A Multi-Fielding SKA Covering the Range 100 MHz – 22 GHz

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1. Background

Various analyses, including the recent IEMT report [1], have noted that meeting the SKA frequency range and sensitivity goals with a single antenna technology is very difficult, principally because sensible high frequency (> 2 GHz) optimizations result in too little effective area at low frequencies. When independent multi-fielding is added to the list of goals, the attractiveness of a technology split increases. Aperture phased arrays offer multi-fielding at low frequencies but are not feasible above ~1.5 GHz from either an economic or performance viewpoint. The other proposed SKA multi-fielding technology – Luneburg lenses – has been disadvantaged in that lenses which are big enough to perform well at 100 MHz are too lossy at high frequencies. In this short paper we outline a hybrid, or composite, SKA solution which exploits the optimum performance regime of both antenna components. It uses aperture arrays to 1.5 GHz and small Luneburg lenses to cover the range 1.0 – 22 GHz. As expected, there are some compromises if the total budget is to remain in the range USD 1 – 1.5 B. While optimizations are not explored in this brief submission, we have selected a representative design in which the original SKA sensitivity goal of 20 000 m^2K^{-1} is approached at 1.4 GHz. The SKA design space is still very wide and part of our motivation in presenting the suggested hybrid is to establish a practical design boundary for the multi-beaming domain.

2. Independent Multi-Fielding

A review of the scientific merits of multi-fielding is given in [2]. The ability to place widely-separated (“independent”) fields is a special feature, intrinsic to a telescope design. The summary in [2] shows that attempts to recover limited capability in this domain (e.g. by sub-arraying a single-field instrument) usually lead to inefficient use of the collecting area. If multi-fielding is important, our conclusion is that the SKA design must reflect this from the outset – it is truly a primary driver in the choice of antenna technology.

Whilst there are sound scientific reasons for choosing a multi-fielding approach (Section 4), we believe that the potential operational gains alone are so great that this capability should be thoroughly studied in the SKA design process. A complementary view is that area re-use maximizes the investment return on a mega-science project.

3. Our Proposal

We propose an SKA incorporating aperture arrays (AAs) and small Luneburg lenses (LLs), along the lines depicted in Fig. 1. The concept draws on material presented in both the 2002 AA and LL whitepapers [3, 4] and the 2003 updates [5, 2]. We retain, for the present, the four-FOV specification of the constituent AA and LL components and have based our design on shared infrastructure, including the remote station and signal transmission hardware. With the LL component dominating demands for bandwidth, most of the infrastructure is as described in [4]. The great flexibility of this design allows many possible observing options, including simultaneous use of AA and LL collecting area (providing parameters such as observing bandwidth are chosen appropriately).

Significant changes to the ideas presented in the updated whitepapers include:

- Halving the physical area of the three AAs to give effective areas of 1, 0.49 and 0.26 km^2 at spot frequencies of 0.2, 0.4 and 0.9 GHz, respectively;
- Reducing the diameter of the LL concentrators from 7 m to 3.5 m and increasing the number of lenses to 92 lenses per station, giving about one third of the LL area in [2]; and
- Using efficient, low-cost, solid-state, “consumer-grade” coolers for the LL receivers.

Table 1 summarizes some important parameters of our design, while Fig. 2 is a plot of the sensitivity of the hybrid SKA as a function of frequency. Fig. 3 shows the cost of the telescope apportioned across various major components, with the split between antenna technologies explicitly identified.

Luneburg Lenses

We use a total of 27 600 lenses of 3.5 m diameter, saving nearly 80% of the dielectric material needed for the array of volumetric concentrators in [2]. In light of recent measurements, a slightly lower dielectric loss has been adopted (tan $\delta = 0.75\text{x}10^{-4}$). The weight of a single lens is reduced to 960 kg and the smaller antenna is easier to manufacture, transport and erect. For costing purposes we retain a four-arm feed positioner [2]. However, with steel and mechanical components now dominating antenna costs, a more advanced focal-plane feed positioner (similar in principle to those used for fibre positioning in new-generation optical spectrographs) may be attractive, especially as the requirement to move large feeds is now relaxed. We see opportunities for wider international mechatronics partnerships in this area (Section 5).

