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# Reflectarrays in Radio Telescope Design: a Preliminary Analysis

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## Abstract

The antenna technology employed by radio astronomy has changed very slowly during the last few decades and thus an important question is whether novel antenna technologies might bring down the cost of collecting area for new facilities. In this work I discuss a few examples of application to the design of radio telescopes of a relatively new technology: *reflectarrays*. A reflectarray is a flat, planar, compact structure consisting of an array of isolated radiating elements which are predesigned with a particular phase delay to re-radiate and scatter the incident field to form a desired wavefront. Reflectarrays have become widely used for communications and radar applications, but so far there have been no proposals to use them in radio astronomy. Here, I will analyze the potential use of reflectarrays for radio astronomical applications, concentrating in particular on their ability to perform beam-scanning electronically.

## 1. Introduction

A dual-reflector antenna, such as a Cassegrain/Gregorian antenna, is the most common optical configuration used for the design of radio telescopes since it has many advantages over a single reflector antenna. Various works have been published about replacing the surfaces of a dual-reflector antenna with reflectarrays [1,2], which are physically flat but behaves electrically as a curved reflector. The reflectarray is typically illuminated by a feed and consists of an array of isolated re-radiating elements. These unit cells are predesigned with a particular phase delay to re-radiate and scatter the incident field to form the desired wavefront in front of the aperture. Reflectarrays are manufactured by photo-etching and bonding processes which are a well-established technology in multi-layer printed circuit boards. The reduced bandwidth of the printed elements used on the reflectarrays and the differential spatial phase delay limit their total bandwidth. To overcome this problem, different techniques have been applied, which will not be reviewed here.

The main, the subreflector or both reflectors in a dual-reflector configuration can be replaced by reflectarrays, thus providing several important advantages in the antenna performance and especially in the manufacturing process. Various dual-reflector antennas with a reflectarray as the subreflector (or *sub-reflectarray*) have been proposed in the literature [1,3]. In this technique, a reflectarray acts as a flat subreflector and by properly adjusting the phase shifts of the unit cells they can mimic an ellipsoidal- or hyperboloidal-type subreflector for a dual reflector system. If also the main reflector is replaced by a flat reflectarray, a *dual-reflectarray* antenna is obtained [2,4,5]. In general, the two-surface control permits to improve the performance of the antenna and extend the applicability of reflectarrays.

In a previous and more thorough review [6] I have already discussed some properties of reflectarrays that make them potentially attractive for radio astronomical applications, such as ease of construction, low fabrication cost and electronic beam-scanning. In particular, the ability to perform beam-scanning electronically, without the need of a mechanical pointing/tracking system, is particularly attractive for its potential application to radio telescopes. It is thus of interest to analyze which optical configurations are best suited to exploit this technological capability of reflectarrays.

Therefore, I will analyze a few specific design examples and will discuss their advantages as well as their limitations. Please note that I will not simulate the actual reflectarray network. Instead EM simulations of standard antennas will be used to evaluate the phase distributions that would be required by the *ideal* reflectarrays, replacing the standard antenna, in order to reproduce the desired wavefronts. All EM simulations discussed in this work have been carried out with the commercial software GRASP[1], and I have used Physical Optics (PO) as the analysis method to determine the antenna power pattern. The simulations have been performed at a frequency of 8 GHz in order to keep the computation time below ~1 hr. Examples of a single-dish reflectarray antenna are analyzed first in Sect.2, followed by the analysis of a dual-reflectarray antenna in Sect.3 . In both sections I will discuss EM simulations devoted to the analysis of the beam-scanning properties of the antennas.

[1] https://www.ticra.com/software/grasp/

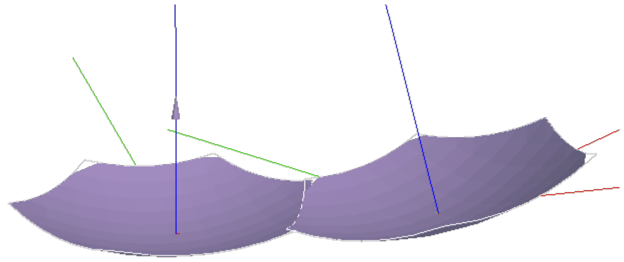

**Figure 1.** Parabolic reflector with $F$=0.4 and an hexagonal rim. Also shown are the Gaussian feed at the focus of the reflector, and a second adjacent hexagonal panel tilted at an angle.

