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Analysis of the Strut and Feed Blockage Effects in Radio Telescopes with Compact UWB Feeds

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I. Introduction

The international radio astronomy community is currently pursuing the development of a giant radio telescope known as the Square Kilometre Array (SKA). The SKA reference design consists of several wideband antenna technologies, including reflector antennas fed with novel multi-beam Phased Array Feeds (PAF) and/or wide band Single Pixel Feeds (SPFs) that can operate at frequencies from 1 to 10 GHz [1], [2]. The baseline of this design represents an array of several hundred to a few thousand reflector antennas of 15-m diameter and that will realize sensitivity of 10,000 m^2/K. During the past years, several different reflector and feed concepts have been proposed and examined, but only a small number of these design options (that have a sufficient level of maturity) will be built and tested in a set-up that is closely resembling the final SKA system [3]. These tests are aimed to evaluate the overall system performance as well as construction and operational costs. The final choices for the dish and feed evaluation tests might include: (i) off-set Gregorian and axi-symmetric reflector antennas and; (ii) an optimized octave corrugated horn and the single-pixel wideband feeds such as quad-ridged horn and Eleven antenna [2], [4].

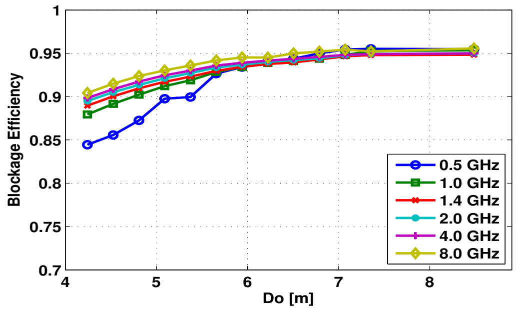
II. Objectives and Methodology

The goal of this paper is to facilitate the performance trade-off analysis of the antenna system, and in particularly to quantify 'expected' deterioration of the telescopes' performance due to the aperture blockage provided by the feed and its supporting struts in axi-symmetric antennas [3]. The key concerns relate to experience with many traditional instruments that employ multiple narrowband feeds and receivers requiring large and heavy supporting structures. The aperture blockage caused by these structures is known to significantly reduce the antenna efficiency and increase the spillover noise temperature as well as the sidelobe and cross-polarization levels [5]. On the contrary, the offset Gregorian systems with the same projected aperture area have more enhanced performance given that there is no direct blockage in the aperture field. Nevertheless, the antenna design will be more complicated, and the operational manufacturing costs are higher.

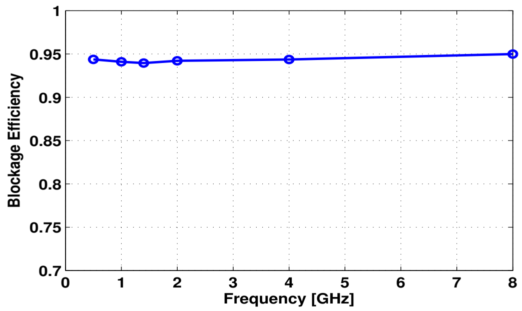
Herein, we presents a detailed numerical study of the blockage effects in axi-symmetric reflector antennas such as being proposed for the SKA dish design in [6] with the aperture diameter of 15 m and focal ratio $\mathrm{F/D} = 0.42$ (the subtended semi-angle of 62°). We argue that for such systems, the difficulties in supporting multiple receivers will not be as large as for conventional telescopes, due to more advanced technologies for struts design (available now) and optimized choice of wideband feeds. When a set of a few 2-3-octave feeds is used instead of a collection of multiple single-octave horn feeds, the overall weight of the feed cabin will not be very large. The numerical results will be shown for the antenna system with ultra wideband Eleven feeds (such as in [2]) operating from 500 MHz to 8 GHz. In practice, it can be realized with a set of two highly optimized Eleven feeds, each operating with the 4:1 bandwidth. The blockage area of the feed cabin will be determined by the lowest frequency and equal to 660 mm x 660 mm. This cabin can be supported by relatively thin struts. In our study, we have modeled four symmetrically located struts of circular cross-section of 80 mm-diameter. The simulations have been carried out by using the canonical PO approach as realized in TICRA's GRASP software. The performance parameters under study include: the antenna blockage efficiency, sidelobes, cross-polarization, ground noise pick-up and sensitivity; that have been analyzed for different strut positions. The position of the strut was defined by the start and end points connecting it to the feed box and reflector. The start point was fixed and the end point was varied. This variation - measured by the distance from the reflector axis $\mathrm{D_o}$ - was used here as the strut position parameter. We have considered $\mathrm{D_o}$ values ranging from 3 to 8 m, where $\mathrm{D_o} = 7.5$ m corresponds to the end point at the rim of the reflector.

