Next Generation Very Large Array Memo No. 3

Possible Configurations for the ngVLA

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Introduction

The process for choosing a configuration for the ngVLA goes through the following steps: first is the definition of the desiderata for choosing between possibilities; second is the choice of the overall design; third is the tuning of those design parameters for optimum results and matching them to the scientific use cases; fourth is the fitting of the chosen configuration onto the site chosen; and fifth, the actual civil design of the antenna stations. All during this process, the configuration studies interact with other parts of the design, so that documentation of the current state of this process, as well as of the progress in science use cases, antenna design and receivers needs to be kept at an up-to-date level. This memo is intended to start discussion of the first two steps of this process.

Desiderata

The general ground rules for the design of the array are first, that it be a substantial step forward relative to the VLA in both collecting area and resolution, and second, that operational costs must be held to a minimum. For purposes of the current investigation, we consider an array of 255 elements (the number is chosen for having convenient factors of three and five). For eighteen meter elements with higher efficiency at high frequencies, this gives about ten times the effective collecting area of the VLA. We consider baselines of order one hundred kilometers. Along with a doubling of the highest frequency, this gives ten times the resolution of the VLA. But, for current purposes, neither of these is very important. The conclusions of this memo are not likely to be much affected by scaling the array to a larger or smaller size, or by building twice as many antennas of twelve meter size. 255 eighteen meter elements are chosen only to give concrete realization to the principles.

The desire for low operational costs has one consequence that makes this study different from other studies of general purpose arrays. This militates in favor of elements at fixed locations that are not reconfigured. The primary benefit of reconfiguration is to move collecting area from long baselines to shorter ones. This is problematic for the ngVLA. An eighteen meter antenna will weigh something over 100 tons, and cannot be transported whole over public roads. Maintaining several hundred kilometers our own paths that could bear that weight would be an intolerable operational cost. There another sort of reconfiguration we could consider - to build excess antenna elements, and transport receiver and drive packages around the array as needed. This sort of reconfiguration may be contemplated again when relative costs are known, but we will not deal with it here.

The most important science drivers tend to fall into two broad categories – thermal continuum studies and thermal spectral line studies. There are many other categories of science that can be studied with an array constructed for these general thrusts, but which do not, individually, provide a significant input for constraining the design. In both cases the instrumental requirements demand good surface brightness sensitivity. Many of the desired observations are of material at temperatures of a few Kelvin. There is higher temperature material in, for instance, HII regions, and there are regions of interest which are optically thin, such that the desired sensitivity is much less than one Kelvin, but in broad terms, we are looking at a desired surface brightness sensitivity of a few Kelvin.

For thermal continuum wide bandwidths may be used. At the highest frequency, the 3mm band is limited on either side by oxygen absorption features in the atmosphere. A low system temperature can only be attained in the center 25 GHz of the band. At lower frequencies, the usable bandwidth is limited by the bandwidth of the receiver, typically half the center frequency. For spectral line observations, the frequency resolution desired is of order one or a few kilometers per second, therefore about 10^{-5} as large, resulting in sensitivities $10^{2.5}$ times as large, meaning that, with comparable collecting area, baselines must be about $10^{-1.25}$ times as large. So one important desideratum, possibly the most important for the ngVLA, will consist of looking at the surface brightness sensitivity on two different spatial scales about a factor of ten different.

Note that, since the desired parameter is surface brightness, the overall scale of the array is fairly sensitively dependent on other parameters of the system. The supportable size of the array depends directly on the antenna element size and on the square root of the number of elements. It depends inversely on the square root of the attainable system temperature and (for the continuum case) on the fourth root of the bandwidth.

We shall calculate a “taperability” parameter for the various array configurations. To do this, we will adjust the overall scale of the various configurations to give the same natural weighting hpbw of 6 milliradians per kilometer. The taperability parameter is calculated as the relative sensitivity (as the inverse of the effective number of elements) of the array with natural weighting within a 8 km Gaussian taper (11 km at half weighting).

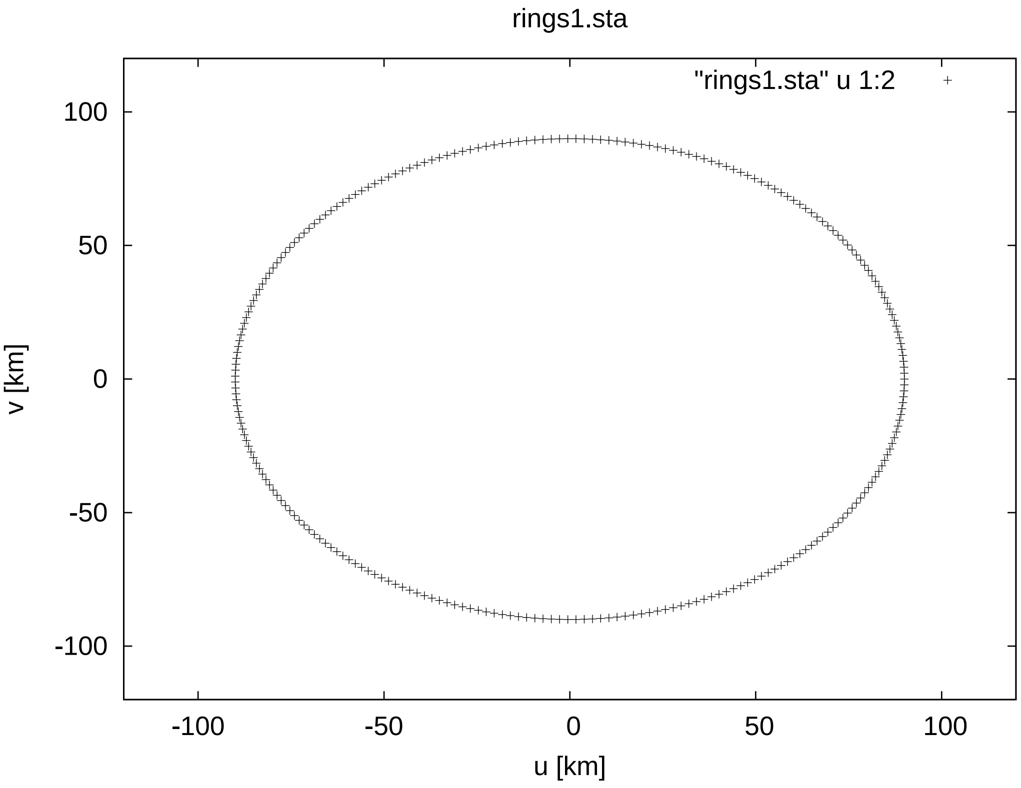
We shall discuss in general terms four overall design concepts: A ring distribution; A power law distribution (the VLA utilizes a power law distribution); A novel hierarchical tree distribution, and the Conway concept of Alma Memo 283, which is a hybrid, comprised of a ring, an exponential spiral, and an inner core.