## 2 Single-Dish Reflectarray Antenna

### 2.1 Parabolic Reflector with Focal Ratio < 1

As a first test case I analyze a simple single-dish where the parabolic reflector has been replaced with a flat reflectarray. Two specific cases will be analyzed, with different focal ratios and thus with different limitations. I will start by analyzing a parabolic reflector with a focal ratio $F$ < 1. The rim of the antenna used in these EM simulations is hexagonal (see Fig.1), since it is assumed that this could be just a panel of a larger surface composed of many such hexagonal panels. A Gaussian feed (with a taper of -12 dB at the edges of the reflector) is assumed to illuminate the parabolic reflector, which has a size of 2m[2] and a focal ratio $F$=0.4. A 2m size would require ~5000 unit cells at 8 GHz, easily fabricated with standard microstrip techniques.

Figure 2 shows the amplitude and phase distributions when the feed is moved off-axis to achieve an equivalent angular shift on the sky of 5 beams. Specifically, Fig. 2 shows that each individual element of the equivalent reflectarray would be required to have a ~360 deg phase range. This simple example shows that the surface of a flat reflectarray could create a collimated beam with an angular scanning range of up to 5-10 beams. For wide-angle scanning, however, other techniques must be used, such as a composite, larger curved surface with piecewise smaller flat panels, or also using *curved reflectarrays* (also known as conformal reflectarrays). The latter method, however, will not be discussed here.

As an example of the first approach, in Fig. 1 a second hexagonal antenna is shown adjacent to the central panel. This second antenna is tilted at an angle in order to extend the angular range covered by the central panel. In the actual reflectarray implementation, two flat reflectarrays would replace the parabolic antennas. However, Fig. 1 shows that in order to illuminate (on-axis) the second panel an additional feed would be required, with its own mechanical mount and cryogenics. Alternatively, this second panel could be illuminated by the same feed as the central panel, but a mechanism to move the feed and align it with the second panel would be required.

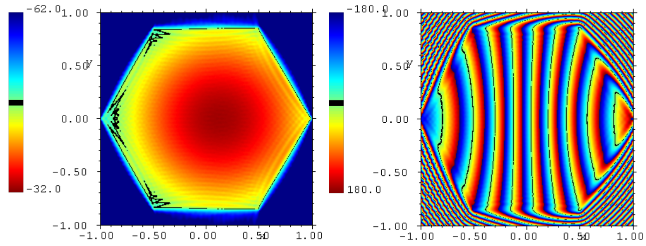


**Figure 2.** Amplitude (dB) and phase (deg) distribution for off-axis (5 beams) illumination of the $F$=0.4 parabolic reflector shown in Fig. 1. In this and the following figures we use the GRASP-defined power normalized currents and fields (axes units are meters).

In order for the system to work with a single feed and reduce to a minimum the mechanical complexity, the second panel could be illuminated using an off-axis configuration (currently under examination). Although this method would require the design of a different parabolic surface, a flat reflectarray would simply require the modification of the phase to be applied to the individual unit cells. Figure 1 shows two panels only, but this concept could easily be extended to further hexagonal panels, each one illuminated under a different optical (i.e., focal ratio) configuration by the same feed.

### 2.2 Parabolic Reflector with Focal Ratio > 1

A somewhat different situation occurs if the generating antenna has a larger focal ratio, > or >> 1. Figure 3 shows the example of two antennas with the shape and size as those discussed in Sect. 2.1 but with an $F$=5 focal ratio. Figure 4 shows the amplitude and phase distributions on the aperture plane of the central panel when the feed is moved off-axis to achieve an equivalent angular shift on the sky of 2 beams. The required phase range for the individual elements of an equivalent reflectarray is comparable to that estimated for the $F$=0.4 reflector.

The main advantage of this optical configuration is that an off-axis optical configuration is not required to illuminate the second panel with the same (mechanically rotated) feed, thus easily extending the beam-scanning range with minimal mechanical complexity. However, in this case the feed and its hardware would require a larger and stiffer mechanical support.

## 3 Dual-Reflectarray Antenna

The next configuration analyzed in this work is a dual-reflectarray antenna, where both main reflector and subreflector are replaced with reflectarrays. An example of a baseline dual-reflector antenna with a Cassegrain optical configuration and final focal ratio $F_{cass}$=5 is shown in Fig. 5. The corresponding amplitude and phase distributions for the main and secondary reflectors, in the case of an off-axis illumination of just 0.5 beams, are shown in Fig. 6. For consistency with the previous sections we use the same hexagonal rim.

[2] As measured along the diagonal passing through the geometrical center of the hexagon.