III. Results and Conclusions

Figure 1 shows the blockage efficiencies of the reflector antenna as (a) function of the strut location parameter ($\mathrm{D_o}$) for several frequencies between 500 MHz and 8 GHz and (b) function of frequency for $\mathrm{D_o} = 6.5$ m, as an example. These efficiency curves have been calculated from the directivity of the reflector antenna which is illuminated by the feed pattern

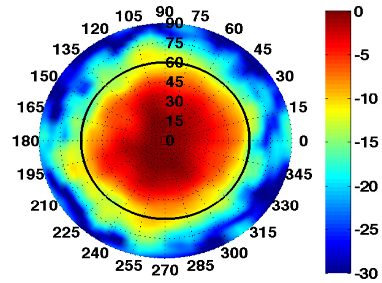


(a)

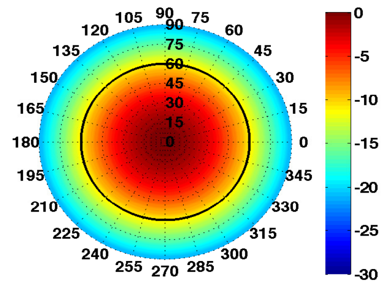


(b)

Fig. 1: The aperture efficiency reduction due to the feed central blockage and four support struts for the Eleven antenna feed (a) at different frequencies versus the strut position parameter $\mathrm{D_o}$; and (b) for $\mathrm{D_o} = 6.5$ m over the frequency band.



(a) Eleven feed

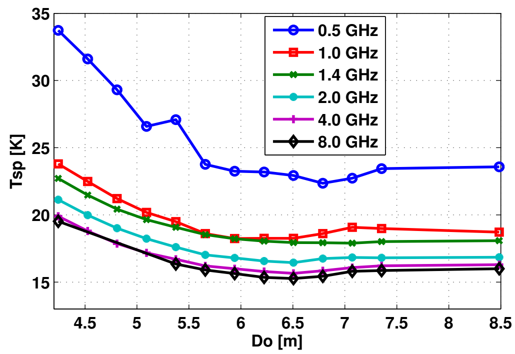


(b) Horn feed

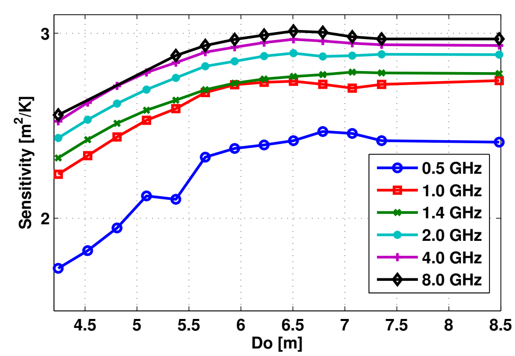
Fig. 2: The normalized far-field patterns plotted in logarithmic scale of (a) the Eleven antenna based on the measurement data (see [2]) at 5.6 GHz; and (b) the horn feed which was designed by using the CST software and procedure in [7]. Note that the aperture efficiencies calculated for the unblocked system are close to 63% and 76% for the Eleven antenna and horn feed, respectively.

as shown on Fig. 2(a) for the Eleven antenna. The feed pattern was left unchanged during the simulations over the frequency band in order to separate the frequency dependent effects associated with the reflector and its blocking structure from the effects attributed to specific feed design. As one can see in Fig. 1(a), the antenna efficiency is severely affected by the blockage provided by the feed and struts when the struts are located in the inner region of the reflector's aperture. The overall blockage efficiency for this case can be as low as 84% at 500 MHz, whereas when struts are positioned closer to the reflector's rim, it approaches $\sim 95\%$ and becomes less dependent on frequency.

