The LAR concept for the Square Kilometre Array: responses to EMT and ISAC comments

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Contents

1 Recent advances in studies of the LAR concept

Since the LAR-concept White Paper was written, several areas of technical investigation have been advanced, which we summarize breifly here.

Beam forming: Our focus in this area has been in improving our understanding of how to make efficient wide-band beam-formers. We have continued our studies of coarse channelization and different channel weights to mitigate performance degradation over broad bands (Veidt 2003a). We have also started investigating other possible solutions, ranging from fine channelization via FFTs to wide-band correction with shaped FIR filters. This problem has also been studied in detail for acoustical applications, and a good candidate for a cross-over solution to microwaves is a scheme where FIR filters derive the weights (amplitude and phase) as a function of frequency (see, for example, DeLap & Hero 1993).

Multi-frequency feed: One attractive feature of Vivaldi antennas is the broad frequency range over which they can operate. Operation over a 5:1 frequency range has been demonstrated (e.g., Kragalott et al. 2000; Holter et al. 2000) but even this range is not sufficient to cover the complete SKA frequency range with a single Vivaldi antenna array. Although it is possible to have multiple feed packages that are exchanged whenever the observing band is changed, this is operationally inconvenient and would be incompatible with observations that require rapid changes in frequency. With a modest increase in array area and weight, a number of observing bands can be incorporated into a single feed package. We have started to explore various ideas for multi-frequency feed-plate layouts.

Data transmission: The large field-of-view specification requires the use of a large focal plane array of antennas. We have been investigating the data transmission requirements of such an array, in terms of the station-to-correlator demands, and the total bandwidth of the correlator. This is discussed in more detail in sections 2 and 3.3.

2 Responses to EMT questions

> *1. Can the authors outline the reasoning of how the "Small-N" LAR SKA implementation might achieve the specified dynamic range for the SKA? The comment (p.5) regarding the focal plane array and the small individual cluster beam size play a part in achieving the required performance could be expanded.*

The SKA specification is ~ 10 nJy in 8 hours with 10^6 dynamic range. Achieving this dynamic range will be a challenge. Standard aperture synthesis techniques now routinely achieve a dynamic range of 10^4, and 10^5 in some special cases. Table 1 summarizes the implications of these three

Table 1 The implications of 1.4 GHz source counts for various levels of dynamic range. S is the flux density of a source that will leave artefacts above 10 nJy. $N(>S)$ is the number of sources at this flux density or greater per square-degree (Ciliegi et al. 1999), and $N_{\rm LAR}(> S)$ is the number per LAR primary beam area.

Dynamic Range	S (mJy)	$N(>S)$ (deg^{-2})	$N_{\rm LAR}(> S)$ (beam^{-1})
10^4	0.1	10^3	3
10^5	1	10^2	0.3
10^6	10	10^1	0.03

levels of dynamic range in terms of source counts at 1.4 GHz.

Even for a dynamic ranges of order 10^6, the sky density of sources strong enough to leave artefacts above 10 nJy will be of order 10 per 1-square-degree field-of-view. Significant advances in data processing will be needed in order to achieve the required dynamic range in the presence of these sources.

The LAR concept's multi-beam approach to wide-field imaging actually offers substantial benefits in this area, as any dynamic-range problems caused by strong sources will be limited to the beam in which that source falls, with sidelobe suppression in adjacent beams of ~ 20 dB. Since there are 350 beams, at a 10^6 dynamic range we expect that typically only $(10/350) \simeq 3$% of the field will be contaminated by artefacts.

> *2. With the favoured Vivaldi feed arrays, some of the benefits conferred by a 'clean' optical path are negated, especially in polarization studies. The high cross-polarization sidelobes caused by the offset primary parabola will be variable in time as the offset angle changes. Can the authors outline what level of polarization performance they may expect?*

In what follows, all cross-polarized response levels are referred to the co-polarized primary beam at zenith angle $0°$ (the "reference beam"), as this will define the useful field-of-view of a given beam.

