Summary of the second SKA Design Convergence Workshop

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September 2004

The second workshop on SKA design convergence was held on 22 July 2004 during the SKA2004 meeting in Penticton, BC, Canada. Its purpose was to review more detailed descriptions of the hybrid concepts selected during the first Workshop in Cape Town in January 2004, and to map out the steps needed to converge on a hybrid design. Input material to the Workshop included 3 papers on hybrid concepts: small dishes + cylinders (SD+CYL), small dishes + aperture array tiles (SD+AAT), and the Large Adaptive Reflector (LAR) as a concept that covers the complete frequency range of interest to the SKA. An additional concept which has arisen out of the ongoing hybrid concept discussions was presented at the Workshop without an accompanying paper: small dishes + phased arrays in their focal planes (SD + fpa). The papers and presentations made during the Workshop are included, with this summary, in the international SKA Memo series as Memo 53.

This document summarises the main points of the Workshop. It is not a set of minutes and does not ascribe individual comments in the Discussion to individuals at the meeting, but attempts to draw together the various strands of discussion that took place at different times during the session. The Workshop Programme is included as Annex 1.

1. Introduction

The timeline for design concept selection is currently foreseen to be:

- 2004-7 demonstrator development
- 2006 Dec external review of design concepts
- 2008 selection of technical design
  submit proposal for international SKA pathfinder
- 2009 start construction of pathfinder

In January 2003, the ISSC defined the options for selecting the SKA design concept as being, in order of desirability

i) mutual convergence to a single cooperative design concept that is inclusive and engages the global community
ii) down-selection amongst cooperative designs including combinations of two or more concepts (hybrids), and
iii) down-selection amongst individual concept team proposals

The ISSC also recognised that the SKA is affordable only through a global collaboration, so ways need to be found to keep all SKA players on-board even if their national or regional antenna concept is not selected.

Eighteen months on, option i) looks increasingly unlikely in view of the timelines for proving the individual concepts via demonstrators. Many of the demonstrators will come to fruition only shortly before the selection in 2008, so there will be little time to achieve mutual convergence.

We can already see that no single design concept can meet all the key science requirements on frequency range, spectral resolution, surface brightness sensitivity, and angular resolution, combined with wide field of view. So we need to ask how viable is option ii), the hybrid idea? Are there combinations of designs that capture all the key science goals, and yet remain within the nominal 1B€/$ budget? Or, must we rescope the project either as a hybrid or as an individual concept with less than the full key science complement (option iii)?

At the first Workshop, the SD+CYL, SD+AAT, and LAR hybrids were identified as worthy of further investigation, as well as two hybrids involving Luneberg lenses (LL+CYL and LL+AAT). The Luneberg Lens hybrids were not pursued in the interim since the Cape Town meeting because the LL concept will not be developed further for the SKA. In order to make the concept of hybrids more concrete, specific information was requested by the Project Office from the proposers in time for review by the EWG (formerly IEMT) and SWG (formerly ISAC) ahead of the Penticton meeting.

The following table lists the information requested.

1. The total frequency range covered by the hybrid, with the design range for each component specified explicitly.
2. A sketch of the arrangement of component collecting areas within stations and central arrays.
3. Any updated costing information on the hybrid concept.
4. Aeffective/Tsys for each component of the hybrid at centre frequencies and band edges (also specify explicitly component and total SKA sensitivities at 1.4 GHz).
5. The type of antenna elements used in each component, and the dimensions of any concentrators.
6. The number of independent, widely placeable, fields-of-view provided by each component of the hybrid array.
7. Parameters for each component, including: equivalent number of stations, station FOV, number of antennas per station, physical area per station, effective area per station, station dimensions and antenna shadowing limits (if applicable).
8. A broad indication of the array configuration, the total bandwidth transmitted in representative distance regimes, and the total entity (station or antenna) FOV at chosen spot frequencies (including 1.4 GHz).
9. The nature of the feeds employed (single or phased array), phased array tile dimensions or the level of RF beamforming employed (if applicable), and the domain scale in any aperture array component (see http://www.skatelescope.org/documents/SKA_EUR_CONCEPT_IntegratedApertureArrayPanels_17072002.pdf , page 15 for terminology).
10. The physical temperature of receivers used in each component (15K, 80K and 300K might be standard choices).
11. The quantization accuracy at the receiver output (1/2/4/8 bits might be standard choices).
12. The accuracy at the correlator input (1/2/4/8 bit choices).
13. The scale of the proposed correlator and the field-of-view able to be processed, given observing bandwidths consistent with SKA science goals.
14. Comments on the amount of station and central infrastructure (civil, signal processing and distribution, computing) likely to be shareable between components, and an estimate of the amount of new infrastructure needed to support the hybrid SKA.
15. Comments on non-imaging or new operational modes (e.g. simultaneous observing at widely separated frequency bands) supported by the hybrid SKA.

