The Large Adaptive Reflector as an Element of the Square Kilometer Array

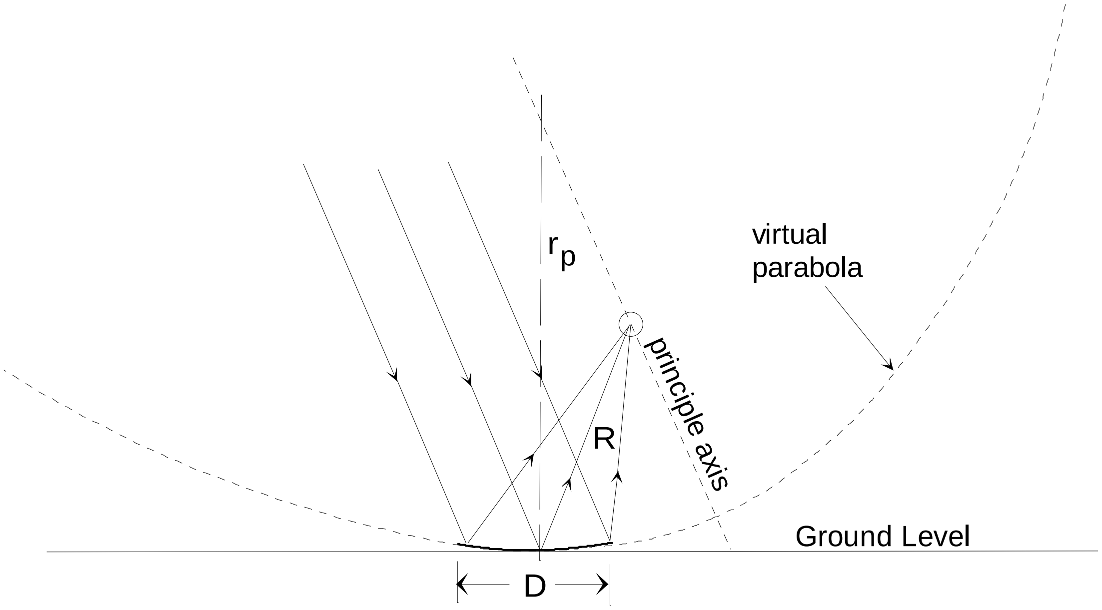
P. Dewdney
National Research Council of Canada
Herzberg Institute of Astrophysics

ABSTRACT

The Large Adaptive Reflector (LAR) is a concept for a large, low-profile parabolic reflector. If key technical challenges can be met (the design of a tethered aerostat platform for the focal-plane equipment and a large phased-array feed), the LAR will provide a cost-effective solution for the elements of the Square Kilometer Array (SKA). It meets a very large fraction of the SKA design goals, especially the scientifically important wavelength coverage, most of the field-of-view (FOV), and sky coverage. However, it cannot provide widely-spaced, instantaneously deployable beams on the sky - useful for rare transient events and pulsar research. Its reflective optics system ensures high utilization of physical collecting area (apart from the foreshortening factor). Between 40 and 60 LAR's would be required to meet the SKA goal of $A_e/T_{sys} = 2 \times 10^4$ m^2/K at 1.4 GHz. As this ratio is fairly constant over wavelengths from 2 m to 1.4 cm, full SKA wavelength coverage can be provided with a single solution. Dynamic range simulations indicate that the LAR can easily provide high-quality images of the sub-microJy sky at 1.4 GHz. Although the cost is presently high for a signal processing and correlator system for the SKA utilizing LAR's, feasibility is not in doubt. The LAR design does not heavily depend for its success on improvements emanating from "Moore's Law" assumptions. Nevertheless, such improvements can be harnessed very efficiently, because the concentration of receiving and signal-processing electronics at the focus of the LAR is very amenable to periodic replacement without jeopardizing the entire SKA investment. Although imaging is still a great challenge, the relatively modest numbers of baselines in the array will enable imaging of the entire FOV to be possible.

