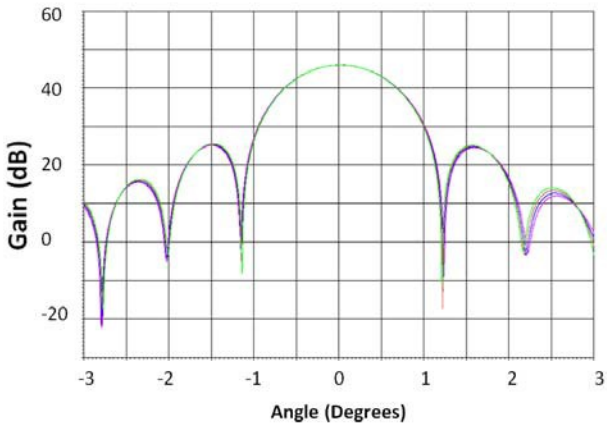

Figure 6 Radiation pattern in the plane of offset (φ = 0°)

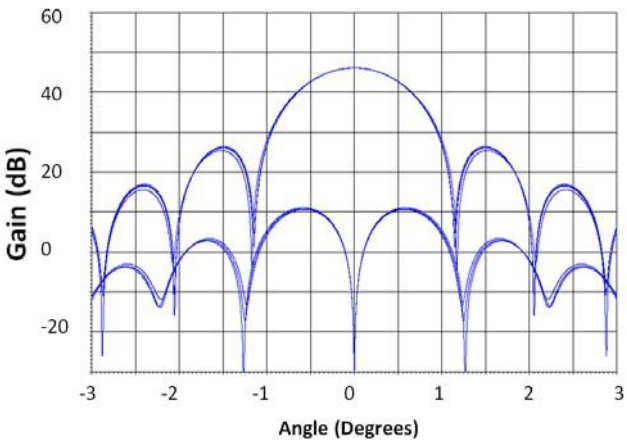

Figure 7 Radiation patterns for φ =9 0°

V. IDEAL FEED

An ideal feed for the designed dual reflector optics would be a constant feed pattern over frequency with a -16 dB taper at the edge of the subreflector. It is modeled as a cos Q type pattern with Q=3.314.

The efficiency, noise temperature and A_e/T_{sys} over the frequency range of 0.3 to 10 GHz is shown in Figures 8, 9, and 10. The noise temperature includes the antenna, sky and background radiation. The A_e/T_{sys} assumes a constant 15K amplifier. It is to these patterns that all other feeds are compared.