2. Hybrid designs

2.1 SD+CYL (Bunton and Lazio)

This concept is composed of high-and low-frequency sub-arrays.
i) the low-frequency sub-array is composed of two sets of 600 cylindrical reflector stations, one operating below approximately 2 GHz and the other below 0.7 GHz

ii) the high-frequency sub-array is 2500 12-meter parabolic dishes (LNSD) operating between 0.47 and 24 GHz.

The frequency overlap encompasses H I emission at redshifts *z* < 2 as well as providing coverage of the OH line.

Extension of the cylinders to 5 GHz may be possible and would provide improved timing accuracy of pulsars. The maximum frequency of 0.7 GHz for the low frequency cylinders is chosen so as to satisfy the science requirements for high survey speeds at a redshift of 1.

The cost estimate is €/USD 1273M, excluding management costs and contingency.

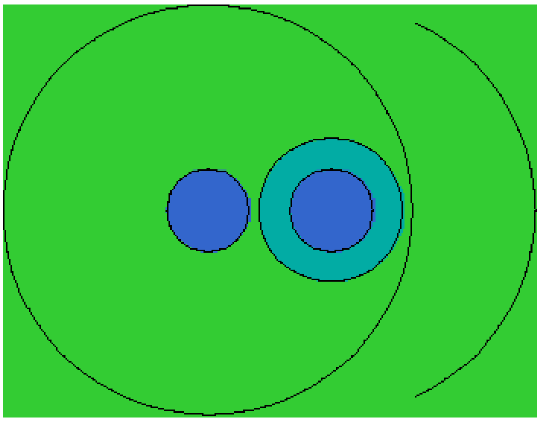

Fig 1. The cores of the SKA sub-arrays. Shown are the overlapping cores for the small dishes and cylindrical reflectors. The lightly shaded green regions are 5 km in diameter. The heavily blue shaded region is 1 km in diameter with the small dishes on the left and the high-frequency cylinders on the left. Surrounding the high-frequency cylinders is an annulus of low frequency cylinders.

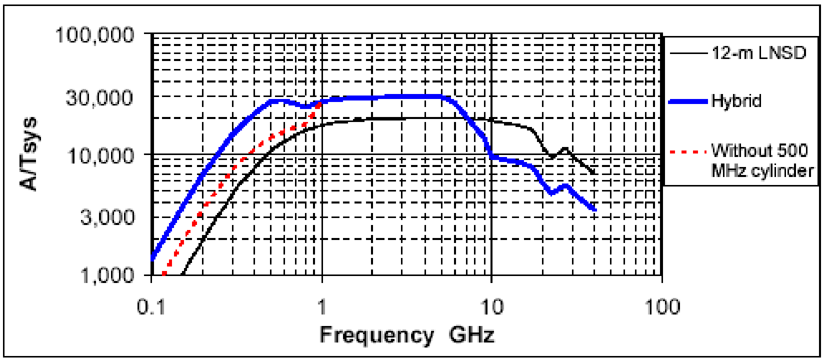

Figure 2. Sensitivity for dual cylinder plus 12-m hybrid

2.2 SD+AA (van Ardenne and Lazio)

This hybrid solution is composed of high- and low-frequency sub-arrays designed to cover the frequency range from 0.1 to 25 GHz:

i) the low-frequency sub-array is composed of aperture array stations, each consisting of three sets of aperture arrays—a low-frequency AA covering 0.1 to 0.22 GHz, a mid-frequency AA covering 0.22 to 0.8 GHz, and a high frequency AA covering 0.53 to 1.7 GHz
ii) the high-frequency sub-array is 2500 12-meter parabolic dishes operating between 0.47 and 24 GHz.

