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A Case for the Luneburg Lens as the Antenna Element for the Square Kilometre Array Radio Telescope

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Abstract. *For the proposed square kilometre array (SKA) radio telescope, the Luneburg lens is one of the few configurations for the antenna element that offers the multiple advantages of optical beam forming, inherent wide bandwidth, and very wide field of view. The Luneburg lens is capable of placing simultaneous beams across a large portion of the visible sky for multiple observations or interference mitigation reasons. Furthermore, it provides an almost ideal solution to many of the other technical demands placed on the antenna element for a large array radio telescope such as the SKA. In the past, the most significant challenge associated with the use of Luneburg lenses has been that of construction. This is especially the case here for the so called mid-band SKA, intended for operation over a wide frequency range at centimetre wavelengths, where several thousand large lenses would be implemented over a large geographical area. In this paper the primary challenges of the mid-band SKA are identified and considered. To meet these challenges, two options for the SKA antenna element, designed around the Luneburg lens, are proposed as possible solutions to the specifications.*

1. Introduction

The square kilometre array (SKA) is a new radio telescope proposed for the next century with, as the name implies, an effective collecting area of a square kilometre [1]. Planned for construction around 2010, the main scientific justification for this enormous array is to study the early universe at centimetre wavelengths and to complement next generation telescopes operating at other wavelengths. To date, the major contenders for the SKA antenna element have been based on either phased array or reflector antenna technology. Both have their advantages and limitations with no one obvious solution emerging. As an alternative solution to meet the ambitious specifications for the SKA, we propose here two alternatives based around the Luneburg lens [2]. As we shall show, the Luneburg lens is in many ways an ideal solution to meet the demands of the SKA, with the primary difficulties in realising the lens being in the areas of fabrication and material characteristics. These problems are highlighted and possible ways of overcoming them are shown to exist or can be developed.

2. The SKA Specifications

While the final and detailed specifications for the SKA are still under discussion and development, the main features of this array with an overall collecting area of a square kilometre are as follows.

A wide frequency range. While there is interest in frequency coverage from 0.03-22 GHz, it is recognised that a single instrument is unlikely to cover this range effectively. Three instruments are a possibility with a mid-band SKA covering centimetre wavelengths over at least a frequency range of 0.2 GHz to 2 GHz.

Sky coverage. Ideally full sky coverage is required, and an effective design must be able to access most of the visible sky.

Instantaneous beams. A major and determining feature of the SKA is the requirement for multiple instantaneous beams on the sky. Although up to 100 beams have been specified, it is likely that a steerable cluster of beams for imaging, together with a few independently steerable beams for interference mitigation and other science purposes, will suffice for most observations.

Dual polarisation. Detailed imaging requires the use of either dual linear or dual circular polarisation for a complete characterisation of the field of view.

Clean beam dynamic range. An imaging clean beam dynamic range $> 10^6$ is required, especially at the lower frequencies, and this demands that the antenna element radiation pattern be characterised accurately.

Beam forming. A hierarchical beamforming arrangement is envisaged. A number of *antenna elements* are grouped together and the signals combined to form an *array station.* The signals from these array stations will then be correlated to produce an image within the primary beam or combined directly to form one or many pencil beams within the primary beam. The number and layout of the array stations are yet to be fully determined, but the initial considerations suggest at least 100 array stations spread over a distance of up to 1000 km, in a manner consistent with the desired *uv*-plane coverage, will be required.

3. The Luneburg Lens

The Luneburg lens is a spherical lens characterised by an inhomogeneous but spherically symmetric refractive index η given by

$$h = \sqrt{2 - r^2}$$

where r is the normalised radial coordinate of the unit sphere. The basic action of the lens is illustrated in Figure 1. Energy from a plane wave incident on the lens is focussed to a point on the opposite side of the sphere. Given the spherical symmetry of the lens, perfect focussing is obtained from all feed positions on the surface. Multiple beams may be produced by increasing the number of feeds, or the beam may be scanned by simply moving the feed.