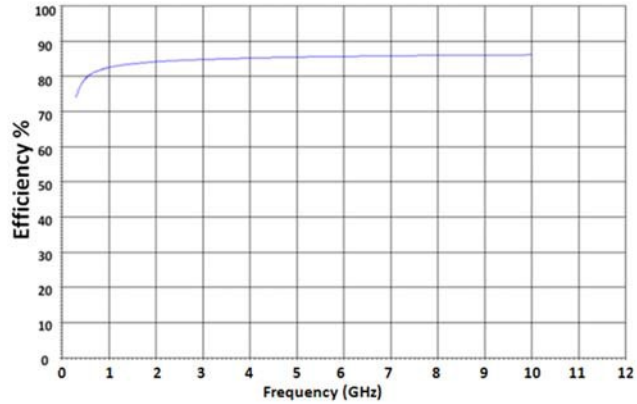

Figure 8 Efficiency as a Function of Frequency for the Ideal feed

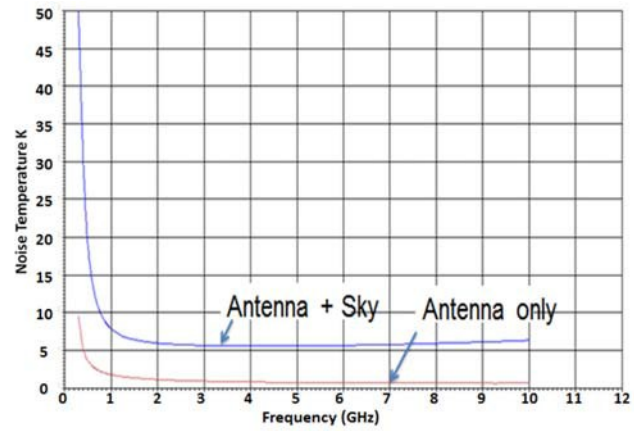

Figure 9. Noise Temperature as a Function of Frequency for the Ideal feed

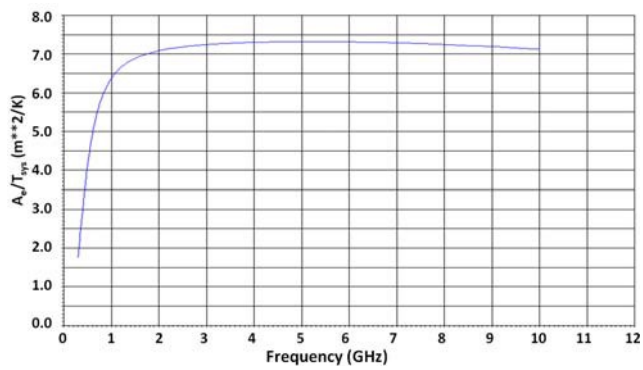

Figure 10. A_e/T_{sys} as a Function of Frequency for the Ideal Feed

VI. TWO CORRUGATED HORN DESIGNS

To be compatible with the range of wideband feeds considered, two octave band horns were designed. Figure 11 shows a ring loaded octave band horn with a 45 degree flair angle which is optimized for narrow (~40 degree) subreflector

opening half-angles, and Figure 12 shows a ring-loaded octave band horn optimized for a wider subreflector (~55 to 60 degree) half-opening angle.

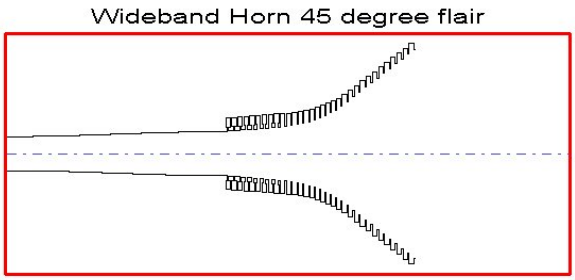

Figure 11. Octave Band Horn with 45 degree flair (optimized for narrow subreflector opening angles)

Figure 12. Octave Band Horn with 57 degree flair (optimized for wider subreflector opening angles)

Three scaled versions of an octave band horn are required to cover the 1.25 to 10 GHz frequency band. One horn designed for 1.25 to 2.5 GHz, one for 2.5 to 5.0 GHz and one for 5 to 10 GHz. A composite efficiency plot comparing the variations of both horn designs is shown in Figure 13. The wide opening angle feed utilized a 55 degree opening half-angle subreflector whereas the narrow opening angle feed used a 35 degree subreflector. Figure 14 compares the noise temperature performance and Figure 15 the Ae/Tsys computed assuming a 15K LNA, an optimum subreflector opening angle and the DVA-1 15 meter optics.

