ARRAY CONFIGURATIONS THAT TILE THE PLANE

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Abstract. Future radiotelescopes need to have high sensitivity. With the limits of receiver sensitivity being reached this can only be achieved by increasing collecting area. Because of this, next generation telescopes will have hundreds if not thousands of large antennas. The large number of antennas greatly increases the possible array configurations or ways of locating the antennas. In this paper a variety of antenna configurations are considered which divides the antennas into two classes

1. A single area of antennas where the antennas are placed on a widely spaced grid.
2. A set of compact components where, within each component, the antennas are closely packed.

With these it is possible to obtain configurations that densely and uniformly sample the UV plane. This allows high quality imaging. The configurations also allow considerable savings in correlator complexity and demonstrate the possibility of asymmetric configurations

Keywords: Antenna, array, UV coverage, radiotelescope, correlation

1. Introduction

A next generation radiotelescope SKA [Smolders and Van Haarlem] is currently under consideration. Its large collecting area, one square kilometre, implies a telescope with at least an order of magnitude more antennas than existing telescopes. This greatly increases the number of possible array configurations. This paper introduces a class of configurations that consisting of compact components and a single area of dispersed antennas.

This class of configurations can provide uniformly and densely sampled coverage in the UV plane (Fourier transform of the image plane)[1]. This can ensure high quality instantaneous imaging and bring the SKA closer in operation to an optical instrument. Although the designs are not, in general, optimal for the SKA they do help in illuminating two general principles

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[1] The SKA when forming images will operate by forming correlations between pairs of antenna. Each correlation gives a measurement of the magnitude and phase of a single spatial frequency. The vector joining the two antennas defines the position of the measurement in the spatial frequency domain. For simplicity it is assumed all antennas lie in a plane. Instantaneously, all spatial frequencies now lie in a plane, the UV plane. A further simplification is that the source being observed is at zenith. At other elevations the UV coverage plots shown in this paper are foreshortened.

that can be applied to the design: asymmetry and the use of antenna of different sizes. Modifications to the designs that bring them closer to an optimal SKA design are also shown.

2. Existing designs

Previous designs for radiotelescopes have contained at most 100 reflector antennas. A list of some existing and past designs is shown below. With small numbers of antennas a linear configuration is preferred and earth rotational synthesis is needed to achieve good UV coverage. These designs usually include moveable antennas to increase the number of possible baselines [Frater] [Ryle] [Hogbom and Brouw]. With more antennas a Y configuration is feasible consisting of three linear arrays each of about 10 antennas. The Y configurations of the VLA and GMRT provide about 400 simultaneous baselines distributed over the UV plane. With this UV coverage, snapshot imaging becomes feasible because at current sensitivities much of the image is blank . The final interesting design is the circular configuration of the Culgoora Radioheliograph [Wild]. At the time, the 3000 channel correlator needed for full synthesis was prohibitively expensive. Instead a simpler method called J^2 synthesis [Wild] was used. This configuration has an excellent UV coverage and is a viable option for the SKA. Its main limitation is its fixed maximum baseline and gaps in the short baseline coverage. Newer designs include the zoomed spiral [Conway] and concentric circles or oval.

Table 1: Previous antenna configurations

	Location	Number of Antennas	Configuration	Synthesis
AT [Frater]	Australia	6	Linear	Complete
5 km [Ryle]	Cambridge	8	Linear	Complete
Westerbork [Hogbom and Brouw]	Netherlands	14	Linear	Complete
VLA [Thompson et al]	New Mexico	27	Y	Complete
GMRT [Swarup et al]	India	30	Irregular Y	Complete
Fleurs [Bunton et al]	Australia	38	Linear + 2	Partial
Radioheliograph [Wild]	Australia	96	Circular	J^2 synthesis

The Fleurs radiotelescope was a highly cost constrained university telescope. In one mode of operation 32 small antennas (5.7m) were correlated with 4 of the larger antenna (13.7m) resulting in 128 correlations. These correlations, with earth rotation, provided good UV coverage except in a NS direction. Correlations between the small antennas could have increased the sensitivity by 2.3 dB but were not affordable because the correlator would have been almost 5 times larger. As with the SKA the objective was to achieve the best performance within the available budget. A much more cost-effective way to achieve the same gain in sensitivity was to form the correlations between the 6 large dishes. The added correlator cost was negligible. The extra UV coverage also helped to fill in a gap in the NS baselines. The sum of the two provided the best imaging obtained with the instrument.

Correlation between the two extra large dishes and the small dishes would have provided the next most cost effective increment in sensitivity but budgets and the lack of improved UV coverage precluded this.

The lesson for the SKA is that there is a need to consider designs where the inputs to the correlator come from antennas with different collecting areas. For the SKA this might be accomplished by beam forming with compact groups of antennas or using different antennas for the two components. The savings in correlator complexity could easily be an order of magnitude or more. For example, with 1000 antennas, each correlated against the others, the correlator has 500,000 channels. If 900 of these antennas are arrayed together into groups of 10 the total number of correlations is reduced to 17,955.

