Optimization of the 0.35-1.05 GHz Quad-Ridged Flared Horn and Eleven Feeds for the Square Kilometer Array Baseline Design

M. V. Ivashina, C. Bencivenni, O. Iupikov, and J. Yang

***Abstract*—Initial optimization results for the wide-band Eleven antenna and Quadruple-Ridged Flared Horn (QRFH), designed to operate as the reflector antenna feeds at 350 - 1050 MHz, are presented and discussed in the context of the next generation radio telescope – the Square Kilometer Array (SKA). First, we describe the procedure that has been developed to carry out time-efficient optimization of the feeds for multiple antenna optics configurations at the system level (so as to maximize the antenna-receiver sensitivity), and then cross-compare the two feed types by assessing the main antenna system characteristics and radio-astronomy performance metrics.**

***Index Terms*—wideband reflector antenna feeds, astronomy**

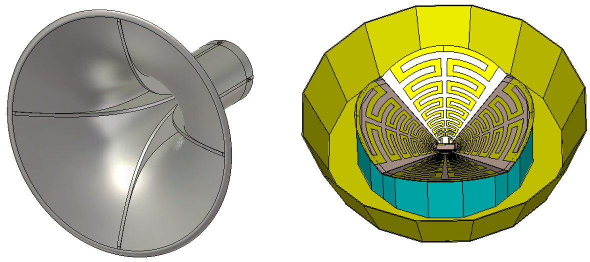
I. Introduction

A large international community of radio astronomers and engineers has been working for more than a decade towards the development of the giant radio telescope Square Kilometer Array (SKA), and has recently moved to the pre-construction phase [1]. To undertake this work, several consortia have been formed to carry out an extensive and systematic study of the major elements of the SKA baseline design that will be eventually integrated in the final optimized system. The baseline starting point is the decomposition of the SKA (at the first construction phase) into the following systems: (i) SKA1-low, a low-frequency planar aperture array; (ii) SKA1-survey, a mid-frequency array of relatively small reflector antennas (referred to as dishes) equipped with multi-beam phased-array feeds, both arrays to be built in Australia; and (iii) SKA1-mid, a mid-frequency array of small dishes, each with a set of single-beam feeds supporting the total frequency band of 350 MHz - 20 GHz, to be built in South Africa [2].

The middle frequencies of SKA1-mid are planned be covered by conventional horn feeds (aiming at high receiving sensitivity over sub-octave bands), while at the highest and lowest frequencies, the sensitivity would be compromised in favor of wider bandwidth, achieved with Wide-Band Single-Pixel Feeds (WBSPFs). This novel WBSPF technology would enable simultaneous observations of multiple spectral lines, increase continuum sensitivity, as well as greatly reduce the system construction and operation costs.

A major challenge for such hybrid antenna design is to determine the optics solution which will optimally match this large variety of the feeds and meet their corresponding requirements. Since this optimum is likely not feasible, the Dish Element SKA consortium has decided to design the 'best compromise' optics for all the feeds and frequency bands [3]. For this purpose, a set of 18 unshaped and 5 shaped optics solutions (optimized on the ideal Gaussian feed models for different beamwidths and illumination tapers) have been first selected, then their performance has been investigated by considering the realistic feed models optimized for each configuration.

M. V. Ivashina, and C. Bencivenni, and O. Iupikov and J. Yang are with the Department of Signals and Systems of Chalmers University of Technology, Göteborg, Sweden, e-mail: marianna.ivashina@chalmers.se, carlo.bencivenni@chalmers.se, oleg.iupikov@chalmers.se, jian.yang@chalmers.se.



(a) QRFH feed (b) Eleven feed

Fig. 1. Wide-band single-pixel feeds for reflector antennas, as considered for the baseline design of the SKA1-mid Band (350 - 1050 MHz).