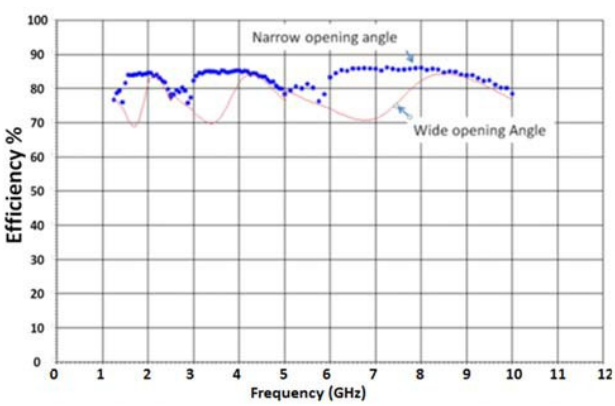

Figure 13. Octave Band Horns Efficiency

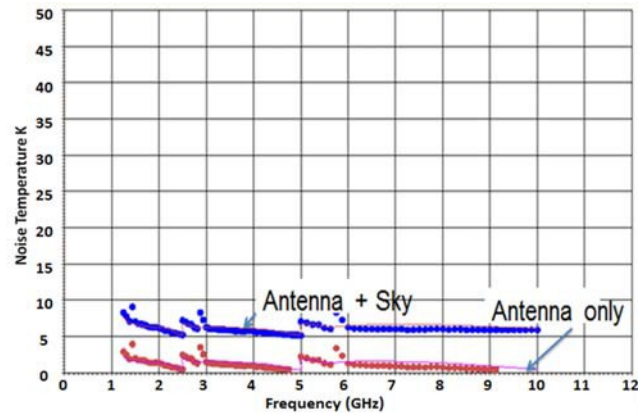

Figure 14. Octave Band Horn Noise Temperature

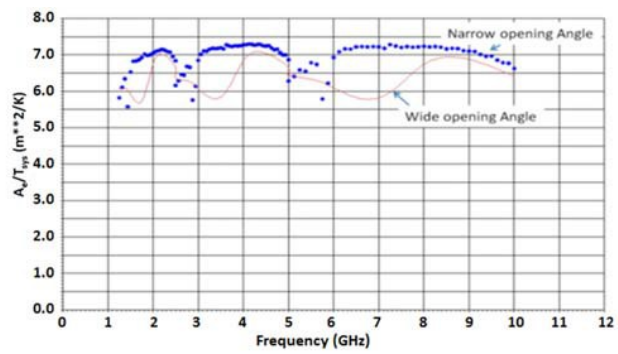

Figure 15. A_e/T_{sys} for the Octave Band Horns

VII. Quadridged Feeds

A quad-ridged, flared horn (Figure 16) achieving nearly constant beamwidth and excellent return loss over a 6:1 frequency bandwidth was developed at Cal Tech. A 2-12 GHz version was fabricated and tested [1]. Radiation pattern measurements show excellent beamwidth stability from 2 to 12 GHz. Measured return loss is > 10 dB over the entire band and > 15 dB from 2.5 to 11 GHz. There are several designs under consideration for the SKA and there is both measured and calculated data available. For the Lindgren data there is measured data patterns for one of these feeds inside of a cryostat from 2 to 19 GHz and it is being used on the GAVRT antenna [2, 3].

For the selected Quad-ridged design, the subreflector opening half-angle that optimized Ae/Tsys was 45 degrees.

Figure 17 shows the efficiency, Figure 18 the Noise temperature and Figure 19 the Ae/Tsys as a function of frequency. As expected, the performance is not as good as the corrugated horn, but nontheless quite acceptable as a wideband feed

Figure 16 CIT Quad-ridge Flared Horn (QRFH)