Cross-polarization in the LAR will be generated by both the Vivaldi feed elements, and by the off-axis optics. Polarization performance at the beam centre is determined by the feeds, which will give a cross-polarized response $\sim$ 20 to 30 dB below the reference beam. The worst-case optically-induced cross-polarization lobes occur for a beam at the centre of the field of view, at a zenith angle of $60°$. Under these circumstances the cross-polarized response is ~ 17.5 dB below the reference beam at its half-power radius (Veidt 2003b). Additional processing will therefore be required in order to correct this response to meet the SKA's -40 dB specification for polarization purity.

Two methods of correction are possible. The first is to observe with short exposures (snapshots) and then to apply a correction determined from the far-field radiation patterns to the images. The second is to exploit the capability of a focal-plane array/beam-former system to correct for optical aberrations and to modify it so that the polarization purity is improved in real-time. This would require an expansion of the beam-former so that it processes signals from both planes of polarization for each polarized output.

In either case, the corrections must be to the level of 1% in order to gain the required 20 dB in polarization purity. Key factors that will determine the level of cross-polarization contamination in the final radio-astronomical images will include such issues as: the number of bits to which the data and the beam-former weights are quantized, the maximum number of inputs to the beam-former, the accuracy of the computer model of the telescope that generates beam-former weights and beam patterns, the accuracy to which the Vivaldi-element properties (far-field pattern, residual cross-polarization) can be known, and the residual motion of the focal-plane platform and its magnitude and speed.

> *3. Presumably the LAR concept is subject to the same costs as e.g. Luneburg lenses or small-D dishes when it comes to transporting raw or beamformed data from stations. A filled fov is only retained if all the station cluster beams are transmitted. Would the authors quote their estimates for data transmission from stations and, if their concept requires data to be discarded (e.g. by not transmitting all station beams), could they outline a representative arrangement for signal transmission across the array?*

The output bandwidth of the LAR beam-former is a linear function of the number of beams (M), the required number of bits/sample (N) and the signal bandwidth (B). For two polarizations, and assuming Nyquist sampling, the data rate is $4BNM$. The number of beams required by the LAR to cover 1 square-degree at 21 cm is 350 (to compensate for foreshortening at zenith angle 60°). Thus, for the SKA-specified bandwidth of 800 MHz at 21 cm, the maximum beam-former output is $1120N$ Gbit/s. Since the SKA transmission bandwidth is likely to be a limiting factor, the beam-former output can be reduced by either reducing the number of bits/sample, the receiver bandwidth, or the number of beams. For example, for 1 beam at 21 cm, the rate is $3.2N$ Gbit/s.

In spite of this high bandwidth requirement, simple calculations show that data transmission requirements do not differentiate between SKA concept proposals. Any station-based concept (Large-N, Small-N, etc.) require data rates from station to correlator that are proportional to the effective collecting area of a station (see Veidt & Dougherty 2003). For the same observed field-of-view, the total data rate into the correlator is the same within factors of a few, regardless of how the collecting area is configured. Thus, Large-N arrays require comparatively lower-capacity data links than required for a Small-N array, but proportionately more links are required.

Potentially the data-transmission infrastructure for the SKA will be cost-limited, and upgrades will occur only infrequently (e.g., only a limited number of optical fibres would be available). In this case, either the bandwidth or the field-of-view will have to be scaled accordingly. Presumably, however, the need for very large instantaneous fields-of-view will decrease at large baselines.

> *4. Hydraulic rams (including the types mentioned on p.37) operating in hostile environments need attention in areas such as seal replacement. Are the actuators envisaged suitable for use in a range of potential SKA sites or might there be problems in e.g.. very sandy, environments? What level of maintenance might be needed and does this look feasible for perhaps 10,000 long stroke units?*

Environment. Hydraulic cylinders are used in a large range of industrial applications because they are able to survive harsh operating environments. The modern hard surface finishes applied to cylinder rods, effective wipers and seals, and constant lubrication from the hydraulic fluid enable hydraulic cylinders to operate reliably in dirty environments. This is evidenced by their almost ubiquitous use on earth-moving equipment. The operating environments of possible SKA sites do not appear to be particularly harsh compared to many locations where hydraulic cylinders are in use, e.g. offshore oil platforms, steel mills, open-pit mines. In addition, the immediate environment of the actuators can be controlled to further improve the operating conditions e.g. actuator boots.

