Asymmetric SKA array configuration

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Introduction
The design of the array configuration presents some unique challenges not seen before. The SKA will for the first time will be a synthesis array that can achieve instantaneously complete UV coverage on baselines up to tens of kilometres. Up to baselines of hundreds of kilometres complete coverage with earth rotational synthesis should be possible. All this can be achieved without the use of moveable elements.

Design parameters
It is generally agreed that the total collecting area of the SKA will be divided into three components:
1. About 40% of the area (the compact array) will be designed to achieving high surface brightness sensitivity
2. Another 40% (the imaging array) will used to achieve high resolution imaging, about 0.1 arcsec at 1.4 GHz. The antenna stations will allow correlations with baselines up to 300 kilometres to be measured.
3. The final 10 to 20% of the area will be placed so that the antenna location are suitable for VLBI.

To achieve high surface brightness sensitivity the individual receiving elements should be placed close together. This leads to a compact array of elements covering a couple of square kilometres. The other receiving elements will be divided into 100 to 1000 antenna stations. Fewer antenna stations will seriously compromise UV coverage and more will make the correlator too expensive.

The compact array
The compact array will have a collecting area of about 400,000 m². If this were a single dish it would be over 700m in diameter. In practice this area will be made up of smaller receiving elements arrayed together. Let us assume for the moment that these receiving elements are parabolic dishes or Luneburg lenses. If it is also specified that no shadowing should occur for elevation down to 15 degrees then the receiving elements must be spread over an area of about 3 km in diameter (713m /\sin(15°) .v(p/4)). Grading the UV coverage would increase the area further.

When imaging is considered two high resolutions images there are two sets of correlations to consider. Those between the compact array and the imaging array and correlations between elements of the imaging array. If both the compact array and the imaging array can be considered as being made up of N antenna stations then:
1. Number correlations between compact stations and imaging stations = $N^2$
2. Number correlations between imaging stations = $N^2/2$.

Two thirds of the longer baseline sensitivity is due to correlations between the imaging stations and the compact array. To a first approximation the locations of the imaging antenna stations can be optimised simply by considering their correlation with the compact array. This is a much simpler task than the general case.

**Medium length baselines**

With the compact array giving effectively complete antenna fill over an area 3 km in diameter the easiest way to achieve good UV coverage over medium length baselines is to place antenna stations on a 3 km grid. If the compact array covers a 3 km square then the external antenna should be on a square grid. If the compact array covers a circular area then a hexagonal grid is better. For the sake of simplicity assume a square grid.

But a 3 km square grid of antenna stations out to 300 km would need tens of thousands of antenna stations in the imaging array. This is at least an order of magnitude greater than the desirable number of stations. Complete UV coverage is possible only over some distance significantly shorter than 300 km. Let's assume the full SKA contains the equivalent of about 1000 antenna stations. This means that the imaging array contains about 400 antenna stations. Further assume that half of these antenna stations are devoted to medium length baselines. Thus for medium length baselines there is 4 times as much sensitivity associated with correlations between imaging antenna stations and the compact array than between imaging antenna stations. The correlations between the medium length baseline (MLB) antenna stations can be largely ignored.

An important observation that can be made at this point is that correlations between the compact array and an MLB antenna station generates two points in the UV plane. The points are reflections of each other through the origin. There are many ways to use this symmetry but one of the simplest is to confine the MLB antenna stations to a 180-degree sector from the compact array. This restriction has a small impact on the UV coverage, it halves the longest MLB to MLB correlation in one direction. These points will be filled in with the rest of the imaging array antenna stations.

The 180 degree restriction to antenna placement halves the land area that the MLB antenna stations covers. This reduces the cost of cabling, land acquisition and travel for servicing.

With 220 MLB antenna stations the configuration shown in figure 1 is a possibility. This configuration provides essentially full UV coverage for baselines out to 31.5 km. From directly overhead each MLB antenna station generates a pair of square UV patches each 3 km by 3 km in size. Thus the total UV coverage is $9 \text{ km}^2 \times (2 \times 220 + 1) = 3969 \text{ km}^2$.

The configuration shown ignores the possibility of dithering antenna locations to avoid redundancies, grading of the grid spacing with baseline length and other griddings such as hexagonal, spiral or circular arcs. This rather simplistic design does show an economical approach to obtaining full UV coverage over medium length baselines.
It is also suggested that the array be aligned as shown by the north-pointing arrow. With this alignment the inter MLB correlation extend further NS than EW which will help the beam pattern when observing northern and southern sources.

![Diagram showing array alignment](image)

Figure 1 Complete UV coverage with asymmetric grid of 220 medium baseline antenna stations.

**Longer baselines**

Beyond about 30 km it will become impractical to obtain complete UV coverage. Again it can be shown that correlations between the outer array stations (30 to 300 km) and the MLB and compact array antenna stations provide almost all the sensitivity at longer baselines. But now there are two separate components to consider, correlations with the compact array which provides most of the sensitivity and correlations with MLB antenna stations which provide about one third of the sensitivity.