Ring Distributions

The ring distribution has a remarkably uniform u,v coverage. This is good, in that it makes a much smaller naturally weighted beam for overall size of the array than centrally peaked distributions. On the other hand, it is bad, in that if one tapers the observation to observe low surface brightness, the u,v coverage becomes very sparse. Figure 1top is the array.   The ring shown has a 60 km radius, adjusted to provide the reference beam we will use for this memo. The primary disadvantage of the simple ring is a shortage of very short baselines. For this 60 km ring, the shortest baseline is the spacing of antennas along the ring 1.5 km. The effect on the inner part of the u,v plane is illustrated in Figure 1 bottom. For spacing much longer than 2 km, though, the coverage is very good.   The taperability coefficient at 8 km is 0.27.

Although there are still a large number of u,v points within 8 km,the lack of baselines shorter than 1.5 km is a serious fault. A way to remedy that fault would be to take some percentage of the stations and put them into a smaller ring. Since the two rings would be tackling different problems much of the time, they can be operated independently, as two instruments. Doing so, however, loses the baselines connecting the two rings, and is a serious loss of sensitivity at the highest resolutions. It is better to place the rings close enough together to let them be operated as one instrument as needed. Making the rings concentric results in a circle of very high density of baselines at the radius of the large ring, corresponding to baselines between the small ring and the elements on the large ring. It is better to make the rings tangent, as shown in Figure 2. This array is an outer ring of 170 antennas at a radius of 68 km and a small ring of 85 antennas with a radius of 5 km. Note that the baselines connecting the two rings cover the full range of v, but only half the range in u, making the natural weighted beam elliptical. The minimum spacing of 370 meters is still too large, but this configuration gives very good coverage on baselines of about 8 km, scientifically interesting for thermal spectral line studies. The taperability coefficient at 8km is 040.

The minimum spacing can be addressed by adding an inner core. A particular example of such a configuration is an outer ring of 153 antennas at 70 km radius, a middle ring of 81 antennas at 5 km radius, and an inner ring of 21 antennas at 150 m radius. The inner part of the u,v plane is shown in Figure 3. The taperability coefficient is 0.43.



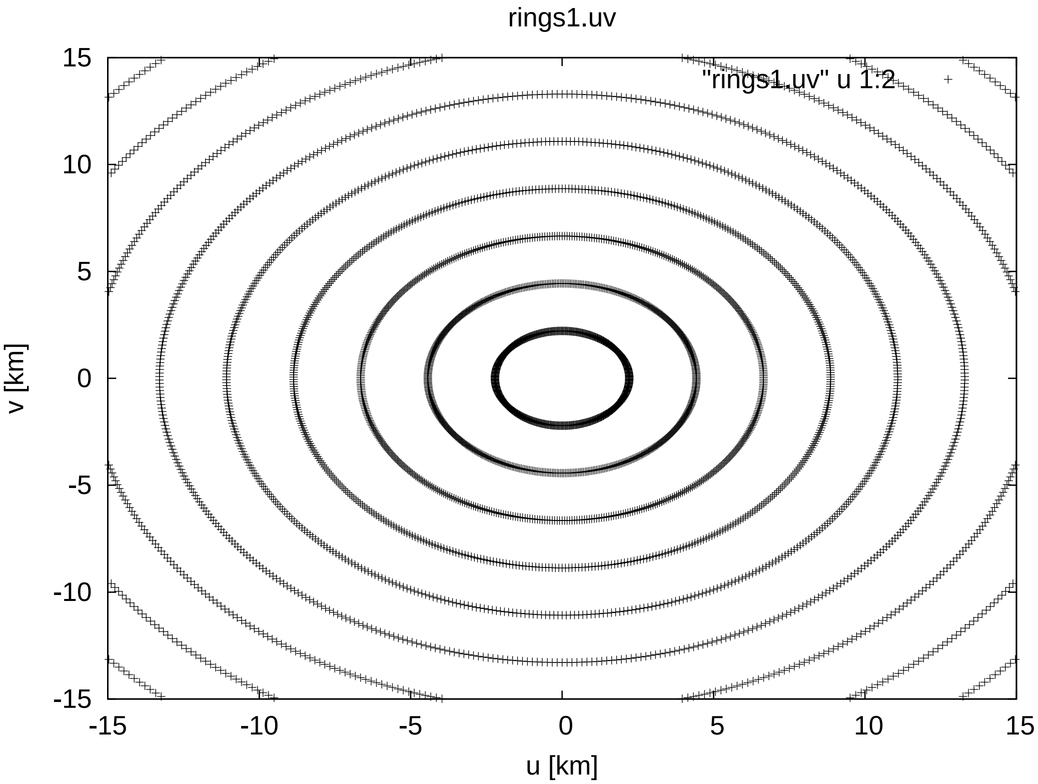


Figure 1. Simple ring. Top – Station layout, bottom, inner u,v plane.