By varying the refractive index profile, the focus can be moved to any point inside or outside the lens, the latter being important for practical feeds. Another important variation is the ‘virtual source’ Luneburg lens [3] shown in Figure 2 where the lens is placed on a ground plane passing through its equator. In this case the ground plane also acts to support the lens.

The Luneburg lens has the dual advantages of optical beam forming and a very wide field of view. This gives a number of attractive features for use as the antenna element for the SKA:

1. for each lens there is a single beam per feed;
2. by symmetry, the beam shape is invariant with scan angle, and, by implication, no gain loss on scan;
3. because of the continuous aperture, frequency dependent scan blindness (a phenomenon common in phased arrays) does not occur;
4. the optical beam forming is inherently wide band, giving true time-delay beam forming throughout;
5. multiple beams and beam steering are simply achieved as outlined above.

The primary potential disadvantage of the Luneburg lens from an electromagnetic point of view is the loss through the lens. However, given the availability of materials with very low loss tangents and the likely maximum limit on the size of each lens in the array imposed by mechanical and structural constraints, this issue is not anticipated to be a serious one.

More serious objections to the Luneburg lens relate to total mass of material required for its manufacture and the implications for cost and weight. In the past, Luneburg lenses have been built with graded refractive index and with stepped approximations, from both rectangular “building-blocks” and concentric spherical shells of uniform material. The spherical shell design seems the most attractive for accurate control of the lens, and some designs of this type have been built with as few as three layers and others with many more. Thus, in principle, manufacture appears to be feasible. However, for the SKA to operate at the lower frequencies, a lens of at least 5m in diameter is likely. Even with the lightest of materials, the mass will be considerable. However, lenses of this size and larger have been considered and built in the past [4]. If the lens were to be much larger than 8 metres in diameter, then the self supporting ‘virtual source’ Luneburg lens configuration of Figure 2 would appear to be the most practical solution. This, together with issues associated with provision of multiple beams, is described later.

4. Contenders, Challenges and Comparisons

Given the specifications in Section 2, several technologies have been proposed for the SKA antenna element. Reflector antennas in the form of spherical reflectors with scanning feeds compatible with geographical features [5], a large adaptive reflector with an aerostat mounted feed [6], a cylindrical doublet [7], and planar phased arrays [8] are among those that have received attention from various groups. Of these, the extremes are represented by the traditional reflector technology and modern phased array technology and, therefore, used as a basis of comparison with the Luneburg lens. Their key features are now summarised.

4.1. Reflector Technology

Reflector technology has traditionally been used for radio telescopes due to the availability of constant collecting area over a wide bandwidth. For the SKA, however, the very large collecting area requires either a moderate number of large reflectors or a very large number of small reflectors; the latter suitable only for the higher frequencies of interest. Moreover, the emphasis on simultaneous multi-beaming capability across the visible sky effectively precludes conventional reflectors. Doublet configurations with scanning line feeds [7] go some way to providing coverage of a proportion of the sky, but do not fully satisfy the requirements. Finally, complex mechanical steering arrangements may be necessary to move heavy antenna structures, requiring considerable infrastructure at each array element site.

4.2. Phased Array Technology

Modern electronic components at centimetre wavelengths are increasing in performance and decreasing in cost, leading to proposals for the use of a phased array as the SKA antenna element. The advantages cited by proponents of the phased array technology are multi-beaming and flexible beam forming opportunities. Phased arrays, however, require complex interconnections and architecture, especially for the many thousands of antennas required for each array station. There remains the inherent gain loss on scan and significant bandwidth and scanning limitations with closely packed arrays.

4.3. The Luneburg lens and basis of comparisons

In order to compare the Luneburg lens with reflector and phased array technology it is necessary to have a well reasoned basis for making such comparisons. The following four factors are identified as forming this basis.

1. **Compatibility with scientific objectives**. The SKA will have agreed scientific objectives which must be accounted for in the design of the radio telescope hardware. Moreover, the next generation of radio telescopes must exhibit the capability to mitigate the effect of interference in an increasingly populated spectrum in order to achieve their scientific objectives. It must be shown, therefore, that a given technology has a reasonable probability of meeting the scientific objectives.

