PROGRESS TOWARDS A LÜNEBURG LENS SOLUTION FOR A LARGE, WIDEBAND, MULTI-BEAM ARRAY RADIO TELESCOPE

Graeme James, **John Kot, Andrew Parfitt, Nasiha Nikolic**

CSIRO, Telecommunications & Industrial Physics,
PO Box 76, Epping NSW1710, Australia
Email: first name.last name@csiro.au

ABSTRACT

The Lüneburg lens has been identified as a candidate antenna element for the Square Kilometre Array (SKA) radio telescope. As the important attributes of such a lens approach have been articulated elsewhere, we present in this paper an update on the work in progress to determine whether or not such a solution to the SKA is economically and technologically feasible. Given that there are many issues associated with the array itself that are common to any solution to such a large problem, we concentrate on three areas of particular concern to the Lüneburg lens solution.

INTRODUCTION

The SKA radio telescope [1] is planned for construction around 2012. With an effective collecting area likely to be around one square kilometre, this enormous array to study the early universe at centimetre wavelengths will complement next generation telescopes operating at other wavelengths. From the outset there has always been the desire for the SKA to provide a distinctive capability (aside from increased sensitivity) not currently available on any other radio telescopes. To this end, one possibility is that of having a multi-beam instrument with several independent beams anywhere on the sky at any one time has scientific applications as well as opening-up new ways of how one observes the radio sky. This multi-beaming capability was the major consideration behind the NFRA proposal for a phased array as the SKA antenna element [2]. While there have been several alternative schemes subsequently put forward for the antenna element, the only other option to-date providing truly independent widely-separated multiple beam capability is the Lüneburg lens proposal outlined in [3], [4] and illustrated in Fig. 1 below. All the other proposals have, in principle, limited multi-beaming capability, ranging from the cylindrical reflector 'doublet' [5] where multi-beaming is possible within a fan beam, down to multi-beaming within the main beam of a conventional reflector antenna [6]-[8].

From the outset cost has been a major parameter driving the design. To build the SKA at an affordable price within the next 10-15 years, heavy reliance is being placed on Moore's law, the economies of scale and some clever engineering. Another major consideration is upgradeability. In building such an expensive multi-national telescope, the ability to readily upgrade and extend the instrument's capability over its lifetime is an obvious attractive feature in any design. In this regard, the Lüneburg lens approach has a distinct advantage over all other proposals.

We consider now three areas of particular concern to the Lüneburg lens solution.

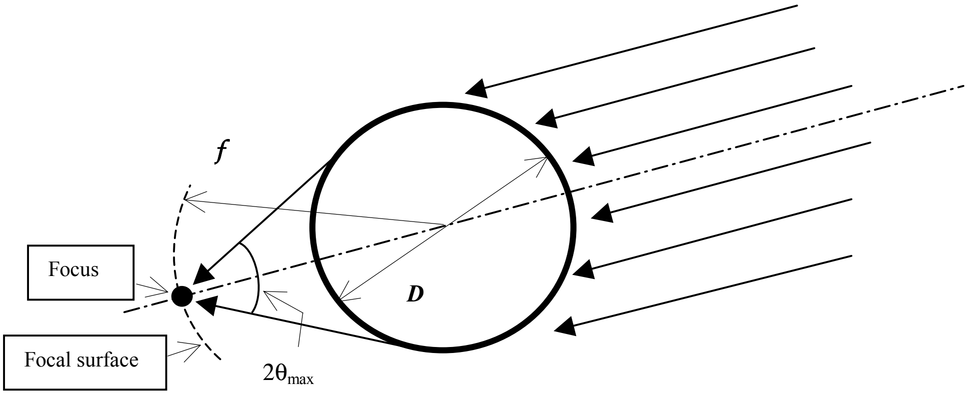

Figure 1: Lüneburg lens focussing an incoming plane wave

LENS MATERIAL

A Lüneburg lens requires dielectric material ranging in relative permittivity from a maximum in the centre, depending on the value of *f/D* as shown in Fig. 2, to a value of 1 on the outer surface. Since the lens is volumetric in nature, a low loss material is required to minimize the receiver loading.

To construct the lenses for the SKA out of conventional dielectric materials is not a viable proposition given weight, loss and cost considerations. From the outset, the CSIRO SKA proposal utilising the Lüneburg lens has been contingent on the successful development of artificial dielectrics where weight, loss and cost are reduced to a significant degree compared to presently available materials. Currently within CSIRO we are attempting to develop suitable artificial dielectric materials for constructing the Lüneburg lens. While details cannot be given here as there are patents pending on some of the processes involved, in outline, low density (20 kg/m^3) low loss (loss tangent < 0.0001) foam is being doped with graded small amounts of high dielectric low loss ceramics such as rutile (4,250 kg/m^3; $\varepsilon_r \approx 100$; loss tangent < 0.001) to produce artificial low loss (loss tangent ~ 0.0001) low permittivity ($\varepsilon_r < 2$) dielectrics.