**Medium length by outer correlations**

Applying the same arguments to the MLB array as was applied to the compact array sees the outer antenna stations being placed on a 60 km(NS) by 30 km(EW) grid over an area extending 300 km to the west (or east) and 300 km to the north and south. With these
110 antenna stations the correlations with the MLB array form a regular grid in the UV plane covering all baselines out to 300 km with a spacing of 3 km. Just this information allows instantaneous imaging with map sizes of 200 by 200 pixels. Note this process does not use the correlations with the compact array optimally and only half of the 200 antenna stations allocated to the outer baselines have been used.

Compact array with outer correlations
Because of the small size of the compact array it is impossible to achieve anything like full UV coverage with correlations between the compact array and the outer antenna stations. This then poses the question as to what strategy is to be used when dealing with these correlations. We could simply double the density of outer antenna stations and simply have double the coverage. A better policy is to acknowledge the incomplete coverage and design the configuration so as to guarantee complete coverage after sufficient earth rotational synthesis.

Full coverage after 12 hours of synthesis is achieved by forming a complete linear array of stations (say EW) starting at the compact array and extending to 300 km. The correlations from this array form a complete unbroken line of UV data samples which over 12 hours sweeps out a completely filled ellipse in the UV plane. The number of stations needed to achieve this is one station every 3 km over a distance of 270 km (the first 30 km is already filled by the MLB array). As there is already a station every 30 km the total number of extra stations is about 80. Adding a northern or southern arm with another 80 to 90 antenna stations reduces the time for complete UV coverage to about 8 hours. The interesting fact about this configuration is that the UV coverage is complete, it has no holes. With a sparse grid, spiral, circle or random configuration the UV traces cross each other randomly leading to a build up of data at some UV locations and no data at others. This randomness leads to a randomisation of the sidelobes. With complete UV coverage the point spread function can be designed to have controlled low-level sidelobe level and the resulting maps start with good dynamic range and are easy to clean.

If 12 or 8 hours for a full synthesis is too long then further compromises are needed. The only way to reduce the time for complete synthesis is increase the number of arms. With 5 arms complete synthesis is possible in about 3 hours. Allocating 120 antenna stations to the arms means there is a total of 24 antenna stations in each arm. With a 3 km station spacing each arm extends from 30 to about 100 km. Reduced time to full synthesis has reduced the maximum baseline over which complete and uniform UV coverage is obtained.

Note, asymmetric placement of the arms does not degrade performance. As an example, either 36 or 72 degrees spacing between the arms of a 5 arm array give the same UV coverage for correlations between the arms and the compact array. Again the dominance of correlations with the compact array mean that an asymmetric array as shown in figure 2 does not lead to significant asymmetry in the UV coverage.
The configuration in figure 2 shows a complete SKA design, except for the VLBI antenna stations. There are probably insufficient antenna stations to completely fill the five arms shown which means that the outer sections of the arms will be only partially filled. For example, with 33 antenna stations per arm the first 11 could be spaced at 3 km, the next 11 at 6 km and the last 11 at 15 km giving a total arm length of 264 km. Add to this the 30 to 40 km of baseline due to the MLB array and the maximum baseline is about 300 km. The correlations with the MLB array are now needed to fill in the gaps due to partially filling the arms. The fill is incomplete and the UV coverage is no longer complete. With the antenna station placement given above, the incomplete fill will lead to grating lobes. The alternative is a zoomed array along the arms that will spread the energy in the grating lobes over the whole map. Fewer arms gives better fill of each arm and more complete UV coverage but only with longer observation time. Complete instantaneous coverage the space between the arms is covered with antenna station placed on a 60 by 30 km grid. However the instantaneous coverage is far from uniform.

Figure 2 Possible SKA configuration
**Redundancy**

The regular structure in the MLB array, the arms and dispersed antenna station leads to significant redundancy. The arrays that show redundancy are at most one half the area of the compact array. Thus correlations that show redundancy contribute at most 20% of the information available. For the MLB array on a regular grid the correlation are highly redundant, about 100 per baseline. Thus it may be advisable to reduce the level of redundancy. A good approach to this is to apply a slight zoom factor to the array so that antenna stations near the compact array area space at about 2 km intervals and at the edge of the array the spacing has increased to just over 3 km. Larger spacings at the edge of the array will lead to gaps in the instantaneous UV coverage.

If the grading on the array is done in sections then significant but great reduced redundancy result. This residual redundancy can be used to good effect in providing rapid calibration of the array in a manner similar to the system employed at Westerbork. This online calibration and good UV coverage will provide rapid high-quality snapshot imaging.

**Conclusion**

This report describes a design method for the SKA which flows from the realisation that correlations involving the compact array dominate the system sensitivity at all baselines. This leads to the possibility of complete instantaneous UV coverage for baselines of up to a few tens of kilometres and a fully sampled but incomplete UV coverage for baselines up to a few hundreds of kilometres. In addition to this the use of filled multiple arms coupled with earth rotational synthesis gives complete and uniform UV coverage for full-length observations.

The advantage of complete arms correlated with the compact array over other configurations is yet to be proved. But the concept does provide an array configuration that should be able to provide proven high performance against which other configurations can be tested.