2. **Realisability**. The anticipated performance limitations with realistic components must be assessed for each technology to ensure that the hardware can be realised in practice with performance compatible with the scientific objectives.
3. **Cost.** The chosen technology will need to be realised within the constraints imposed by projected funding. This inevitably drives the need for low cost hardware, low cost manufacture and low cost infrastructure.
4. **Reliability/Maintainability.** The SKA will need to be operated and maintained over more than a decade of usable life, dictating the requirement for reliable and easily maintainable hardware.

Against these criteria, reflector hardware is seen to be incompatible with the scientific objectives (as currently stated) due to its lack of widely-spaced multi-beaming capability. Complex phased array hardware, while potentially meeting the scientific requirements, would appear to rely to some extent on both the continued extension of Moore's law for high speed signal processing and the continuing development of cheap low loss combining and switching hardware over the next decade to bring the cost in line with expected funding. In addition, it is has not yet been demonstrated that the scanning performance of a planar phased array can be maintained over the wide bandwidth required. From the foregoing discussion the Luneburg lens would seem to meet the scientific objectives and electromagnetic performance requirements best. With its few, if any, moving parts, reliability and maintainability are not seen to be major concerns. The key issues associated with realisation of the Luneburg lens are therefore the cost of materials, the manner of manufacturing the lens and the feed design requirements. These issues are addressed in the next Section.

5. Addressing the Challenges of the Luneburg Lens

In addressing the challenges of the Luneburg lens for the SKA antenna element under the various sub-headings of this Section, we consider two possible solutions; one based around a 5m diameter spherical lens and another around a larger 16m hemispherical lens.

5.1. Lens Size and Dielectric Loss

The minimum size of each Luneburg lens in the SKA will be determined mainly by the lowest operating frequency and, for the hemispherical case, the feed blockage that can be tolerated given the requirement for widely-spaced multiple beams across the visible sky. The maximum size will be set mainly by the mass of the lens and on the allowable loss through it.

One proposal for the SKA is for 100 array stations where each array station consists of 400 5m diameter Luneburg lenses as shown in Figure 3. Each array station is roughly equivalent in collecting area to a 100m diameter reflector. For a 5m lens constructed from low loss materials having loss tangents ~ 0.0001, the loss is predicted to be < 0.1 dB at 21cm wavelength (1.4 GHz) rising to about 0.5 dB at 10 GHz, corresponding to receiver noise loadings of < 7K and 35K. The estimates depend somewhat on the distribution of available materials throughout the lens and any structural materials required to fabricate the lens. Nevertheless, these values show that operation is possible to quite high frequencies with acceptably low values of noise temperature prior to the feeds. The feeds will be located underneath the lens and most likely fixed in place. They will provide an unblocked aperture down to an elevation angle that is a function of the f/D of the lens with elevation angles down to at least 30 ° possible in a practical design. A concern with the 5m diameter lens is that it may be too small to operate effectively at the lowest band edge. (The magnitude of this, and other concerns, will become clearer with further study.)

An alternative proposal is to use a much larger lens of around 16m diameter in the virtual source Luneburg lens configuration of Figure 2. Assuming, as before, 100 array stations, we would need to have 40 such lenses to form a single station. Such an array station, designed to operate down to 30 ° elevation, is illustrated in Figure 4 where, on each lens, we show a possible rotating feed arm configuration (to be discussed later). Indeed a number of feed configurations are possible. With respect to loss, a 16 metre lens constructed from low loss materials (again, with a loss tangent ~ 0.0001) gives a predicted loss of 0.25 dB at 1.4 GHz. While at higher frequencies this larger lens will not operate as effectively as the previous example due to increased loss, its beam shape at lower frequencies will be superior. The disadvantage compared to the spherical Luneburg lens is the need for some feed movement.

5.2. Material Characteristics

Various options are available for the lens material having refractive indices in the required range. The main types of material are foamed natural dielectrics, either plastics or inorganic materials, or artificial dielectrics made from inorganic or metal particles embedded in a low-density foam. The actual choice of material will depend on the trade-off between factors such as loss, total mass, cost, isotropy and uniformity.