Figure 3 presents the spillover noise temperature $\mathrm{T_a}$ (due to the ground thermal noise pick-up) and receiving sensitivity of the Eleven feed that were calculated for the antenna pointing direction at the elevation angle of 45° (a typical case). The sensitivity was computed as the ratio of the antenna effective area $\mathrm{A_{eff}}$ to the system noise temperature $\mathrm{T_{sys}}$, where $\mathrm{T_{sys}} = \mathrm{T_a} + \mathrm{T_{rec}}$. The receiver noise contribution $\mathrm{T_{rec}}$ is assumed to be constant and equal to 20 K. The results demonstrate that the antenna noise contribution is strongly dependent on the position of the struts, and that there exists a minimum of the $\mathrm{T_a(D_o)}$ function. At most frequencies, this happens for $\mathrm{D_o} \sim 6.5$ m which provides the optimum range of scattering angles for the antenna fields (due to the primary and secondary currents on the reflector and struts) that are radiated mainly towards the sky and insignificantly in the directions of the ground. It is important to realize that for electrically large reflector antennas, for which the edge diffraction effects can be assumed negligibly small, this optimal range of scattering angles is determined by the geometry of the reflector and strut's position, but not the frequency. This means that the optimal design of the antenna system with low-noise performance can be realized at a single frequency, and it will hold over a wide range, at least for wideband feeds with relatively constant beam shapes. As can be seen on Fig. 3(c), this design will also lead to the maximum sensitivity, since the aperture efficiency is weakly dependent on parameter $\mathrm{D_o}$ for struts placed close to reflector's rim (see Fig. 1). Figures 3(c) and 3(d) present $\mathrm{T_a}$ and $\mathrm{A_{eff}/T_{sys}}$ calculated over the frequency band for the unblocked and blocked apertures for $\mathrm{D_o} = 6.5$ m, both for the Eleven antenna and horn feed (see the horn's pattern used for the simulations in Fig. 1(b)). Note that this value of Do was optimized for the Eleven feed pattern, so it is sub-optimal for the horn.. These figures show that the system performance is virtually constant, but degrades below 1 GHz as the dish becomes electrically smaller and edge diffraction effects start playing a more important role.. In the optimal operational range from 1 to 8 GHz, the system noise temperature is ~ 5 K higher than that of the ideal system without blockage. The corresponding relative reduction of the sensitivity is $\sim 20\%$ that is the result of the combined effect of the aperture efficiency loss (5%) and larger $\mathrm{T_a}$ (due to the higher side lobes in the directions of the



(a)



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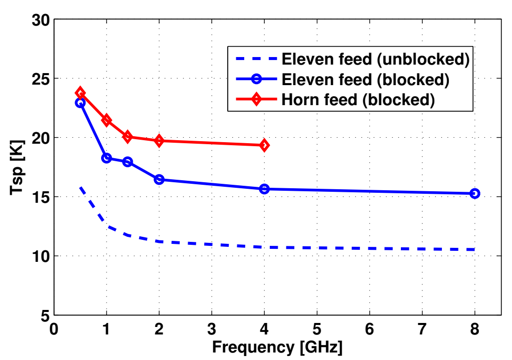
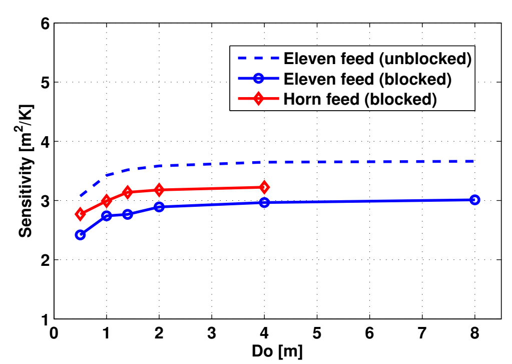


(c)



(d)

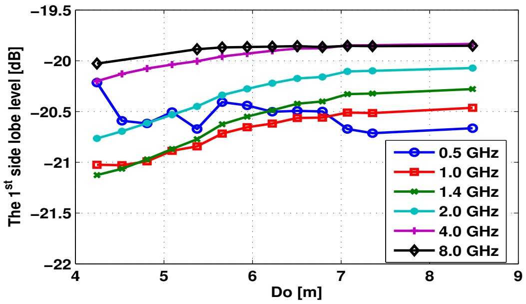
Fig. 3: (a) The antenna noise temperature due to the ground thermal noise ($T_{ground} = 300$ K) and (b) the sensitivity for the elevation angle of 45° for the Eleven antenna feed at different frequencies versus the strut position parameter D_o. (c) The system noise temperature and (d) sensitivity of the Eleven feed for $D_o = 6.5$ m over the frequency band for the unblocked and blocked apertures of the reflector (due to the feed and struts.)

ground.)