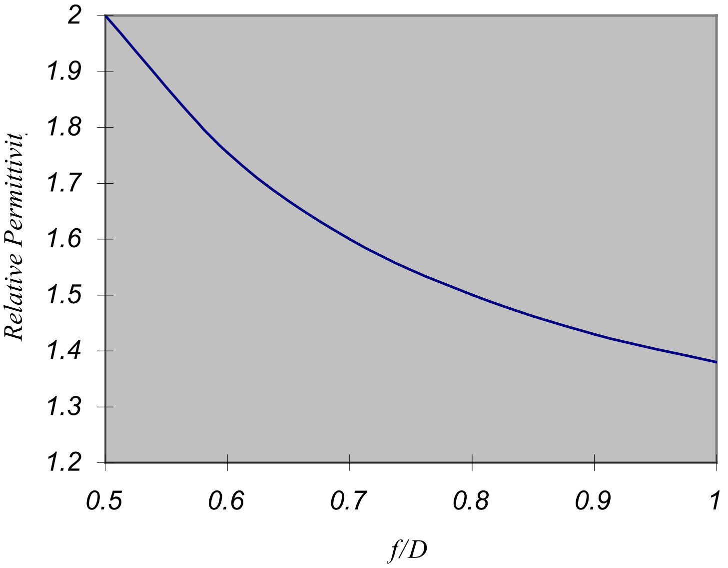

Figure 2: Maximum Permittivity as a function of f/D

LENS CONSTRUCTION AND ARCHITECTURE

Assuming an artificial dielectric can be constructed from the materials above, we can make some estimate as to the loss, weight and the cost of constructing the lenses. The choice of parameters for the lens is basically very simple; *f/D* and *D*. It became clear from a parametric study (and for more details see [4]) that the limits on lens diameter, *D*, were such that for *D* < 5m the number of lenses required by the SKA, and hence the cost of feeds, became excessive. Furthermore, operating down to ~ 0.3 GHz is not effective when the lenses become too small. For larger lenses, where *D* > 7m, the quantity and weight of the materials required to construct the lenses became a problem. Also, the larger lenses limit the upper frequency of operation given the small but finite loss through the lens. Weight and cost were also related to the *f/D* ratio. As seen from Fig. 2, small values of *f/D* require a larger range of permittivity which leads to greater cost and weight. In addition, the choice of *f/D* is a crucial parameter in the feed design (discussed below). To summarise, an *f/D* in the range 0.7-0.8 together with a *D* in the range 5-7m were found to be optimum [4].

An alternative to the full spherical Lüneburg lens is the hemispherical 'virtual source' Lüneburg lens. Here the half lens is placed on a perfectly conducting ground plane and the resultant mirror image provides a complete lens for operation in the upper half-space. The advantages of this arrangement are that only half the material is required and that it is fully supported by the ground plane. Furthermore, there are mechanical advantages in implementing feed movement with this configuration. The disadvantages are that an adequate ground plane must be provided (not a trivial task and shown to cost considerably more than the savings in the cost of material to make the lens) and the feeds will in many instances provide blockage in the signal path. It is for these reasons that the full spherical Lüneburg lens is preferred if possible to the 'virtual source' configuration.

A peculiar advantage of the Lüneburg lens solution is that, with a little thought, it can involve a minimal amount of earth works with subsequently significant cost savings especially having in mind the likelihood of the antennas being located in remote sites. As the lenses are static they need only be supported sufficiently high above the ground to allow for feed movement. A possible low-cost scheme is discussed in [4] and will be outlined in the talk.

FEED SYSTEMS

The variation of maximum feed illumination angle with *f/D* is shown in Fig. 3. With preferred values of *f/D* in the range 0.7-0.8 the maximum permittivity in the centre of the lens is only 1.5 to 1.6, and with θ_{max} ~ 42º (Fig. 3), we find that this is an excellent fit to an available wide-band feed.

To a first approximation, if we set the half power beamwidth (HPBW) equal to θ_{max}, the feed radiation pattern level at θ_{max} will be in the vicinity of 12-15 dB below the on-axis value and this gives close to optimum figure-of-merit performance. Given the two engineering drivers of low cost and wide bandwidth, frequency independent antennas [9] are an ideal place to start for the feed design. From a survey of possible suitable feed designs, having in mind the need for HPBW ~ 42º, the zigzag antenna described in [9] seemed to be an optimum choice. This antenna is pyramidal in shape with the same zigzag configuration on all four sides. It provides dual linear polarisation, is very simple in construction, compact in size for its beamwidth and essentially self-scaling in frequency with a HPBW which is highly symmetrical, particularly as the HPBW becomes narrower. Our requirement of ~ 42º HPBW is ideally suited to this design.* The main disadvantage, which applies to all end-fire antenna types, is that the phase centre moves along the antenna with frequency. Thus we will need to provide radial movement of the feed to retain optimum performance.