3. *Complete UV coverage, single compact component.*

To maximise surface brightness sensitivity a large fraction of the SKA antennas should be tightly packed into a single area giving a single compact component. UV coverage at baselines greater than the diameter of the compact component could be obtained by surrounding the compact component with a regular grid of more widely spaced antennas. The number of spaced antennas increases as the square of the radius. For an SKA made from a large number of smaller antennas this approach should be useful for baselines of up to 10-50 km. Most of the sensitivity for these medium length baselines can come from correlations between the compact component and the grid of spaced antennas. For example, if there are 2N antennas in the compact component and N antennas in the widely spaced grid then the correlation can be considered to consist of three types.

1. Compact-Compact correlation between antennas within the compact component ($2N^2$ correlations). Information at short baselines only.
2. Compact-Spaced correlations between the antennas of the compact component and each of the antennas in the widely spaced grid of antennas ($2N^2$ correlations)
3. Spaced-Spaced correlation between antennas within the widely spaced grid of antennas ($N^2/2$ correlations)

Only the Compact-Spaced and Spaced-Spaced correlations provide information at medium length baselines. If the Spaced-Spaced correlations are ignored the total number of medium baseline correlation is reduced by 20% which is equivalent to a 10% loss of collecting area. With the Compact-Spaced correlations there is no loss of on axis sensitivity if the signals from the compact antennas are first summed, before the correlation. The total number of correlations needed to provide medium baseline information is reduced to N or three orders of magnitude less when N~400. The savings made in the correlator can be spent on increasing the collecting area and so reduce or recover the lost sensitivity. A consequence of the reduction in correlator size is a reduction in the field of view. Multibeaming and subdividing the compact component can reduce this loss. In the end, the final configuration of the SKA will be a complex tradeoff between field of view, antenna numbers, antenna beam forming and correlator size. But as correlator cost is expected to halve every two years it is probably advisable to start with a minimum correlator configuration and add the remaining correlations later.

When the correlations with the compact component dominate, the problem of calculating the UV coverage is greatly simplified as correlation between antennas external to the compact component can be ignored. A single antenna at (x,y) correlated with the compact component generates correlations at (u,v) and the conjugate point (-u,-v) in the UV plane. If the compact component was at the origin of the XY plane then moving the single antenna to (-x,-y) results in the same points in the UV plane being measured. Thus it is possible to bisect any configuration of spaced antennas by a line passing through the compact component. If all antennas on one side of the line are relocated to their conjugate position on the other side of the line then all the spaced antennas lie in a 180^0 arc. An example of the resulting configurations is shown in Figure 1. If the maximum distance between adjacent spaced antennas is equal to the diameter of the compact component then the resulting UV coverage is fully sampled out to the maximum baseline and very high quality mapping is possible.

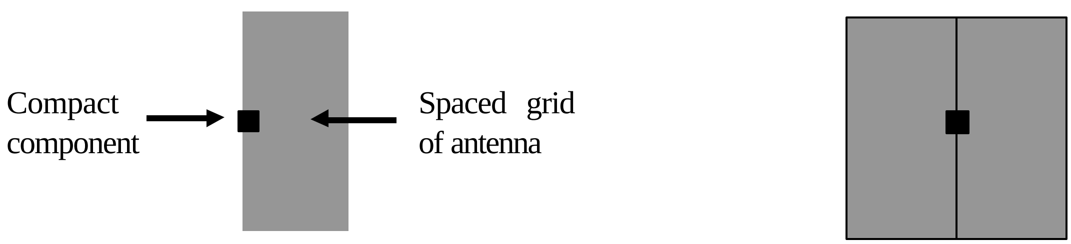

Figure 1 Possible configuration with one compact component. Resulting UV coverage is shown on the right. Spaced-spaced correlations omitted.

4. Multiple Compact Components

Breaking a single compact component into *N* multiple compact components will reduce the area of each by a factor of *1/N* and the maximum internal baseline by $1/\sqrt{N}$. Many baselines originally within the single compact component now occur between the widely separated multiple components. The total number of baselines within a single compact component is reduced by the factor $1/N^2$. Including all *N* compact components gives a total reduction in short baselines of 1/*N*.

Interestingly, the sensitivity of the shortest baselines is largely unaffected. Consider a linear equal-spaced array of *M* antennas. There are *M*-1 baselines with a length equal to the shortest spacing. If a very large array was broken up into groups of 5 antennas then the number of shortest baselines is still 80% of the number in the large array. Extending this to two-dimensional arrays shows that compact components of about 25 antennas have a shortest baseline sensitivity that is still 80% of the maximum possible. With just 4 antennas the sensitivity is still 50% of the maximum.

An incidental advantage of multiple compact components is that each can be identical except for a rotation. Thus the number of non-overlapping rotations possible can increase the completeness of the short baseline UV fill. With this added flexibility the shorter UV coverage becomes sets of rings like those generated by circular array configurations.

Multiple compact components will also be useful for VLBI, as long as each compact component is sufficiently sensitive. With a single compact component the UV track of any correlation between a VLBI antenna and the compact component will be approximately equal to the width of the compact component. With multiple components there will be multiple tracks with the greatest separation equal to the maximum separation of the multiple compact components. As an example, with multiple components spread over a 50km area adding 20 VLBI in an EW line can give a VLBI system with the mapping quality equivalent of Westerbork or the Cambridge 5km telescopes. With 20 compact components there are 600 VLBI baselines which are sufficient for complete imaging at a one milliarcsecond resolution in a 1 degree field.

