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A model for the SKA

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ABSTRACT

This memo reviews the strawman design for the SKA telescope. The design favors a hierarchical array comprised of clusters of antennas into stations. Each cluster can be phased into a number of station beams. The beams from each station are cross-correlated to form an image with the resolution of the whole array. The image fidelity depends on the station beams and on the uv-coverage. If there are too few antennas at each station, the station sidelobe response is too high; if there are too few stations, the sidelobe response of the synthesised array beam is too high. The SKA may be limited by confusion noise from astronomical sources and interference within the time variable and imperfectly calibrated sidelobe structure.

We explore an alternative model where individual antennas are correlated to image the full field of view when needed. The correlator is treated as a resource which can be re-allocated to best satisfy the science goals and calibration requirements of the SKA. Signals are digitized and packetized at each antenna and transmitted to one or more data processing centers. The data packets should contain the information needed so that delays in data transmission are not critical and the packets can be correlated within some reasonable capture time at the data processing centers. The correlator hardware should evolve and be upgraded with minimum interruption to array operations, with real time allocation of correlator resources.

The data centers are an integral part of the SKA. They should provide complete support for processing and analyzing SKA data, including data and image archives, pipeline processing, and analysis tools. The high data rate favors an operational model where users reduce data at the processing centers.

1. Introduction

The Square Kilometer Array is a next generation radio telescope being planned by an international consortium. It will allow observations at 0.15 to 20 GHz in order to image structures in the early universe with over 100 times the currently available sensitivity. Alternative technologies are being explored to realize these goals. The current design goals for the SKA are given in Table 1.

Table 1: design goals

Frequency range:	0.15 to 20 GHz
Imaging field of view:	1 square degree at 1.4 GHz
Number of beams:	> 100
Angular resolution:	< 0.1 arcsec at 1.4 GHz
Number of pixels:	10^8
Brightness sensitivity:	1 K at 0.1 arcsec (continuum)
Bandwidth:	0.5 + 0.2 x frequency GHz
Number of spectral channels:	10000
Sensitivity:	A/Tsys = $210^4 m^2 K^{-1}$
Dynamic range:	10^6 at 1.4 GHz
Polarization purity:	40 dB

2. Hierarchical Arrays

2.1. Strawman design

The strawman design aggregates the collecting area into a number of stations with correlations between stations, and up to 100 beams per station. The station beam is a phased array beam for each cluster of antennas. The beams from each station are cross-correlated to form an image with the full resolution and sensitivity of the whole array, but with a limited field of view determined by the station beam. The sensitivity for each beam = 138 mJy Hz$^{0.5}$ sec$^{0.5}$. We can start with a few beams and add beams as we can afford to handle them.

The station beams form the primary beam pattern for the synthesised array beam. The station beams are fully steerable within the primary beam of the basic receiving elements (antennas). The station beams are functions of time; modified by projection geometry, calibration and interference suppression. SKA images are formed by cross-correlating the stations. The image fidelity depends on the station beams and on the uv-coverage. If there are too few antennas at each station, the station sidelobe response is too high; if there are too few stations, the sidelobe response of the synthesised array beam is too high. For short observations, the station has sidelobes $\sim$ 1/(number of antennas per station). We want the station beams to be very clean for mosaicing, so we need a large number of antennas in each station. We also want the synthesised array beam to be very clean to resolve complex structures at the highest resolution. Both are important, so we set the number of stations = number of antennas per station = sqrt(total number of antennas). For example, with an antenna aperture of 100 m^2, 100 antennas per station and 100 stations, the sidelobe level $\sim$ 1% both in the station beam pattern and in the synthesised array beam. Both fluctuate with time and cannot be perfectly calibrated; the SKA may be confusion limited. Confusion noise can be reduced by building the SKA with more, smaller apertures, but there are other considerations. The best antenna size is determined from a cost versus performance analysis. The smaller antennas give a bigger primary field of view. Smaller antennas permit cheaper manufacturing methods. However, the unit cost of the antennas, may be dominated by antenna drive systems, cryogenics and receivers, favoring larger antennas. The correlator cost is not negligible, but the cost of the digital logic is expected to decrease with time.