5.3. Structural Design and Strength

Predictions of the mass indicate that the weight of a 5m Luneburg lens will be at least 50 tonnes and a 16m diameter virtual source Luneburg lens would lie in the range of several hundred to several thousand tonnes, depending on the dielectric material used. With the virtual source Luneburg lens, however, the weight of the lens is supported directly on the ground plane. Studies [4] show that it should be possible to produce a self-supporting hemispherical Luneburg lens of this diameter.

In order to operate at higher frequencies, 30 to 40 layers or more may be required to minimise problems with scattering from dielectric discontinuities. To form the layers a number of options exist: the lens could be built from preformed blocks of dielectric and, in the case of the large 16m lens, transported to the site and assembled against a moulded internal hemisphere of approximately 2m in diameter. Alternatively, material could be formed on site by mixing and spraying, using the future feed assembly temporarily fitted-out to act as a guide for the process.

Although the structures, being volumetric in nature, are inherently heavy, it is not anticipated that the mass alone will prohibit assembly. Note that a 5m spherical lens takes about 66 cubic metres of low-loss dielectric whereas a 16m diameter hemispherical lens requires just over 1000 cubic metres of material.

5.4. Ground Plane for the Hemispherical Lens

The virtual source Luneburg lens requires a ground plane extending beyond the diameter of the lens. The extent of the ground plane, *R*, will determine how low in elevation a beam can be scanned. To a first approximation $R = a / \tan a$ where a is the elevation of the beam and a the radius of the lens. For a typical minimum of 30° elevation the ground mat must extend to just under twice the lens radius, the case shown in Figure 4, whereas for 10 degrees elevation 6 lens radii is required. The shape of the ground plane can be selected to allow lower elevation where it is of most interest, and the ground plane can be shared by several lenses in a single station if shadowing is not produced by close spacing of the lenses. Compared to the spherical lens design in Figure 3, low elevation angles (viz. < 30°) are probably easier to realise with the hemispherical lens. Finally, the quality of the ground plane, particularly its surface roughness and porosity, will determine how good the image of the lens is in its resemblance to a full Luneburg lens and to how much additional noise is introduced into the system. Meshes that have been used for ground mats at lower frequencies could be adapted to form a suitable low maintenance ground plane providing acceptable performance over the required range of elevation angles.

5.5. Feed Structure and Feed Elements

One of the attractions of the Luneburg lens design is the considerable flexibility it provides to the feed designer to cater for the many astronomical needs, both now and in the future. This is an important attribute given the critical nature of the feed configuration generally in any radio telescope. A problem particular to the Luneburg lens is the inherent edge brightness of the collimated beam [9] which, without correction, leads to reduced gain and higher sidelobes. The edge brightness effect reduces significantly in designs where the focus is displaced away from the lens surface. This not only allows easier realisation of a uniform beam by appropriate feed design but also results in a smaller range of permittivity of dielectric in the lens leading to easier manufacture.

For the full spherical lens design in Figure 3, the feeds will ideally remained fixed. At low elevation angles these feeds will block the signal path. For observation down to an acceptable 30° in elevation, the f/D of the lens needs to be around 0.7. A larger f/D will provide still lower elevation angles at which observations are possible, with diminishing returns for f/D > 1 where the unblocked elevation angle is 15°.

In the case of the hemispherical lens design, some feed movement will be necessary. The simplest approach is to provide azimuth rotation only and have some form of feed array provide the elevation coverage. This could be in the form of several "arch" line feeds to image different portions of the sky independently and simultaneously. Indeed, calculations have shown that for the 16 metre diameter lens, up to 200 feeds with a size compatible with the effective *f/D* of the lens can be accommodated before blockage becomes severe. Consequently it is possible for there to be three or four small cross-section arms having almost independent movement (subject to mechanical blockage) providing line fields-of-view on the sky. Elevation coverage would be available from just under zenith down to an elevation angle limited by the extent of the ground plane. Alternatively it can be shown [10] that up to 140° of azimuthal coverage can be accommodated simultaneously by a large array without blockage. This "shell array" is the option illustrated in Figure 4 where the f/D of the lens is 0.7. While the "shell" rotates to view different parts of the sky as required, it does not offer full simultaneous sky coverage.