Aperture Arrays

In general, we adopt the hierarchy described in [5] for SKA signal aggregation in aperture arrays. The flow from elements to tiles to patches to station sits well with the now-familiar LL architecture and its associated signal processing architecture. For topology design purposes we establish the rough equivalence of “patches” (typically 40 mid-band tiles) with an individual 3.5 m LL; the compatibility with subsequent station DSP is then almost exact. We accept that, on a 2015 timescale, some level of RF beamforming will be necessary at the tile level. However, we wish to explore possibilities for the international development of achromatic beamformers (Section 5).

4. Science

Few of the SKA goals explicitly demand operation above 10 GHz [6]. The main high-frequency drivers include S-Z, high redshift CO and solar system observations. The AA-LL hybrid offers the moderate sensitivity needed for these applications whilst still providing sufficient sensitivity for all mainstream SKA applications identified by the science working groups. While the A/T compromise will result in longer integration times, this hybrid uniquely enables multi-fielding across the entire frequency range. Many of the advantages come in the hitherto poorly explored time-resolved regime and give substantial science returns in areas such as pulsar, transient and SETI studies. Our enthusiasm for multi-fielding is bolstered by the recognition that important extended programs may simply never be scheduled on a single FOV instrument. We see a multi-fielding instrument as offering much more opportunity to explore new parameter space whilst still permitting the currently envisaged base science studies. Appendix 1 shows some first thinking in this area.

5. Links With Other SKA Concepts

As with previous LL proposals, much of the system design and many major components of the AA-LL hybrid are applicable across a range of SKA concepts. With active programs in Australia, Europe and the USA in areas such as wideband feed design for concentrators, dense phased arrays, highly integrated receivers (cooled and uncooled) and scaleable DSP systems, we see many opportunities for work on the AA-LL hybrid (or its constituents) to contribute to whichever SKA technologies are eventually selected. We feel that it is important to pursue the possibility of low-cost achromatic phasing systems for phased arrays, and we would be interested in gauging international interest in this area. (While a full digital approach may be feasible for some focal plane applications, a level of accurate, low-loss, RF beamforming is necessary in most other applications). Finally, we are especially interested in exploring the mechanical, mechatronic and manufacturing engineering ingenuity of (for example) Chinese colleagues across a number of SKA concepts, including the AA-LL hybrid.