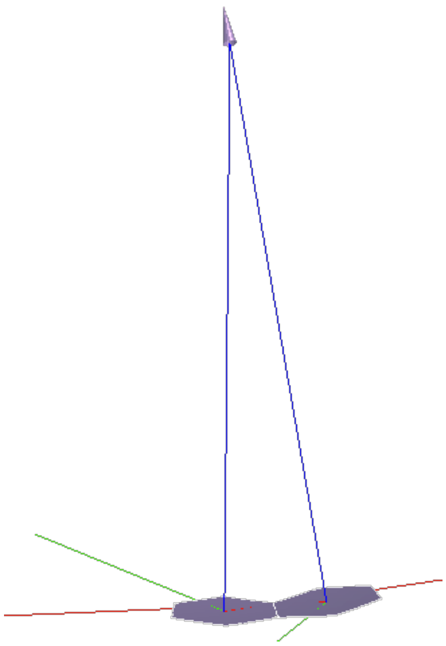

**Figure 3.** Parabolic reflector with *F*=5 with the same hexagonal rim as in Fig. 1. Also shown is the Gaussian feed at the focus of the reflector, and a second adjacent hexagonal panel tilted at an angle. The feed is oriented to illuminate the second, tilted panel.

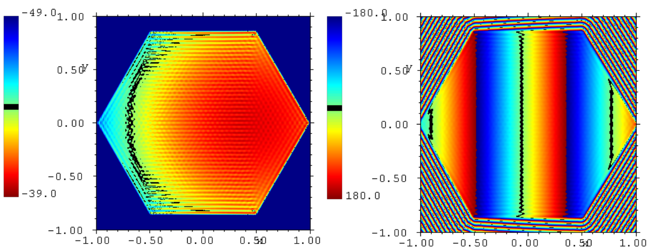

**Figure 4.** Amplitude and phase distribution on the aperture plane for off-axis (2 beams) illumination of the *F*=5 parabolic reflector shown in Fig. 3 (units as in Fig.2).

This specific test had to be limited in terms of beam-scanning range since the small electric diameter (D/λ~50) of the antenna used in this work leads to a significantly under-illuminated subreflector, even for small angular offsets. Therefore, more extensive EM simulations need to be performed in order to estimate the optimal D/λ and focal ratios. Despite this limitation, this test provides a useful information since Fig. 6 shows that the angular range required by the ideal reflectarrays is larger on the subreflector than on the main reflector. In terms of design and fabrication, this is a significant advantage compared to the single-dish configurations analyzed earlier since the sub-reflectarray would be composed by a much smaller number of individual phase-changing elements, requiring a greater phase range for beam-scanning operations.

Unfortunately, contrary to the single-reflector case, for the dual-reflector/reflectarray configuration it is not easy to extend the beam-scanning range, even in the case of larger D/λ, without a mechanical tracking/pointing system. However, even in this case the dual-reflectarray would still retain all the advantages of using flat surfaces with much limited weight and volume. Because this limitation

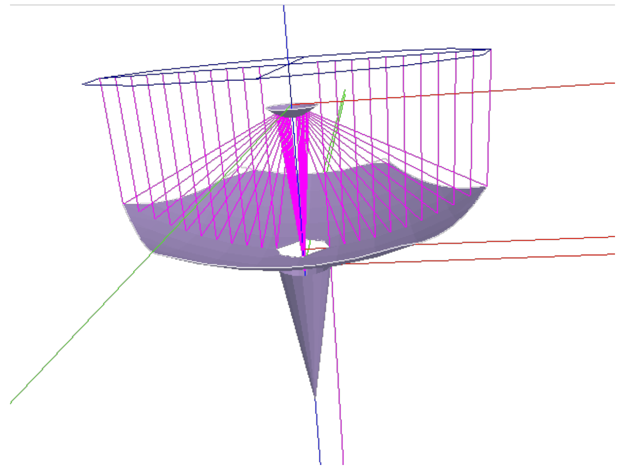

**Figure 5.** Dual-reflector antenna with *F*=5 at the Cassegrain focus, still using the same hexagonal rim as inFig. 1. Also shown is the Gaussian feed at the Cassegrain focus.

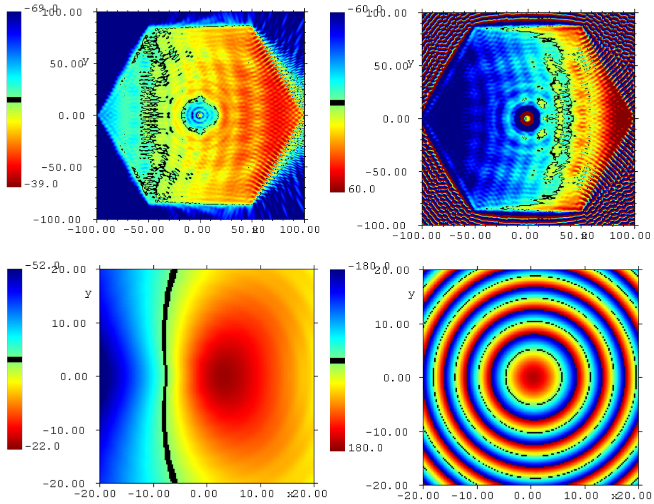

**Figure 6.** Amplitude and phase distribution for off-axis (0.5 beams) illumination of the main reflector (top panels) and subreflector (bottom panels) shown in Fig. 5 (units as in Fig.2).

would cancel one of the main advantages of using reflectarrays, an alternative option is discussed in the next section.