The frequency overlap encompasses H I emission at redshifts $z < 2$ as well as providing coverage of the OH line.

In order to cover the frequency range from 0.22 to 1.2 GHz with the large fields of view required (~ 100 deg^2), three sets of aperture arrays would be used. One set would cover the lowest frequencies and make use of droopy dipoles in a LOFAR-tile technology. The other two sets would cover the higher frequencies and utilize Vivalidi antenna elements.

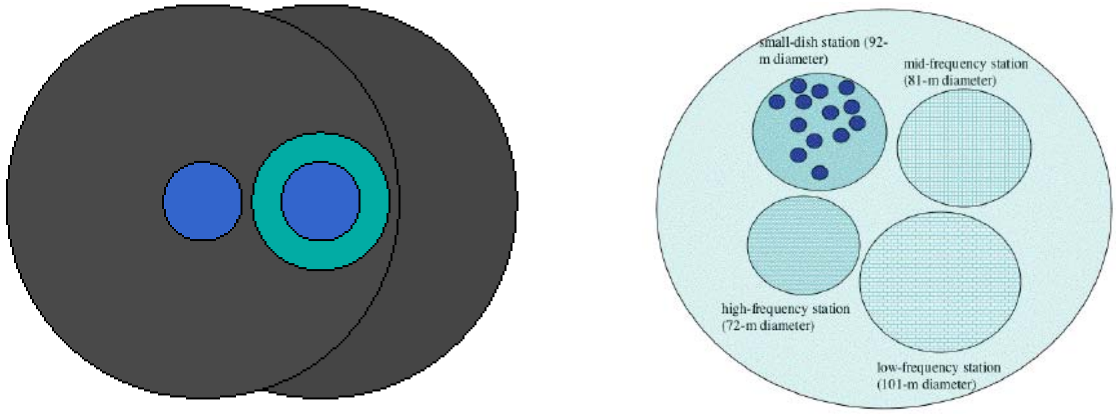

Figure 2 (left). The cores of the SKA sub-arrays. Shown are the overlapping cores for the small dishes and aperture arrays. The grey regions are 5 km in diameter. The heavily blue shaded region is 1 km in diameter with the small dishes on the left and the aperture arrays (38 stations) on the right. In the 1 – 5 km diameter annulus for the aperture arrays, the 58 stations may be distributed in rings, the first of which is depicted in green.

Figure 2 (right). Possible arrangement of antennas in an antenna station outside of the core.

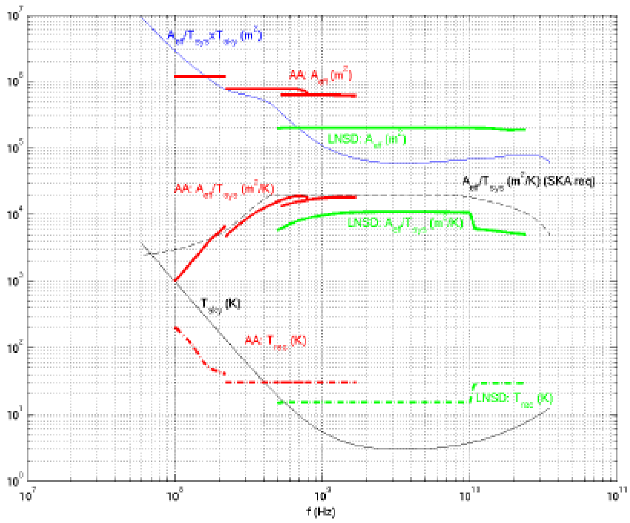

Figure 3. SKA AA + SD hybrid sensitivity. The red curves show the performance of the aperture arrays while the green curves show the performance of the small dishes. The top curve for each element shows the effective area, Aeff, as a function of frequency. The bottom curve for each element shows the receiver temperature, Trec. The light solid curve shows the sky temperature Tsky. The middle curves show the effective performance Aeff/Tsys, where Tsys = Trec + Tsky

The estimated costs of the SD+AAT hybrid (excluding contingency and management) are €/USD 1450M.