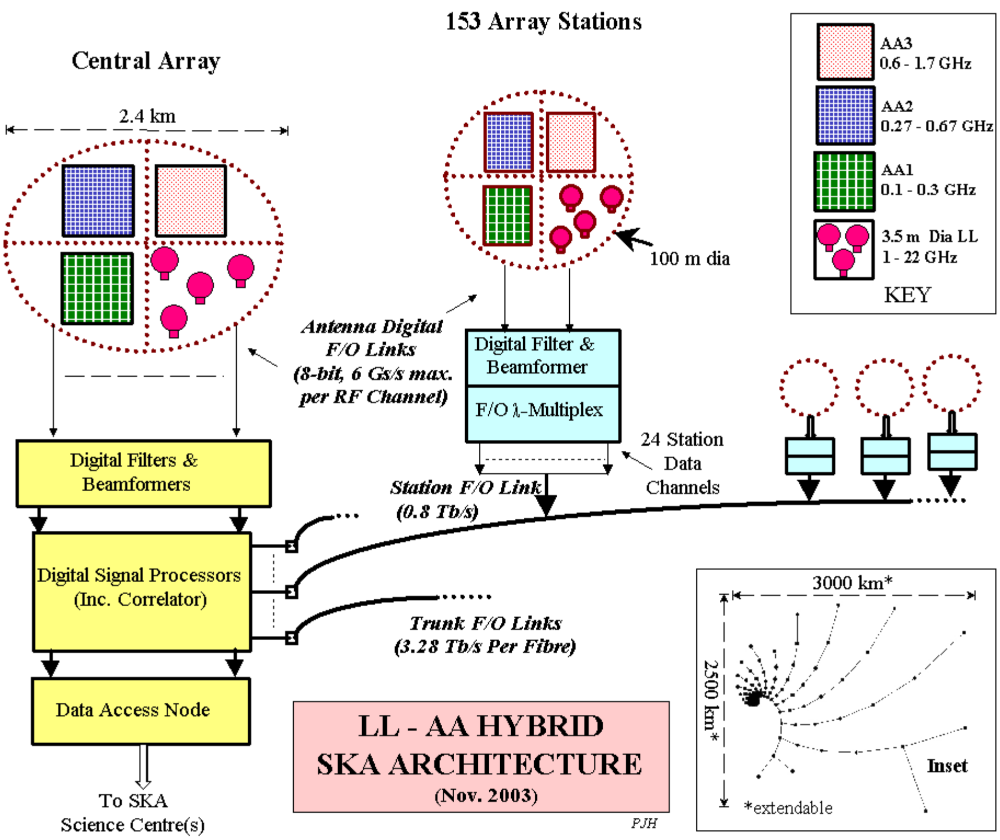


Fig. 1. Pictorial overview of hybrid SKA.

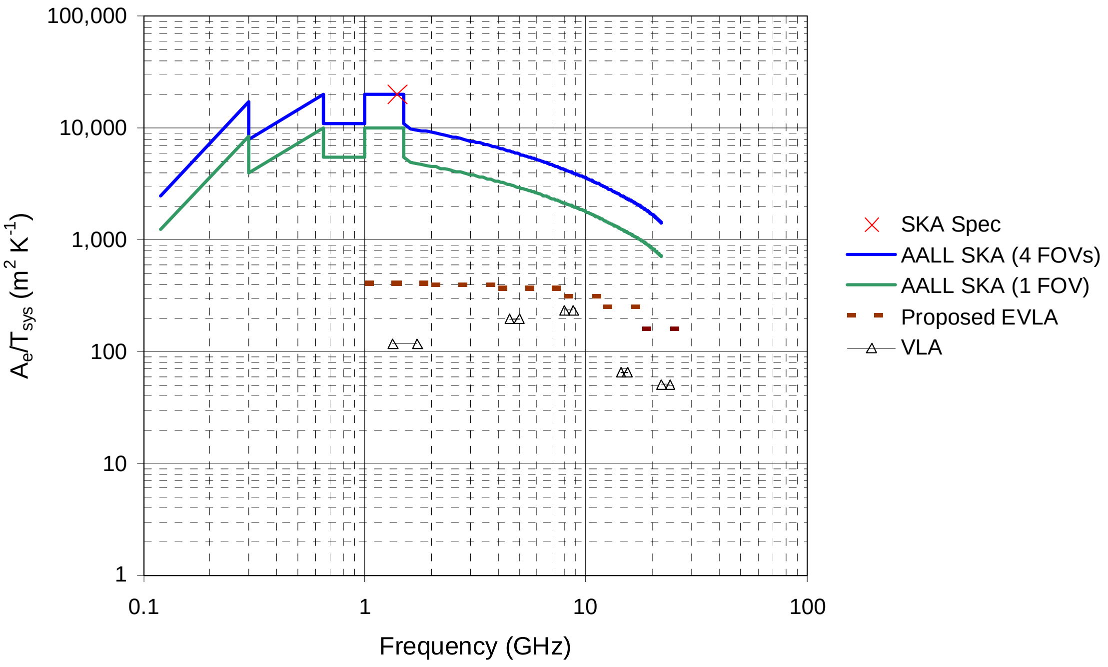


Fig. 2. Sensitivity curves for AA-LL hybrid.

Table 1 – Abbreviated Specifications of AA-LL Hybrid SKA

Antenna types	3-band aperture phased array + 3.5 m Luneburg lens
Frequency coverage (GHz)	0.1 – 22 GHz
Number of independent fields	4
Field-of-view (each field) 0.1 GHz 1.4 GHz 22 GHz	 312 deg^2 14 deg^2 (LL); 10.5 deg^2 (AA) 0.056 deg^2
Number of stations (N)	300 (153 outside central 2.4 km dia array)
Station composition	~ 40 AA patches (0.35 GHz) + 92 lenses
Station diameter	100 m (LL component)
Total number of lenses	27 600
Longest baseline (Australian site)	3 000 km (5 000 km possible)
Physical area 0.1 GHz 1.4 GHz 22 GHz	 1.25 km^2 0.60 km^2 0.27 km^2
Sensitivity (A_{eff}/T_{sys} per FOV)	See Fig. 2
Best array angular resolution 0.1 GHz 1.4 GHz 22.0 GHz	 0.15 arcsec 0.011 arcsec 0.0005 arcsec
Number of polarizations	2 linear
Number of spectral channels	8192
Number of simultaneous frequency bands	Flexible within station data transport limits