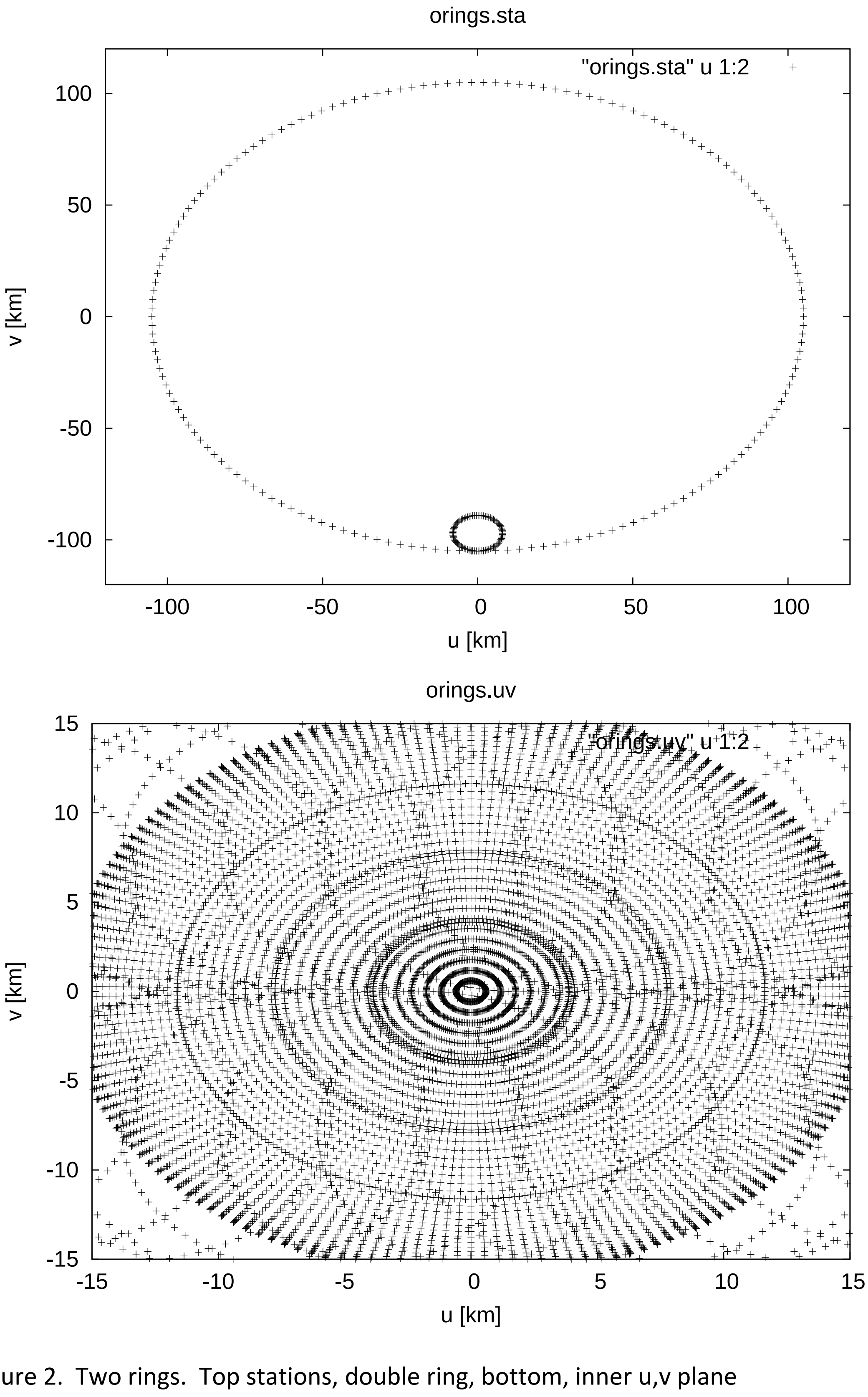


Figure 2. Two rings. Top stations, double ring, bottom, inner u,v plane

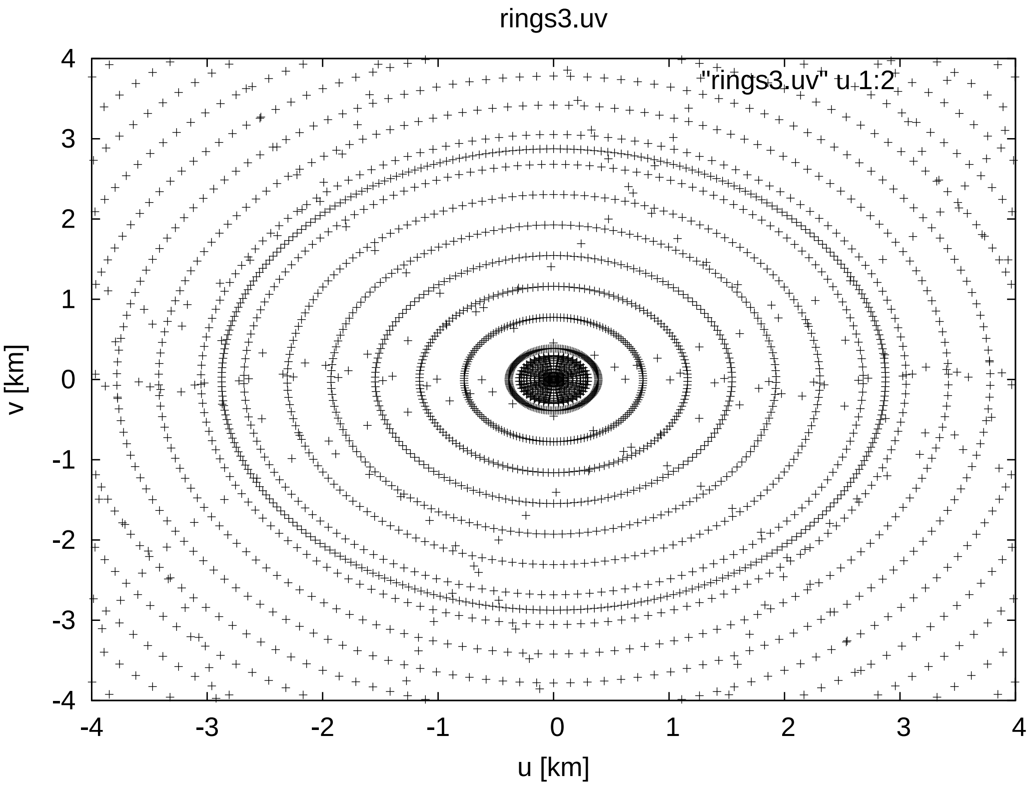
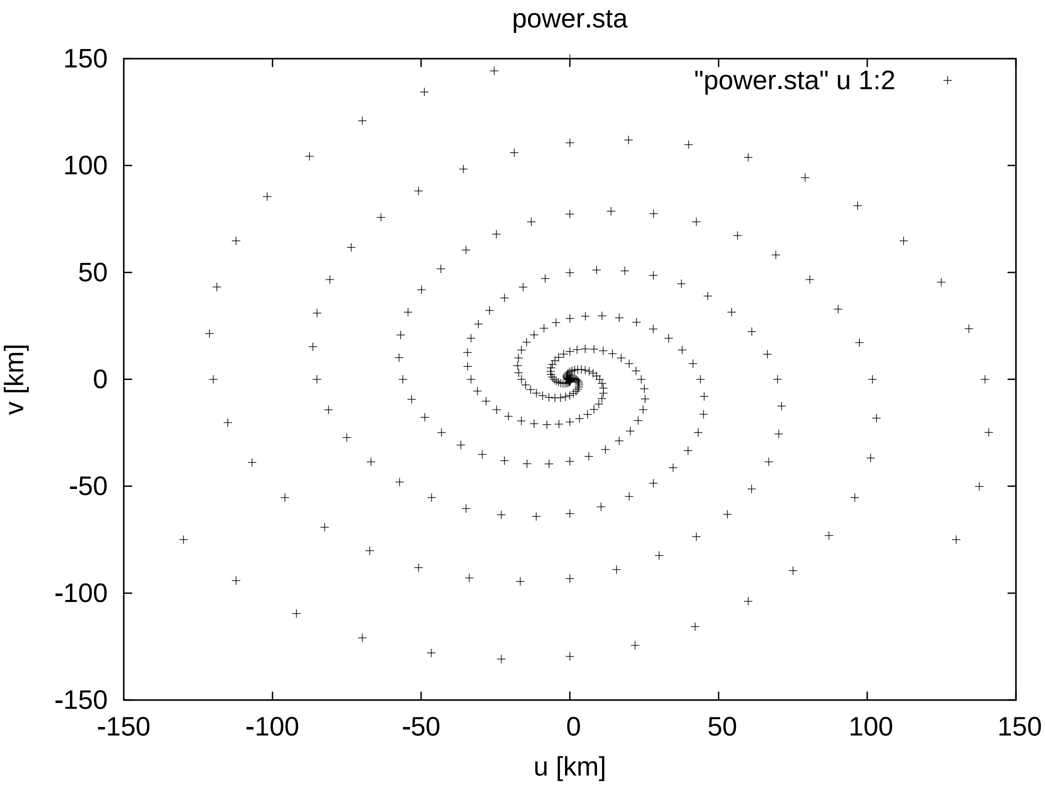