Using multiple compact components with each being treated as a single antenna will increase the size of the correlator compared to a single compact component treated as a single antenna. But the size of the correlator is now directly proportional to the field of view. With N compact components the maximum internal baseline is proportional to $1/\sqrt{N}$. Hence the field of view, in square degrees, is proportional to N as is the size of the compact-spaced correlator.

5. Complete UV Coverage with Multiple Compact Components

When multiple compact components are allowed there are many new configurations that provide a complete sampling of the UV plane. Some of these new configurations for 2, 3 and 4 compact components are shown below. With 2 compact components 4 copies of the space grid of antennas are available to tile the plane. This reduces to 3 if two copies tile to the same central location by placing one compact component in the centre of a square or hexagonal spaced grid. The example of 4 squares is shown in Fig. 2. Other possibilities are 4 hexagons and 3 rectangles. Examples of the more general case for these last two are shown later, Figs 9a and 7.

For the case with 3 compact components then either 5 or 6 copies of the spaced grid of antennas are possible. The only compact tiling possible is shown in Fig 3, which is based on 6 triangles forming a hexagon.

The natural formation with 4 compact components is shown in Fig 4. This tiling has 6 hexagons surrounding a centre hexagon that is formed by the baselines between the central compact component and the spaced grid together with the conjugate of these points. This folding of the hexagonal tile on itself doubles the sensitivity of the centre tile. An 8-tile pattern is also possible by taking the design in Figure 2 making the spaced grid rectangular and adding two more compact components above and below, or to left or right. The more general case of this arrangement is shown in Fig 6a.

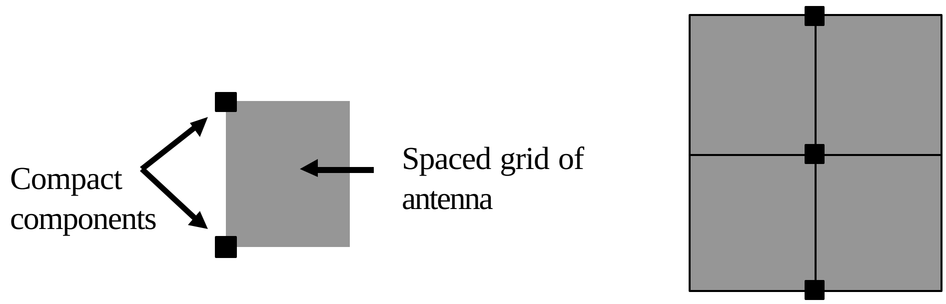

Figure 2 Possible configuration with two compact components. Resulting UV coverage is shown on the right. Spaced-spaced correlations omitted.

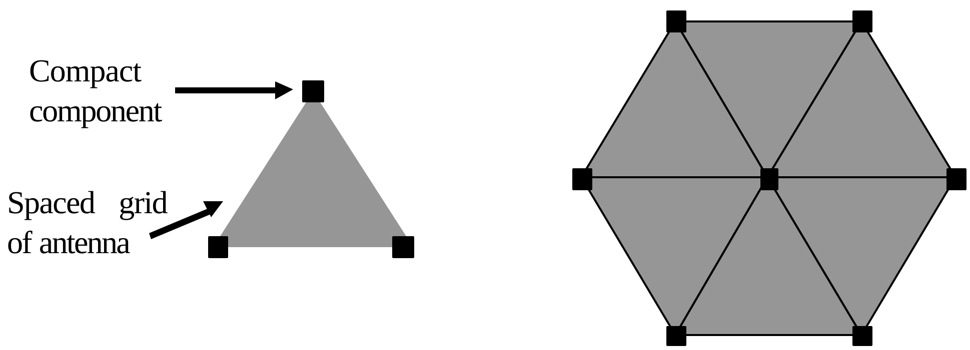

Figure 3 Possible configuration with three compact components. Resulting UV coverage is shown on the right. Spaced-spaced correlations omitted.

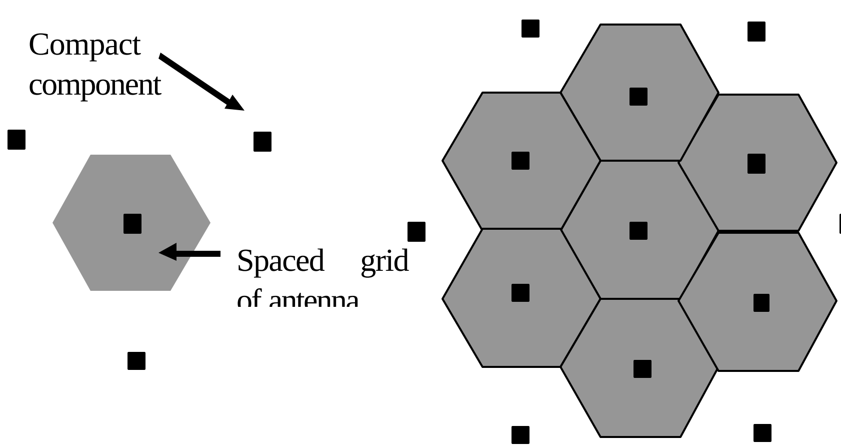

Figure 4 Possible configuration with four compact components. Resulting UV coverage is shown on the right.

