Report on the Mechanical Design Options for the Luneburg Lens System.

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1. The Luneburg Lens

The Luneburg lens is a spherically symmetric lens which has been considered for implementation in the Square Kilometre Array radiotelescope. Various documents (ref) point out some of the primary features of the Luneburg lens system. In particular, the Luneburg lens is well suited to multibeaming, that is, observing in multiple simultaneous directions. Multibeaming is achieved by placing multiple feeds (receivers) around the sphere on the focal surface. The direction of each beam is then associated with the position on the sphere of its respective feed. Demands on the observing possibilities of the lens translate directly into demands on the positioning system of the feeds. For this reason, this report details some design options for the Luneburg lens feed positioning system.

1.1 Focussing

Figure (1) shows the focussing action of the Luneburg lens. The lens brings plane waves incident from a particular direction onto a region near the point of focus. [1]

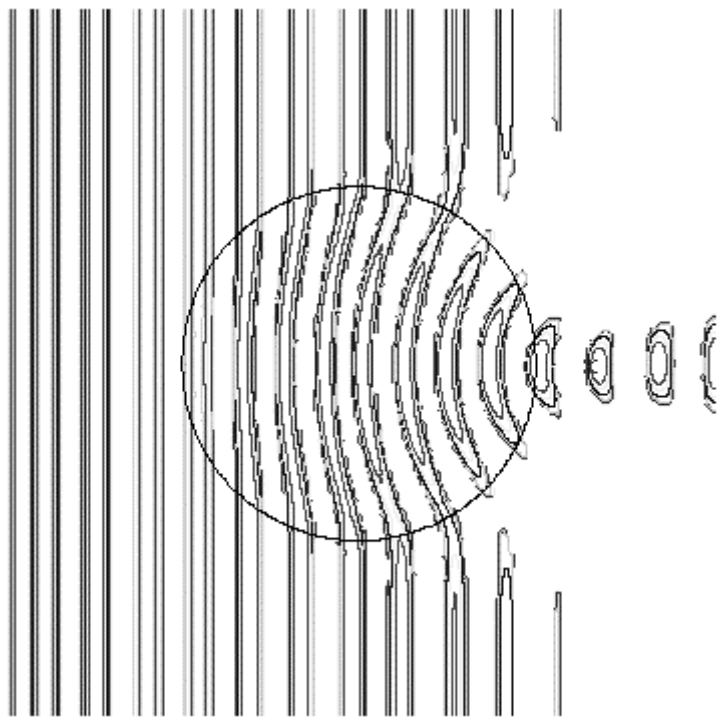

Figure 1: The Focussing action of the Luneburg lens. [2]

The size of the focus region determines the required accuracy for the positioning system.

1.3 Full Sphere and Hemisphere Luneburg lens designs

A Luneburg lens arrangement involving only a hemisphere also exists [3]. In this arrangement, half of the lens is emulated by reflection from a ground plane. Feeds which would otherwise be located below the lower half of the sphere (to be directed towards

sources above the horizon) are located above the top half. The ground plane also provides advantages in terms of mechanical support since the most dense parts of the lens are directly supported on a wide base. The hemispherical arrangement has disadvantages in terms of feed blockage, since feeds block themselves and/or other feeds depending on the geometry. Mechanical supports of the feeds also present blockage.
The ground plane is also a significant component that adds to the cost of the system. The ground plane covers a large area and must be flat within a controlled tolerance. The preparation of this large area of ground is a significant problem in earthworks and civil engineering.
Various aspects of the half-sphere architecture were considered but are not described in detail here.
Most of the concepts presented here are amenable to the half-lens architecture as well as the full lens architecture in the full scale, with some significant modifications.

2. The Prototype, Demonstrators and Full Scale Design

The designs which are presented in this report were intended for immediate application to a small Luneburg lens of approximately 1 metre diameter. The prototype is intended to demonstrate a possible feed positioning system architecture, to develope mechanical design concepts that are applicable to the full scale lens, for demonstration purposes of the whole Luneburg lens concept and to produce a platform for testing other parts of the system.
Each of the component designs developed for the 1 metre lens was intended to be generally applicable to the full scale system, however, being of a different size and mass, there are some differences between the full scale lens and the prototype.

3. The Mechanical Support Problem

The prototype lens weighs approximately 100 kg, while the full scale lenses will have a mass of the order of 10^3 kg. The internal deformation of the lens is an important consideration in the design of the lens. The lens will deform due to its own weight and the support reaction forces.
The support system is required to constrain the lens against gravity and wind loading. In addition the deformation of the lens must be taken into account. The deformation must either be smaller than a tolerable threshold (determined by the focussing properties and the requirements of the user), or alternatively the deformation must be able to be corrected or compensated. This correction or compensation may be achieved by employing special packing schemes for the foam and pre-distorting the shape to compensate for deformation, or it may be achieved in software by knowing the shape of the deformation and calculating the effect of the deformation on the focussing system.

The mechanical support system must coexist with the feed positioning system. In some concepts proposed for the mechanical support, the positioning system and the support share some common facilities.

The support must also maintain the alignment of the lens and the positioning system within a certain tolerance.

3.1 Outline of Mechanical Support Solutions

The support may be distributed over small patches or pads which are then supported by any standard structure, as is used on the Konkur lens. For example, the lens may be supported by a single column under the centre of the lens. The weight of the lens places the column in compression. A cup or pad is necessary on the surface of the lens to spread the load of the weight over an area. This prevents excess deformation of the material just above the base. Approximate calculations can be made to estimate the deformation and therefore the required size of the cup. The column must be sized according to tolerance for vertical compression and sideways deflection due to wind loading.