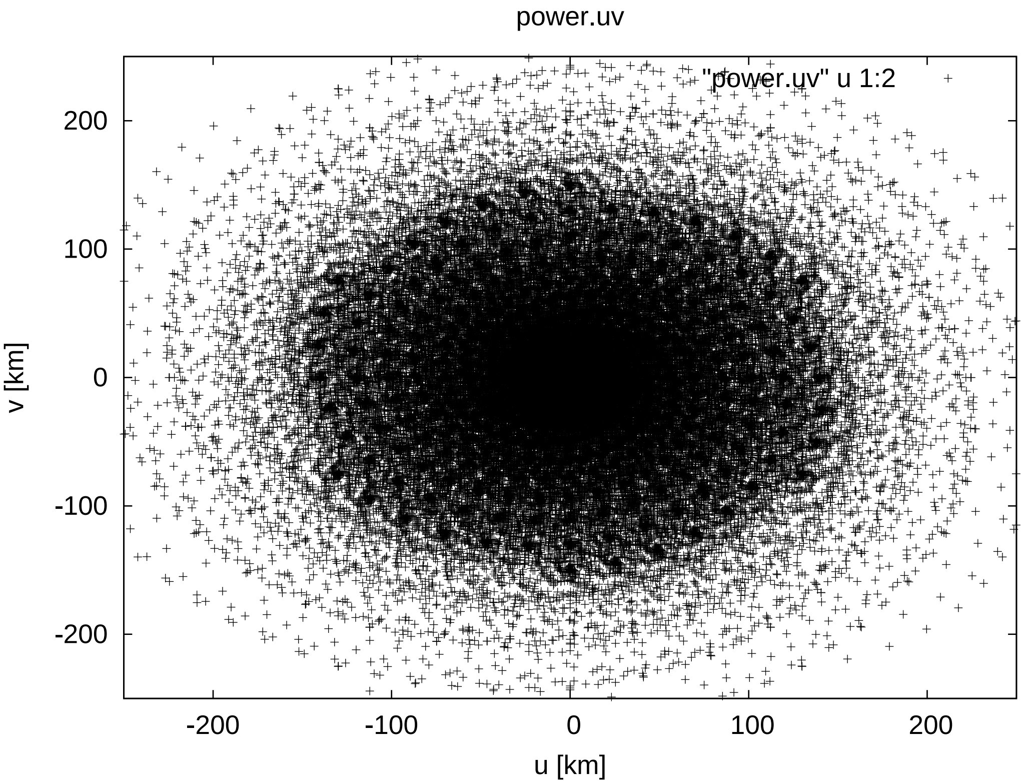
Figure 3. Three rings, inner u,v plane.

Power Law Distribution

It has been shown that distributions of antennas along curved arms yield generally more satisfactory u,v coverage than along straight arms. That granted, the u,v coverage is not very strongly dependent on how curved the arms are. The main effect of adding additional curvature to the arms is to further smear the points on the outer edges of the u,v diagram. This is mainly a cosmetic effect as these points create effects easily removed by the deconvolution algorithms.

With 255 antennas, 85 on each of three arms, the choice of a power law distribution with index two provides a good u,v coverage at all distances . That is, the location of the nth antenna along each arm is proportional to n^2. As mentioned above, the tightness of the spiral appears to be unimportant. The station locations for such an array are shown in figure 4, and the u,v coverage in figure 5 top. The u,v coverage is strongly peaked at the center, so the natural weighted beam is much larger than that of the ring distribution with the same overall size. Therefore, the extent of the array in figure 4 has been expanded to get our canonical natural weighted beam of six miliradians per kilometer. The good coverage of the u,v plane near the origin is shown in Figure 5 bottom. The formal taperability coefficient at 8 km is 0.31.