Either the full operating frequency range is covered by a single feed or else several feeds for different frequency bands must be used. Moreover, dual polarisation is required to fulfil the SKA specifications. For cost reasons, printed circuit antenna technology is desirable, and focal plane arrays with integrated low-noise amplifiers and digital receivers may be considered. It is worth re-emphasising that phasing is not required for an array feeding the Luneburg lens unless some correction to the phase due to lens imperfections is envisaged or unless there is a particular need for a fully- or over-sampled multi-beam array. For signal routing, optical signal combining and distribution after digitisation provides the most flexibility.

5.6. Analysis and Design of the Luneburg Lens and Feeds

Electromagnetic scattering by a lens constructed of uniform spherical shells has an exact analytic solution in terms of spherical waves, and techniques exist to implement this solution numerically for lenses up to at least 100 to 200 wavelengths in diameter [11] which would cover the range of lenses considered here. Interaction with the feeding network, and the effects of deformation of the lens due to gravity or manufacturing tolerance would require a different approach. Computational electromagnetism techniques such as finite difference time domain and boundary element methods provide the highest degree of flexibility in this regard, and computing resources exist to permit detailed design studies to be undertaken. It should be possible to provide a full characterisation of the electrical performance of the two Luneburg lens systems subject to mechanical constrains and tolerances, a feature that is also true for reflector antenna technology but not yet available in a reliable way for phased arrays.

5.7. Infrastructure Requirements

The possibly remote location of the SKA array stations makes the infrastructure requirements an important consideration in the choice of antenna element. The infrastructure requirements relate firstly to the construction of the SKA, and secondly to its operation. For construction, transportation of materials, support structure for the lens, assembly of the feed structure, assembly of the lens itself and, in the case of the hemispherical lens, a ground mat, will require an infrastructure compatible to the construction of a reflector antenna and its mount. However, given that the structure can be weatherproofed and only in the case of the hemispherical lens is there a small number of lightweight moving parts, the electrical power and other support required for operation is minimal. Power requirements should be compatible with solar and battery operation, which is highly desirable for the large number of SKA antenna elements envisaged.

5.8. Cost of Materials

The primary cost of materials is in the construction and forming of the dielectric layers of the lens. Given the large quantity of material and the number of lenses required, as well as the potential of the Luneburg lens design for many other applications, it is in the area of manufacture that effort is required to minimise the cost and hence feasibility of the Luneburg lens for the SKA antenna element.

6. Concluding Remarks

We have identified the major advantages and challenges of designs based around the Luneburg lens for the antenna element of the SKA. In almost all regards the Luneburg lens offers attractive performance features. Many of the major material and structural challenges have been addressed and solutions proposed. It remains to ascertain the parameters governing the cost, and the impact on SKA funding given the potential benefits of the structure to the astronomical objectives of the project.

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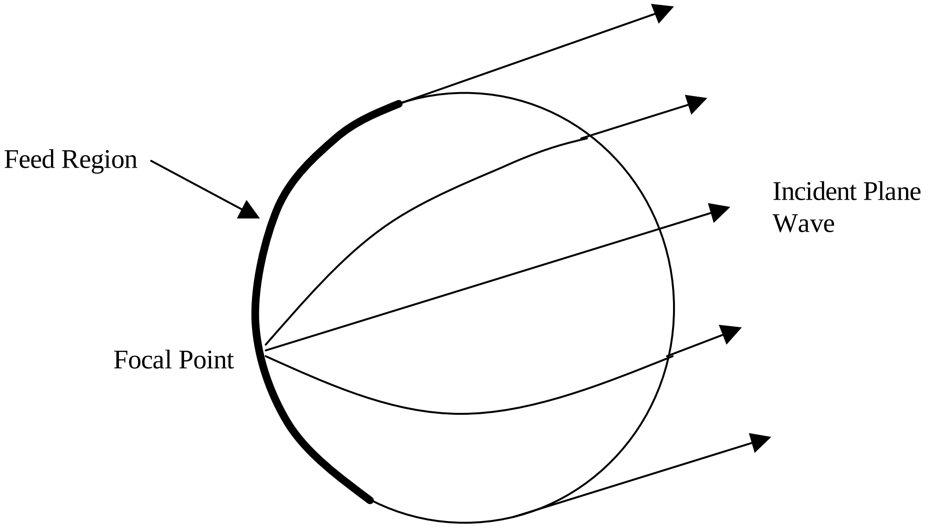
Figure Captions