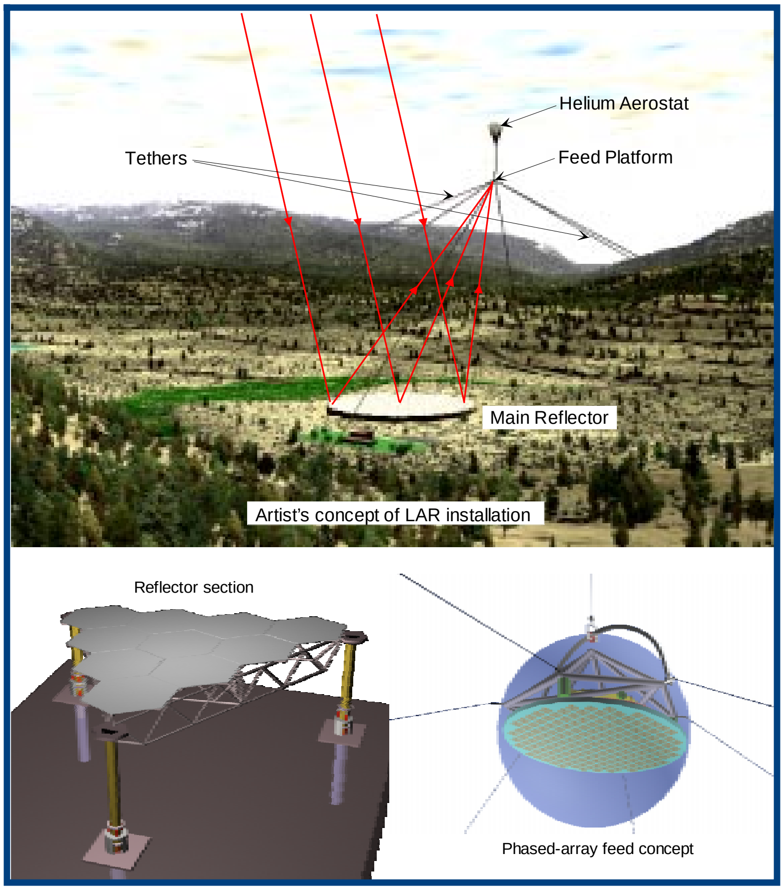
The advantages of the LAR for the SKA are a) The LAR covers the entire wavelength range. b) The risk factors are concentrated in a few areas that can be independently verified. c) The correlation and imaging problems are not too far from being solvable. d) The performance of the SKA is fairly uniform with wavelength, and can be accurately predicted. e) The construction and operational cost can easily be derived from a prototype, and does not depend upon scaling assumptions. Thus, an SKA design utilizing LAR's will provide a high degree of surety that a high-performance telescope can be constructed in 10 years.