Actuator reliability. Data from the Reliability Data Center (http://rac.alionscience.com) shows the failure rate of hydraulic cylinders to be 0.008 failures in 10^6 operating hours. This implies that for a 60-element SKA with a total of 10 800 cylinders, on average one could expect a cylinder failure every 1.3 years.

> *5. Can the authors expand on the statement (p.17) that the cost of linear actuators is approx. proportional to throw? If the system is a hydraulic one, would not the need for larger diameters in the cylinder, piston and connecting rod assembly (to resist lateral loads and buckling forces) lead to a steeper cost dependence law?*

To demonstrate that the cost of actuation with hydraulic cylinders is closely linear, we have taken cost versus actuator throw data from a typical hydraulic cylinder manufacturers web site. These data are plotted in Fig. 1. Perhaps surprisingly, the cost/throw relationship is closely linear even for a range of actuator diameter and stages.

We do not anticipate subjecting the actuators to lateral loads since our current actuator designs are pin-ended.

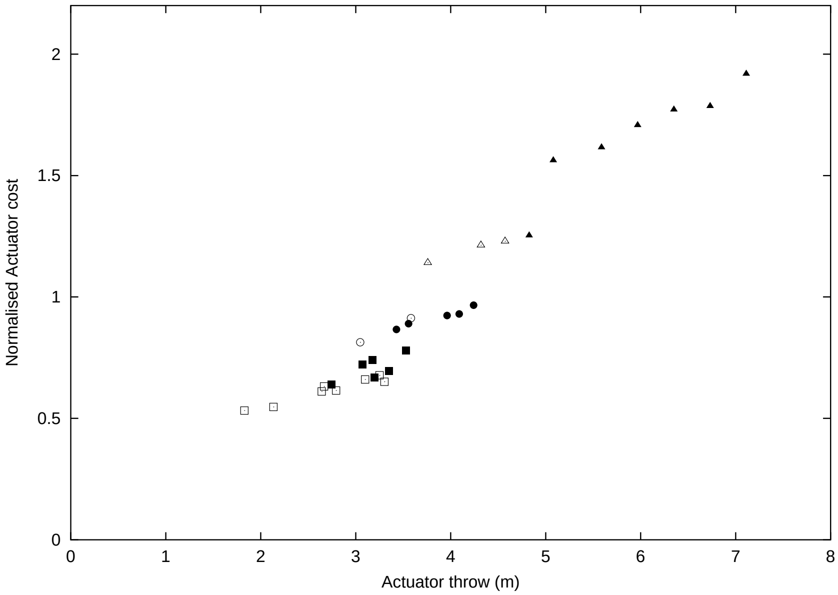

Figure 1 Example actuator costs as a function of throw. Data taken from http://www.baileynet.com. Different symbols represent different cylinder types: 3 stage, 5” diameter 1st stage (open squares), 3 stage, 6” 1st stage (filled squares), 3 stage, 7” 1st stage (open circles), 4 stage, 7” 1st stage (filled circles), 4 stage, 8” 1st stage (open triangles), 5 stage, 8” 1st stage (filled triangles). The cost curve is closely linear over the range of throws required by a 200-m diameter LAR.

6. Can the authors give an indication of typical source-change times, bearing in mind the composite performance of the various mechanical systems?

The source-change time of the LAR is determined by the speed that the tethered-aerostat system can be moved, which is determined by the speed of the winches, and by the amount of power required for reconfiguration of the reflector surface. We discuss these issues more extensively in section 3.2.