The designs shown in Figures 1 to 4 can all be scaled so that the shaded area of the UV coverage, shown on the right, is identical for all designs. The shaded area corresponds to correlations between compact components and the spaced antennas, and the black squares are compact-compact correlations. Spaced-space correlations have not been shown. If the number of antennas in spaced grid and compact components is unchanged then the total sensitivity as measured by correlations per square kilometre, is unchanged. What has changed is that with increasing numbers of compact components:

1. longer baseline sensitivity increases due to correlation between individual compact components
2. medium baseline sensitivity increases due to the decreasing size of the spaced grid of antennas
3. short baseline sensitivity decreases due to the reduced size of the compact components and
4. the very shortest baselines are largely unchanged, as described in the preceding section.

The overall effect of increasing the number of compact components is the sacrifice of longer baselines within the single compact component and the redistribution of these over medium to long baselines. As an example consider a configuration as shown in Figure 1 where the single compact component (2N antennas) is 3 km across and the spaced grid of antennas (N antennas) is 30 by 60 km in extent. As the configuration is progressively changed to those shown in Figures 2, 3 and 4 the sensitivity (as measured by correlations/ km^2) at different baseline changes. Keeping the area covered by compact-spaced correlations constant allows the differences to be seen.

For a single compact component there are $2N^2$ correlations distributed as a square pyramid over 6 by 6 km of the UV plane (+3 to –3km in both directions) and the height of the pyramid is proportional to sensitivity. The volume of a square pyramid is 1/3 Area times the maximum sensitivity and this is equal to the number of correlations.

$$\text{Number of correlation} = 2N^2 = \frac{1}{3} Area.(\text{maximum Sensistivity})$$

$$= \frac{36.\text{maximum Sensistivity (correlation/km}^2)}{3}$$

Thus the maximum sensitivity is $3(2N^2)/36 = N^2/6$ correlations per km^2. This sensitivity falls off linearly as the baseline increases. For the spaced antennas correlated with themselves the maximum sensitivity is $3(N^2/2)/(4$ times area covered by grid$) = N^2/4800$ for the single compact component configuration. For the 2, 3 and 4 compact components the maximum sensitivities are $N^2/2400$, $N^2/1600$ and $N^2/1400$ correlations per square km respectively. For the compact-spaced correlations the sensitivity is uniform and equal to $2N^2$/UV coverage = $N^2/1800$ for the single compact component configuration. This value is maintained for 2, 3 and 4 compact component configurations except for the centre part of the 4 component configurations. For this configuration the compact component is in the centre of the spaced grid of antennas and this doubles the sensitivity at shorter baselines. Finally, with *M* multiple components only 1/*M* of the correlations remain at short baselines. If the newly formed longer baselines are averaged over the area of UV coverage then the sensitivity is $((M-1)/M)N^2/1800$. A table comparing these various sensitivities for the configurations shown in Figs 1 to 4 is shown below.

Table 2: Sensitivity of the various components of the correlation as a function of baseline length in units of $N^2/600$ correlations per square kilometre

	Internal to compact components			Spaced by spaced	Compact by spaced		Compact by compact
No compact components	Min.	1 km	2 km	Short baselines	Short baseline	30km	Av. Over Plane
1	100	66	33	0.125	0.33	0.33	N/A
2	99	50	5	0.25	0.33	0.33	0.17
3	98	44	0	0.37	0.33	0.33	0.22
4	97	33	0	0.44	0.66	0.33	0.25

As described previously the sensitivity on the shortest baselines is unchanged. At baselines of 1 to 3 km there is a very significant degradation as the number of compact components increases. Mostly this component of the sensitivity is now distributed among isolated patches at longer baselines generated by correlations between the individual compact components; last column of table. This is partly compensated by the decrease in the area covered by the spaced grid of antennas, which increases the short baseline sensitivity. Placing a compact component within the spaced grid of antennas, as shown in the 4 component configuration, also increases short baseline sensitivity. The short baseline sensitivity of this last configuration is about 1% of the maximum sensitivity of the compact components. If the number of compact components was to increase then the maximum sensitivity of correlations between spaced components increases. With about 20 compact components the maximum sensitivity outside the internal compact baselines is 3% of the shortest baseline sensitivity.

6. General Tiling of the UV plane

The UV coverage shown in Figures 2, 3 and 4 suggest that compact components together with a spaced grid of antennas can be used to tile the UV plane. Such tilings increase the number of compact components. Contraction in the size of the spaced component would improve sensitivity at baselines of about 1 to 6 km and at the same time the sampling of the UV plane due to correlations between compact components would improve.

The simplest case is a triangular area or tile of spaced antennas. As the tile has two distinct orientations there is only one spatial location for a compact component that generates the correct locations and orientations for the tile in the UV plane. The configuration of compact components that fills the UV plane is shown below.