II. Description of WBSPFs

In this paper, the initial optimization results for the feeds designed to operate at the lowest frequencies of the SKA1-mid (350 - 1050 MHz) are presented and discussed. This study covers two distinct types of WBSPFs which have reached a reasonable level of technological readiness: (i) Eleven antenna and (ii) Quadruple-Ridged Flared Horn (QRFH) [4], [5]. The Eleven antenna represents an antenna array consisting of four log-periodic dual-dipole petals, and its advantageous properties include a nearly constant beamwidth ($\sim 120°$ at -10dB level), a fixed phase center location, low relative cross-polarization and a very compact low-profile geometry. A known problem with this feed is the difficulty to control the beamwidth, so as to optimally match the dish optics with the narrower subtended angles, and the need of impedance transforming baluns or differential low-noise amplifiers (LNAs) with high input impedance that are directly connected to the antenna ports. In this regard, the QRFH feeds is more versatile and simpler for integration with standard single-ended

LNAs, but suffers from stronger variation of the beamwidth over the wide band, higher cross-polarization level and larger dimensions. The former two characteristics can be improved up to certain extent by, e.g., careful optimization of the ridge profiles and adopting differential active feeding [6], [7], but these solutions are still under investigation.

The studied models of the Eleven and QRFH feeds are illustrated in Fig. 1. These models include the complete antenna structure and their balun networks, and hence account for the effects of realistic feeding implementation on the antenna impedance and radiation characteristics. It is worth to mention that the previously developed Eleven feeds had 8 ports for dual polarization, and hence required 8 single-ended (or 4 differential) LNAs. In the present design, the center-bridge connection was introduced which makes this feed a 2-port antenna. Another function of this connection is to minimize the mutual coupling effects between the two ports. A shielding cone has been also introduced to reduce the side-lobe levels.

III. Feed optimization procedure and results

The Eleven feed has been designed by using the optimization procedure, which minimizes the antenna reflection coefficient while maintaining high aperture efficiency. The antenna efficiency has been evaluated based on the close-form solution for rotationally symmetric reflector antennas [8]. To carry out this optimization in a time-efficient manner, we used so-called Social Civilization Algorithm (SCA). The key idea of SCA is emulating the basic social mutual interaction behavior among individuals, which is very common in all human and insect societies. Compared to Genetic Algorithm we used before, the SCA has been found to be faster. More details about this procedure can be found in [9].

The model of the considered QRFH feed is based on the design in [5], which was developed for the VLBI2010 applications ($2.2-14$ GHz). First, we reproduced this particular design, so as to validate our simulation models across the published data, then we re-optimized the frequency scaled model for the SKA1-mid Band 1. Regarding the choice of the feed optimization strategy and expected performance, it is important to underline the differences with the QRFH design in [5]. Firstly, much larger physical dimensions of the feed at $350-1050$MHz make it practically impossible to integrate the entire antenna structure inside the cryostat (together with LNAs), and hence realize very low receiver noise temperature T_{rec}. The estimated values of $T_{\rm rec}$ for this band are in the range of 15-20K. Secondly, the optics of the antenna system becomes electrically smaller at these frequencies, and hence degradation of the antenna efficiency and spillover ground-noise pick-up can be expected. Due to these complexities, we have adopted an optimization procedure that utilizes electromagnetic simulations of the reflector antenna system in combination with the feed (to accurately evaluate the antenna efficiency and spillover noise) and also accounts for the noise temperature contributions due to the noise sources generated in the frontend (e.g. ohmic losses in the conductor and dielectric materials of the antenna structure and its feeding network, LNAs and losses associated with the cables connecting the feed at 300K and LNAs at cryogenic temperature) as well as in the sky.

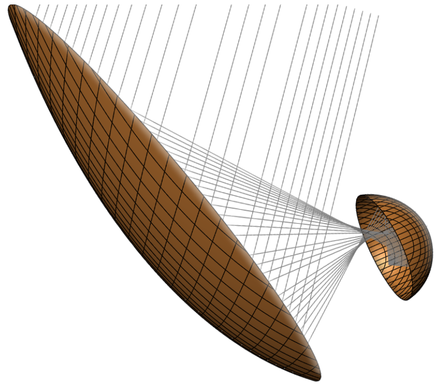


Fig. 2. Off-set Gregorian reflector antenna model.