Figure 1: Basic focussing action of Luneburg Lens

Figure 2: Virtual Source Luneburg Lens

Figure 3: Artist's impression of SKA stations composed of 5m diameter Luneburg lenses

Figure 4: Artist's impression of SKA stations where 16m diameter virtual source Luneburg lenses are supported on a ground plane and fitted-out with a rotating feed arm



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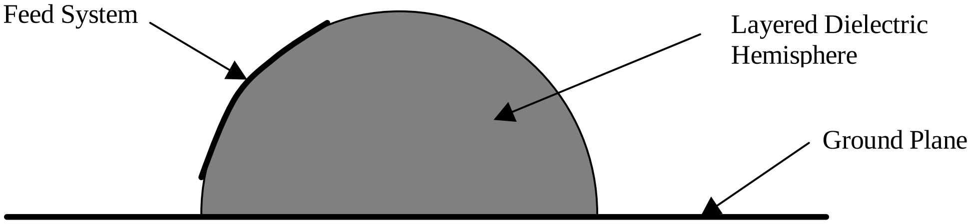

Figure 2: Virtual Source Luneburg Lens

Figure 3: Artist's impression of SKA stations composed of 5m diameter Luneburg lenses

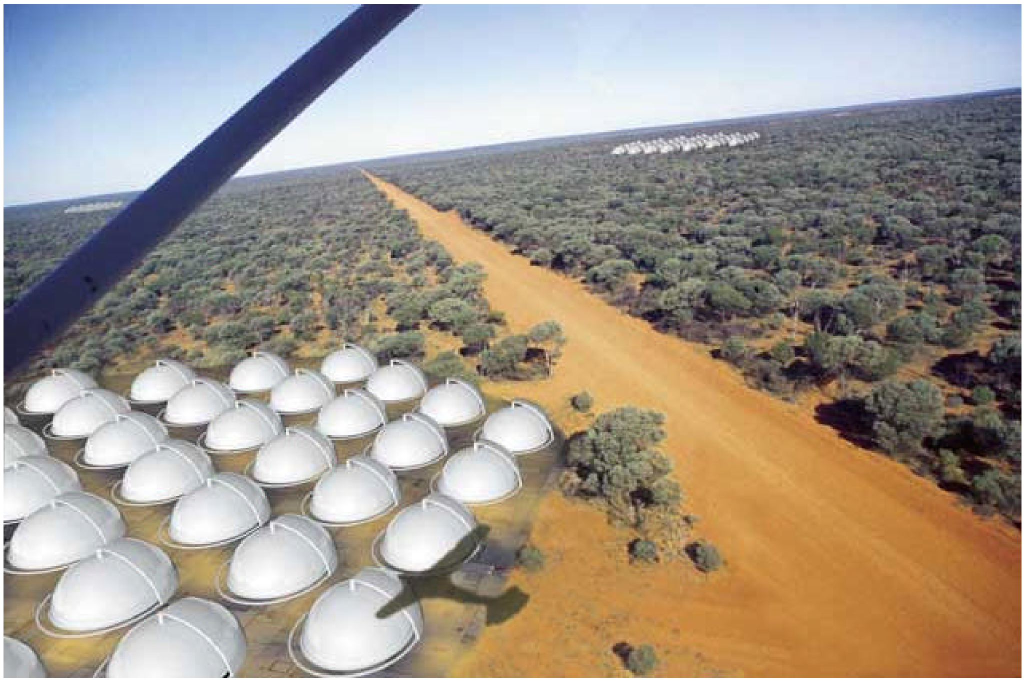

Figure 4: Artist's impression of SKA stations where 16m diameter virtual source Luneburg lenses are supported on a ground plane and fitted-out with a rotating feed arm