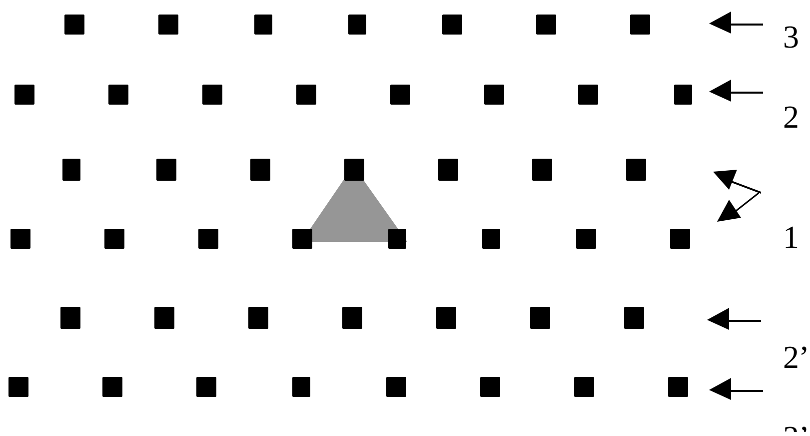

Figure 5 UV filling configuration with single triangular tile of widely spaced antennas and many compact components

This arrangement has some flexibility because the tilling occurs in strips. Thus the row pairs 22’ and 33’ can be displaced horizontally without affecting the completeness of the coverage. For example, a displacement of the 22’ rows can make the compact components lie on two rectangular grids, one above and one below a horizontal centre line. Randomising the displacement of pairs of rows can be used to help randomise the UV coverage generated by correlations between compact components. As can be deduced from figure 5 the UV coverage due to correlations between compact components will form a regular grid. Randomising the rows will tend to fill the rows in the UV coverage but leave the gaps between rows untouched. If the rows were orientated close to NS this randomised design becomes useable for observations near 0 degrees declination. Even greater flexibility is possible if squares
are used

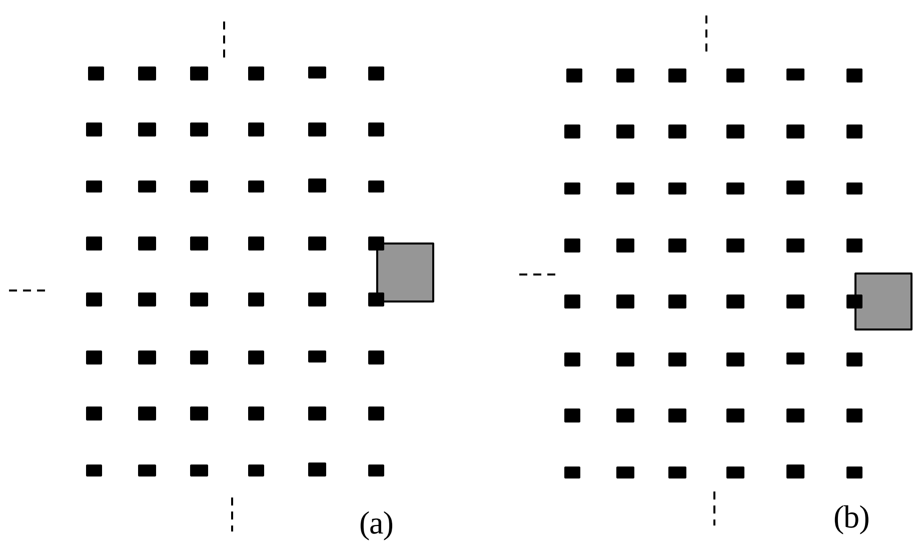

Figure 6 A configuration that tiles the UV plane and has increased sensitivity in the centre tile.

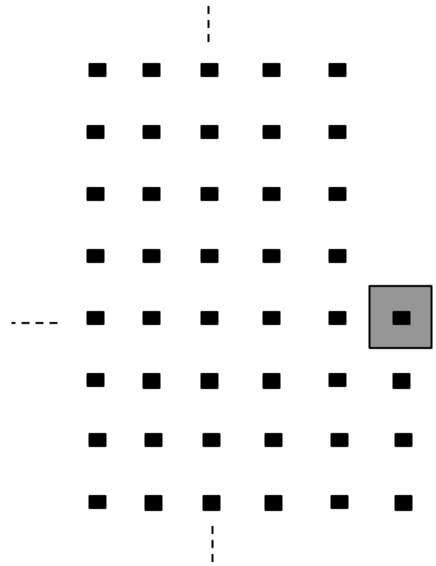

Figure 7 Two configurations consisting of a single square tile of widely spaced antennas and many compact components that uniformly tile the UV plane when correlated together.

Figures 6a, 6b and 7 show antenna configurations that tile the UV plane with square tiles. Designs with the square spaced grid of antennas placed at any position between those shown in figures 6a and 6b are also allowed. These designs are asymmetric with all of the compact components lying within a 180^0 arc of the square tile containing the spaced grid of antennas. As with the design using a triangular tile some randomising is possible. For the designs above, any column can be shifted vertically. The UV coverage between compact components becomes regularly spaced but largely filled-in columns.