Alternatively the cups or pads may be placed around the lens, most likely in a tripod arrangement at some angle below the equator. The resultant force from several pads contributes to support the lens. The pads may provide support through compressive or shear loading on the lens. Two pads (on a diameter) are used on the Konkur lens and support the lens through compressive and shear loading.

Alternatively the support may be distributed over a ring, or over a large, continuous portion of the lens.

The lens may have a tough and semi-rigid outer layer which helps to protect the lens and to spread the support forces over a larger area.

Employing a distributed support over a large portion of the lens would involve making the outer layer sufficiently rigid. The semi-rigid outer layer would then be supported in any preferred method.

Widely distributed support can also be achieved by methods such as a mesh in tension around the base or support by fluid pressure difference between the top and bottom halves.

The design choices need to be evaluated in terms of the deformation caused and the consequences of the deformation on the performance of the lens.

The designs proposed here employ the currently existing supports on the Konkur lens.

4. The Feed Positioning Problem

A feed positioning system is required to place feeds on desired points or trajectories. The system must be effective and low cost. Some specific performance requirements are detailed below.

4.1 Performance Requirements

4.1.1 Positioning Accuracy in two dimensions around the sphere.

The feeds must be positioned at the region illuminated by the desired source within a region of error determined by the size of the region of illumination. For a preliminary calculation, it was assumed that the angular size of the region of illumination could be approximated by:

$q = \frac{1.22\,l}{d}$ where θ is the angular size of the region of illumination. λ is the wavelength. d is the diameter of the lens.

The angular positioning accuracy is required to be a sufficiently small fraction of the size of the region of illumination. The angular positioning accuracy, ϕ, was chosen to be: 0.1 θ

From this, the allowable positioning error was calculated as the length of the arc (on the focus sphere) which subtends ϕ. The radius of the focus sphere is typically 1.3 to 1.5 times the radius of the lens. (This is the focus/radius parameter)

frequency (GHz)	Lens diameter (metres)	Focus/Radius parameter	Positioning accuracy (mm)
1.0	1	1.5	27.5
1.5	1	1.5	18.3
5.0	1	1.5	5.5
10.0	1	1.5	2.7
1.0	5	1.3	23.8
1.5	5	1.3	15.9
5.0	5	1.3	4.8
10.0	5	1.3	2.4

Table 1: Positioning accuracy requirements vs. frequency and lens diameter

Table 1 shows the results of this approximation. The positioning accuracy does not depend on the lens radius, since the projection from θ to arc length varies in proportion to the radius, while ϕ itself varies inversely with the radius. The positioning accuracy is determined primarily by the maximum operating frequency.

4.1.2 Positioning in Radius.

The currently preferred design for the feed requires that different locations along the feed be placed on focus, depending on frequency [1]. For this reason the feed positioning system will provide the facility for radial adjustment of the feed.

4.1.3 Slew Speed

The slew speed is the maximum rate at which the telescope can move. This is the type of movement used to change through large angles to change observation from one source to another, for example. Accurate positioning is not required during slewing. For ease of scheduling, faster slew speeds are desired by the users. The ATCA at Narrabri has a slew speed of around 40 degrees per minute and the Parkes radiotelescope has a slew speed of around 24 degrees per minute [4],[5]. The Luneburg lens positioning system should aim for similar or higher slew speeds than existing telescopes.

4.1.4 Shadowing and Blockage

Blockage of the field of view caused by feeds and mechanical structures is to be minimised. Some blockage is tolerable; In many radiotelescope architectures there may

be structures supporting receivers or secondary reflectors, for example. On the other hand, where design choices exist, care must be given to blockage considerations.

4.1.5 Visibility Zones

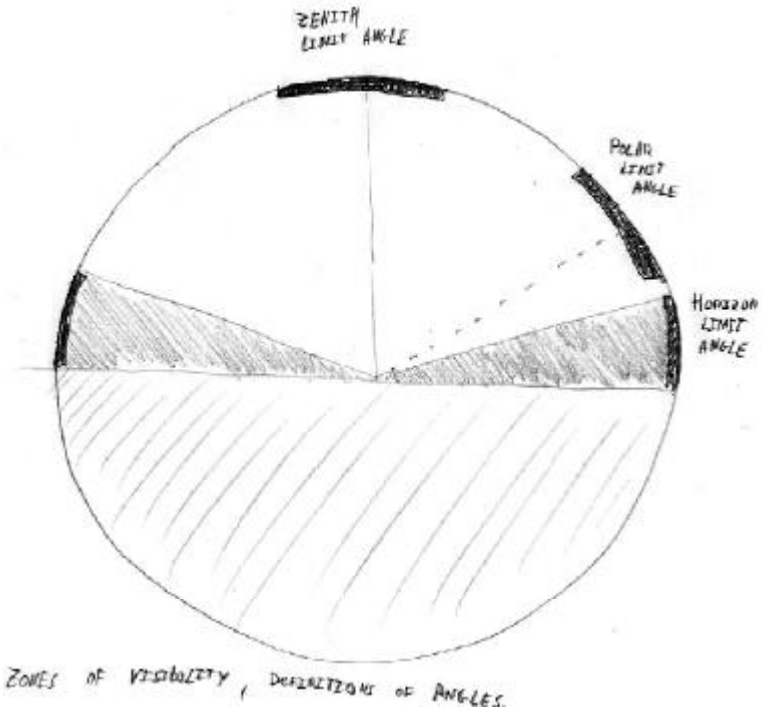

Figure 2: Zones of visibility, definitions of angles

The users of the telescope want to be able to view as much of the visible sky as possible. Depending on the overall architecture of the telescope there may be parts of the sky that are not visible. Figure 2 defines the zenith limit angle, the polar limit angle and the horizon limit angle. Each is to be minimised.
A note on terminology used here: Visibility zones are limited by the physical ability of feeds to be placed in certain regions of the sphere. Shadowed and blocked zones are caused by obstruction of the view from those regions of the sphere.