LAR Principle



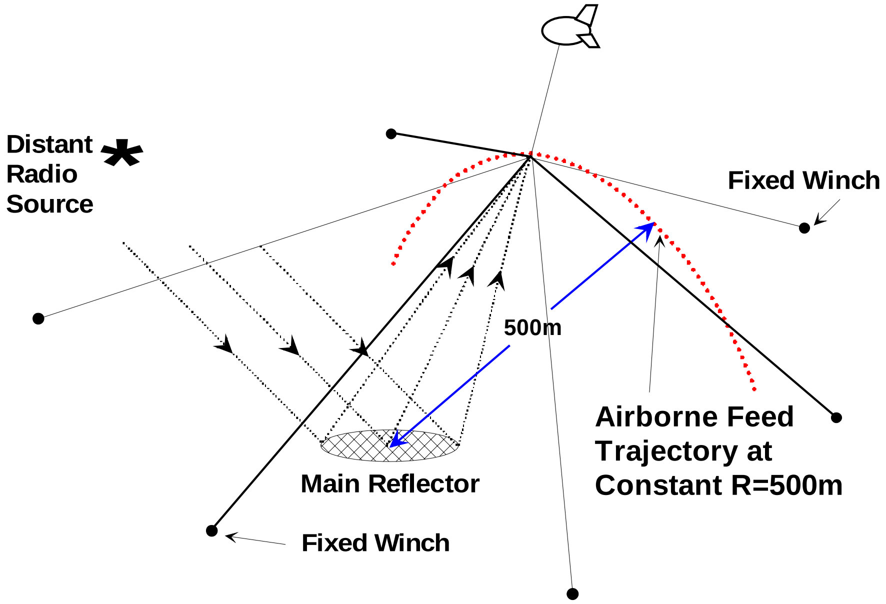
The LAR surface forms part of a much larger “virtual” parabola (shown in section along with its principle axis in dotted lines). For a fixed R, as Zenith Angle (Za) pointing changes, the height of the surface must only change a small amount along the x-axis (in the plane of the figure). Larger Za changes requiring larger actuator strokes occur along the y-axis (out of the plane of the figure). Note also that there is foreshortening of the available collecting surface area as Za increases. The sky-area weighted foreshortening efficiency for an Elevation Angle limit of 30º is about 75%. There are essentially no scattering objects in the ray path from the sky to the focus.

Construction Concept for a 200-m LAR



The installation includes the main reflector, the multi-tethered aerostat system, the feed platform at a focal length of 500 m, a surface measurement system (not shown) and a feed platform position measurement system (also not shown). The feed is held in place by a tension-structure, consisting of three or more tethers tensioned by the lift of a large, helium-filled aerostat - a stiff structure that effectively resists wind forces. The telescope is steered by simultaneously changing the lengths of the tethers with winches (thus the position of the feed) and by modifying the shape of the reflector. At all times the reflector configuration is that of an offset parabolic antenna, with the capability to point anywhere in the sky above ~15º Elevation Angle. Details of a main reflector section and the prime-focus phased-array feed concept are shown at the bottom of the figure. A full main reflector will contain about 150 sections. Each triangular section is supported by a space frame, and is 20 m on a side. Space frames are supported by large-stroke actuators that are shared with neighbouring space-frames. The phased-array feed contains pointing and stabilization mechanics, phasing networks, and cryogenic coolers. At 1.4 GHz, the feed is about 8 m in diameter and contains approximately 2300 elements which enables it to produce about 150 primary beams over an area of sky about 0.8º in diameter.

Tethered Aerostat System



The principle of a tension-structure is that there is sufficient tension force in the tethers to offset external horizontal wind forces (i.e. the tethers are "pre-tensioned"). Wind-induced deflections are small if there is sufficient tension that deflection forces do not significantly change the profile of the tethers, but stretch the tethers instead. An aerostat provides a lifting force (about 40 kN) sufficient to maintain tension in the tethers, as well as to carry the load of the feed platform. The strength-to-weight ratio of the tether material is critical. Strong, lightweight cables that have eight times the strength-to-weight ratio of steel cable are commercially available. The tethered system contains several components: the tethers, the feed platform, the winches, the aerostat, and a control system (to drive the winches). The aerostat is offset from the confluence point by a "leash", which is about 100 m long. The leash acts as a mechanical low-pass filter that minimizes coupling of aerostat motion to the feed platform. The minimum number of tethers is three. However, six tethers have been found to reduce the footprint of the telescope, to improve Azimuth pointing and to increase slightly the open-loop stability of the system.