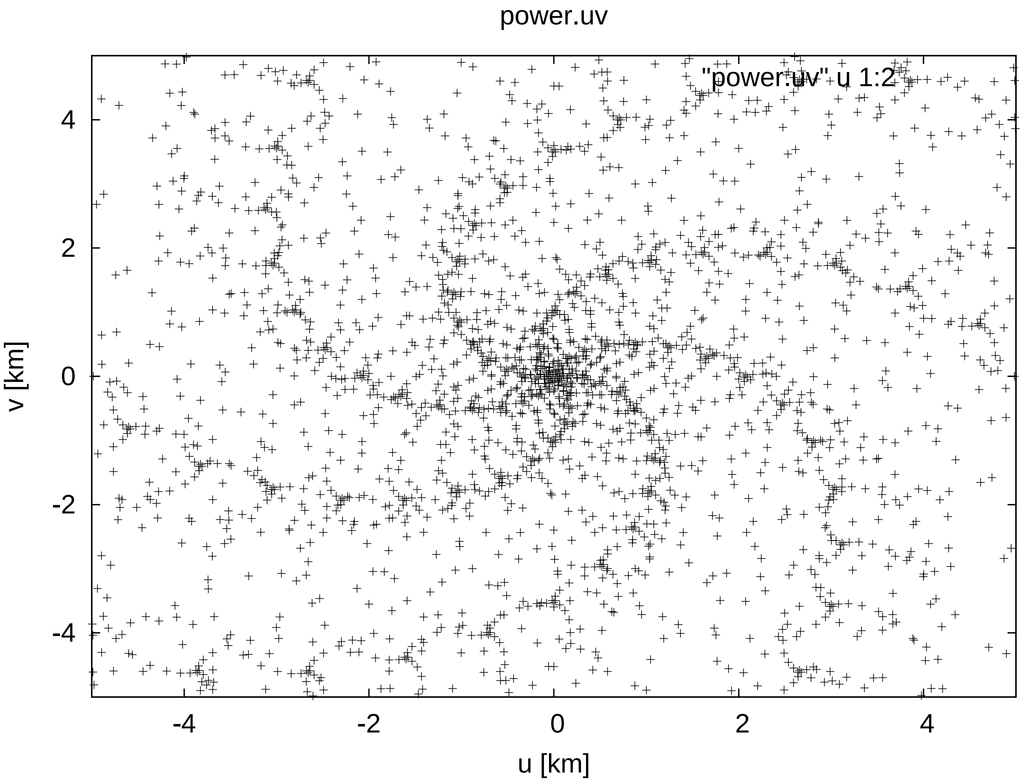


Figure 5. u,v coverage of the power law array. Top, full plane, bottom, inner plane.

A Coreless Hierarchical Configuration

The usual way of constructing configurations tends to have short baselines near the center of the array. This is not a necessary constraint. There is a certain attraction to having short baselines scattered across the x,y plain. For instance, having small groups allows common infrastructure, such as LO transmitters and receivers, rather than needing each station to have the long connection to the center of the array. It also permits the use of one of the group in a 'calibrator array', always watching a calibrator to evaluate the atmosphere above the group. The array described here is a hierarchical, tree-like construct. The trunk of the tree has three branches, in a spiral-like configuration. At seventeen places along the main branches there are twigs. Each twig has three leaves. Each leaf consists of three fairly close spaced antennas. The antenna locations are shown in figure 6 top, and the u,v plane in figure 6 bottom. Although the u,v coverage looks rather blotchy in Figure 6 bottom, it does not get much worse on smaller scales, as shown in Figure 7. The formal taperability coefficient is 0.28 at 8 km taper.

As in the case of the rings, this configuration can be tailored to emphasize a second u,v range smaller than the extent, by tuning the size of the twigs to be the scale of interest.