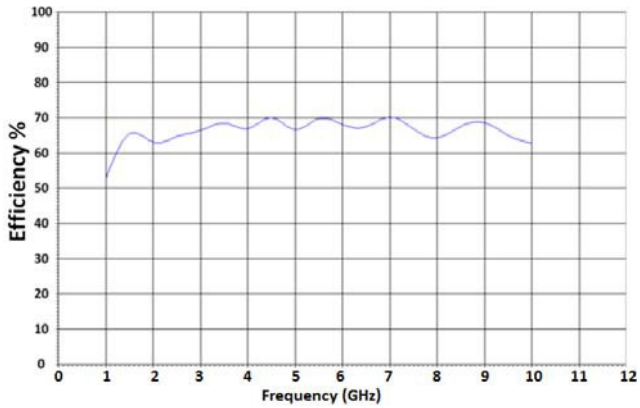

Figure 17. Quad-ridged feed efficiency

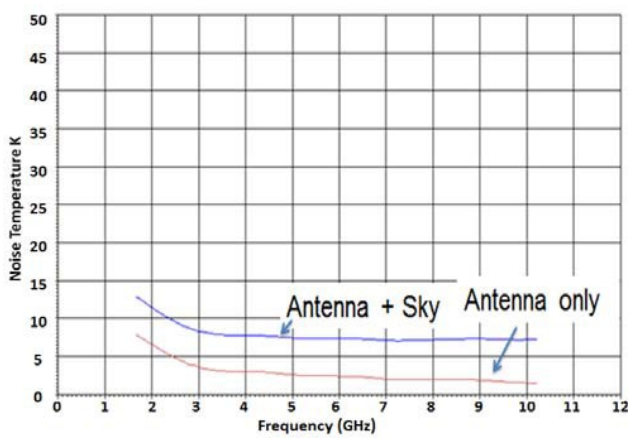

Figure 18. Quad ridged feed Noise Temperature as a function of frequency

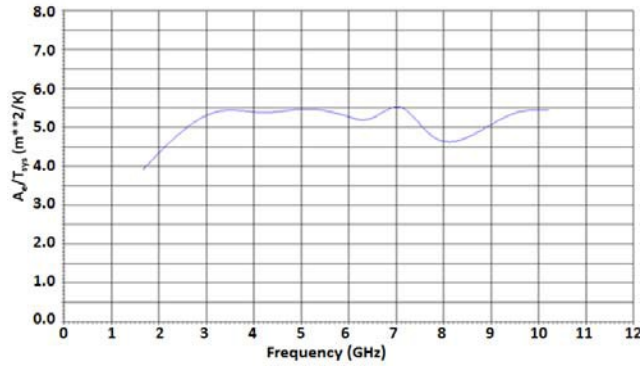

Figure 19. A_e/T_{sys} of the Quad ridged feed as a function of frequency

VIII. THE QSC FEED

The QSC feed (Figure 20) is an ultra-wide band feed that has a measured input match better than -10 dB over 10:1 bandwidth [4]. There are three versions being considered for the optics design: the first one is based on measured data from an actual QSC prototype that operates from 0.4 to 4.0 GHz, the second, QSC in a can, is based on calculated pattern data of a QSC model inside of a metallic cylinder, the presence of the wall of the can actually improves the directivity without compromising the input match. The third is the QSC-i, a new and improved version of the QSC feed that is intended to operate from 1 to 10 GHz, and for this there are calculated patterns. The performance of the QSC-i feed is shown in the following. For the dual shaped design, the optimum subreflector opening half-angle is between 55 and 65 degrees with nearly the same A_e/T_{sys} performance at both opening angles. Figure 21 shows the efficiency, Figure 22 the Noise temperature and 23 the A_e/T_{sys} as a function of frequency. The noise temperature performance is not as good as the previous feeds, and consequently A_e/T_{sys} is poorer.