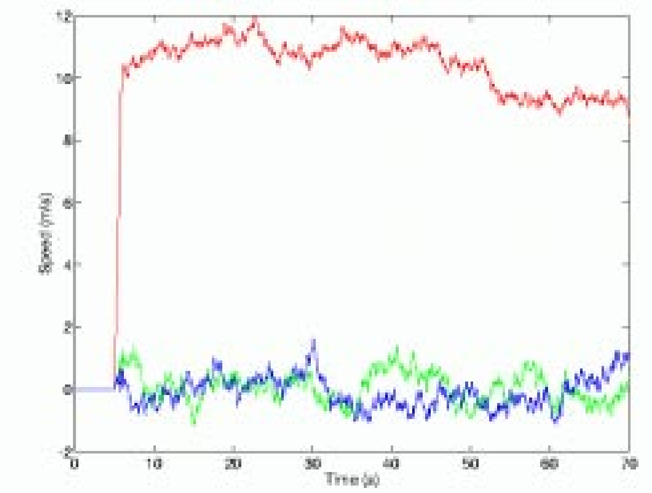
Feed Stability

The following factors are important in considering the stability of the feed system:

a) The actual position of the feed need not be controlled accurately. Only its rate of motion need be kept in check. Any slowly varying offsets (or constant offsets) can be tracked by imparting a tilt component to the shape of the main reflector. Since the reflector is fully actuated, this does not require additional equipment.

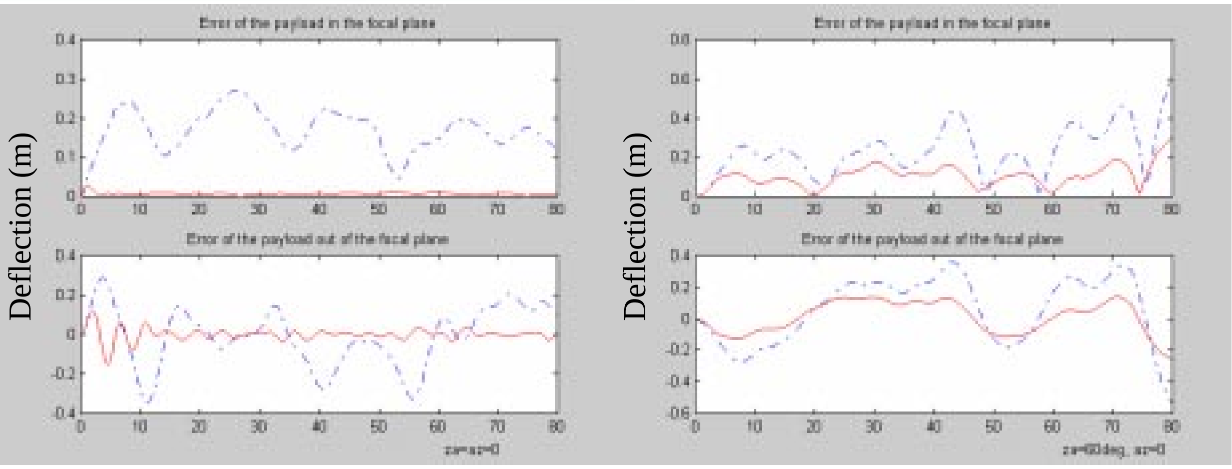
b) The stability requirement scales with the size of the feed system. At low frequencies where the feed system is largest, the stability requirement is least stringent and at the highest frequencies where the feed is smallest, the stability requirement is most stringent.