A slew of 180 degrees in azimuth, from zenith angle limit (60°) to zenith angle limit, can be done with a modest power requirement. In this case, the bulk of the available power is used for moving the aerostat since the reflector only undergoes a small reconfiguration. Increasing the power of the winches leads to increased slewing speeds, and in section 3.2 slew rates as high as 4.6 degrees/second are considered.

The power available for slewing is severely impacted when it is necessary to move the reflector surface. The largest reconfiguration of the reflector surface occurs for an azimuth change of 90°. Here, the slew rates could be as low as 0.1 degrees/sec (see section 3.2 for details). Typical slew rates will lie between the two extremes quoted.

3 Potential links between the LAR concept and SKA sites

3.1 Requirements or limitations associated with particular terrain and climate:

Large aerostats have been operated in desert to arctic conditions. The aerostat envisaged for the LAR will be very robust in most weather conditions, even in high winds. Its altitude can be adjusted almost independently of other parameters, to suit the terrain and local turbulence. Nevertheless, conditions of extremely destructive weather, such as hurricanes and frequent severe thunderstorms would be a concern.

3.2 Approximate energy requirements for central array and remote stations

The major demand on power for the LAR concept is during slewing. As a bench-mark, we adopt a 500 second slew from azimuth $0°$, zenith angle $60°$ to azimuth $180°$, zenith angle $60°$ that requires 120 kW (Nahon, Gilardi & Lambert 2003). Under the assumption that the drag on the aerostat increases as the square of the air speed, we have calculated slew speeds for several different input power levels.

There are two extreme *peak power* cases to be considered. Case 1 is an azimuth angle change of $180°$ from zenith angle limit to zenith angle limit. Here there the reflector surface moves very little, and the power required is dictated by the drag of the aerostat. Case 2 is for an azimuth angle change of $90°$. This requires the largest change in reflector configuration, which dominates the power budget.

In Table 2, the slew times and rates are given for several different levels of available power. A headwind of 10 m/s ($\equiv$ 36 km/h) is assumed in all cases. An overall power efficiency of 65% has been assumed. We also assume that the power required by the feed package is small compared with the peak power required to move the aerostat and/or the reflector.

For case 1, essentially all available power is used to move the aerostat-supported focus platform.

Table 2 Slew rates for different levels of available power

	Case 1: $\Delta\mathrm{Az.} = 180°$		Case 2: $\Delta\mathrm{Az.} = 90°$	
Input Power (kW)	Slew time (sec)	Slew rate (°/sec)	Slew time (sec)	Slew rate (°/sec)
100	165	1.1	960	0.1
250	86	2.0	384	0.2
500	57	3.2	192	0.5
1000	39	4.6	97	0.9

However, in case 2 only $\sim$ 8% of the available power is used for moving the aerostat—the majority of the power is required for reflector adjustment, which results in the slew rates being lower than in Case 1.

Table 2 shows the power requirements for various slew rates of an individual LAR element. The power requirement of a core cluster can be readily determined by multiplying by the number of elements in the core.

3.3 Requirements for data processing and transport, including any need for local large-scale data processing or aggregation, as well as typical demands on international communications infrastructure.

In terms of over-all data rate, an LAR-based SKA places no more special demands on long-distance communications than the other proposed array concepts (see response to EMT question 3). The LAR concept is, in fact, very flexible with regard to data transmission and bandwidth requirements. Signals from the focal-plane array will feed a beam-forming network, thereby greatly reducing the total signal bandwidth, as only the beam data, and not the data from individual receivers, will be transmitted to the central correlator.

As shown in section 2, the data rates from the LAR can be scaled in various ways, depending on such aspects as the bandwidth that is economically available, the bandwidth required for the observation, the desired field of view, and the desired number of bits per sample. For example, in high-resolution observations requiring continental-scale baselines, the full 1-square-degree field-of-view will likely not be needed, so a small number of beams rather than several hundreds could be transmitted back for correlation.