## 4 Spherical Reflector with Sub-Reflectarray

Spherical reflector antennas are easy to fabricate and are capable of achieving wide-angle beam scanning while maintaining the integrity of the radiation pattern. The inherent spherical aberration, however, causes great performance degradation and different methods to compensate for this aberration have been developed. A novel method to overcome the performance degradation induced by the spherical aberration consists of using a microstrip reflectarray as a subreflector, illuminated by a primary feed. By properly adjusting the additional phase shift provided by the sub-reflectarray, the aperture phase errors caused by the spherical aberration of the main reflector surface can be compensated [7]. Thus, the antenna system effectively behaves like a classical dual reflector system with the single primary feed relocated at the image of the focal point with respect to the reflectarray plane.

In a recent work Olmi & Nesti [8] have further analyzed the sub-reflectarray method previously described in the literature for the case of large, Arecibo-like spherical reflectors. They have shown that compensation of the spherical aberration can be achieved without rotating the feed system in a limited scanning range. However, they have also shown that in order to achieve an angular scanning range for astronomical applications, other solutions are required. One option consists of using a mechanical tracking system which can rotate the single primary feed and the compensating sub-reflectarray about the center of curvature of the spherical reflector (and also in azimuth, see below). An alternative solution, which does *not* require a mechanical tracking system, would use an assembly of small sub-reflectarrays arranged in a piecewise-planar configuration and a multi-feed system, as shown schematically in Fig. 7. In order to maintain the number of feeds to a minimum, the only mechanical movement required would be an azimuthal rotation of the whole sub-reflectarrays/feeds system, so that the desired target on the sky can be pointed and tracked. In this case, the feeds need to be located only on one side of the rotating turret, as shown in Fig. 7.

Clearly, this method can be applied also to smaller antennas, and a careful engineering study would be required to determine which option (single- or multi-feed) would represent the optimum trade-off given the reflector diameter, required angular scanning range, frequency range, the technology adopted for the design and construction of the sub-reflectarrays and of course the projected final cost. Both solutions, however, can benefit from the low-profile, low-mass and low-cost features of the reflectarray technology.

## 4 Conclusions

I have analyzed various optical configurations incorporating the reflectarray technology, which would allow to design and fabricate a radio telescope with minimum mechanical complexity and at a much lower cost compared to the current construction paradigm. Both single- and dual-reflectarray configurations have been analyzed. Although a dual-reflectarray telescope would be able to point and track a target within a small angular field, a large scanning range for astronomical applications would still require the mechanical movement of the antenna.

A single-reflector telescope, with a large focal ratio (>1 or >>1) and composed by many individual reflectarrays arranged in a piecewise configuration, would indeed be able to extend the angular scanning range with minimum mechanical movement of the feed support system. The most promising solution, which could provide the largest angular range with minimum mechanical complexity, is a spherical primary reflector with either a single moving sub-reflectarray/feed support, or a system composed by

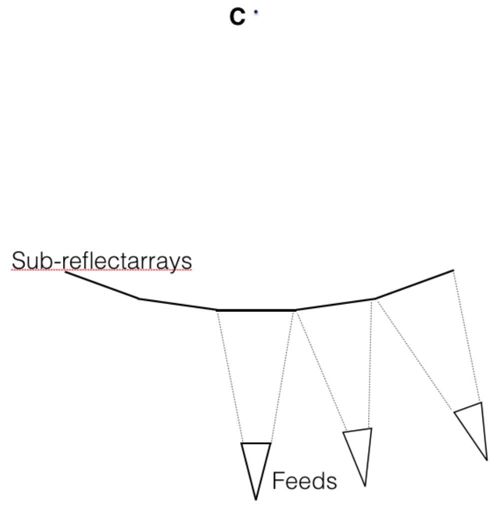


**Figure 7.** Proposed method to extend the scanning range of a spherical reflector by using an assembly of small sub-reflectarrays arranged in a piecewise-planar configuration and a multi-feed system. The point ”C” represents the center of curvature of the main spherical reflector.

multiple sub-reflectarrays/feeds which would only require an azimuthal movement.

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