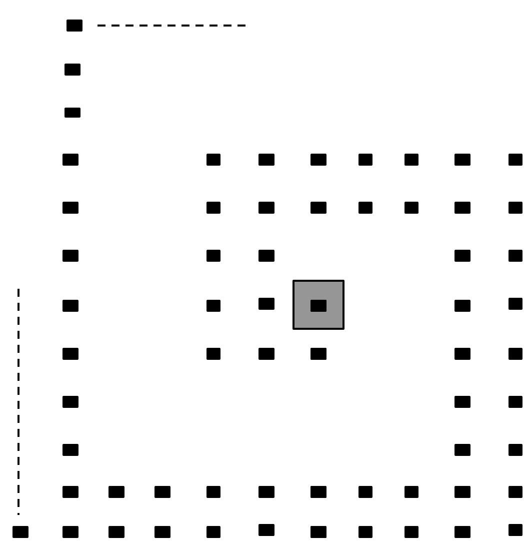

Figure 8 Design shown in Figure 7 reconfigured as a dual spiral.

A second degree of freedom with square tiles is that the UV plane (compact with tile correlation) is preserved when any of the compact components is reflected through the centre of the tile (spaced grid of antennas) to its conjugate position. Using this principle the design in Figure 7 can be reconfigured as a dual spiral as shown in Figure 8. Many other configurations are possible.

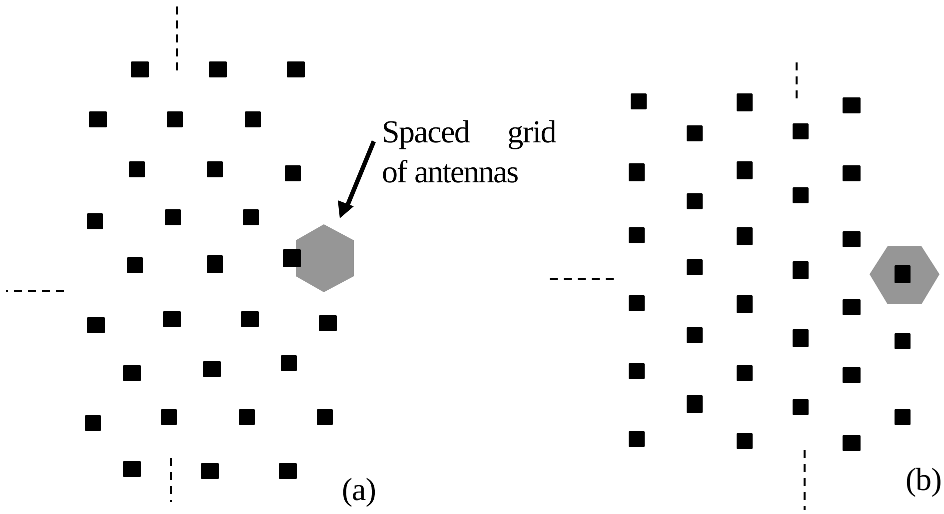

Figure 9 Configurations that tiles the plane with hexagons. Configuration (b) has higher sensitivity for correlations within the central hexagon.

The final regular polygon that can tile the plane is the hexagon. Two designs that tile the UV plane with hexagons are shown in figure 9. Totally asymmetric designs are shown for both cases. As with the square tile configurations compact components can be reflected through the centre of the spaced grid of antennas without affecting the compact-spaced UV coverage. But displacement of rows or columns of compact components is not possible because of the way hexagons interlock when tiling the plane. When triangles and squares tile the plane there are slip lines which provide this extra degree of freedom.

The three-fold symmetry of the hexagon allows the compact components of the design shown in figure 9b to be arranged into a triple spiral as shown in figure 10. For a given number of compact components this doubles the maximum baseline between compact components and halves the redundancy between these correlations. Even so, the redundancy is still high. Figure 11(a) shows a 19 compact component (small circles) configuration, the single spaced grid of antennas is indicated by the hexagon. In Figure 11(b) it is seen that all the compact-compact correlations fall on a regular hexagonal grid. The resulting point spread function (PSF), Figure 11(d), shows the first of the grating responses that result from this regularity. As the size of the compact components will be small compared to their separation there will be many orders of grating responses within the field of view.

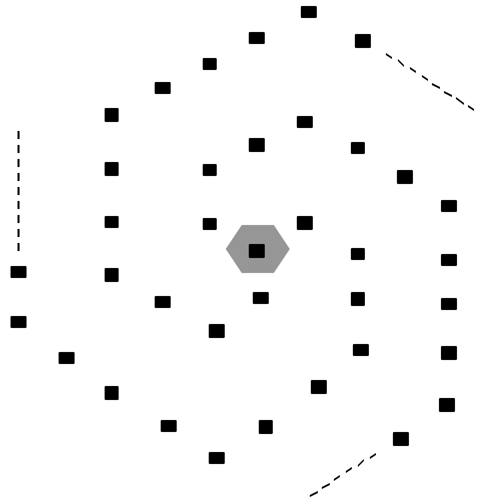

Figure 10 Rearrangement of figure 9(b) into a triple spiral.