TABLE I
Main design parameters of the QRFH feed

Total length, [mm]:	1300	Taper angle β_{ridge}:	71.94°
Aperture diameter, [mm]:	1410	Taper angle $\beta_{sidewall}$:	73.19°
Throat diameter, [mm]:	276	Ridge thickness, [mm]:	20.14

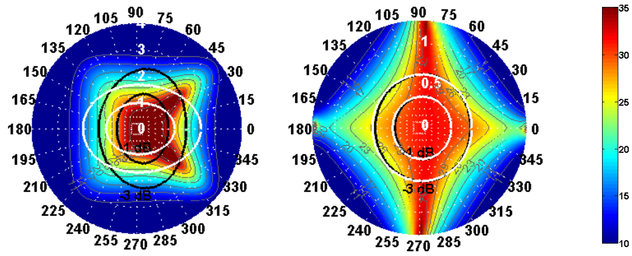
TABLE II
Main design parameters of the Eleven feed

Aperture diameter (excluding the shielding cone), [mm]:	750
Total aperture diameter, [mm]:	1200
Total length, [mm]:	250

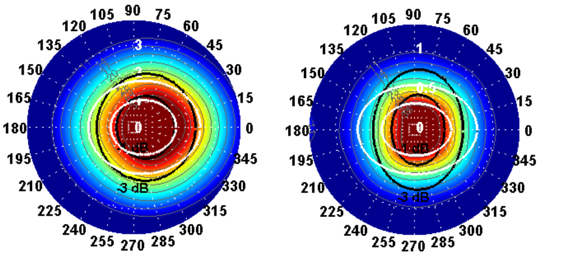
To implement this approach, we have developed a MATLAB based numerical tool that interfaces the full-wave electromagnetic FDTD solver (realized in CST MICROWAVE STUDIO) for modeling the feed, Genetic Algorithm for efficient parametric search, Physical Optics & Physical Theory of Diffraction solver (realized in GRASP) for modeling the reflector antenna patterns and an in-house antenna-receiver simulator (see. Sec. 3 in [10]) for the system level analysis. In the course of the optimization, we aimed at the maximum system sensitivity, where the fitness function for each design iteration has been defined as a weighted average sensitivity, prioritizing the high frequencies, according to the SKA1-mid specifications (see Table 6 in [2]).

To determine the parametric search space of the QRFH model, we have exploited the fact that, from the modeling point of view, the horn can be decomposed into two parts (the throat and flared sections), each of which can be optimized virtually independently. Particularly, some parameters, including the diameter of the circular waveguide section, size of the back-short cavity, the ridge thickness and gap width, can be determined before the main optimization process (by e.g. minimizing the reflection coefficients at the ports of the throught section [7]) and then kept fixed when optimizing the flared section of the antenna (including the horn length, aperture diameter and taper). This decomposition approach proves effective and enables time-efficient optimization of the feed for multiple optics configurations. Obviously, one can further improve the realized optimal design, once the 'best compromise' optics has been selected.

The resulting performance characteristics of the reflector antenna system fed with the optimized QRFH and Eleven feeds are presented in Fig. 3 and Fig. 4. This system was found to provide the best dish-feed combination – yielding the highest sensitivity for both feeds – among the considered optics configurations. The GRASP model of this system is shown in Fig. 2, where the diameter of the sub-reflector aperture is 4-m and its semi-subtended angle is 58°. The surface of the sub-reflector is shaped and has an extension shielding the spillover radiation in the ground region. It is worth mentioning that results have been validated against full-wave analysis in FEKO (MLFMM solver) and the accuracy was found to be within a few percent for the predicted antenna efficiency. More validation tests are currently in progress (this work is done by Dr. T. Carozzi). The main design parameters of the optimized feeds are presented in Tables I and II. Table III summarizes the optimization results for several considered feed-optics configurations, by comparing the sensitivity values averaged over the range of elevation angles and frequency bands $350-600$ MHz and $600-1050$ MHz, respectively. Best feed-dish combinations are shown in bold.