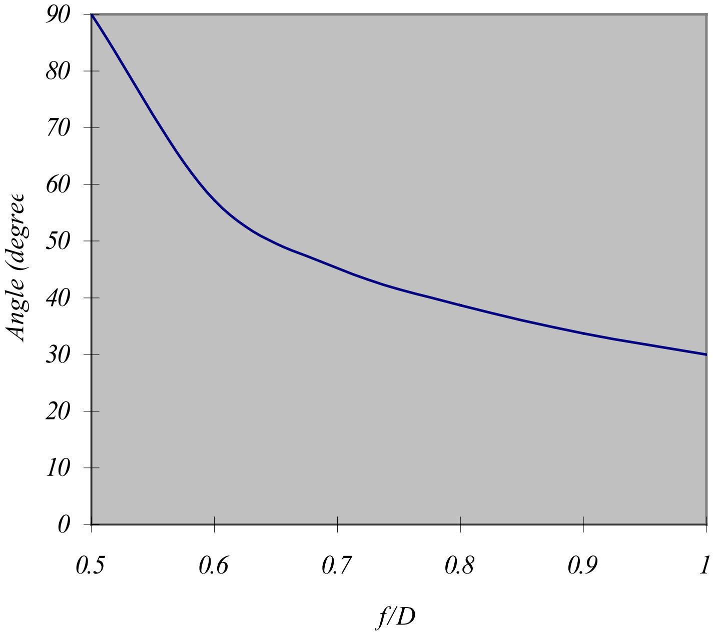

Figure 3: Maximum Feed Illumination Half-Angle

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[*] It is interesting to note that this particular zigzag design appears to be the basis of the feed for the Allen Telescope [7].

A POSSIBLE DESIGN

As discussed above, the Lüneburg lens solution to the SKA antenna element will involve small diameter lenses in the range 5-7m in diameter with the lower limit set, in part, by the need to operate down to ~ 0.3 GHz. Figure 4 shows an outline of a possible configuration where two zigzag feeds are used in this design to cover the 0.3 – 5 GHz bandwidth. Further investigation is continuing into possible antenna configurations, including such studies as an accurate finite-element analysis of the lens to determine its structural deformation under gravity. Above all, it is the development of light-weight, low-loss and low-cost artificial dielectrics that remain the key to the successful implementation of the Lüneburg lens as the antenna element for the SKA.

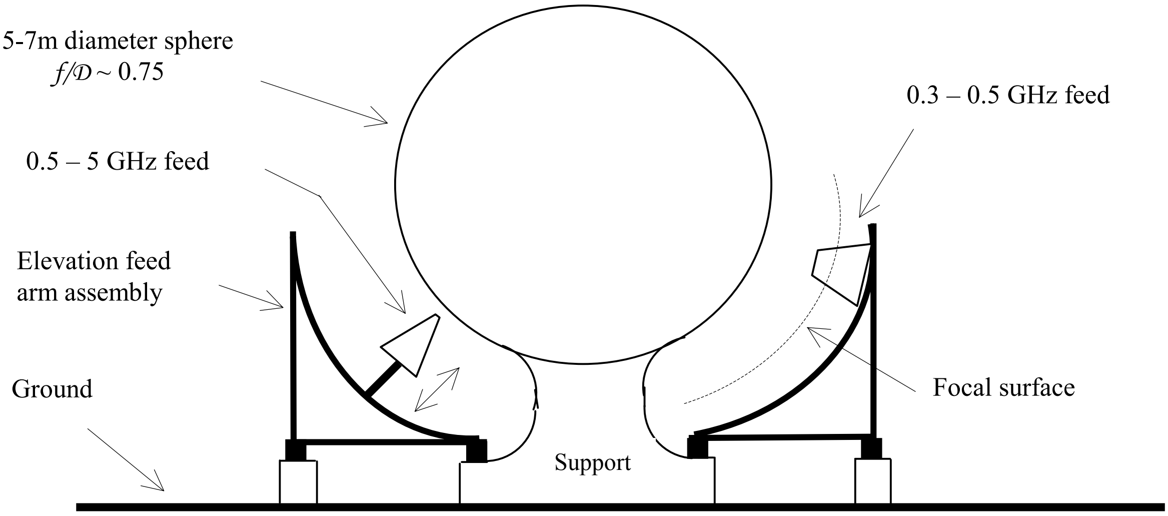

Figure 4: Outline of a possible Lüneburg lens configuration

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