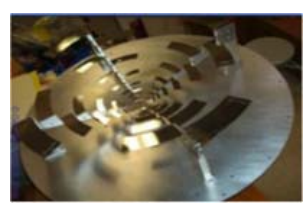

Figure 20. The QSC feed

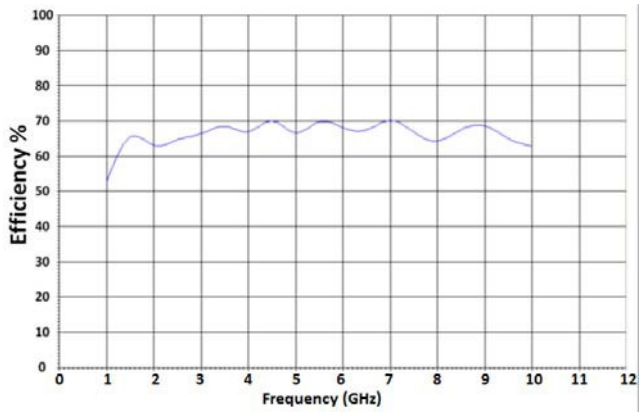

Figure 21. Efficiency of the QSC-i as a function of frequency

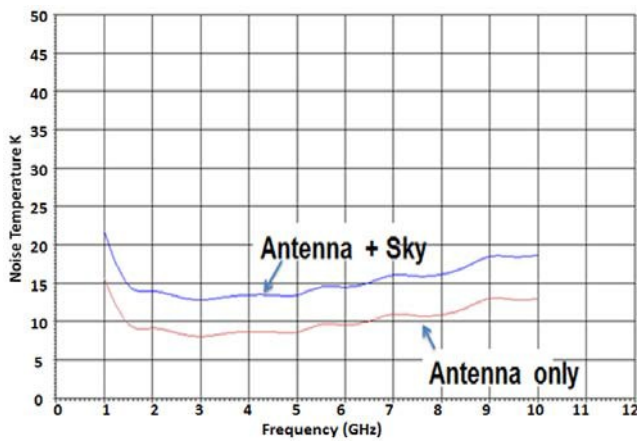

Figure 22. Noise Temperature of the QSC-i as a function of frequency

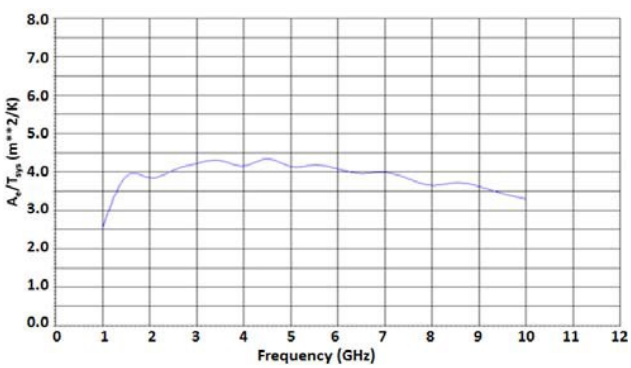

Figure 23. A_e/T_{sys} of the QSC-i as a function of frequency

IX. ATA Log-Periodic Feed

An earlier version of the ATA feed is shown in Figure 24. The ATA feed has frequency coverage in excess of 15:1, with a good match over the band [5]. There is currently another version under development but the measured data is not available at this time. The following calculations utilize measured data taken on a reduced size feed on the Cal Tech antenna range. The optimum subreflector opening half-angle is 45 degrees. Figure 25 shows the efficiency, Figure 26 the Noise temperature and Figure 27 the A_e/T_{sys} as a function of frequency. Since there are wide angle lobes from the feed that spill past the optics, the noise temperature performance is quite poor and consequently A_e/T_{sys} is low. Because of these lobes the ATA feed would be significantly helped with noise shields for the dual shaped optics.