(a) Eleven feed at (left) 350 MHz and (right) 1050 MHz



(b) QRFH feed at (left) 350 MHz and (right) 1050 MHz

Fig. 3. Polarization performance over the field of view, as realized by the polarimetric beam pair (see the white and black controur lines corresponding to the -1dB and -3dB levels), in terms of the intrinsic cross-polarization ratio IXR [11] for the same feed-dish combinations as for Fig. 4.

IV. Conclusions

Our study has demonstrated that the extension (shielding the spillover in the ground region) and shaping of the sub-reflector surface play a determinant role in the optimization of the reflector antenna performance (such as selected for the SKA baseline design), regardless of the choice of the considered feeds. For the best antenna optics-feed combinations, the predicted receiving sensitivity over the range of elevation angles and frequencies is slightly below the required minimum (4.1 m^2/K), where the relative difference between the Eleven and QRFH feeds is $\sim 10\%$; the former outperforms at higher frequencies while the later is better at the lower part of the band. The directions of further improvement cover the reduction of the frequency ripple of the antenna characteristics for the Eleven feed, and the enhancement of the antenna efficiency and suppression of the cross-polarization level at high frequencies of the QRFH feed. Other important study points include the imaging and calibration performance; such study should provide us with additional results that, together with the present electromagnetic analysis, are necessary for the selection of the optimal radio-astronomy antenna design.

V. Acknowledgments

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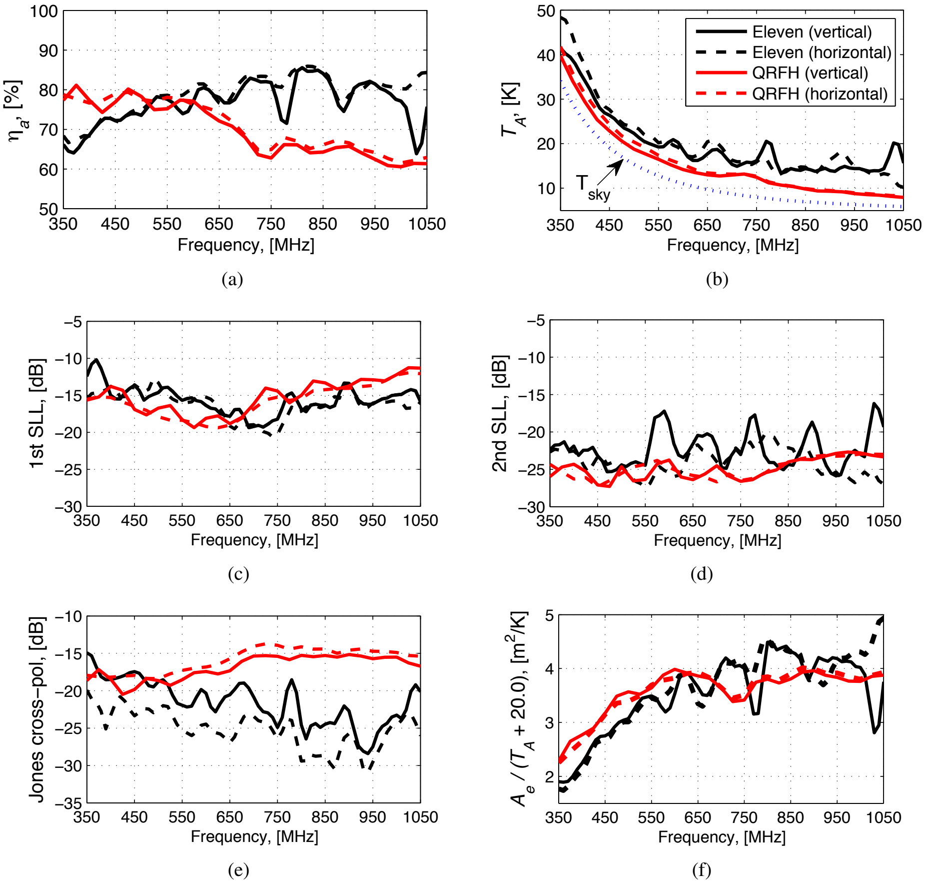