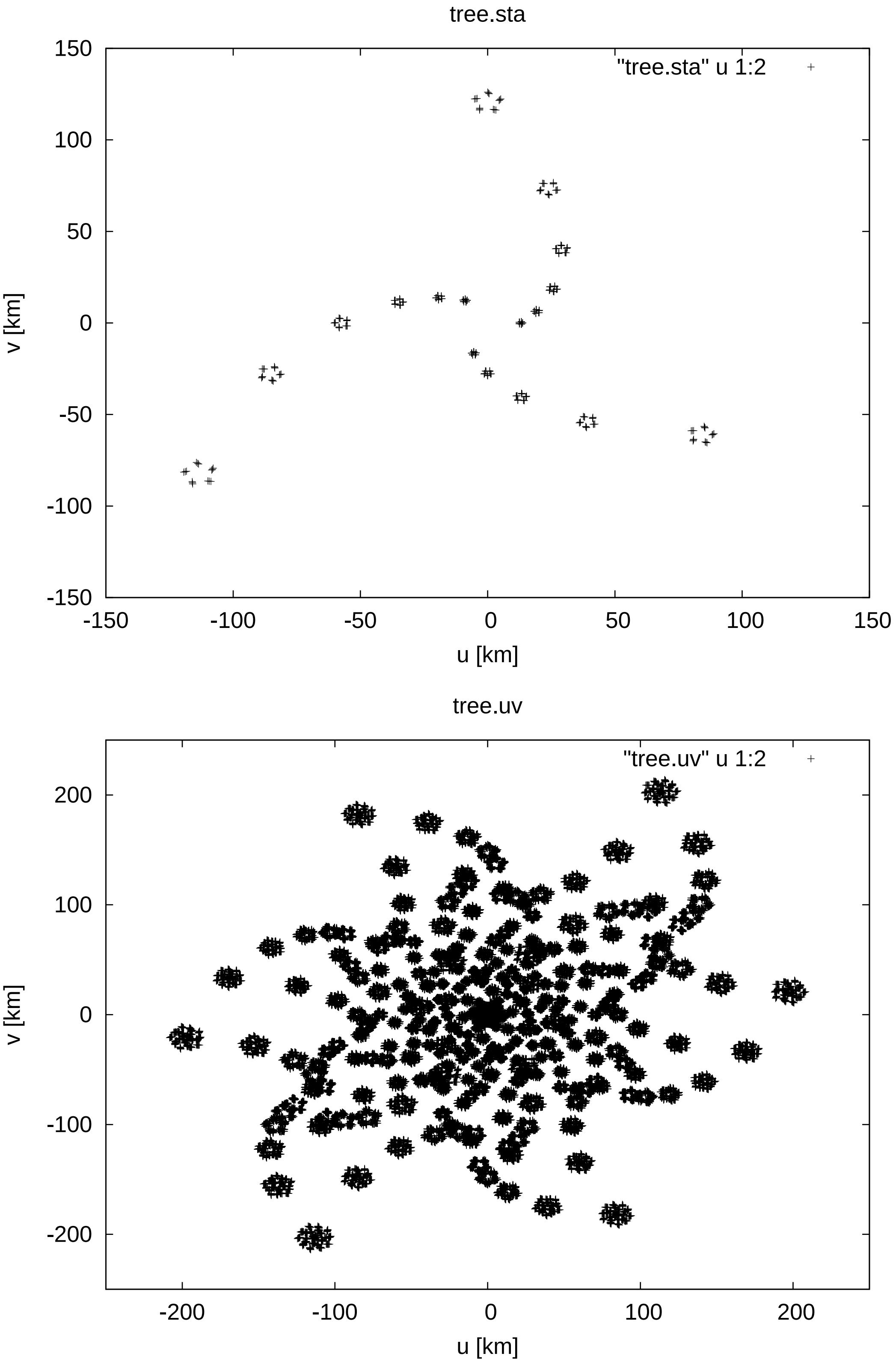


Figure 6. Hiarchical Configuration. Top – station locations, bottom – u,v plane

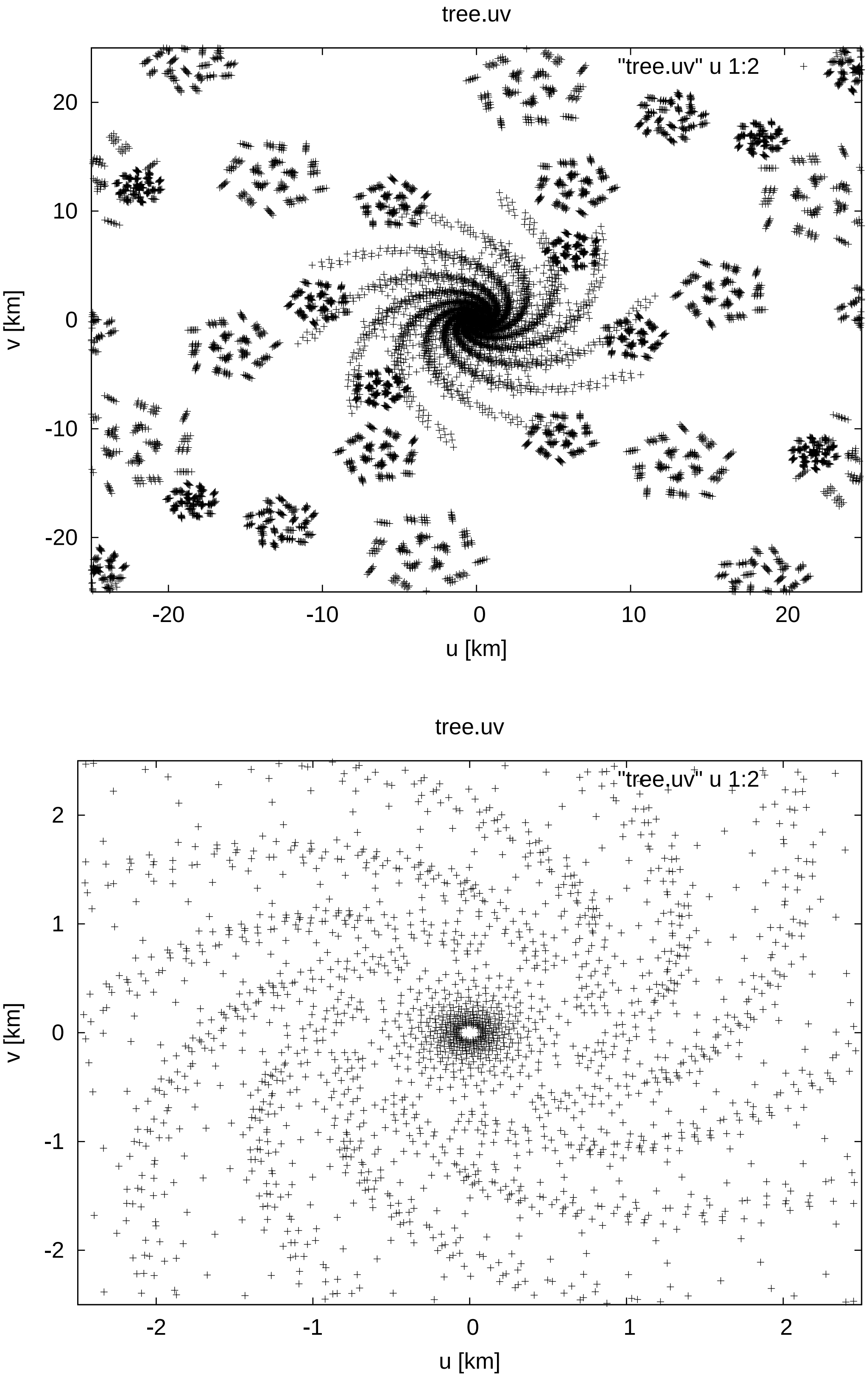


Figure 8 – Hiarchical configuration – inner u,v plane.

Conway's ALMA Configuration

The configuration proposed by John Conway in ALMA memo 283 is a hybrid of several different concepts. It has a ring around the outside, which tends to eliminate the sharp points around the outside of the u,v coverage as seen in Figure 4 or Figure 8. Inside this is a fairly tightly wound logarithmic spiral, and in the center a core to provide the short spacings. One of the design considerations was that the u,v coverage should be reasonably complete within a given distance if the entire configuration is not occupied. This is not a consideration here; as stated in the introduction, we regard the concept of reconfigurations as undesirable for the ngVLA.

For this exercise, the core has been taken to be a rectangular block of antennas on forty meter spacing. This results in an unnecessarily lumpy distribution in the u,v plane near the origin. In a practical implementation, one would soften the core distribution a bit to smooth things out. The particular version illustrated here has 36 antennas in the ring, 183 antennas on the spiral (61 on each arm), and 36 antennas in the core. The station layout is shown in Figure 9, the u,v plane in Figure 10, and the inner part of the u,v plane in Figure 11. The formal taperability coefficient at 8 km is 0.50, noticeably better than the other layouts discussed above.