2.3 LAR (Dewdney)
Since the LAR can be used over the full frequency range of the SKA, it has been designated as a "hybrid". The figure below shows the aperture efficiency expected for the LAR over the full frequency range. It can achieve the A_{eff}/T_{sys} specified in Memo 45 with the use of cooled receiver elements at frequencies above 2 GHz.

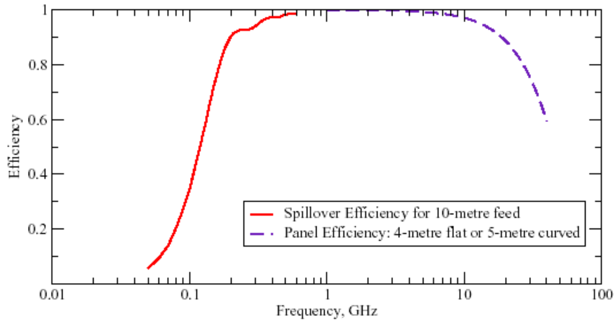

Fig. 4: Expected aperture efficiency of an LAR

The cost of an LAR of 60 x 150m diameter reflectors is expected to be about €/USD1000M (excluding contingency and management).

2.3 SD+focal plane array (Ekers)

In his paper on "System Optimisation of Multi-beam Aperture Synthesis Arrays for Survey Performance" (EXPA Special Issue on SKA Technology, in press), Jaap Bregman has pointed out that, to the first order, the optimum distribution of expenditure among antennas, receivers and correlator in an interferometer is dependent on whether the primary motivation is to carry out surveys or to maximize point source sensitivity. For a survey telescope, the distribution should be 3:2:1, and for point source sensitivity, 6:2:1. So for surveys, optimum solutions will have more receivers and fewer dishes.

The SD+fpa concept presented is for a survey telescope concept involving 15 m diameter dishes, operating to a maximum frequency of a few GHz with a 10x10 element focal plane array forming 50 beams and covering 100 sq. deg at 1.4 GHz. To cover the full frequency range for the SKA, it should be combined with a high frequency solution optimized for point source detection. The cost of 50 such dishes to build a 1% demonstrator with significant scientific capability has been estimated as USD 10M. For USD100M a wide FoV low frequency pathfinder which addresses at least two of the SKA key science goals could be built. No estimates have been made for a combination of these dishes with, say, the LAR or LNSD concepts at high frequency.

3. Comments by the EWG (see also SKA Memo 56)

1) On hybrids in general
- Does not reduce the risk of reaching cost or performance goals for the SKA
- Expands some of the capabilities of the SKA
- Changes the "trajectory" through parameter space
- Likely to have a higher cost and/or lower A_{eff}/T_{sys} , at least at mid to high frequencies
- All hybrids rely on dense phased array technology, used either in the aperture or focal plane; we are therefore seeking to lever from (currently) rather immature technology, increasing the uncertainty of cost and performance projections and underlining the importance of demonstrator projects.

2) On CYL+SD
- Offers very wide field-of-view at low frequencies
- Does not provide independent widely-spaced beams
- Wide-band, dual polarization, line feed (focal plane array) yet to be demonstrated
- Dependent upon phased-array feed technology
- Although many beams within a large field-of-view are available, only the central beam can be pointed independently. How will these other beams be used? There are also potentially compute-intensive field rotation effects to be accounted for.
- Requires more thorough investigation of the fabrication cost of cylinders