It may well be the case that any SKA concept will be limited by available data transmission bandwidth. While the optimistic point of view is that the costs and capabilities of fibre-optic transmission systems will continue to improve so that any of the likely data transmission scenarios can be accommodated, a conservative view is that the telecommunications industry will stagnate and that costs and capabilities will be similar to what we have today. The LAR's flexibility in this area could therefore be a significant asset.

4 Response to ISAC assessment of LAR Concept

The ISAC has assessed the capability of all concepts for the SKA to address the Level-1 science goals of the project based on the concept White Papers submitted in Spring 2002. In this section, the assessment of the LAR concept by the working groups of the ISAC regarding these goals is summarised, followed by comments on the major issues arising.

The assessment of the LAR concept by the ISAC is summarised in Table 3. Columns 1 and 2 give

Table 3 The LAR concept and SKA Level-1 science goals

WG	Science	ISAC Grade[a]	Our Grade[a]	Comment summary
1	Galactic HI	3	5	Compact configurations
			5	Low surface brightness sensitivity
1	Galactic NT& Magnetic fields	3	5	Compact configurations
			5	Low surface brightness sensitivity
2	Transients	2	4	Subarrays
			4	Response time
2	Pulsars	2	2	Beam separation
			4	Subarrays
			4	Response time
2	SETI	2	4	Response time
			5	Independent IF's
3	EOR	4	5	Low surface brightness sensitivity
			5	Low frequency limit
4	HI Surveys/LSS	4	5	Compact configurations
			5	Low surface brightness sensitivity
4	Continuum Surveys	4	5	
4	CO Surveys		5	
5	High redshift AGN	2	4	Subarrays
			5	Longest baselines
5	Inner AGN	2	4	Subarrays
			5	Longest baselines
6	Proto-planetary disks	5	5	
7	CMEs	3	5	Low frequency limit
			5	Configuration
7	Solar System bodies	4	5	Brightness sensitivity
8	IGM (Non-thermal)	4	5	Compact configurations
8	IGM (Thermal)	4	4	Upper frequency limit
			5	Longest baselines
9	Spacecraft tracking	3	3	Upper frequency limit
9	Geodesy	4	4	Upper frequency limit
9			5	IF separation

[a] Grades of compliance of the LAR concept and Level-1 science – 1=No 2=Maybe 3=Maybe 4=Yes 5=Yes, adopted from the compliance matrix.

the working group and the Level-1 science goal being addressed, column 3 the ISAC grade of the LAR's ability to address those science goals and column 4 is our own assessment of how well the LAR addresses the science. As is readily seen we believe that the LAR concept can address all the Level-1 science goals set by the ISAC.

The major concern of the ISAC working groups relates to the configuration capability of the LAR concept, particularly compact configurations, and specifically baselines in the range 200-1000 m. In the original LAR White Paper, studies of potential SKA configurations were largely missing. We redress this situation in Section 4.1 where configuration studies are discussed. The other concerns raised include sub-arrays, response time, beam separation, the number of independent IFs and the upper and lower frequency capability. Each of these are also discussed below.

4.1 Array Configurations with the LAR

The LAR concept involves a 200-m diameter collecting area with a $\sim$ 1400-m diameter tether anchor-point footprint. The large tether footprint prompts the question of whether it is possible to attain compact, well-filled configurations using LARs, especially since such configurations require the tethers to be intermeshed. In this section, we demonstrate that compact configurations can be attained using the LAR without tether conflicts, and highlight the brightness temperature capability of such arrays.

The most important constraint on array configuration for LARs is the need to avoid tether intersections between tethers from different antennas separated by less than 1400 m. The bulk of our efforts in LAR configuration studies have been devoted to determining the tether separations for various configurations, assuming a zenith angle range of 0° to 60°, and 360° of azimuth. Our calculations assumed that each 200-m diameter LAR has a 6-tether system with a 1400-m diameter footprint. Each tether is separated by 60° in azimuth, and the focus is 500-m from the centre of the reflector.