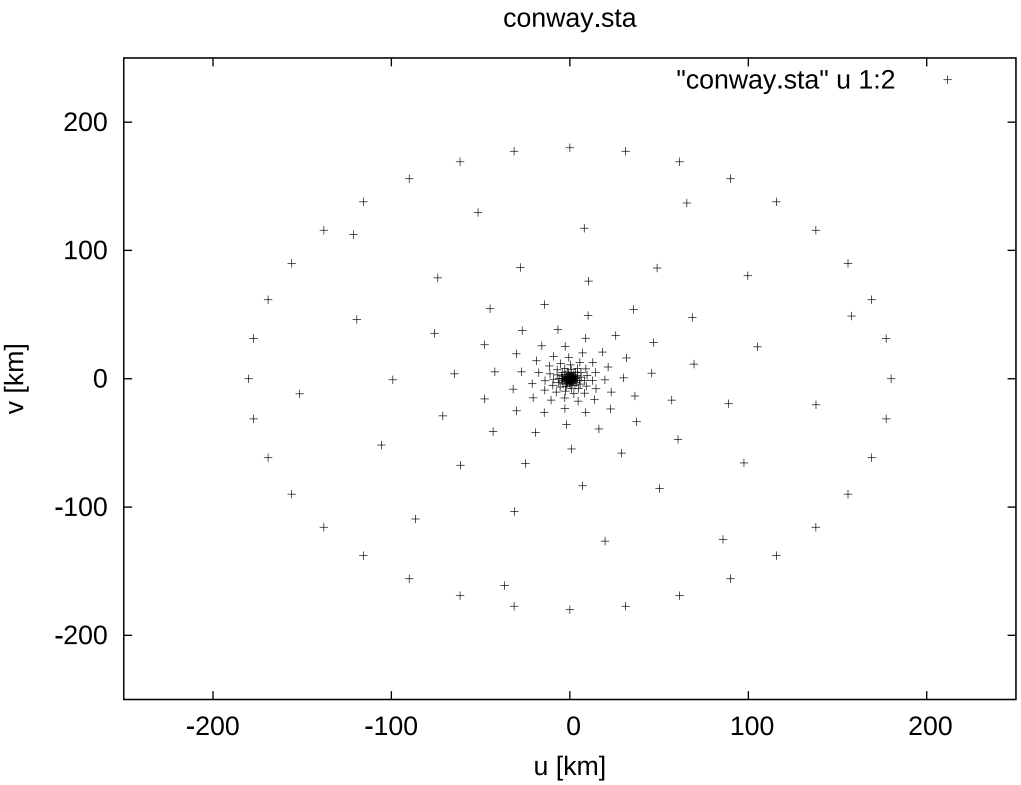


Figure 9. Station layout for the Conway array.