2.2. Calibration

In the strawman design, the antennas within each station must be accurately calibrated to determine the station beams and the array calibration. The antenna gains (amplitude and phase versus time) include tropospheric and/or ionospheric phase correction on timescales of 1-10s, and interference rejection on shorter time scales. The calibration and interference rejection can be determined from self-calibration, but require sufficient sensitivity, and cross-correlation of antennas within each station. These correlators need not be located at each station, and indeed are more flexible and easier to upgrade if they are more centrally located. The calibration (temporal, bandpass, polarization) could also benefit from the sensitivity and interference characterization using other stations within the array. In this case the signals from all the antennas must be transported to the correlator. This requires a smaller total bandwidth to each station if the number of antennas per station is smaller than the number of beams. The antenna gains can be measured continuously using self-calibration with a detailed model of the source brightness distribution. The model would benefit from the full resolution and sensitivity of the SKA. A spectral line correlator is required to handle the wide bandwidth and narrow interference features, as well as for spectral line observations.

2.3. High Brightness Sensitivity, Low Resolution Science

The correlations within each station could also be used for science at low resolution and high brightness sensitivity. The uv-data from each station can be combined to make low resolution images. The array sensitivity when the stations are added incoherently is given in Table 2. We could vary the antenna configurations within each station to provide different uv-coverage, so that the uv-data could be combined as multiple configurations. However, it is more efficient to provide resolutions intermediate between stations and the full array by using a central concentration of antennas and making all cross-correlations of these antennas.

2.4. Station Geometry

The station diameter determines the station beamwidth. In principle the stations can have quite different antenna configurations and diameters, since we need to handle a time variable primary beam model for each station in any case. Having different station beam shapes and sizes would avoid having a fixed scale size in mosaicing with station beams for the full array. A more compact station configuration gives better brightness sensitivity, a larger field of view, and better phasing at each

Table 2: Hierarchical Array Configurations

ant diam [m]	nants	nstations	station diam. [m]	δS station [Jy $Hz^{0.5} sec^{0.5}$]	δS incoherent [Jy $Hz^{0.5} sec^{0.5}$]	station beam [armin]
4	79577	282	152	38.94	2.31	5.7
6	35367	188	186	25.96	1.89	4.7
8	19894	141	214	19.47	1.64	4.0
10	12732	112	239	15.68	1.48	3.6
12	8841	94	263	12.97	1.33	3.3
14	6496	80	283	11.20	1.25	3.1
16	4973	70	302	9.80	1.17	2.9
18	3929	62	320	8.74	1.11	2.7
20	3183	56	338	7.84	1.04	2.6

station. Interference rejection in the phased station beam may be worse for a more compact station. Setting the average antenna spacing $\sim$ 2 times the aperture size avoids most shadowing. The antenna configuration at each station can be optimized to give low sidelobes within the constraints of local topography and land use.

With these characteristics, Table 2 gives the number of antennas (nants), the number of stations (=number of antennas per station), the station diameter and beamwidth.

3. Homogeneous Arrays

We explore an alternative model, suggested by Jack Welch, where individual antennas are correlated to image the full field of view when needed. A homogeneous array could be designed to optimize the uv-coverage with a wide distribution of the individual antennas. If there are close to as many beams as antennas at each station of the hierarchical array, it would be better to send back the data from each antenna. In this case, we could have distributed the individual antennas to produce a much more versatile and robust array, with snapshot uv-coverage better than could be obtained in 8 hours with the antennas clustered in stations. Two major problems are the very large correlator required, and the logistics of signal distribution. Both appear to be possible from an extrapolation of current trends. Both are related to the array configuration.

3.1. Array Configurations

Ron Ekers, Mark Wieringa and others have proposed criteria for SKA configurations which provide a good match to the science goals for sensitivity and resolution on several scales. There should be good instantaneous uv coverage out to $\sim$ 300 km, with good uv coverage provided by earth rotation on the longest baselines. The synthesized beam should have low sidelobes. A survey of potential users by Ron Ekers suggests $\sim$ 40% of the collecting area as compact as possible, $\sim$ 40% out to $\sim$ 300 km, and $\sim$ 20% out to the longest baselines. Starting from the premise of correlating individual antennas, we can design array configurations which match the science goals over a wide range of resolutions and fields of view. The density distribution of antennas can be arranged to provide complete uv coverage with low sidelobes over the full field of view of individual antennas. A logarithmic density distribution with radius provides scaled arrays over a wide range of frequencies and resolutions. For example, with $\sim$ 1000 m^2 for each factor 2 in radius between $\sim$ 1 km and 2048 km could provide almost complete uv-coverage with earth rotation from $\sim$ 1 to 2048 s depending on the sensitivity, resolution and field of view required. In practice, the antennas can become increasingly more clustered as a function of radius, as earth rotation is required to provide complete uv-coverage. The best sensitivity is obtained by making as many cross-correlations as possible for imaging the required field of view at the appropriate resolution. For more limited fields of view, and on longer baselines it may be better to correlate phased clusters of remote antennas.