Aerodynamic Modeling



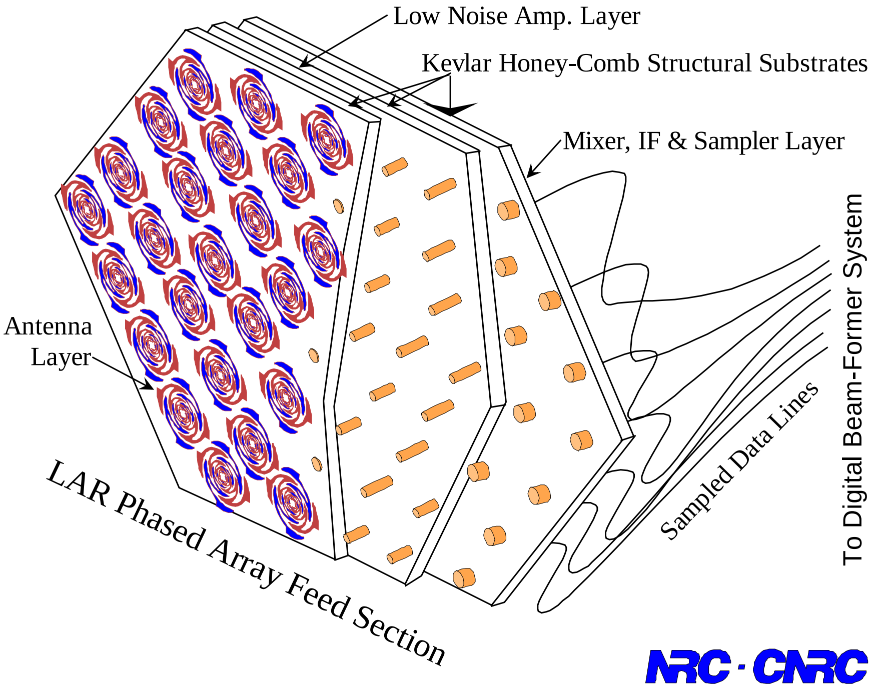
Preliminary Results:
Tethered Aerostat Simulations

Left: Simulated wind velocity in the x, y, and z directions (red, blue, green respectively). The mean wind speed at 500-600 m altitude is 10 m s^{-1}.
Bottom Left: Aerostat deflections in the focal plane (open loop - dotted blue; closed loop - solid red) at the Zenith.
Bottom Right: Aerostat deflections at a Zenith Angle of 60 degrees.



Extensive work has been done to model the dynamical motion of the feed in gusty wind conditions. The model's computer code has its heritage in the computer simulation of towed robotic undersea vehicles, where it has undergone extensive experimental validation. The results indicate that a 6-m size feed system can be stabilized to within 10-20 cm in typical wind conditions, using only the tethers and a controlled winch system. The actual feed must be stabilized to an accuracy of ± λ/4 (for a focal ratio of 2.5) in the focal plane to maintain accurate pointing of the telescope to 1/10th of its primary beam. At a wavelength of 20 cm (1.4 GHz), the focal plane stabilization requirement is about 5 cm. Orthogonal to the focal plane, the stabilization requirements are much less severe (about 5 m at 1.4 GHz), due to telescope's large depth-of-focus. The smallest motions will be compensated on board the feed platform. The above figure contains preliminary simulation results for a three-tether system, and a rudimentary control system. Considerable improvement is expected with six tethers and a more sophisticated control system.