Calculations of the tether separations for array configurations were made with the goal of avoiding tether intersections. The position angle of the tether system was the only parameter manipulated in this study, largely to avoid tether anchor points falling on reflector surfaces, but also to maximize tether separations. More complex variations in tether set-ups are possible (e.g., varying the angle between adjacent tethers, altering the radius of individual tether anchor-points) that give more freedom for optimization of the tether configuration, but these were not required in the array examples we have examined.

4.1.1 50% of the area within 5 km

The ISAC report from Groningen (Carilli et al. 2002) suggested that the compact central core required by many of the Level-1 science goals should be ~ 5 km diameter and contain $\sim 50\%$ of the total collecting area. As explained in the LAR White Paper, to attain the specified $A_{\rm eff}/T_{\rm sys}$ requirement for the SKA using an array of LARs, accounting for all the various efficiencies and the sky-weighted foreshortening, would require a 60-element array. In this section, we investigate placing 30 LARs within a diameter of 5 km.

In Fig. 2 an example of an array is shown where 30 elements have been placed within a diameter of 5 km such that there are no tether conflicts for all azimuth and zenith angles under consideration. For a source in the Zenith, the maximum and minimum baselines are 4950 and 200 m respectively. We stress that this array is just one example of an array of LARs that satisfies the criteria set out in the ISAC report and is by no means unique. Other configurations can be readily achieved.

The brightness-temperature sensitivity is given by

$$\Delta T_b = \frac{T_{sys}}{f\sqrt{B\tau}},$$

where T_{sys} is the system temperature, B is the bandwidth in Hz, τ is the integration time and ζ is the filling factor, defined as

$$\zeta = A_{ant}/A_{core} \approx N_{ant} d^2/D^2,$$

where N_{ant} is the number of elements of diameter d in an array with a maximum baseline D. The 31-element array described above has a filling factor $\zeta \sim 31 \times (200/4950)^2 = 0.05$. Assuming a system temperature of 50 K, this implies a brightness temperature sensitivity of 1000 K in 1 sec and 1-Hz bandwidth. Taking 1 hr of integration and a bandwidth of 5 kHz ($\Delta v \sim$ 1km/s at 1420 MHz), this array achieves a sensitivity of 236 mK.

4.1.2 Short-spacing recovery in the LAR concept

The Small-N approach to the SKA design necessarily has large antennas, with diameter $D \simeq 200\,\rm m$ in the case of the LAR concept. The primary beam of such a large antenna is small, and physical baselines between antennas are limited to D or larger.

To overcome the concomitant problems of small field-of-view and inability to image spatial structures on the scale of the primary beam and larger, the LAR design uses a focal-plane array to produce multiple, simultaneous beams on the sky. These beams are formed in such a way as to overlap and provide a large field of view (up to 1 square-degree at 1.4 GHz). It should be stressed that these beams are formed *simultaneously*, and do not involve trade-offs from time-multiplexing, etc.