4.1.6 Cable and Collision Management

The use of multiple feeds requires consideration of how the feeds will share the space around the sphere. Collisions must be avoided; This is in principle able to be implemented in software, given that the feeds will be able to be positioned and moved accurately.
Each feed may require several cables for power and communications. Some alternatives to cabling are possible, such as the use of solar panels for power, radio or optical links for communication. However, in general, it is supposed that there will be some cabling. Tangles and collisions with cables must be avoided. The mechanical design must take the cabling issues into consideration. Some cabling issues may also be able to be managed in software.

4.2 Implementation Requirements

4.2.1 Stepwise Upgradeability

The Luneburg lens based telescope, consisting of a large numbers of identical units and utilising optical beamforming, inherently has the ability to be progressively upgraded after installation. Improvements in the sensitivity and resolution of the overall instrument can be obtained by progressively adding further array elements. On a similar theme, the multiple beaming concept also lends itself to stepwise upgradeability. The lenses, once installed, may have further feeds added in order to increase the number of beams.
The mechanical design should therefore include the ability to easily add additional feed elements.

4.2.2 Servicing Requirements and Resilience to Local Conditions

The Square Kilometre Array will be distributed over a large area where the local conditions may vary between the extremes of desert and coastland. This means that the design is required to be resilient to dust, wind, rain, sunlight, hail, corrosion, interference by plants and animals, and other hazards.
Being distributed over a large area also means that servicing the array elements will be difficult and expensive. Therefore all components must be designed for infrequent servicing and/or long lifetimes.

4.2.3 Cost of Components and Manufacturing

The Square Kilometre Array will be a low budget instrument. Estimates of the total budget are around $A1000M. Estimates of the number of lenses are around 40 000 units. At $25000 per lens, including materials and manufacture of the lens itself, the positioning system must obviously be extremely cost effective.

5. Proposed Solutions

5.1 Independent Rovers

Independent rovers are units which carry the feeds around on the surface of the Luneburg lens. They are able to move independently of each other and are all supported on one or two spherical shells. They are able to track a wide range of trajectories across the sky, making them suitable for interference mitigation purposes (where tracking satellites in many different orbits may be required) as well as tracking most astronomical objects, where tracking is necessary mainly for cancelling the earth's rotation.
Independent rovers were first considered as a 'high tech' solution to the feed positioning problem, inspired by automated robotic systems and 'mechatronic mice' projects. The advantages of automation and independence of the rovers do not come for free; There are considerable mechanical issues as with any proposed solution.

5.1.1 Mechanical Support

The rovers are attached onto a thin spherical shell which is concentric with the Luneburg lens. The shells and the lens can be supported by various arrangements:

- Column support: A beam at the centre supports the outer shell and the lens. A cap around the base of the lens may be necessary to distribute the load of the lens' weight.
- Disc support: A continuous disc supports the lens around the circle, at an angle below the equator. The support shell is attached onto the disc. Framework attaches onto the disc to support the entire structure. See figure 05-12 #8
- Air pressure support: As mentioned briefly in section 1.4, depending on the deformation properties of the lens material, it may be preferable to support the lens by fluid pressure difference between the top half and the bottom half of the lens. Structures used to seal the lower half of the lens could provide restraints to maintain the relative positions of the shell and the lens, whilst not deforming the lens with undue concentrated loads. See figure 05-12 #9

These two support architectures provide access to both the zenith and the equatorial axis without problems, as is visible from figures 05-12 #8, 05-12 #9. In principle, low horizon angles are also achievable using these designs.

5.1.1.1 Using one support shell:

Support method used for holding the rovers onto the shell:

- Support by vacuum cups. Several feet are pressed against the shell by pressure difference and the rovers are supported by friction between the shell and the feet. Pneumatic accessories and facilities (compressed air or vacuum) would be required. See figure 05-12 #4
- Magnetic Attachment. The rovers are pressed against the shell by attraction between a pair of magnets, one on the rover and the other on the opposite side of the support shell. The rovers are supported by friction between the wheels and the support shell. See figure 05-12 #6

Mounting the rovers on the inside (concave side) of the support shell has advantages over exterior mounting.

- The rovers are protected from the weather by the shell.
- The feeds are able to be translated radially to suit focussing requirements.
- The rovers can pass underneath the structures supporting the shell on the outside.

5.1.1.2 Using two support shells:

Support method:

- Between spheres support. The rovers' wheels bear against both the inner and the outer support shells. This provides thrust which enables the rover to be supported by friction between the wheels and the shells. This support method has advantages over single shell supports in that the supports are well spaced around the centre of mass of the rover. This means that the load on each support point is reduced. See 05-12 #5

5.1.1.3 Electromagnetic Compatibility of the Support Shells

The placement of concentric shells around the entire base of the Luneburg lens may have consequences for the electromagnetic properties of the system. Reflections from the support shells may cause problems. If support shells were to be employed, further consideration of the electromagnetic consequences would have to be taken.