3) On AAT+SD
- *Heavily* dependent upon low-noise phased arrays
- Need to construct much more than a square kilometre in total area because each receiving band has a separate aperture
- Requires a huge number of receivers
    - need to be very low-cost; there is some uncertainty concerning cost extrapolations (via large-scale manufacturing projections)
    - Moore's Law helps electronics, but not radomes, support structures, etc.
- Although EMBRACE will be completed by 2008, it will have had a very limited operational track record

4) On LAR
- Phased-array feeds are essential for the LAR so that the feed pattern matches the elliptical profile of the reflector and so that the nominal 1 sq. deg. field-of-view is obtained
- Uncooled LNAs may be adequate to ~2 GHz, and cooled required above; phased arrays are huge by current standards (several metres on a side)
- How confident will we be in 2008 that high-performance phased-array feeds can be built for the LAR?
- How confident will we be in 2008 that high-performance <u>*cooled*</u> phased-array feeds can be built for the LAR?
- Memo 45 calls for 200 square degrees field-of-view at 0.7 GHz which is impossible for the LAR
- Memo 45 also sets a goal for independently-steerable widely-separated field-of-views, either by sub-arrays or phased-array techniques. Note that small-N arrays (such as the LAR) will have poor performance in sub-array observing modes, and no capability for independently-steerable FOVs.

5) Preliminary risk analysis
(to be included?)

6) Are hybrids affordable?
For a given mid-band Aeff/Tsys a hybrid will be more expensive than individual concepts and, in addition, will have twice the NRE costs, and added operational expenses.

4. Comments by the SWG

The tradeoffs – A/T vs Frequency vs FoV vs cost - need to be considered in the context of the Key Science Programs. From the science point of view, the project should avoid imposing too tight technical constraints too early or 'parameter space' will be lost. Rescoping should take place only when absolutely necessary. This is of course a continuing challenge for the engineers, but the SWG expects to have a much clearer picture of the tradeoffs once the focused workshops on key science goals have been held in 2005.

5. Discussion

The discussion focussed on the following two main issues:

1) Should we continue to consider hybrids?
   Are they affordable?
   What trade-offs have to be made?
2) What is the development path to the SKA?
   Will it help to designate a design reference concept at this stage?

The presentations on hybrids made it clear that even with the reduction of collecting area at high frequencies by 50%, the costs are likely to be 1.5-2 B€/$ (including contingency and management). In addition there are greater NRE costs involved and the operations costs are likely to be higher. It was noted that the LAR may be a cheaper option. Concern was also expressed about any loss in sensitivity, given the reliance of many of the science drivers on high sensitivity.

So what are the options?

1) increase the target cost for construction to 2 B€/$, and continue to investigate combinations of antenna technologies to allow the full complement of key science to be done

2) forget the hybrid idea and make hard choices to stay within the 1 B€/$ cost goal. The SKA will not be the last radio telescope ever built!

We need to keep the cost, risk, and benefit clearly in focus during these considerations. Designing the SKA as a survey instrument or a point source instrument is an important issue to be taken into account from the start.

2000M €/USD

The majority of opinion in the meeting was that requesting 2000M €/$ for the 2010-2020 decade was unlikely to be successful. But since radio interferometers can be built in stages, evolution in capability can easily be contemplated. Possible routes could be:

- short baselines to long
- low frequency to high
- high frequency to low

What makes most sense at the time of the proposal will depend on the scientific drivers and on technology developments. For example, it can be argued that since high frequency technology is more or less ready and will not reduce significantly in cost except for data processing aspects, the SKA should begin life as a high frequency instrument. On the other hand, some saw the low frequency science as the more compelling and the technology within reach already (eg SD + focal plane arrays).

Can we propose an “evolving telescope for studying the evolution of the universe”? This would require a continuing investment model, much like industry routinely puts into practice. In the research infrastructures world, this is not a model that has been followed so far; instruments often have to wait for 20 years for funding for major upgrades.

Industry often mixes low and high risk components by dealing with the high risk part as a separate activity within the main project. This is a model that could be applied to the SKA, for example to develop the Aperture Array technology for a longer time than other aspects with a view to implementing it later in the project.