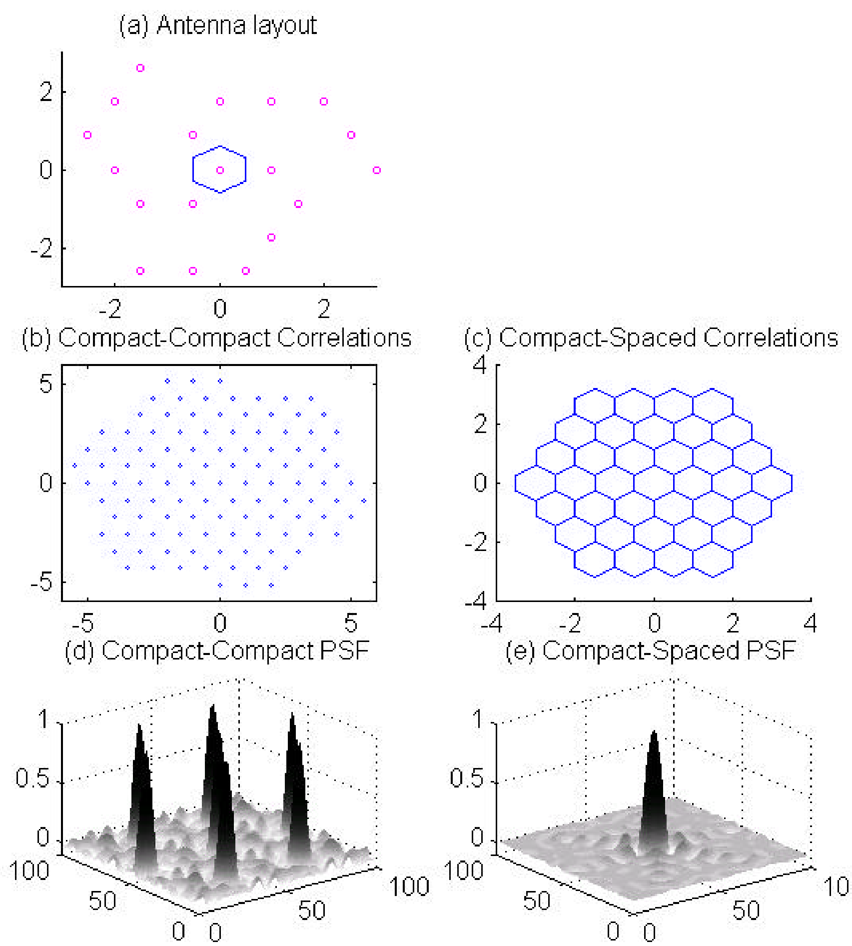

Figure 11 A 19 compact component triple spiral.

The compact-spaced correlations essentially fill the plane as shown in Figure 11(c). The resulting PSF Figure 11(e) can be made to have no grating responses but because the maximum baseline is half that of the compact-compact correlation the width of the main peak is larger. But as the coverage is uniform it is less than twice the width. Applying a suitable grading function to this coverage can give PSFs with very low sidelobe level. However, for best sensitivity the compact-compact must be included which reintroduces grating responses and sidelobes.

7. Non Regular tiling

In general, uniform coverage of the UV plane will not be optimal. Even for a design that is optimised for a particular resolution the UV sensitivity needs to be higher on the shorter baselines. For the SKA where resolutions at many scales are required the degree of deviation from uniformity promises to be even greater. For the designs described in this paper some of the strategies that increase short baseline sensitivity are:

1. Decrease the spacing between compact components nearer to the spaced antennas.
2. Increase the size of compact components nearer to the spaced antennas.
3. Increase the number of antennas in the spaced component
4. Add extra compact components, especially within the area of the spaced components.

Table 3: Sensitivity of the various components of the correlation as a function of baseline length in units of N^2/600 correlations per square kilometre

	Internal to compact components			Spaced by spaced	Compact by spaced		Compact by compact
No compact components	Min.	1 km	2 km	Short baselines	Short baseline	20km	Av. at 20km
1	100	66	33	0.125	0.33	0.33	N/A
19	80	0	0	2.4	0.66	0.33	0.3
19 zoomed	80	0	0	2.4	2.66	0.33	0.3

As seen in Figure 11 regular spacing between compact components leads to grating responses. This suggests that the best way to improve short baseline sensitivity is to alter the spacing between compact components. This can be achieved by moving triples of the compact components in towards the spaced grid. In the 19 compact component configuration shown in Figure 11 there are 6 triplets. Scaling the six triplets by .35, .45, .6, .63, .75 and .7 respectively gives the zoomed tiling shown in Figure 12(a). The zoomed tiling no longer exactly tiles the plane; instead the tiles overlap. This overlap is greatest at short baselines. Using the same parameters as section 4 gives the results in Table 3 which shows estimated sensitivity for the various components

