Hybrid Solutions for the Square Kilometre Array: Perspectives from the LAR Group

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1 Key issues that should drive the SKA design

We believe the following are important points to consider when discussing SKA hybrid designs.

1. Any design, hybrid or otherwise, needs to have maintain the capability required for Level-0 science. Presumably, this will encompass science goals compatible with other future instruments addressing mainstream astronomy questions of the day e.g. studying high-redshift galaxies at $z \sim 5-9$ (complement to JWST), or high-redshift CO (complement to ALMA).

2. It is important to maintain the sensitivity of the SKA *relative* to contemporary telescopes, namely the VLA. The SKA sensitivity specification is derived from the original goal to build a telescope 100 times more sensitive than the VLA, yielding $A_{eff}/T_{sys} = 20 \times 10^3$ m^2/K. However, the VLA will be improved during the time that the SKA is planned and constructed.

Assuming a reduction of T_{sys} to 30 K (EVLA Phase I) and an increase of A_{eff} to 9300 m^2 (8 new dishes in EVLA Phase II), A_{eff}/T_{sys} for the VLA at 1.4 GHz will be increased 55% from 200 to 310 m^2/K. If this improvement in the VLA is not tracked, there is a danger that along with a few other compromises, that the SKA sensitivity will be significantly less than two orders of magnitude better than the VLA.

3. It is necessary to decide whether multiple fields of view are essential and also whether high frequency capability is essential.

4. Some science, such as searching for the signature of the Epoch of Reionization, may be best done by a dedicated instrument. There is a precedent for this: Cosmic Microwave Background science is done with special-purpose telescopes. What we are seeing at the moment is that EoR science is distorting the SKA specifications by pulling the low-frequency limit down so that the SKA will have a significant overlap with LOFAR. This will likely drive up the cost of the SKA and may make some technologies unsuitable. If instead a special-purpose EoR telescope is constructed, it would probably see first-light at an earlier date than an EoR-capable SKA, and would be better-matched to EoR science than a general-purpose SKA. However, if a dedicated EoR instrument is not possible, it may be worth considering a "LOFAR-hybrid" which has additional elements optimized for EoR science since the EoR signature is believed to fall within the LOFAR frequency range.

5. We also recognize that a variety of hybrids are possible:

   (a) **Frequency hybrids**: where one station concept cannot cover the full SKA frequency range, add a different station concept so as to extend the overall range. There should be significant frequency overlap (presumably at $\nu \sim 0.5 - 1.5\,\mathrm{GHz}$) to maximize A_{eff}. The downside of this approach is that outside the overlap band, A_{eff} is significantly less than $10^6 m^2$ and we are really building two instruments that share some common infrastructure (roads, power, fibre-optic transmission system, correlator, data reduction centre). This is currently the definition of hybrid that has been used in discussions within the SKA community.

   (b) **Complementary hybrids**: this is a hybrid of elements that share similar frequency ranges, but somehow complement each other. For example, the surface-brightness sensitivity of an array of small concentrators may be greatly enhanced with the addition of at least one large-diameter element near the centre of the array.

(c) **Technology hybrids**: a single implementation may be composed of several classes of technology. The cylindrical reflector is a very good example of this. Elevation pointing of the cylinder is accomplished mechanically, while pointing in the meridian distance direction is done electronically using phased-array techniques. Similarly, focusing in the vertical plane is a result of standard reflection optics, while focusing in the horizontal direction is achieved electronically in a beamformer. It could be argued that a hybrid like this will have a lower cost than either a system using entirely conventional components (ie. fully-steerable reflector antennas) or one using new, all-electronic technology (ie. an aperture array). By removing one dimension from each, the cost is reduced by eliminating a large number of mechanical components and by reducing the size of the electronic array.

(d) **Risk hybrids**: much like a prudent investment portfolio that has both lower- and higher-risk components, the SKA could be constructed with a combination of "safe" technology (such as small-diameter reflectors) and new, less-proven technology (such as LAR, Luneburg Lens, Aperture Array, or Cylindrical Reflector). Most of the collecting area would be constructed with the "safe" technology. Elements constructed with the more experimental technology would augment the capabilities of the overall SKA, and would provide operational experience and time to develop the new technology. Over time, if the new technology is both scientifically useful and is technologically practical, then more elements could be added to the SKA.