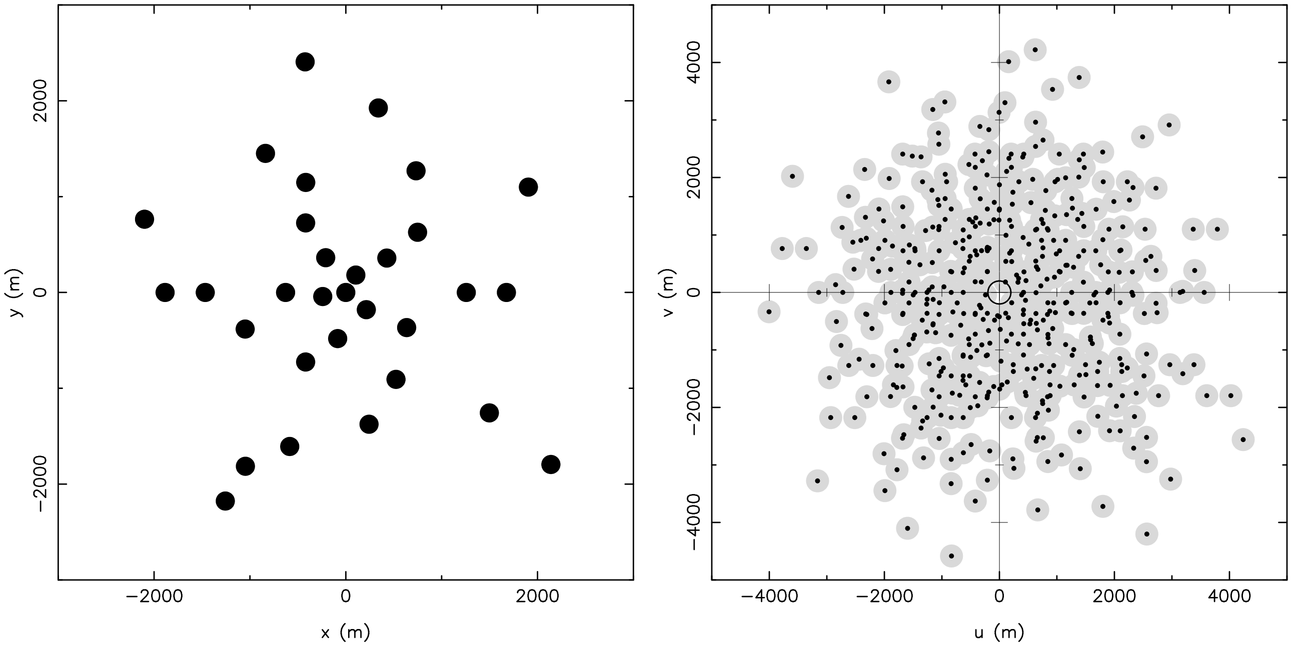

Figure 2 The left-hand figure is *one example* of an array where 50% of the total area of an SKA formed of LARs is within 2.5 km of the centre of the array *where there are NO tether conflicts* over all azimuth angles and for a zenith angle range of 0–60°. The array is based on a 3-arm spiral pattern, with 10 elements per arm, plus a central element. The right-hand image shows the instantaneous uv-coverage of a source in the zenith being observed with this example array. The black points are the nominal baselines and the grey areas are the $u - v$ patches recovered by mosaicing the multiple, simultaneous beams of the focal-plane array (see section 4.1.2). The circle at the origin represents the spatial frequency range of a 200-m aperture.

The issue of sensitivity to large structure will be addressed through the application of so-called "mosaicing" techniques (based on Ekers & Rots 1979), which allow the multiple, overlapping fields-of-view of the focal-plane array to be "stitched" together, simultaneously recovering the $u - v$ patch measured by each interferometer pair; that is, out to $\pm D/\lambda$ from the nominal spatial frequency.

Since LARs can, in principle, be placed immediately adjacent to one another, it will be possible to recover spatial frequency information corresponding to baselines significantly shorter than 200 m. In practice the sensitivity on the very shortest baselines will be limited by the aperture illumination (see Cornwell, Holdaway, & Uson 1993), but better knowledge of these spacings will be obtained by using the single-antenna map of the field-of-view obtained from total power measurements in each of the focal-plane array beams.

4.1.3 Shadowing

The LAR is essentially free of any shadowing problems. The worse case of shadowing is when a focus package is in the main beam of a reflector. In this situation, with a 10-m diameter feed plate, the shadowing of the field of a 200-m reflector is $(10/200)^2$, or less than 0.3%. Although the aerostat is quite large, it is transparent at radio wavelengths, and thus does not contribute to shadowing. This represents the maximum degree of shadowing to be expected.

With the LAR concept, the reflectors can be placed side-by-side without concern of shadowing from the adjacent reflector structure. The maximum displacement of the outer rim of a 200-m diameter reflector is 8 m, and so the maximum angle subtended by an LAR reflector structure by the adjacent reflector is 8/100 radians ($4.6°$). Since the minimum elevation angle of the focus package is $30°$, there will be no shadowing of the optical path by adjacent reflector structures.