1000M €/USD

If we stay with the 1000M €/$ cost of construction goal we may have to give up on one or more of the following:

- high frequencies
- low frequencies
- long baselines
- extremely wide field of view

These are hard choices that would need to be based on the scientific goals, the technical realities, and the availability of other instruments even if they are nearly as powerful as the SKA.

The meeting agreed that it would be premature to make any such choice before the cost/risk/benefit analysis of the technologies and science has been completed.

Hybrids and the SKA development path
At the current time, the separate SKA concepts are being developed nationally or regionally, in competition with each other. This carries the risk that we may not reach a final design in which all regions would accept to be partners.

An alternative convergence plan is to establish a reference SKA design. All of the regional research efforts would then viewed as attempts to improve that reference concept. In addition,
–all SKA partners would devote some of their effort to developing the reference concept
- it is likely to promote a more integrated joint effort by international partners, and
–it would allow the SKA to be more easily promoted to world astronomical community

Such a reference design
–should achieve a significant fraction of key science goals
–should have a high confidence factor that it can be built. But note that budgetary constraints may limit sensitivity, and
–should motivate innovative technology development

A possible option for a reference design Is a frequency hybrid with the transition between technologies being between around 1 GHz. A possible example is small parabolas plus aperture arrays. The EWG uses this as an informal technical "strawman" as it comes closest to meeting the listed SKA science requirements (cost considerations aside).

Concern was expressed that formally calling something a reference design was tantamount to a selection of that design. Selection on the basis of low risk will discourage innovation.

Fund-raising
Do we start small with a pathfinder, and then progress on to the full array seeking funds via the traditional routes? Or can we look at alternative approaches to fund-raising, eg by looking at what industry wants to build, and adapting this for our own purposes. Radio astronomy is particularly suited to this because of the convergence of radio and digital computing technologies. LOFAR has pursued this approach successfully in Europe. The competition is then with other (eg civil) infrastructure rather than other astronomy projects. It was pointed out that the motivations for providing large sums of money for infrastructure are different in different parts of the world. This may create quite a challenge in aligning the funding in those different parts of the world for the international SKA project.

6. Conclusions

Based on the interactions and comments during the Workshop, the International SKA Project Office will not pursue the descriptive process of hybrids any further until after the planned detailed cost estimations and risk analyses of the constituent technologies become available over the next couple of years. The system definition document and cost/performance tool in preparation by the EWG, the reports from the technology demonstrator projects, and the focussed key science workshops organised by the SWG, will be crucial in focussing attention on these aspects. This information is essential input to any decision on whether a hybrid solution would be beneficial and can be pursued. At that time it may be opportune to designate a design reference concept.

In addition, a generic approach to costing synthesis arrays, perhaps as an extension of the ideas promulgated by Jaap Bregman, needs to be developed further.

Annex 1: Convergence Workshop Program

1330 Introduction, Richard Schilizzi (ISPO)

1345 AA + LNSD, Arnold van Ardenne (ASTRON) & Joe Lazio (NRL)

1400 Cylinders + LNSD, John Bunton (CSIRO ICT) & Joe Lazio (NRL)

1415 LAR, Peter Dewdney (NRC/HIA/DRAO)

1430 12m Dishes + Focal-Plane Arrays, Ron Ekers (CSIRO ATNF)

1445 IEMT Comments on Hybrids, Bruce Veidt (NRC/HIA/DRAO)

1500 ISAC Comments on Hybrids, Steve Rawlings (Oxford)

1515 coffee break

1545 Discussion, to include:

– are hybrids viable? Comment by Ken Kellermann
– is a strawman hybrid desirable?
– can we define a design reference concept?
– what are the science goals for a global demonstrator?
– what are the funding paths to a global demonstrator?
– further actions

Annex 2: Papers and presentations

1. The input papers for the convergence workshop can be found on the SKA webpage www.skatelescope.org/pages/p_docsandpres.htm

2. Comments on these papers by the Engineering Working Group can be found in Memo 56.

3. Links to the presentations made during the Workshop can be found on the SKA webpage attached to this summary: www.skatelescope.org/pages/p_docsandpres.htm (Memo 53)