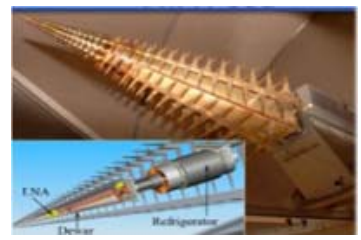

Figure 24. The ATA feed used on the ATA telescope

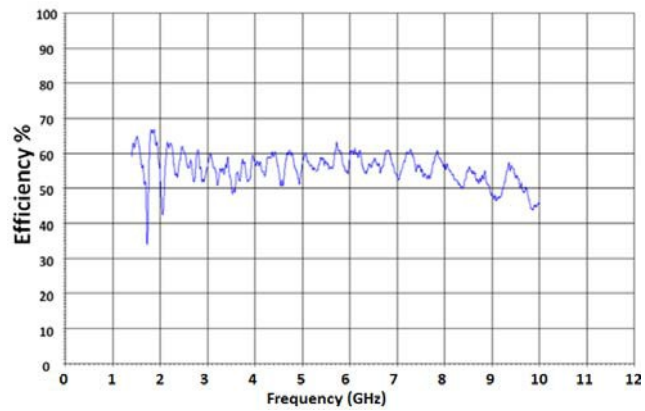

Figure 25. Efficiency of the ATA feed as a function of frequency

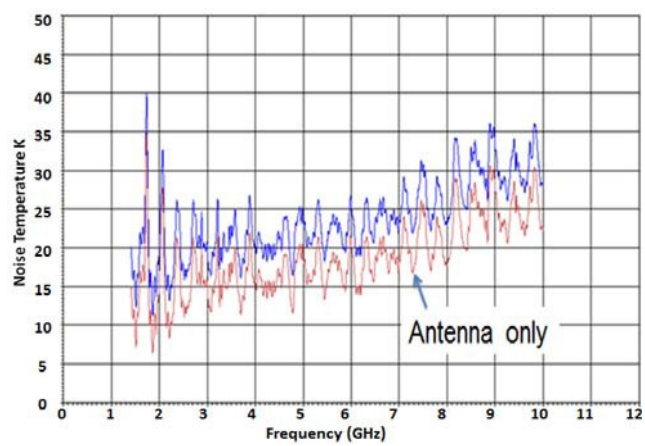

Figure 26. Noise Temperature of the ATA feed as a function of frequency

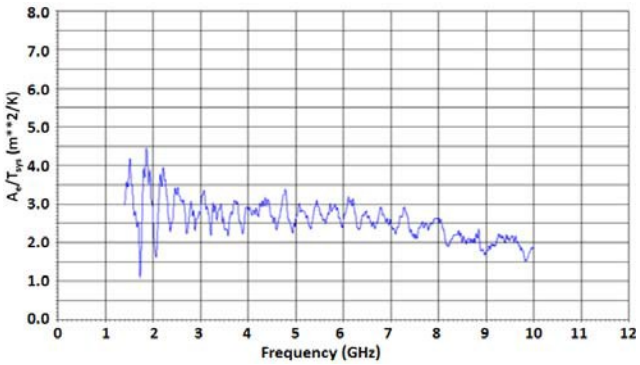

Figure 27. A_e/T_{sys} of the ATA feed as a function of frequency

X. ELEVEN FEED

The Eleven feed [6] shown in Figure 28 is a compact feed based on a parallel folded dipole configuration over a ground plane, with frequency coverage of 10:1. There is measured data over a 2 to 12 GHz range. However, since the lower portion of the frequency range performed rather poorly and could be improved by making the feed larger, the following calculations use the measured data over the 2.5 GHz to 10 GHz range with the data from 1.4 to 2.5 GHz simulated by scaling the measured 2.5 to 4.5 GHz data to the 1.4 to 2.5 GHz range. The subreflector opening half-angle that optimized Ae/Tsys was 55 degrees. Figure 29 shows the efficiency, Figure 30 the Noise temperature and 31 the A_e/T_{sys} as a function of frequency. Since the Noise Temperature performance is good, the A_e/T_{sys} is quite good and comparable to the Quad ridged feed performance

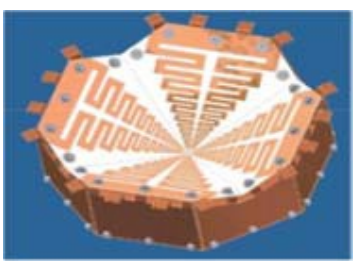

Figure 28. The Eleven feed

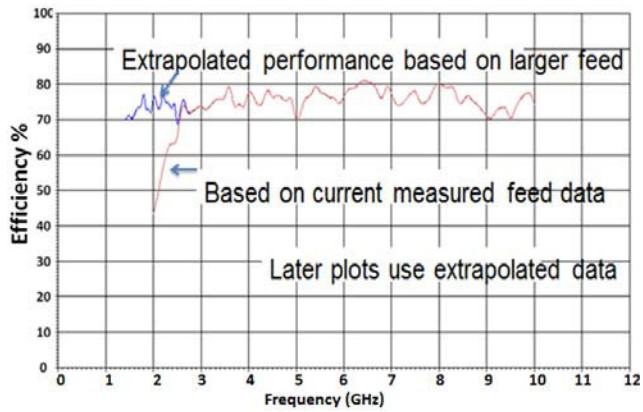

Figure 29. Efficiency of the Eleven feed as a function of frequency

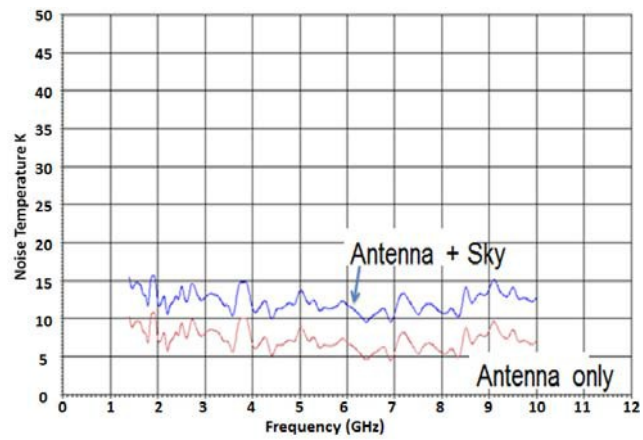

Figure 30. Noise Temperature of the Eleven feed as a function of frequency

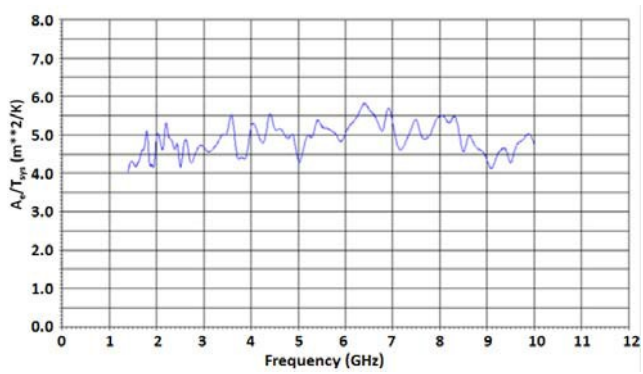

Figure 31. A_e/T_{sys} of the Eleven feed as a function of frequency

XI. SUMMARY

The key performance parameters for both corrugated horns and wideband single pixel feeds were computed for the dual-shaped Gregorian reflector system. The key performance parameters included both the efficiency and noise temperature as a function of frequency in order to evaluate A_e/T_{sys} for each feed type. In addition the performance of an ideal feed was shown to provide a basis with which to separate the effects of the feeds from that of the optics.

ACKNOWLEDGMENT

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