5.1.2 Position Measurement Of the Rovers

5.1.2.1 Incremental and Absolute measurement systems in general

Incremental measurement systems involve the recording and integration of small steps. Incremental systems have the disadvantage that as an integrator, it can only measure the offset of the system since it was last reset. In the event of an accident that causes the loss of the record of the current position, the object must move to a reference position and reset the recorded position accordingly. Any counting mistakes accumulate and cause positioning errors.

Absolute measurement systems involve the direct reading of current position from an array of markings. Absolute measurements systems overcome the disadvantages listed above. On the other hand, absolute measurement systems involve more complex markings and reading equipment and are therefore more expensive.

Hybrid approaches exist, such as the use of incremental markings with a coarse overlay of absolute position markers. This way, accumulation of mistakes is reduced by periodic reset of the position to the correct position. In the event of a loss of the position record, the object does not have to travel far to reach a reference marker.

5.1.2.2 Markings on the surface of the sphere

Small CCD cameras could be used to observe special markings on the surface of the sphere in order to obtain the position of the rover. The markings would have to be of sufficiently fine resolution to give the required positioning accuracy.

- Planar two dimensional patterns exist which have the property that a small view of the pattern can be used to uniquely determine the location within the pattern. If such a pattern could be transformed to fit onto a spherical surface, it could be used as an absolute position measurement system. Examples may include fractals or patterns of dots.
- Grid points could be specifically marked with an encoded form of their coordinates. (Absolute measurement system)
- The relative movement of arbitrary markings on the sphere across the view of the camera can serve as the basis for an incremental measurement system. (PC optical mouse systems use this technique)

Markings on the surface are difficult to produce. The cost of the video camera hardware and processing hardware and software are also considerations.

5.1.2.3 External Reference Position Measurement Systems

See figure 05-12 #13

Observing systems can be placed outside the lens which can measure the angular position of the rovers. Several such systems per lens enables the position of the rovers to be

calculated. Commercial packages exist for the location (angle and distance) of objects using laser scanning.
Commercial packages at present cost around $7000 and have an angular resolution of 0.25 degrees. This projects an error of approximately 10mm in diameter, for a 5 meter lens. This is sufficient for low frequency operation but the cost does not encourage their implementation.
Imaging cameras would work if they could be sufficiently calibrated (from image position to actual angle of view).
Beacons could be placed on the rovers to improve their visibility. The shells could be constructed of transparent material.

5.1.3 Actuators for the Rovers

Rolling between a wheel and a sphere (as opposed to slipping) will occur if the axis of rotation of the sphere is in the plane containing the sphere centre and the axis of the wheel. Therefore, two rollers with axes oriented arbitrarily, and the sphere centre uniquely define a spin axis for the sphere.
See figure 05-12 #10
This means that a rover with two powered, steerable wheels and a third free wheel will be able to manoeuvre freely over the surface of the sphere, including two dimensions of translation and a single axis (normal to the sphere) of rotation.
A single wheel with the ability to both drive and steer requires two motors and a complex mechanical arrangement, at least at an initial consideration. Therefore, four motors are required for each rover in this scheme.

5.1.3.1 Generic Requirements for motors for the Luneburg Lens positioning system.

The maximum force that the feed positioning system would need to exert is its own weight, when travelling almost vertically upwards at the side of the sphere. (This may be compared to estimates for the force due to background friction and the force required for reasonable acceleration). Supposing some estimates for slew speed it is possible to calculate estimates of the power required.
For a 5 kg feed unit, travelling (upwards) at 2 cm per second (~26 degrees per minute on a 5 metre diameter lens) the power required is 1 Watt. This calculation applies regardless of the feed positioning architecture.
Miniature electric motors of approximately 1 Watt are available from industrial suppliers for less than $A5 each.

After considerations of motor power, lifetime and cost will be the next considerations. The decision will most likely be between brushed and brushless DC motors. Brushes are components in electric motors that transfer electrical contact between the rotating and stationary parts of the motor. They continually rub (brush) and tend to wear out eventually. From a preliminary consideration, brushless motors have longer lifetimes than brushed motors but are more expensive. On the other hand many improvements are available on brushed motors that make them a possible solution at low cost.
DC motors are more amenable to simple electronic control than AC motors.

Stepper motors are not a consideration because they have poor mechanical properties (Torque, speed etc) for their cost; Instead, they are optimised for accurate motion in discrete steps. This is not needed here since the position measurement facilities provide position feedback, meaning that the actuators can be inaccurate in their positioning ability. The accuracy is in the measurement and feedback, not in the actuators themselves.
The motors must have the ability to run continually, with a long lifetime. The motors may have to be sealed against the ingress of dust and this would inhibit the heat dissipation ability. These factors will need to be considered.
The recommended speed of the motor will determine the properties of the gear box. A detailed choice of motor specifications is still required.