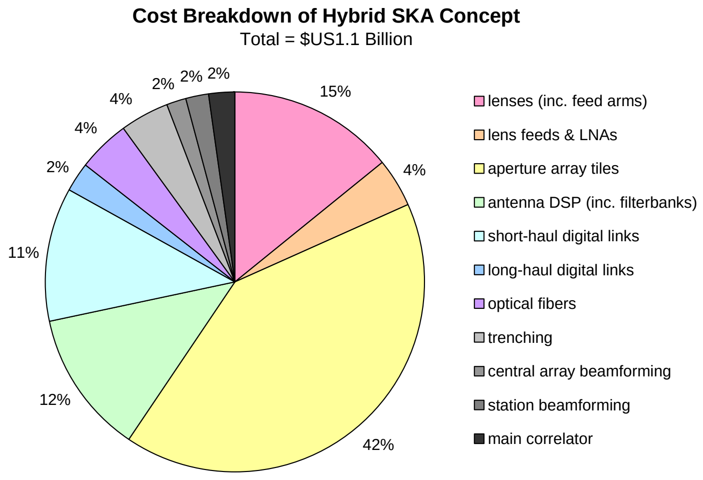


Fig. 3. Component costs for AA – LL hybrid SKA. The full SKA cost estimate includes an additional infrastructure allowance of 200 M and a software estimate of USD 130 M, making a total of USD 1.43 B.

6. References

1. Hall, P. J. (Ed.), Report to the ISSC by the IEMT, October 2003. (http://www.skatelescope.org/documents/EMTreport_%20031003.pdf)

2. Chippendale, A. P. (Ed.), Eyes on the Sky: A Refracting Concentrator Approach to the SKA. Concept Extension and Update, May 2003. (http://www.skatelescope.org/documents/EMTreport_%20031003.pdf)

3. Hall, P. J. (Ed.), Eyes on the Sky: A Refracting Concentrator Approach to the SKA, July 2002. (http://www.skatelescope.org/documents/SKA_AUS_CONCEPT_Luneburg_17072002.pdf)