A Mid-Band Feed Concept



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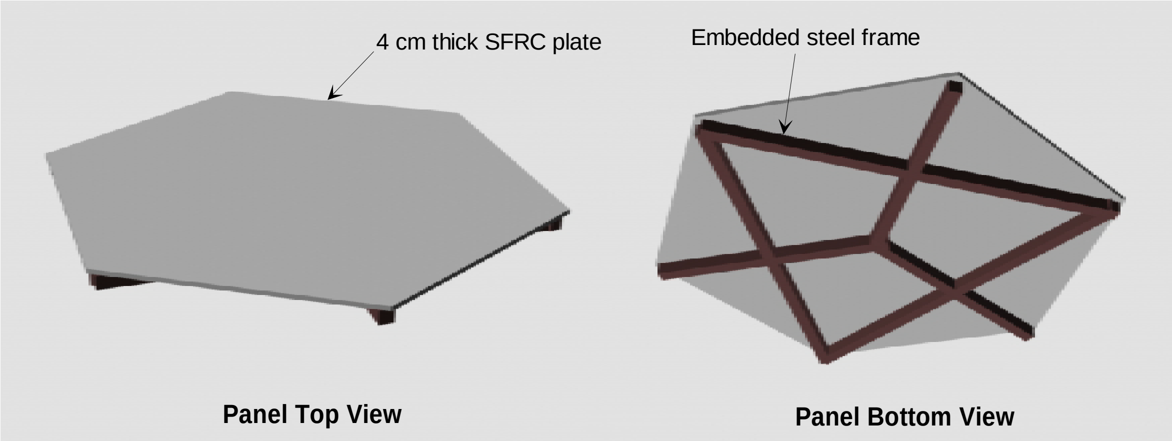
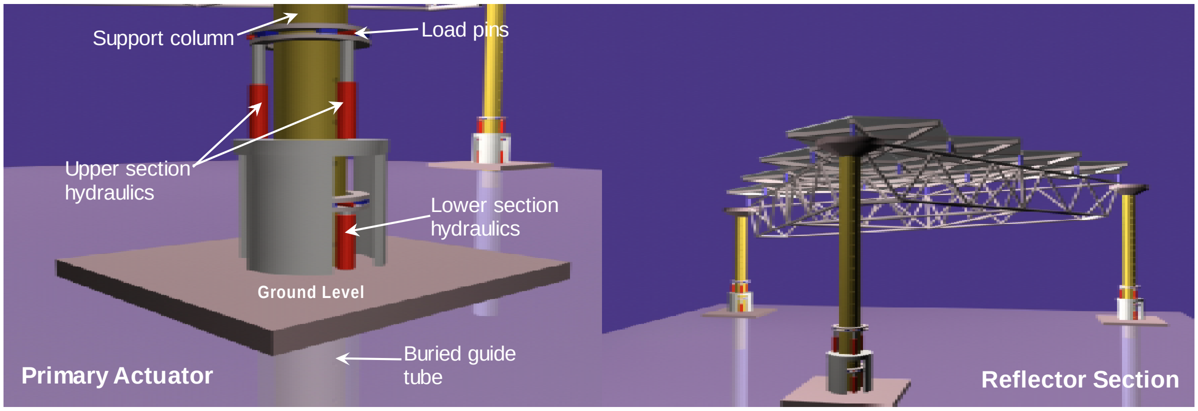
The feed will be mechanically steered to avoid scan-angle problems associated with electronic steering. Delay compensation and phase-shifter networks are not required. Shown is a hexagonal "construction block", probably 2-3 m in size. A number of such blocks would be joined together to make the full array. The elements are a sinuous, dual-polarization design, arranged in a hexagonal pattern. The bandwidth of the feed is about 700 MHz at a center frequency of about 1200 MHz. The bandwidth is limited mainly by the array pattern. The element spacing must be slightly less than the shortest wavelength in the band (e.g. 0.9 λ_{short}) to avoid a grating lobe in the plane of the array. The array is constructed in layers. The layers are fabricated separately, using high strength-to-weight materials for mechanical support, and then assembled. Hidden electrical contacts are made following procedures used in the printed circuit board industry. Local Oscillator signals, sampling clock signals, and possibly liquid nitrogen coolant lines are distributed on networks in the appropriate layers. The sampled signals go to a digital beam-forming system which, using the WIDAR beam-forming technique, produces beams across a number of sub-bands. The result is a very high-quality system that should be capable of accurately controlling the LAR illumination pattern, and producing an overall field-of-view about 0.8° in diameter.

Reflector Panels



Proposed to be constructed of a low-density concrete composite, the panels are supported by short stroke (10-15 cm) secondary actuators that provide final surface adjustment. Radio reflectivity is provided by “self-healing” zinc coating. The requirements for the reflector panels are that they are inexpensive, easy to construct, and stiff enough to meet the surface accuracy requirements for operation at a wavelength of 1.4 cm (rms surface accuracy of about 0.7 mm). Because of the long focal length, the panels can be fixed shape (nearly flat) and need not be particularly light. A concrete-and-steel construction ensures that wind-induced deflections will negligible.