5.1.4 Cable Management

Two general schemes for cable management are proposed.
Firstly, a hardware cable network. See figure 05-12 #14. In this arrangement, the cable for each feed is routed via other feeds back to a suitable exit point near the structural supports. Each feed is able to move around to some extent, but the overall topology of the network is fixed. Cable drives that can push or pull the cables in or out could be used to take up slack or relieve tension in the cables, and allow movement of the feeds relative to each other.
Secondly, cables are run freely in the same space as the rovers themselves and exiting near the structural supports. The overall topology of the arrangement of feeds and cables is recorded in software. Mechanisms on the rovers can be used that allow them to push cables ahead as they move. When cables are deflected beyond reasonable limits, or when the topology of the arrangement needs to be changed, tracking can be interrupted and appropriate manoeuvres made to rearrange the feeds and cables. See 05-12 #15
If schemes could be proposed such that rovers could cross over (or under) other rovers' cables, then the rovers could be completely free to follow independent trajectories. This is the main aim in using independent rovers.

5.1.5 Implementation Requirements

The independent rovers architecture is stepwise upgradeable since additional rovers can be inserted as required.
The use of mechanical support shells acts as an external cover for the whole system, thus protecting the lens and positioning system from the weather and local conditions.
Further detailed design is necessary in order to make estimated costs of the components of the system.

5.1.6 Conclusion to the Proposed Rovers system

The main advantages of the independent rovers architecture over other architectures are:

- They permit a wide range of tracking trajectories
- Feeds can partially cross over each other.

The main disadvantages are:

- Positioning systems are complicated; They involve image processing systems.

- The mechanical design of the feeds appears to be complicated, involving more than two wheels, each steerable and driving.
- Cable management issues appear to be complicated, on a first consideration.

The complexity of the independent rovers architecture meant that this architecture was not considered in more detail. Other schemes may certainly be possible to overcome each of the disadvantages listed.

5.2 Structural Arms

In the structural arms architecture, each feed is supported on an individual structure. The arms are positionable in angle corresponding to either azimuth or right ascension (for the altitude-azimuth or equatorial arrangements respectively). The feeds are attached to the feed carriers which are able to move along the arms to position in altitude or declination.

5.2.1 Equatorial and Altitude-Azimuth Mounts

In an equatorial mount, the right ascension axis is aligned parallel to the earths rotation axis, and the declination axis is aligned perpendicular. This way, as the earth rotates, the right ascension axis is correspondingly rotated such that the two cancel out. Only a single axis needs to be moved in order to remove the effect of the earth's rotation.
In an altitude-azimuth mount, the azimuth axis is aligned vertically (ie: parallel to the gravitational field) and the altitude axis is aligned perpendicular to the azimuth axis.
The choice between equatorial and alt-az mounting is an important consideration here.
See figures 07-12 #2 (Equatorial) and 07-12 #4 (Alt-az) within figure 3.
Each mounting type has arms that extend from the rotation axis (azimuth or right ascension) out to the horizon limit. The arms are all the same length, since having arms of mixed lengths or adjustable arms would introduce complexities. As is visible from the diagrams, in the equatorial mounting there is considerably more blockage than in the alt-az mounting.

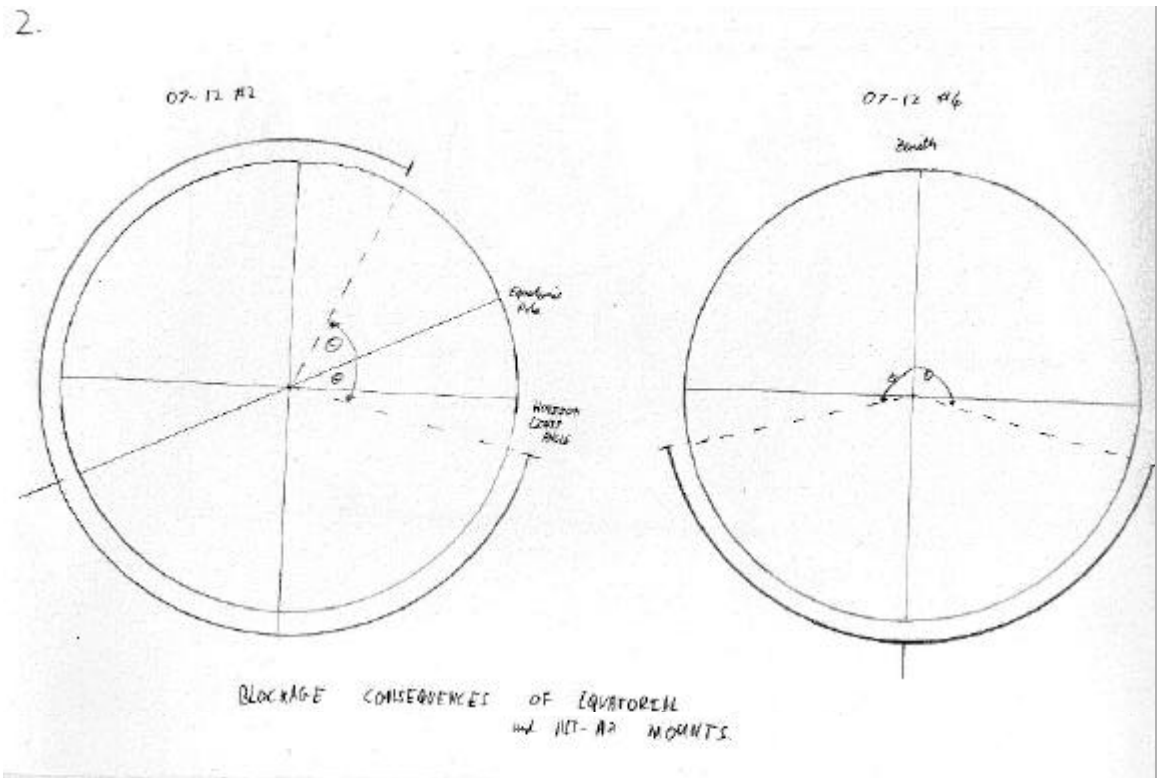

Figure 3: Blockage consequences of equatorial and Alt-az mounts

The choice of mounting has consequences for the tracking of objects. For most typical observations, involving objects at several different locations in right ascension and declination, it is unavoidable that their motions will involve cross overs in azimuth. This means that the structural arms of the alt-az mounting would need to swap places in order to track their respective objects. This problem can be avoided in software by allowing feeds to swap their identities rather than physically swapping in space. This is possible providing that a brief interruption in tracking and signal recording is tolerable.