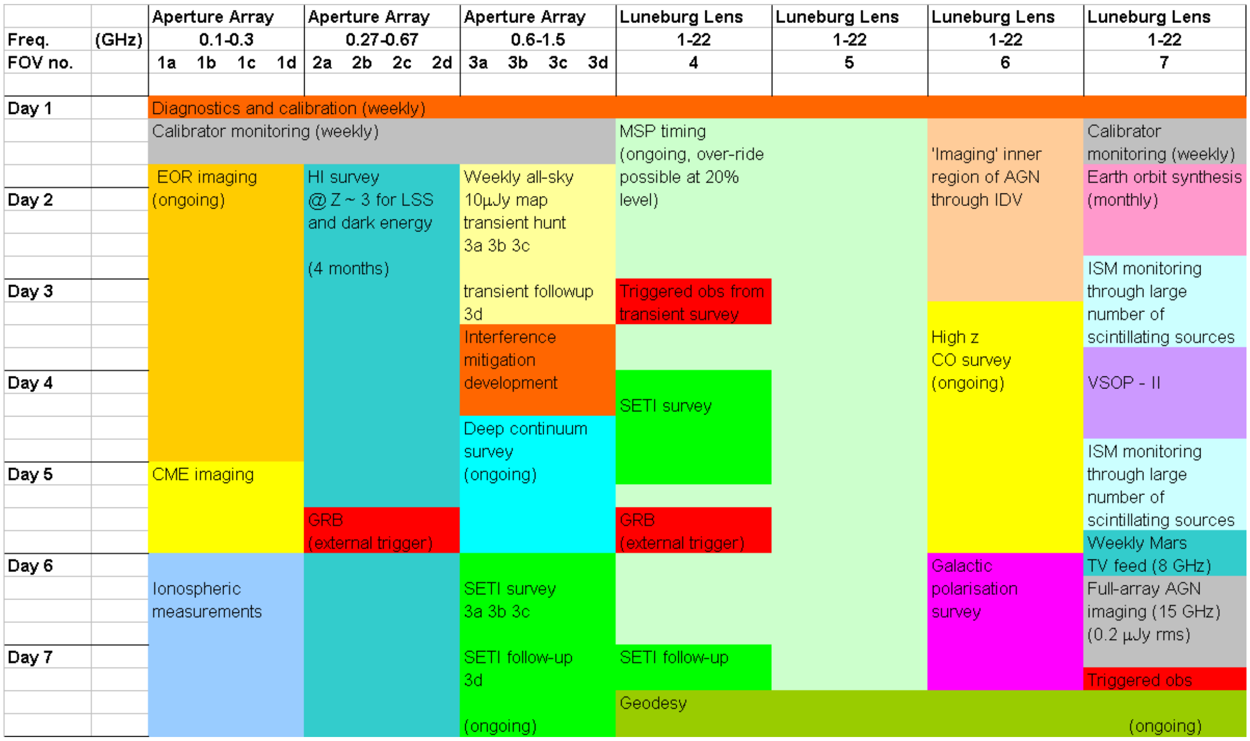
4. European SKA Consortium, The European Concept for the SKA – Aperture Array Tiles, July 2002. (http://www.skatelescope.org/documents/SKA_EUR_CONCEPT_IntegratedApertureArrayPanels_17072002.pdf)

5. van Ardenne, A. and Butcher, H. R. (Eds.), The Aperture Array Approach for the SKA. Concept Extension and Response to Questions, May 2003. (http://www.skatelescope.org/documents/dcwp/AA_Whitepaper_reply_0503.pdf)

6. Jackson, C. A., SKA Science: A Parameter Space Analysis, SKA Memo 29, January 2003. (http://www.skatelescope.org/documents/skamemo29.html)

Appendix 1 – One Week's Work for the AA-LL SKA

We looked at some of the possibilities for exploiting the parallelism of a multi-FOV telescope. Perhaps a week of SKA time in 2018 might look something like the example below.



		Aperture Array	Aperture Array	Aperture Array	Luneburg Lens	Luneburg Lens	Luneburg Lens	Luneburg Lens
Freq.	(GHz)	0.1-0.3	0.27-0.67	0.6-1.5	1-22	1-22	1-22	1-22
FOV no.		1a 1b 1c 1d	2a 2b 2c 2d	3a 3b 3c 3d	4	5	6	7
Day 1		Diagnostics and calibration (weekly)						
		Calibrator monitoring (weekly)			MSP timing (ongoing, over-ride possible at 20% level)		'Imaging' inner region of AGN through IDV	Calibrator monitoring (weekly)
		EOR imaging (ongoing)	HI survey @ Z ~ 3 for LSS and dark energy (4 months)	Weekly all-sky 10µJy map transient hunt 3a 3b 3c transient followup 3d				Earth orbit synthesis (monthly)
Day 2								
								ISM monitoring through large number of scintillating sources
Day 3					Triggered obs from transient survey			
							High z CO survey (ongoing)	
				Interference mitigation development				
								VSOP - II
Day 4					SETI survey			
				Deep continuum survey (ongoing)				
								ISM monitoring through large number of scintillating sources
Day 5		CME imaging						
			GRB (external trigger)		GRB (external trigger)			
								Weekly Mars TV feed (8 GHz)
Day 6		Ionospheric measurements		SETI survey 3a 3b 3c			Galactic polarisation survey	
								Full-array AGN imaging (15 GHz) (0.2 µJy rms)
Day 7				SETI follow-up 3d	SETI follow-up			
								Triggered obs
					Geodesy			
				(ongoing)				(ongoing)

Fig. A1. A week of observing with a multi-FOV SKA.