Actuators and Reflector Construction

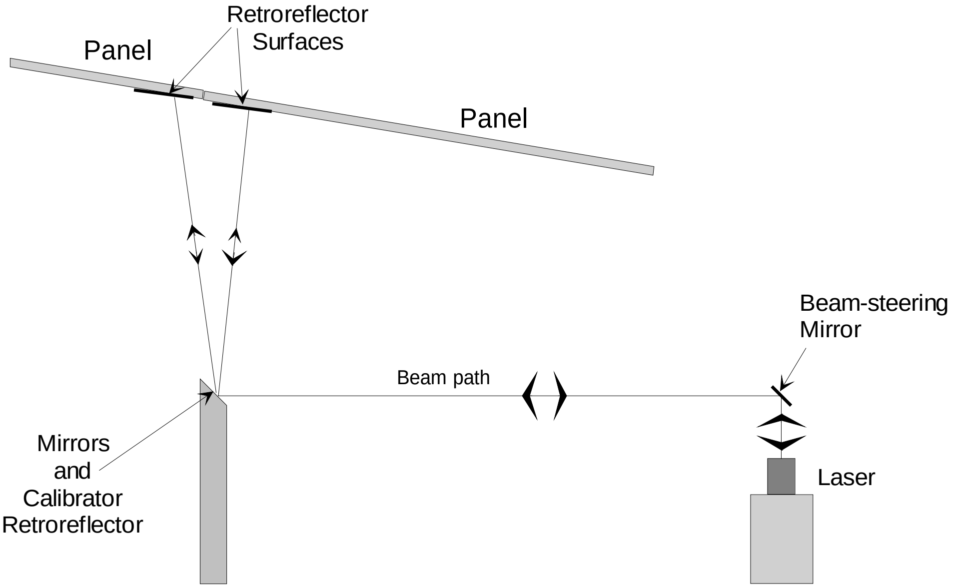


(a) (b)

a) The primary actuator consists of a hollow steel pipe about 45 cm in diameter with 3 columns of holes in which load pins are inserted to support the pipe. The upper and lower sections contain 3 short-stroke (~30 cm) hydraulic actuators. The support column is moved by alternately engaging load pins and driving actuators in the upper and lower sections. The support column slides into a buried guide tube in the ground. The column supports an overturning moment by ensuring that a minimum section of the support column stays in the guide tube even when fully extended.

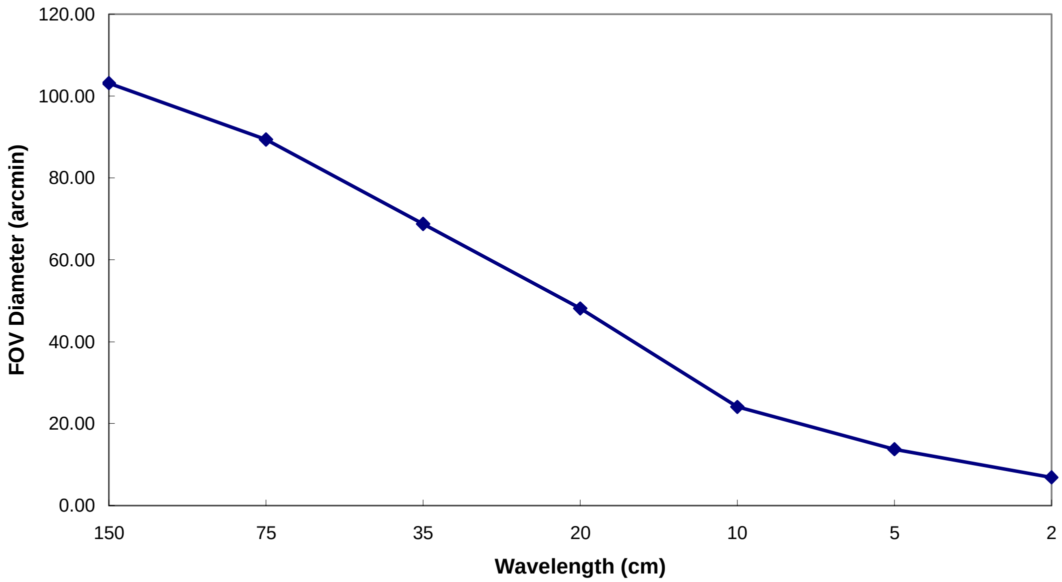
b) A triangular space frame with three supporting actuators. In the full surface, adjacent space frames will be supported by shared actuators. Reflector panels are supported by short-stroke secondary actuators mounted on the space frame. Panels are hexagonal in shape and approximately 5 m in diameter. Space frames are approximately 20 m in length along each of their sides.