4.1.4 Larger configurations

Considering that there are absolutely no tether conflict issues for baselines longer than 1400 m, there are no restrictions on array configuration imposed by the LAR concept for baselines longer than 1400 m, including intercontinental baselines, other than those that are common to all concepts (e.g., data transmission; see sections 2 and 3.3).

4.2 Subarrays

An SKA made up of 60 LAR elements can be sub-arrayed into arrays of smaller total collecting area. There are some restrictions imposed by different pointing directions and the need to avoid tether conflicts for those elements less than 1400 m apart. However, these restrictions are not expected to be critical. With the focal-plane array it will also be possible to observe independent targets using sub-sets of “beams” from within the field-of-view.

4.3 Response Time

Here we assume that response time implies slewing time, since that appears to be the limitation for making an observations of a source triggered by time-critical results from another telescope; e.g., a Gamma Ray Burst source. As seen in section 3.2, the slew rate of the LAR is set by the available power. Rates as high as 4.6 degrees/second have been described.

4.4 Maximum beam separation

The field of view that can be observed by the LAR is determined by the size of the focal plane array. Currently, the largest array being considered has a 1 square-degree instantaneous field-of-view at 21 cm. The beams can be placed anywhere within this field-of-view, but the field diameter (1.13 degrees) sets the maximum separation of simultaneous beams.

4.5 Independent IFs

The LAR concept envisaged for digital beam-forming inherently requires the use of more than one IF per polarization, if the instantaneous fractional bandwidth is greater than approximately 0.5 (Veidt & Dewdney, 2003). The LAR design imposes no particular limit to the number of IFs beyond this minimum. Note also that no reasonable design of data transmission system would impose a particular number of IFs.

4.6 Frequency range of the LAR concept

4.6.1 Low frequency

Given the recent WMAP results we think that it is useful to re-iterate the excellent low-frequency capabilities of the LAR concept. In Table 4 the performance characteristics of a 10-m diameter feed-plate are given, assuming a simple Gaussian illumination function for a zenith angle of 0°. At a given frequency the performance will degrade as zenith angle, and consequently foreshortening effects, increase.

It is clear from Table 4 that excellent antenna performance can be expected at 150 MHz. This

Table 4 Performance characteristics of a 10-m diameter feed plate as a function of observing frequency for an observation at a zenith angle of 0° (from Veidt & Dewdney 1999).

Freq. (MHz)	T_{gal} (K)	Spillover Efficiency	T_{ant} (K)	Beam FWHM (arcmin.)
75	1400	0.64	1000	69
150	200	0.93	210	34
300	35	0.98	40	17
600	8	0.99	9	9

performance level can be maintained at lower frequencies, or improved, with a larger focus package. As yet we have not considered the nature of the antennas required for such low frequency operation.

4.6.2 High frequency

There is no fundamental upper frequency limit inherent in the LAR concept, though at some frequency cost becomes a factor. Good performance at frequencies higher than the 22 GHz maximum quoted in the original LAR White Paper will impose tighter constraints in two areas —feed positioning, and reflector panel size and positioning.

The required positional accuracy of the feed is $\propto \lambda$. Thus, operation at 30 GHz would require improvement of the positional accuracy by a factor of 1.36 over that at 22 GHz. Fortunately, the size of the feed decreases with λ, and the weight decreases between λ^{-2} and λ^{-3}, which will help towards improving stability. At these frequencies, an inertial platform is the concept of choice for reducing residual positional errors. However, even with this system, accurate measurement of position is still required.

The present design of reflector allows for substitution of smaller panels on the underlying "structure units". Large throw actuators move the entire structure units, while smaller-throw trim actuators attach between the structure units and the panels. This construction permits considerable flexibility of design—the small-throw actuators can be specified (within limits) according to the upper frequency limit for the design. As with the feed position, the panel positions must be measured more accurately for higher frequency capability.

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