The equatorial mounting is also considerably more complex to build since the geometry of the frame and structural arms system is aligned at an angle to the horizontal.

The additional blockage caused by adopting an equatorial mount is the main reason why the equatorial mount is no further considered here.

5.2.2 Components of the Design

The proposed design is described in separate components. These are:

- The structural arms
- The centre axis, bearings and mountings at the centre.
- The support rings, wheels and guides
- The feed carrier and the feed.
- The frame or other support.

Insert diagram page 3

5.2.2.1 Large Vs. Small Centre Axis Designs

The diameter of the centre axis compared to the width of the structural arms is an important parameter and has an impact on the design chosen for the arms. Figures on page 12 show wide arms on a thin axis and thin arms on a thick axis, respectively.

5.2.2.1.1 Angular Proximity

Insert page 4.

The figure (on page 4) shows the geometry of two arms in close proximity. Two objects of radius S are mounted on arms at radii R from the centre and touch each other. The angle between the two arms is $\theta = 2 \tan^{-1}(S/R)$ which is approximately 2S/R for small S/R.

S and R may represent:

- S = half the width of the arm, R = the radius of the centre axis
- S = the radius of the feed, R = the radius of the feed from the centre of the axis.

The largest value of θ from these two sets of S, R determines the minimum angular proximity.

In the current design of the full scale lens the feeds have a radius of 0.25 metres, the centre column has a radius of 1 metre. Arms of width 10 cm give $\theta = 11.4°$. The feed at a radius of 5 metres gives $\theta = 5.7°$. However, if the feed is in at a radius of 2.5 metres, $\theta = 11.4°$. The feeds will in general be in the mid-range of their travel and therefore it is most likely, at any instant, that it is the feeds that are causing the limit in angular proximity, not the width of the arms.

It is possible to devise an overlapping arms arrangement which effectively increases the value of R used to find the angular proximity of the arms alone. That way the arms can approach each other closely, only limited by the feeds. This arrangement is useful when the axis is small. However, for the sizes of the full scale lens system given above, it is not worth the extra cost of the overlap system.

5.2.2.1.2 Zenith Access

Arms that pivot off an axis at the zenith cannot view the zenith directly (without causing undue mechanical complication). The fraction of the visible area of the sky blocked by a patch at zenith of full angle 2θ is $1-\cos(\theta)$. For $\theta = 20°$ the portion of the sky blocked is 6%. Thus for reasonable values of the zenith blockage angle, the area is small.

5.2.2.1.3 Mechanical Complexity

The overlapping arms arrangement used on a small centre axis is much more complicated that the non-overlapping arrangement on a larger column. The overlapping arms involves:

- Stacking or tessellating the arms at offset lengths along the centre axis
    - This implies that the arms must have a small thickness in order to fit the many arms within a reasonable length along the centre axis.
- Multiple bearings, rings or collars
- The manufacture of multiple arms of differing radii

In contrast the non-overlapping arrangement involves:

- Identical arms at a single radius
    - Consequently, the arms can be thick, since the arms are not stacked along the axis.
    - Identical arms are more simple to manufacture.
- The use of a common support ring.

5.2.2.1.4 Implications for the Arm Design

The considerations of large and small axis designs encourages the use of non-overlapping arms. The exact angular proximity can be minimised by reducing the width of the arm as much as possible, at the expense of the thickness of the arms. In the case of the prototype it is suggested that the non-overlapping design should be used, for all the reasons above and also to emulate the intended design of the full scale system. In the case of the prototype, the size of the zenith blockage region can be adjusted at a compromise with the angular proximity and the width of the arms.

5.2.2.2 The Structural Arms

As implied in the discussion above in section 5.2.2.1, the arms mount at a radius R from the centre of the axis. This can be achieved by using a support ring on the ground at a radius R from the centre. This support ring enables the positioning system to be independent of the centre column, which helps upgradeability and manufacture. The arms are also supported on a second support ring further out.
The structural arms consist of the circular arc section, the body and the mountings onto the support rings. The arms were designed in terms of their function (to hold the feed carrier), in terms of their close proximity geometry, and in terms of their deformations under load.

5.2.2.2.1 The Arc

The feed carrier drives on the face of the arc of the arms. Since it is required to be able to drive along the arm, with the driving wheel or gear held against the surface and also support itself against arbitrary forces, it should be mounted on the front, back and two sides of the arc. This leaves the centre portion of the back available for access for support of the arc. See figure page 7.