A possible surface measurement method



A time-of-flight laser, steered by a mirror with z-axis rotation, first measures the distance to the panels with mirrors via the path shown. It then measures the fixed distance to a calibrator retro-reflector adjacent to the mirrors that provides continuous absolute calibration. Additionally, it will occasionally measure the distance to LAR perimeter retro-reflectors that form the foundation of the LAR coordinate system. The rate at which panels can be measured will be determined by the rate at which the beam-steering mirror can be re-pointed and by the bandwidth of the laser modulation.

Field-of-View



The projected FOV as a function of wavelength. The main limitation to the size of the FOV is the size of a focal package that could be constructed for each wavelength band. Larger focal packages can be used at longer wavelengths, because stabilization requirements are less stringent.

Using the LAR for the Square Kilometer Array

Wavelength Range

The reflector optics and size of the LAR's permit its use over the full wavelength range, obviating the need for more than one technology (or more than one SKA). Since they must be equipped with feeds for each octave band, the question of the feed costs is central. Although they are complex devices with many receivers, in many respects they can be treated as single subsystems, susceptible to automatic assembly procedures in controlled factory conditions. Although an exact cost is not yet available, it is likely to be only a small fraction of the total cost, much smaller than building several entire SKA's operating over different wavelength ranges.

Output from correlator

For an SKA composed of 200-m LAR's with a maximum baseline of 500 km, the maximum integration time is about 3 s. With 60 LAR's in the array, about 4 x 10^{11} complex visibilities will be collected per hour in a 0.8° diameter field (~200 beams) at λ 21 cm, if there are 1000 frequency channels collected. This amounts to about 3.0 Tbytes per hour for each polarization product.

Imaging

A single LAR beam is about 210 arcsec in diameter (FWHM). The 500 km baseline yields a 0.1 arcsec synthesized beam. The image will need at least three pixels per beam (four is preferable). Thus the image sizes will have to be 13000-16000 pixels on a side to image well below the half power point of the FOV beam (2 x FWHM). About 300 frequency channels will have to be imaged to avoid beam smearing in the very wide factional bandwidth, and to take into account spectral index variations of sources. To image the 0.8° diameter field (200 beams, 300 channels) requires computation and deconvolution of 8-12 Tpixels of images for each polarization. If spectral index variations can be removed, a reduction by a factor of about 300 would be possible. More channels might be needed for spectral line imaging. Although daunting by today's standards, it should just be possible to collect and image with this quantity of data in 10 years time.

Imaging Dynamic Range

The LAR should be able to form beams with very well known characteristics because:

a) The antenna’s unblocked aperture minimizes sidelobes and scattering.

b) At the wavelengths where imaging dynamic range is most needed, the reflector surface is effectively perfect.

c) Because the phased array feed is small and concentrated compared with the main aperture, its design and manufacture can be controlled to high precision. Thus, the off-beam rejection of signals (strong sources and interference) is high. Within the beam, the amplitude response can also be controlled with high precision.

It has been estimated that the range of source strengths in a typical 1 deg^2 patch of sky is about 10^6 times the SKA sensitivity limit. Thus a computer image formed over a 1 deg^2 field-of-view must have an imaging dynamic range of 10^6. The size of a single LAR beam at λ 21 cm is about 3.5 arcmin. Over an average field of this size, the equivalent dynamic range of source strengths is only about 4000, well within range of current techniques. Obviously a few of the LAR beams will contain strong sources, and within those fields it will be much more difficult to image at the full sensitivity of the SKA. But imaging artifacts cannot easily spread to parts of the field covered by different beams.