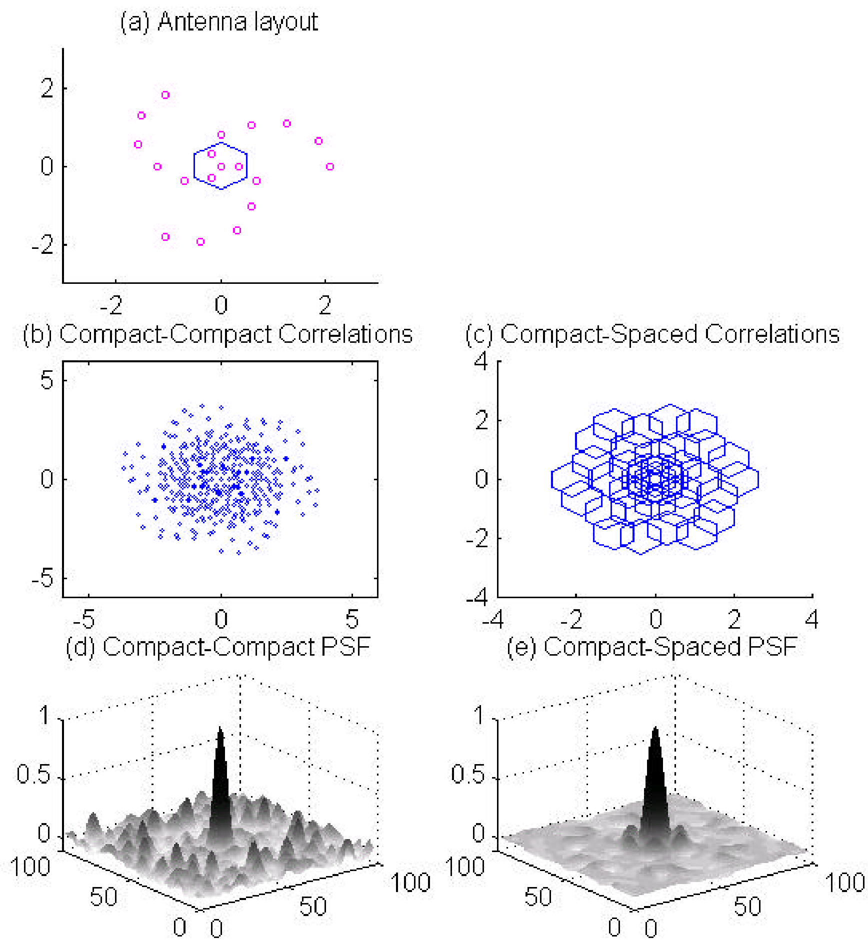

Figure 12 A zoomed 19 compact component triple spiral.

The compact components are now estimated to be less than 1km in diameter and hence do not contribute to the sensitivity at 1 and 2 km. The spaced grid of antennas occupies 1/19th the area, which raises the short baseline sensitivity to 2.4 for both the regular and zoomed configuration. The zoomed configuration brings 3 compact components inside the spaced grid of antennas adds an extra 2 to the short baseline sensitivity giving a total short baseline (about 1km) sensitivity of 5. Longer baseline sensitivity is now due to compact components either through compact-compact or compact-spaced correlation.

The point-spread function due to the compact-compact correlations has improved considerably, compare Figures 11(d) and 12(d). There are no grating responses and the rms sidelobe level is now about 5% of peak. By comparison the sidelobe level has increased in the PSF due to compact-spaced correlations due to the irregularity in the UV coverage. Applying a suitable grading function will restore the very low sidelobe level, for example the PSF could be made to approximate a gaussian. With a gaussian PSF photographic quality imaging is possible without resorting to post processing such as clean. This has come at the loss of additional sensitivity possible if compact-compact correlations are included. Adding the both correlations together with no grading function applied gives the PSF shown in Figure 13.

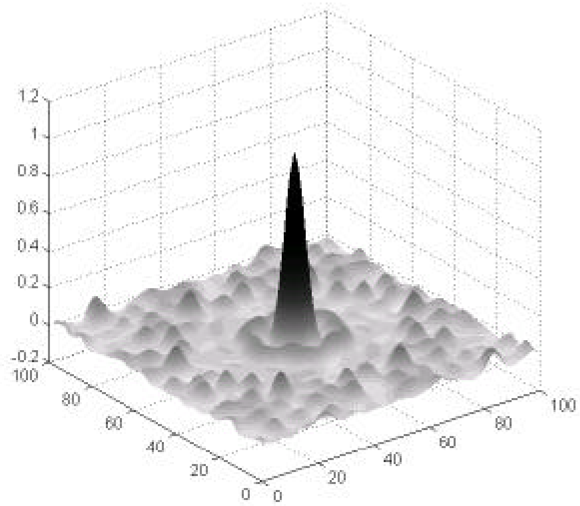

Figure 13 Point spread function for compact-compact plus compact spaced correlation

The relative weighting of the compact-compact correlations is one half. As the compact-compact correlations are responsible for most of the sidelobes the rms sidelobe level is now 2.5%. Without grading of the correlation, post processing is needed. But the availability of the high quality image makes the process much easier. A very low sidelobe image can be used as the starting image. With its compact PSF CLEANing of this image will be very quick and stable. This data can then be used to subtract known sources from all the UV data. With good calibrations a high sensitivity residual map made without any grading will need very little further processing.

8. Conclusion

Sets of general configurations that tile the UV plane have been presented. To achieve this the antennas are split into a number of compact components and a single area of antennas where the antennas are more widely spaced. These configurations can fill the UV plane with points that have a sampling interval given by the antenna spacing of the compact components. The resulting maps can be of photographic quality without the need for any special processing such as CLEAN.

The various configurations also show two possibilities that are not commonly used in modern radiotelescope design: using antennas of different sizes and asymmetry.
Different sized antenna can give significant correlator savings. Larger antennas can be obtained by arraying small antennas or by using different types of antenna. Asymmetry is possible because many of the antennas are concentrated in a small area. With such a central concentration all other antennas can be concentrated within a 180^0 arc without significant loss.

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