3.2. Correlators

Figure 1 plots the total bandwidth of existing and planned radio astronomy array correlators versus the year completed. There are various ways of interpreting this graph. The solid line shows Moore's Law extrapolated from an SKA correlator with 8000 antennas (3.2 10^7 baselines) and 1 GHz bandwidth, completed in 2020. This line is consistent with the planned ATA correlator in 2005. The dashed line corresponds to a doubling every 2 years and falls close to the VLA correlator. The VLA correlator was ahead of its time; we were unable to process the data. Most of the existing correlators show a much slower growth rate, but the steep growth rate of correlators planned for the current decade, using newer technology, is catching up with the long term Moore's Law.

The dotted line joins the VLBA, BIMA and SKA. One might conclude that if the ATA, ALMA, and EVLA correlators can be built, then an SKA correlator for 8000 antennas and 1 GHz bandwidth can be built by 2020. If not, then Radio astronomy has failed to realize the potential of data processing evolution.

We should be able to re-allocate correlator resources appropriate for the science goals. Observing programs can be scheduled according to the required hardware and software resources. Although the antennas are fixed, the correlator configuration can be programmed to provide the best match to the spatial resolution and field of view, as well as the bandwidth, time and frequency resolution required. For example, an observation which requires the full field of view at less than the full resolution should cross correlate a subset of antennas which best match these goals. An observation which requires the highest resolution in a number of limited fields of view could configure the correlator to provide that.

With the data from each antenna in identified packets, the SKA can exploit the development of large commercial data routing and switching networks to provide a very flexible and robust way of moving the data from the antennas to one or more data processing centers where the antenna data are combined and correlated to match the science goals.

We may not initially be able to make cross correlations for all antennas or for a 1 GHz bandwidth, but should plan for the future replacement of the correlator hardware. The rapid growth of computer technology and large size of the SKA correlator argues for a continuous evolution and upgrading of the hardware. A switching network makes it possible to re-route the data to the appropriate available hardware.

3.3. Signal Distribution

The communications logistics and signal distribution to ~ 8000 antennas distributed over ~ 2000 km is not unreasonable in the context of the present rate of growth of wideband networks. The antennas could be distributed in a fractal network with the communications branching out to individual antennas from trunk lines, not unlike a telecommunications system. The cost of a fiber network is increased by having the antennas more widely distributed rather than clustered into compact stations, but not by a huge factor, with a logarithmic distribution of antennas. At larger radii the antennas can be increasingly clustered since one expects to provide uv-coverage by earth rotation if needed. The wideband data links are a valuable asset for nearby communities who could provide substantial political support for the SKA. The incremental cost of providing extra bandwidth for public use is small if the remote antenna clusters are appropriately located near rural population centers. Communities could benefit, not only from the construction phase, but also from the information, education and entertainment infrastructure. Clearly, there is fertile ground for scientific and political research. This memo does not discuss LO and time distribution, which are possibly best done using satellites.

4. Operational Model

The operational model is similar for either hierarchical or homogeneous arrays. For the homogeneous array a station may consist of one or more antennas. An array control center should coordinate observations for the whole array. Observations will be dynamically scheduled with input from observing priorities, equipment availability, and weather. Control data is sent out to the stations; status information is sent back to the control center. Control data for each station such as source coordinates, antenna pointing and phase centers, are sent to a station computer. Pointing, focus, frequency bands, etc. are controlled at the antenna. The data for each antenna are digitized and packetized, and sent to the array processing centers. The data in each packet are uniquely identified and self contained so that they can be routed and cross correlated as desired without ancillary information.

The data are processed at one or more data centers. The processing includes interference rejection, beam formation for time series analysis, correlation and calibration. In front of the correlators, (there may be more than one) is a flexible switching network to route the packetized data to the appropriate correlator inputs. The packets may be delayed in transit, and missing data must be handled. There should be a large buffer to allow correlation of stored data, for example, after a transient event is detected.

5. Imaging

The SKA will be capable of producing data at an astonishing rate. We must include facilities for handling the data and making images in close to real time in order to keep up with the data rate. The full image processing may not be needed for all the data, but it will be important to produce images which can be easily compared (overlayed, cross-correlated) with images from other wavelengths, in order to identify which parts of the images need detailed study. These images must be readily available to the investigators. Fast inspection of SKA images will enable better scheduling of future observations. For long integrations, it is more efficient to store images; for short integrations the uv-data are more compact. Although the SKA is an imaging machine, it is expected that imaging algorithms will continue to be improved and there will be a need to re-process some archived uv-data, especially for transient or time variable sources. The data centers are an integral part of the SKA. They should provide complete support for processing and analyzing SKA data, including data and image archives, pipeline processing, analysis tools, and expertize. The high data rate favors an operational model where users reduce data at the processing centers with fast access to the SKA and the data archives. There may be several data processing centers, perhaps specialized to specific scientific data products. Most investigators will use standard data products, such as fully calibrated images, but the data centers should provide expertize for non-standard experiments which require more user participation. Most users and probably most of the expertize will connect to the data centers electronically.

