A catadioptric antenna for the SKA

Mark A. Walker

Australia Telescope National Facility,
CSIRO, PO Box 76, Epping, NSW 1710, Australia

and

Research Centre for Theoretical Astrophysics,
School of Physics, University of Sydney, NSW 2006, Australia

Overview

If it is decided that *widely-spaced* multiple beams are required for the SKA (see the discussion in Bell and Ekers 2000), then the range of viable antenna designs is greatly restricted. Possible approaches include phased-array technologies (van Ardenne 1998), spherical reflectors (e.g. Braun 1996), and spherical refractors (e.g. Luneburg Lenses; James et al 2000). It is also possible to combine a lens with a mirror, yielding a catadioptric design, as outlined here; more details are given in Walker 2000. The main attraction of this design is that it offers fully-optical beam forming over a very wide field, but with much lower loss and mass (hence, also, material costs) than the Luneburg Lens. The main disadvantage is that the feeds necessarily introduce some blockage, and this constrains the feed design options.

Optical design

An antenna based on a hemispherical reflector offers a limited gain unless its spherical aberration is corrected. Correction can be achieved by making use of a phased array as the feed, or by optical manipulation of the ray paths. It turns out that a hemispherical mirror can be exactly corrected by a spherical lens, providing that the latter has a refractive index which varies appropriately with radius. Only a weak lens is required because the desired corrections amount to only a few degrees — most of the focussing is provided by the mirror. The loss, mass and materials costs of the lens are thus significantly lower than for a Luneburg Lens (by a factor of ten, for the particular design shown below). Impedance matching of the lens to free-space is straightforward to achieve, giving a high throughput, but not all of the mirror aperture can be corrected. The cross-sectional area of the lens defines the useful collecting area of the optics.

Figure 1 (below) shows the ray paths through one particular catadioptric system; this design has a focal surface of radius 1.09 times the radius of the lens. The mirror is shown as a thick solid line, the focal surface as a dashed line, and the surface of the corrector lens as a dotted line. The extremal rays (not shown) subtend an angle of 134° as seen at the feed.

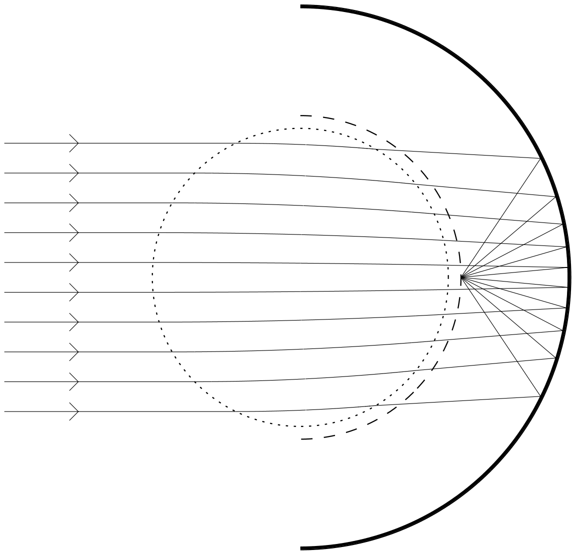


Figure 2 (below) displays the angular response of the antenna shown in figure 1, in the form of a polar diagram. The unvignetted field-of-view is 113° in diameter (i.e. 56° zenith distance), and the antenna has 71% efficiency at 20° elevation.

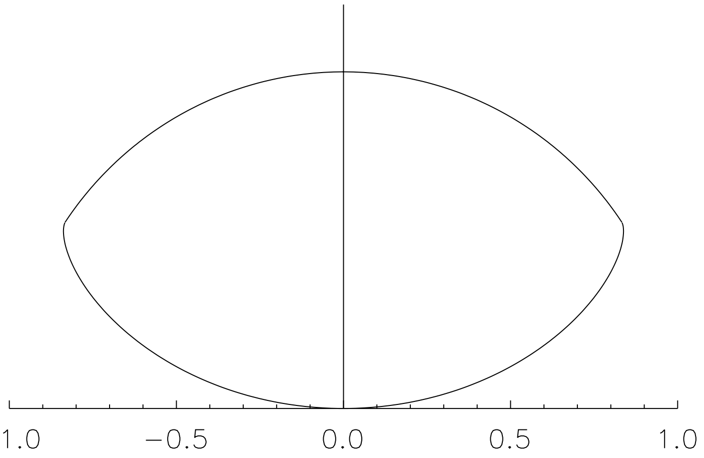
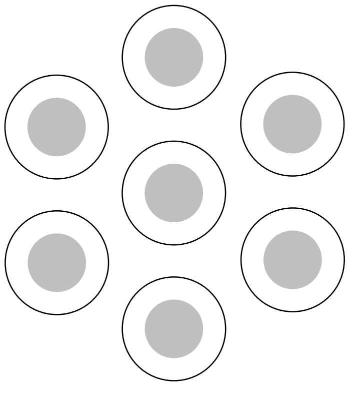


Figure 3 (below) shows an array of catadioptric antennas, seen from above, set at the minimum spacing consistent with no shadowing down to elevations of 20°. For this array the collecting area is 16% of the ground area. The antenna design is as per figure 1.