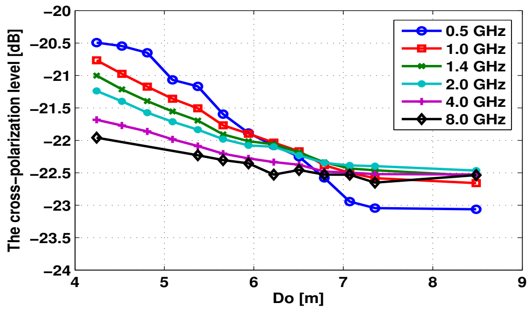
The computed first side-lobe and relative cross-polarization levels of the reflector antenna with the Eleven feed are shown in Fig. 4. We can see that the cross-polarization levels in the region of the half-power co-polarized main lobe can be controlled by repositioning the struts with the best result for the end point of the struts near the reflector's rim. For the optimal parameter $D_o = 6.5$ m, as determined for the maximum sensitivity, these levels appear to be almost invariant over the frequency band and are very close to the cross-polarization levels (-22 to -22.6 dB) of the ideal reflector with no blockage. As for the side lobes near the main lobe, the blockage effects are negligible, but for the far side and back radiation zone these become more visible. To illustrate these effects, Fig. 5 shows the patterns of the antenna with the Eleven feed. We can recognize a very characteristic structure of the side lobes in the form of the four-folded lines due to the support struts, and also see the increased radiation in the backward directions when $90° < \theta < 180°$. The calculated spillover noise temperature was found to be equal to 23 K at 500 MHz and 13 K at 1.4 GHz. For the larger blocking area of the struts (that can be expected for the equivalent set of multiple octave horns needed to cover the same bandwidth), this noise contribution will be larger. Our simulations performed for the octave horn feed and the doubled cross-section of the strut (160 mm) indicate that the temperature T_a will be $\sim$ 20 K in the range of 1–8 GHz and up to 30 K at lower frequencies. Also the blockage efficiency will be lower ($\sim$ 90% for 1–8 GHz), in contrast to 95% for the system with two Eleven feeds and thinner struts. Furthermore, these patterns also illustrate that indeed the performance of the reflector system is not optimal at 500 MHz (compare the side lobes and back radiation with that at 1.4 GHz). An important aspect of the high far side-lobes is that one should account for these when performing the astronomic observations. The problem is to separate the response of the 'unwanted' strong source 'seen' through the high side lobe from the response of the signal of interest that is much weaker. It is therefore important to carry out the end-to-end simulations of the radio telescope's observation performance, so as to quantify both the sensitivity and complexity of the required calibration procedure, as well as to translate these parameters to the scientific (radio astronomy) measures, such as imaging dynamic range and image fidelity.

IV. Conclusion

We have demonstrated that blockage provided by the feed and struts in axi-symmetric reflector antennas can be minimized by optimizing the choice of the feed system and the supporting structure. For the case of the SKA dish design proposed in [6], a compact system with a few 2–3 octave feeds can be used instead of conventional multi-frequency front ends comprising multiple single-octave horns. Our study performed for the wideband 'Eleven antenna' feed as an example, shows that in the optimal operational range of the reflector (from 1 GHz and higher), the relative increase of the spillover noise



(a)



(b)

Fig. 4: (a) The maximum relative side lobe levels and (b) the relative cross-polarization levels at the half-power beamwidth direction (for $\phi = 45°$) of the reflector antenna with the Eleven feed versus strut position parameter D_o. These results show the combined effect of the feed blockage and support struts. The side lobe level of the unblocked system (not shown here) is near -20.2 dB.

temperature and the aperture efficiency loss are ~ 5 Kelvin and $\sim 5\%$, respectively, in comparison with the unblocked aperture antenna.

Acknowledgment

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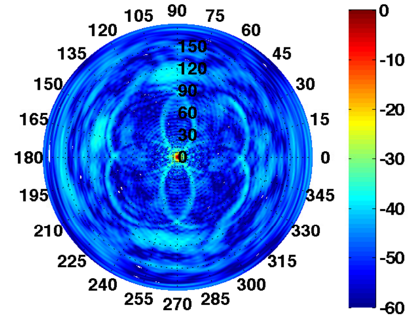
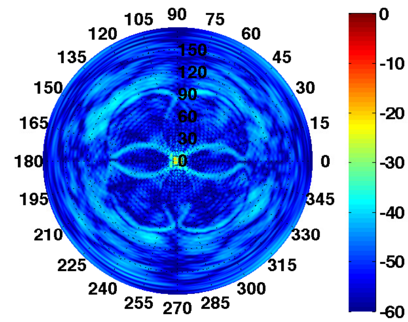
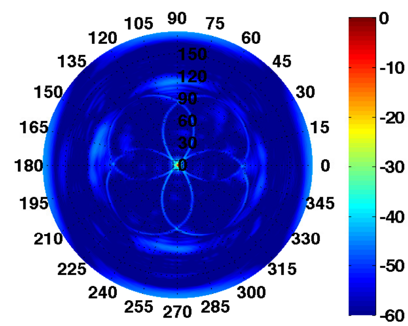


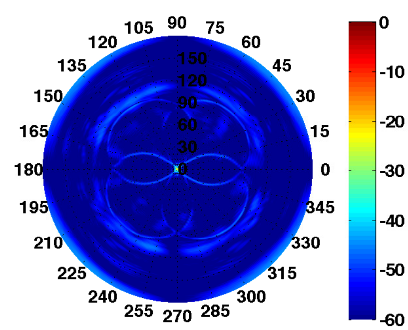
(a) co-polarization component (500 MHz)



(b) cross-polarization component (500 MHz)



(c) co-polarization component (1.4 GHz)



(d) cross-polarization component (1.4 GHz)

Fig. 5: The patterns of the reflector antenna with the Eleven feed and struts with $D_o = 6.5$ m.