5.2.2.2.2 Arm Body Design

The body of the arms is designed according to its deflection under its own weight, and the load. The deflections within the plane of the arm are minimised by emulating a triangular structure as used in pin jointed frames. In this type of structure deflections can

only occur by longitudinal deformation of members in the structure, which are small compared to bending deformations. The deflections perpendicular to the plane of the arm are of greater concern.
The structure is supported on the two support rings, which act as a cantilever support. In the figure page 11, the whole structure can be approximated as a cantilever supported beam, for the purposes of structural analysis of deflections out of the plane of the page. The beam is DB or CB. The cantilever support is at D or C. Section a-a shows the cross section of the beam, which varies with position. Ignoring the flange DE is a simplification, and will give a larger estimate of deflection. The deflection can then be found, once an estimate of the load is obtained. The dimensions of the parts can be found by imposing some maximum deflection condition. The cost of the materials for the arms can be found from the dimensions of the parts.
The construction of the arm is of sheet metal. This is easy to fabricate automatically. The cross section a-a on page 11 can be made using sheet metal. Filling the entirety of the shape BDC with sheet metal gives excellent strength against deflections within the plane of the page and provides greater strength against deflections out of the page than could be achieved by solid beams, for the same weight or cost.
Thin, spread out structures optimise the strength for a given weight or cost. Sheet metal construction is the most simple method of achieving this.

5.2.2.3 The Support Rings, Wheels and Guides

The support rings provide the mechanical support of the structural arms and provide facilities for azimuthal position measurement and azimuthal actuation of the arms.

5.2.2.3.1 The Rings

Each support ring consists of an L beam bent around into a circle. The L profile provides access to horizontal and vertical support of the arms. The L profile provides structural strength without excessive weight, given that the ring is loaded with vertical and horizontal concentrated loads from the arms and supported on a continuous foam support. The inner ring can be produced with a tighter tolerance against radius variations than the larger outer ring since it is of smaller radius. Both rings should have tight tolerances against height variations of their flat faces since the arms will rest on both of the flat surfaces.

5.2.2.3.2 Mechanical Support

Since the inner ring is of higher accuracy than the outer ring, the arms will be designed to be constrained against radial movement by attachment on the inner ring. The attachment on the inner ring will be coupled firmly onto the arms. The attachment on the outer ring will be flexible, allowing for radial variations in the outer ring.

The two support rings must support the arms against downward force due to their weight, radial forces, and three components of torque. Shown on page 13.
For simplicity, the arm will only be driven around the rings on the outer ring. Consideration of the forces involved in driving the arm from the outer ring is given on page 13. The motors push the arm forward with force P, against friction at points B and

C (forces Fb and Fc respectively). Balance of forces and moments requires a moment at C or B. The moment at B would need to have a magnitude of Fb L and direction as shown.
Effectively, this moment is needed to turn the arm in order to keep it pointed along a radius and prevent point C from advancing along the circle and jamming the arm.
This has implications for the placement of the wheels at point B as shown. This moment supporting attachment is consistent with the tight attachment onto the inner ring necessary for radial constraint.

Consideration of a force Fd is given. Fd is directed horizontally and may be due to wind loading, acceleration, or any incidental force. Fd must be supported at B and C by a force and a moment as shown. This has implications for the wheels at B and C as shown.

Other forces as shown on page 13 can be checked to determine a minimal but sufficient arrangement of wheels on the two rings.

5.2.2.3.3 Azimuthal Position Measurement

The azimuth is measured by finding the distance around the arc of the support ring from the arm back to zero azimuth. Length measurement markings can be made on flexible metal tape which is then wrapped around the cylindrical face of the support ring. An appropriate reader is mounted on each of the arms, enabling them to determine their azimuthal position.
The tape should be placed where sufficient accuracy and resolution can be obtained for the minimum cost. The linear resolution required for a given angular resolution varies with radius, so placing the tape at the larger ring means the tape can be of coarse linear resolution. On the other hand, the linear resolution of the tape and the accuracy of the tape is fairly easily improved by choice of the manufacturing process, whereas the accuracy of the support rings would be much more difficult to improve. Therefore, placing the tape on the smaller (more accurate) support ring, and producing the tape at higher resolution seems to be the preferable option.

5.2.2.3.4 Azimuthal Actuation

Motors mounted on the arm at the outer support ring drive the arm in azimuth. The motor and gearbox drive one wheel while another is free running; Both are pressed onto the support ring by a spring. The spring must apply sufficient force that the resulting friction between the wheels and the ring is sufficient to maintain rolling contact while the motor drives the arm.
The position of the two wheels is free to adjust in radius so that the drive mechanism does not require tight tolerances on the radius of the outer support ring. The mounting of the motors and wheels must be sufficiently tight to reduce azimuthal backlash in case of incidental forces in azimuth.
Ideally the azimuth drive motors do no work, since the arms travel relatively slowly and the height of the centre of mass does not change. However, some friction will be present due to the various wheels that attach onto the two support rings. The speed will be low (~2 cm s^{-1}) and therefore it is likely that the 1 Watt motors which were discussed in

section 5.1.3.1 would suffice for the azimuth drives. Of course, a suitable gearbox would be needed to increase the torque of the motor to the required level.

5.2.2.3.5 The Guide Bogie

The connection between the arm and the support ring is through the guide bogie. The guide bogie holds the various wheels, the motor, gearbox and drive wheel, and the encoder reader, as well as mounting onto the arm.
The guide bogie is constructed from sheet metal. Sheet metal is convenient for forming the variety of tabs, arms and brackets within the guide bogie. The guide bogie is subjected to the support loads required as described above in (mechanical support). The sheet metal should be sized according to these loads.
In addition to the main sheet metal of the body, the wheels, motors and other components can be mounted using standard fasteners. Some fasteners or welding may be needed to form reinforcing on some parts of the sheet metal.