Feed design

An obvious constraint on the feed design is that it must be close to two-dimensional, because the focal surface has a radius only slightly larger than the radius of the lens (see figure 1). Thus, if one desires a broad-band feed, the sinuous design would be preferred over a log-periodic structure.

The second key constraint on feed design is that the feeds must, in total, not block a large fraction of the aperture of the antenna. This is a strong constraint on approaches which seek to tile a large fraction of the focal surface with an array of feeds, thus providing latent beams over most of the sky. An interesting possibility (brought to my attention by Jon Bell) would be to utilise an array of plasma antennas as feeds (Borg et al 2000); by activating only the beams which are required at a given moment, most of the aperture remains unblocked because inactive feeds are transparent.

The most conservative feed option would be to use printed circuit boards as the feed elements, and to deploy these feeds mechanically to the desired location of the beam. This solution has the obvious disadvantage of mechanical complexity, with its attendant cost and reliability issues.

Structural and mechanical issues

Antennas which have a field-of-view of several steradians do not need to be moved – "pointing" can be achieved entirely within the feed system – thus eliminating the cost and reliability issues associated with antenna drive systems, and lowering the operational power requirements.

The fact that the antenna maintains a fixed orientation with respect to the vertical eases the requirements on structural rigidity, because the gravitational deformations are fixed. It may therefore be acceptable to utilise a "soft" structure, i.e. one which deforms significantly under gravity, but which deforms into the desired shape. Wind loading, by contrast, will be highly variable and would place much stricter constraints on the mirror stiffness if the antenna were unshielded. This argues for the incorporation of a lightweight wind-shield – e.g. a "tent" – into each antenna structure so as to minimise the requisite mirror stiffness. Such a device would also serve to moderate the radiative component of the thermal load on the optics.

The lens, being a three-dimensional structure, ought to provide no particular problems in respect of its rigidity. By the same token, however, it is likely to dominate the mass of the antenna, and will thus determine the strength of the support structure. Some settling (creep) of the lens structure over time is likely; to minimise this it is necessary to minimise the internal stresses, and the lens should therefore be supported close to its centre.

Costs

To date the antenna design has not been carried through in sufficient detail to admit meaningful cost estimates. Relative to a Luneburg Lens, the corrector lens shown in figure 1 attracts one tenth of the material costs, while other costs associated with lens manufacture will be similar. The lower mass of the lens also admits a cheaper antenna support structure. The catadioptric design incurs an extra cost, relative to the Luneburg Lens, associated with the mirror. However, the spherical figure of the mirror lends itself to assembly from a large number of identical, mass-produced segments, admitting a variety of low-cost manufacturing techniques to be contemplated.

Summary of likely system performance

If we consider the particular optical design shown in figure 1, with a 5 m diameter lens manufactured from tiny quartz spheres embedded in a lightweight, transparent matrix, the following properties would apply:

▷ Frequency coverage: ~300 MHz to 20+ GHz

▷ Field-of-view: elevation $>$ 34° (2.8 sr) at 100% efficiency
elevation $>$ 20° (4.1 sr) at more than 70% efficiency

▷ Ground utilisation: 16% (for an array with a 20° elevation limit)

▷ Lens mass: 5 Tonne

▷ Receiver load: $\Delta T \lesssim 0.2\,\nu$ Kelvin at frequency ν (GHz).

This example is not necesarily optimum in respect of the composition of the artificial dielectric; nevertheless these figures suggest that a catadioptric system may be a good basis for an SKA antenna design.

References

Bell J. and Ekers R. 2000 "Multiple widely-spaced beams for the SKA?"
(http://www.atnf.csiro.au/SKA/techdocs)

Borg G.G. et al 2000 "Plasmas as antennas: theory, experiment and applications"
Physics of plasmas 7(5), 2198
(http://wwwrsphysse.anu.edu.au/~ggb112/index.html)

Braun R. 1996 "Small hemi-spherical reflectors for SKA?"
NFRA note 642,
(http://www.atnf.csiro.au/SKA/archive)

James G., Parfitt A., Kot J. and Hall P. 2000
"A case for the Luneburg Lens as the antenna element for the SKA"
Radio Science 293, 32
(http://www.atnf.csiro.au/SKA/techdocs)

van Ardenne, A. 1998 "The SKA technical R&D program at NFRA"
NFRA Newsletter #15
(http://www.nfra.nl/nfra/newsletter/1998-2/ardenne.htm)

Walker M. 2000 "A catadioptric camera with a wide field of view"
J.Opt.Soc.Am.(A) (submitted)
(http://www.atnf.csiro.au/SKA/techdocs)