Fig. 4. Performance comparison of the Eleven and QRFH feeds designed for the shaped Off-set Gregorian reflector antenna system with the primary reflector having the projected aperture of $D_{\text{prim}} = 15$m and the secondary reflector with $D_{\text{sub}} = 4$m, $\Theta_{\text{sub}} = 58^\circ$ and the extension shielding the ground. The sub-figures show (a) the antenna aperture efficiency, (b) antenna noise temperature for the elevation angle 90°, (c,d) peak 1^{st} and 2^{nd} side-lobe levels, (e) peak value of the Jones cross-polarization at the -1dB and -3dB levels, and (f) the resultant receiving sensitivity $A_{eff}/(T_A + T_{\text{rec}})$ for $T_{\text{rec}} = 20$K.

TABLE III
SENSITIVITY [M^2/K], AVERAGED OVER THE RANGE OF ELEVATION ANGLES $(0-60^\circ)$ AND FREQUENCY BAND, AND ITS MAXIMUM DEVIATIONS [%]. BEST FEED+DISH COMBINATIONS ARE SHOWN IN BOLD, WHERE THE SHAPED AND UNSHAPED CONFIGURATIONS ARE TREATED INDEPENDENTLY

	Unshaped optics						**Shaped optics**				
Half sub. angle	49° $(D_s = 6$**m)**		53° $(D_s = 6$**m)**		58° $(D_s = 6$**m)**		49° $(D_s = 4$**m)**		49° $(D_s = 6$**m)**		58° $D_s = 4$**m**
Extension	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**	**YES**
Sensitivity, averaged over the range of elevation angles and frequency band from 350-600 MHz											
Eleven feed	1.9 m^2/K +44% −40%	2.4 m^2/K +40% −35%	2.0 m^2/K +41% −40%	2.5 m^2/K +38% −40%	2.1 m^2/K +41% −40%	**2.6 m^2/K +39% −41%**	2.0 m^2/K +48% −46%	2.7 m^2/K +40% −40%	2.2 m^2/K +41% −41%	2.8 m^2/K +39% −46%	**3.0 m^2/K +38% −42%**
QRFH feed	2.1 m^2/K +27% −37%	**2.7 m^2/K +21% −35%**	2.0 m^2/K +30% −32%	2.4 m^2/K +27% −28%	1.9 m^2/K +31% −30%	2.3 m^2/K +25% −27%	2.3 m^2/K +39% −40%	3.1 m^2/K +25% −35%	2.5 m^2/K +31% −37%	3.1 m^2/K +23% −34%	**3.3 m^2/K +22% −32%**
Sensitivity, averaged over the range of elevation angles and frequency band from 600-1050 MHz											
Eleven feed	2.9 m^2/K +40% −39%	3.6 m^2/K +29% −29%	3.1 m^2/K +36% −37%	3.8 m^2/K +24% −27%	3.2 m^2/K +27% −34%	**3.9 m^2/K +19% −26%**	3.1 m^2/K +44% −39%	4.2 m^2/K +23% −28%	3.3 m^2/K +38% −37%	4.3 m^2/K +22% −27%	**4.3 m^2/K +18% −35%**
QRFH feed	2.5 m^2/K +16% −24%	**3.1 m^2/K +6% −13%**	2.5 m^2/K +12% −19%	2.9 m^2/K +7% −12%	2.4 m^2/K +10% −19%	2.7 m^2/K +6% −13%	2.8 m^2/K +21% −26%	3.6 m^2/K +7% −14%	3.0 m^2/K +14% −24%	3.7 m^2/K +7% −12%	**3.9 m^2/K +7% −13%**