5.2.2.4 The Feed Carrier and the Feed

5.2.2.4.1 The Feed and Radial Positioning

The current design proposed for the feed is described in reference [1]. The feed consists of a square pyramid, with a hollow cavity on the inside of the pyramid. Different positions along the length of the feed must be positioned on the focus sphere of the lens according to the operating frequency. The feed carrier must therefore be able to translate the feed along a radius of the sphere to adjust the focus according to the frequency. The length of travel required is a fraction shorter than the length of the feed itself.
It is possible that the centre of the feed may be used for parts of the radial translation system that protrude forwards when the feed is retracted. If it is not permissible to put structures inside the feed, then stacking and telescoping arrangements are possible which reduce the length of protruding parts.

The radial translation system consists of a central screw. The feed is attached onto the screw such that when the screw is rotated, the feed is extended or retracted. The feed is supported against rotation and sideways deflection by a set of straight bars near the screw. The whole arrangement of the screw and bars must be sufficiently narrow to fit into the small region near the tip of the pyramid. The bars end before the tip of the pyramid since the length of travel is shorter than the length of the feed itself. The size of the bars must be such that they satisfy a maximum deflection condition under the weight of the feed applied sideways.
A more complicated scheme involves several bars, platforms and screws that can collapse down into a short length if this is needed.

5.2.2.4.2 The Feed Carrier

The feed carrier is required to support the feeds against all forces and moments, and to be able to drive the feed along the arm for positioning in altitude. The feed carrier attaches onto three faces of the arc. Drive wheels are pressed against the face and back surfaces by spring loading, enabling drive and support forces by friction. Having wheels spaced on the width of the arc and also along a small length of the arc allows moment support.

To reduce complexity, the side supports consist of sliding material that presses lightly against the surface of the arc. This slide material is for light loads only, since side loads will be minimal, due only to wind loading on the feed and incidental forces. The sides are also not involved in support against moments, except for torque applied to twist the feed, which would be very unusual. The slide material saves on the complexity of spring loaded wheels on the side but achieves the same results. The materials used are designed for long life under harsh conditions and low loads. Some light spring packing can be used to press against the sides to minimise sideways backlash.

The body of the feed carrier is constructed out of sheet metal, in a similar method to the construction of the guide bogie. Welding or fasteners may be needed for forming reinforcing. The wheels, axels and other components can be made out of standard components.
The radial positioning system and feed are mounted on a flat platform above the wheels and motor of the feed carrier.

5.2.2.5 The Frame

The prototype lens system will utilise the existing supports on the lens, and therefore the support of the lens will be a conventional frame. The frame will be re-built in order to fit the entire positioning system within it. The frame is intended to allow the prototype lens system to be easily transported, since it will be moved around in its role as a prototype demonstrator and test system. The frame will consist of a substantial base frame for the support rings to mount onto, the lens frame to mount onto and for lifting during transport. The lens will be supported by its existing rubber mounts, ball joint and threaded bars. The lens may remain within its current octagon frame, or complete new framework may be built.
A framing system is possible in which each corner or point in the frame consists of plates welded at right angles, and the beams are each fastened onto the plates. The frame is a braced structural frame, where the joints are not required to have large moment strengths.

By contrast, the full scale lens will most likely be supported on a single, wide column.

5.2.3 Other Requirements

5.2.3.1 Cable Management

The cables for power and signals that may be needed for the feed and feed carrier can be routed via the arms to ground. On the arm, the cables can run via standard ‘cable snake’ devices which constrain the cables to a plane but allow movement within that plane. The cable snake devices also limit the minimum radius of curvature of the cables, helping to prolong their life against internal damage. Cables designed for constant flexing exist and should be considered.
The cables can pass to ground by leaving the arm at the inner edge (small radius), wrap around the inside of the inner ring and leave by passing underneath the support rings. The arms will have to be limited in azimuthal range to prevent the cables from accumulating large twists (up to a few rotations). This is not a problem, especially where

there is more than one feed, since the feeds cannot cross over they have limited azimuthal range.

5.2.3.2 Upgradeability

The use of common support rings, and encoders means that adding extra arms over time is not difficult. Additional arms can be placed on the support rings, have wheels tightened on the rings appropriately and signal and power connected.
The system is also very modular; The fixed parts of the positioning system (two support rings) are independant of the lens and the upgradeable parts (arm, feed carrier and feed) are independant of the support rings.

5.2.4 Conclusion to the Proposed Structural Arms Architecture

The structural arms architecture is potentially the most simple and cost effective solution to the Luneburg lens positioning system. Constructing the prototype from this architecture should serve to highlight further design options.

to be completed.

References.

[1] G. James, "Design Of a Luneburg Lens Antenna Element for the SKA", CTIP circulated document, 18/02/2002

[2] A. Parfitt and P. Hall, "Animation of Luneburg Lens Focussing Action", http://www.atnf.csiro.au/SKA/ll_animation.html.

[3] G.L. James, A.J. Parfitt, J.S. Kot and P. Hall, "A Case for the Luneburg Lens as the Antenna Element for the Square Kilometre Array Telescope", The Radio Science Bulletin, June 2000, pp32-37.

[4] Parkes Radiotelescope Observers Guide, "Overview of the operating and control system". http://www.parkes.atnf.csiro.au/documentation/manuals/observers_guide/OBG_4.html

[5] Australia Telescope Compact Array Users' Guide http://www.narrabri.atnf.csiro.au/observing/users_guide/html/node69.html

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