(e) **Political hybrids**: the SKA consortium is an *international* organization that must somehow deal with *national* politics. It may be necessary to construct a heterogeneous array to ensure participation of certain countries. For example, this may happen with the ALMA project. However, we must be careful that such a hybrid does not significantly compromise the performance compared with a homogeneous array.

2 Key considerations for hybrid solutions

1. No impact on Level-0 science goals. This implies no impact on the specifications ie. physical area, frequency range, FoV etc.

2. Frequency hybrids should be designed so that the frequency overlap of the two subarrays is significant, thereby maximizing the effective area in part of the overall observing band.

3. Any hybrid should not increase the projected cost of the SKA. Here are several ways that a hybrid could lead to cost increases:

   (a) Frequency hybrids will not have the full collecting area available over the full band. Therefore to achieve the sensitivity goals of the SKA may require additional collecting area to be constructed. (Will this be the two-square-kilometre array?)

   (b) Having several different element designs could increase maintenance costs because there will be two maintenance crews, two sets of spares, etc. An analogy could be made with the airline industry: the lowest-cost carriers typically have fleets with only one type of aircraft.

3 Potential hybrid solutions to the SKA

3.1 Strengths of the LAR concept

1. Wide frequency range

   (a) The high-frequency limit of the LAR is determined by the panel size. This is because the surface is made up of (nearly) flat panels which form a piece-wise continuous approximation to a paraboloid. At high frequencies the performance drops as the deviation from the ideal paraboloid becomes a significant fraction of a wavelength. However, if the panels are made smaller (at the expense of an increase in the number of vertical actuators), then the deviations become smaller and the reflector is capable of operating at higher frequencies. Currently we have specified panels about 5 metres across that will allow the LAR to observe to around 22 GHz.

(b) The low-frequency limit is determined by the size of the reflector, the size of the focal-plane array, and the focal-length to diameter ratio of the telescope. The reflector is so large (200-metre diameter) that it will function very well into the metre-wavelength region of the spectrum because the aperture will still be many tens or hundreds of wavelength across. However, since the focal-ratio of the LAR is so large ($f/D \sim 2.5$) the feed must have significant gain. Fortunately, spillover can be largely ignored at the low-frequency end of the spectrum because the galaxy is so bright. Therefore we only need to worry about efficiency. Simulations have shown good performance down to $\sim$ 100 MHz.

2. Fully-filled aperture for high surface-brightness sensitivity.

3.2 Hybrids with the LAR concept

The brightness sensitivity of an array of small elements will be improved by adding one or more LAR near the centre of the array. The LAR focal-plane array would match the field-of-view of small-aperture antennas.

This hybrid helps to mitigate some of the perceived weaknesses of the LAR.

- Downtime due to weather, maintenance, etc. Since the LAR-elements would be a fraction of the total collecting area, downtime would be less significant unless surface-brightness sensitivity is required.
- Slow slew speed. Again, the degradation to sensitivity if one or several LAR elements were slow to acquire a transient source would be small. In this case, since transients are point-like sources, the loss of surface-brightness sensitivity is much less important.

3.3 Hybrids without the LAR

In our humble opinion, there are none!!!

4 What can Canada contribute to the SKA aside from the LAR concept?

1. Phased-array technology development
   (a) Currently have two graduate students working on front-end aspects (Vivaldi-element design, integrated LNA design).
   (b) An engineer is working on high-level specification and architecture of digital beamformer.
   (c) Within one year the group currently developing the ACSIS autocorrelator for the JCMT will be available to work on a digital implementation of the beamformer.
2. Correlator development
   (a) The team currently developing and constructing the EVLA correlator will be available later this decade for development of SKA correlators.
3. Image formation techniques
   (a) We have considerable experience within our group in making images from instruments with non-ideal characteristics (such as differing primary beam sizes).
   (b) Also have considerable experience with wide-field imaging, both in terms of the primary field-of-view and mosaicked images.
4. Antenna measurement and array calibration system using multi-tether aerostat technology to provide a stable airborne platform
   (a) Much smaller than an LAR airborne system: transmitter + simple antenna, differential GPS.
   (b) Computer-controlled winches for active control of platform position.
   (c) Can achieve much higher elevation angles than possible with a tower.
   (d) System would be portable so that it could be transported between SKA stations.