6. Conclusion

The SKA is a multifaceted instrument. It has some basic science drivers which should not be forgotten in the inevitable *specification creep* which plagues design by committee. On the other hand, the SKA has the potential to be a very flexible telescope. The basic design must allow the SKA to evolve and develop with the scientific drivers and available hardware and software.

7. Acknowledgements and Caveats

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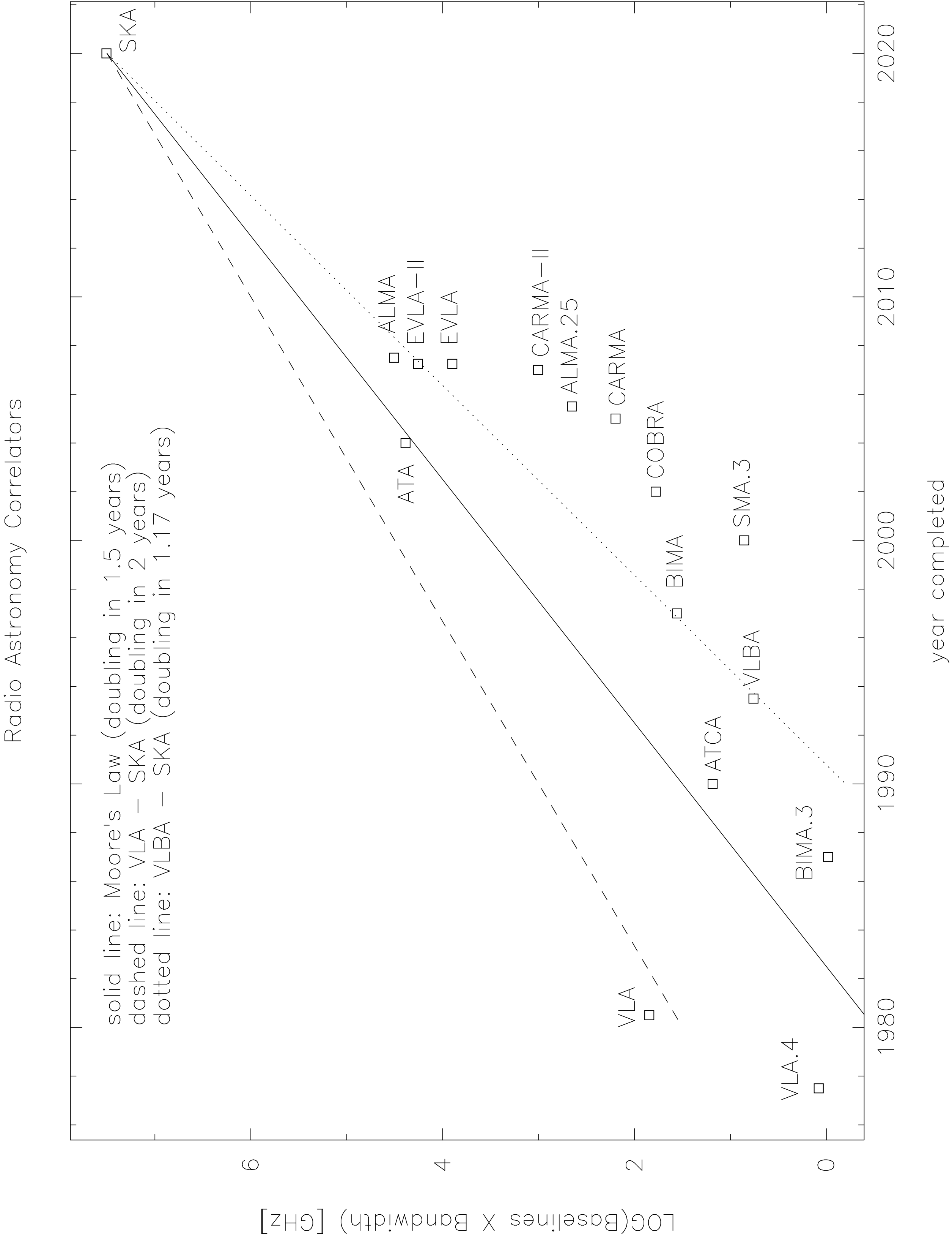

Fig. 1.— Radio Astronomy Correlator Growth