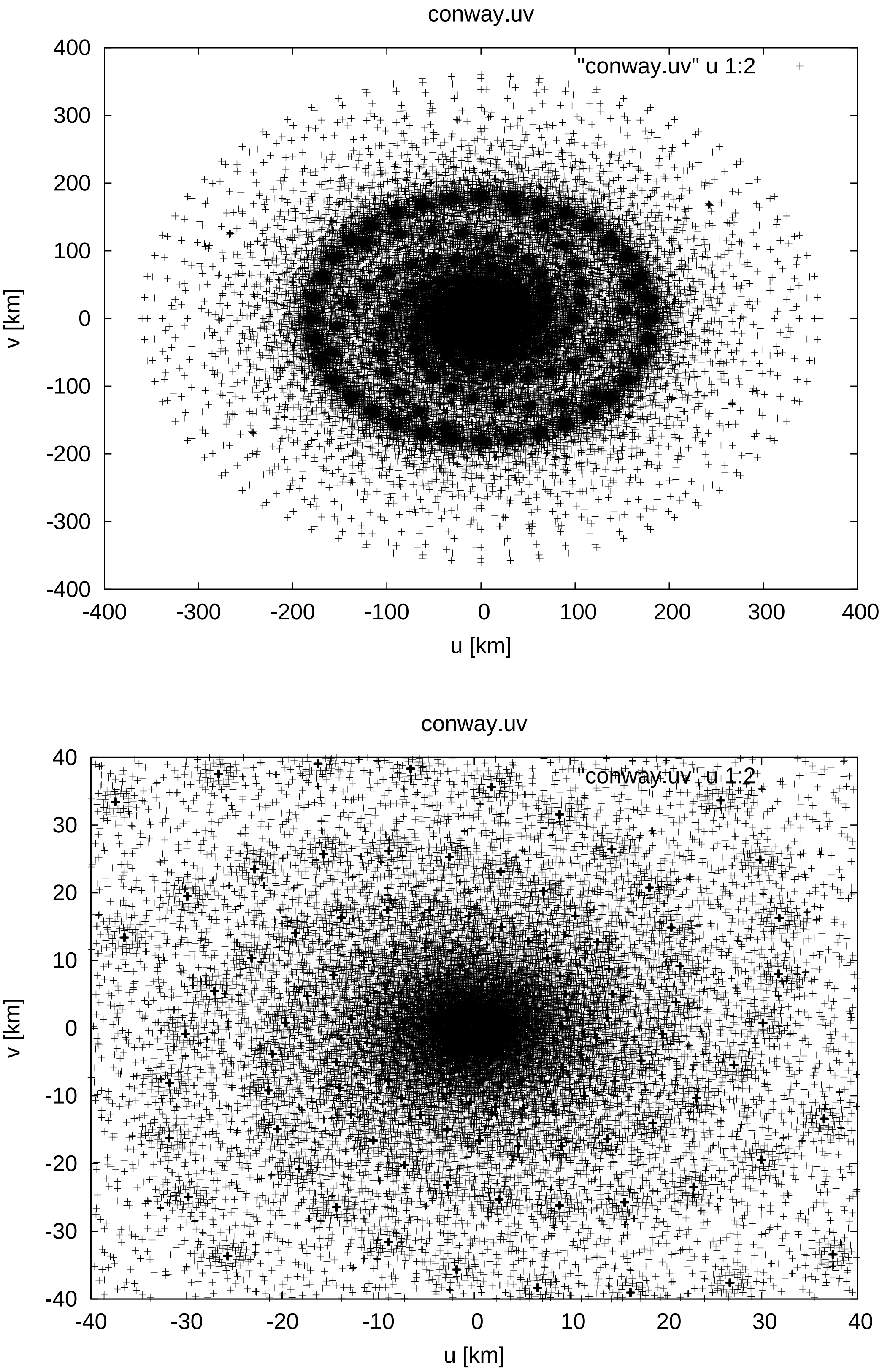


Figure 10. u,v coverage of the Conway configuration

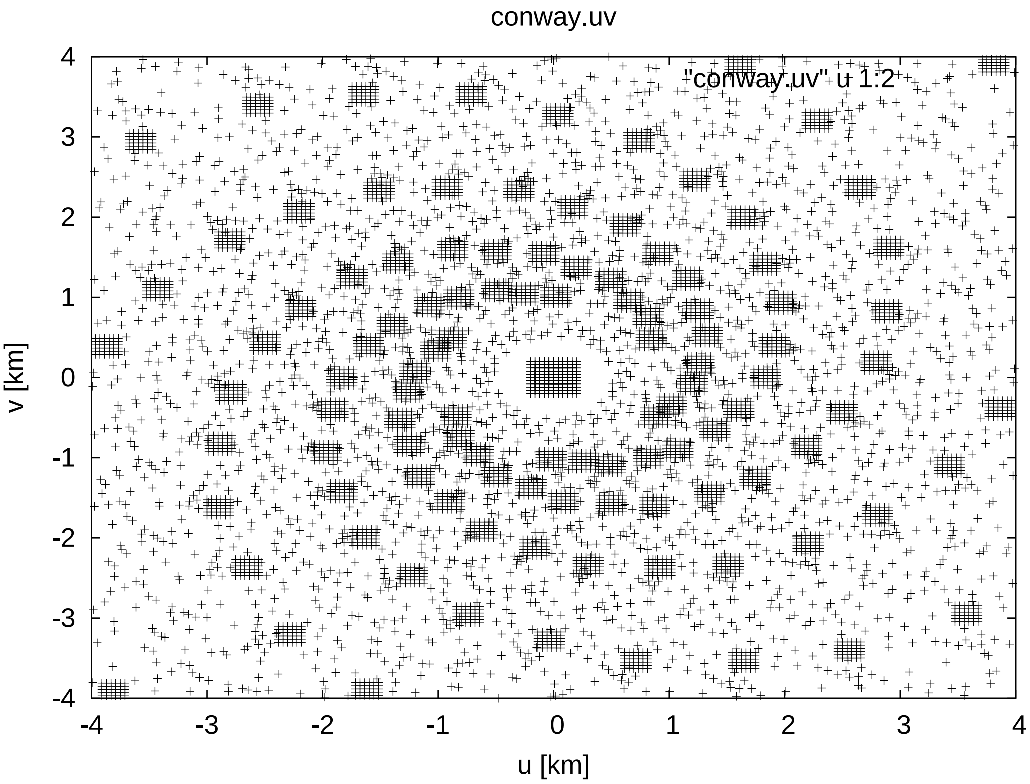


Figure 11. Inner u,v plain of the Conway configuration.

Results and Conclusions

There are clear differences in the behavior of the four types of configurations with respect to tapering to improve surface brightness sensitivity. However, the detailed properties of a configuration of any of these types may be changed by changing the interior details. In particular all of the types except the simple power law configuration may be tuned for good performance at some resolution other than the natural weighting configuration. Therefore, the quantitative measurement of the differences between configuration types given in this memo are not sufficiently definitive to, for instance, generate an entry in a master cost equation. However, the conclusion that the Conway array provides the best response to tapering is probably robust. Whether this is sufficient to drive the choice of configuration type is not clear, or whether other considerations of operational or construction economies of other configuration types may override that preference. However, perhaps the Conway configuration should be considered the default configuration at this early stage of the design.

The rings configuration has an advantage that it is, in some sense, the most compact. That is, the maximum distance from the center of the large ring to the farthest antenna is significantly smaller than the equivalent distance for other configuration types. This is somewhat offset that one would probably choose to locate the operations center at one edge of the large ring, near where the small rings lie.

The tree configuration has a couple of advantages. First is that one may be able to take advantage of the “twigs” structure, and establish a central hub for LO and fiber optic communications in the center of the twig, and from there run a trunk to the operations center. The second is that the antennas of a “leaf” are fairly closely spaced, and this makes possible calibrating by assigning one of the three antennas to a “calibration array” which would look at a calibrator full time to monitor atmospheric changes. This, of course, would cost a factor of 1.5 in sensitivity, but this is only a little greater than the loss to calibrating by fast switching.

Examples

It is informative to consider a few examples. There are a few parameters independent of the particular problem. In what follows I use the following parameters:

255 antennas of 18m diameter

Array scaling as shown in the figures above, to give a natural weighted beam size of 0.006 radians per kilometer.

70% efficiency except in the 3mm band, where 50% is used.

System temperatures as in the table below.

Frequency	Trec	Tsys
115 GHz	45	90
100 GHz	30	45
40 GHz	22	30
25 GHz	15	25
15 GHz	10	25

Dust Emission

The most interesting problems have very high dust densities, approaching being optically thick at 3mm wavelength, and temperatures of a couple of tens of Kelvin. The brightness temperature of the dust falls roughly as the inverse of wavelength. At 100 GHz the beam is about 4 mas, and the brightness sensitivity is about 3 K RMS after a 6 hour observation.

At 40 GHz the natural weighted beam is about 10 mas. The sensitivity at full resolution would be about 15 K RMS, probably too high to be of interest. To reach a more interesting brightness sensitivity of 1K RMS, the different configurations have very different performance. The table below gives the beam size when the array is tapered to produce a brightness RMS of 1 K, 0.1 K and 0.01 K.

	Rings	Power Law	Tree	Conway
1 K	39 mas	85 mas	83 mas	27 mas
0.1 K	195 mas	220 mas	130 mas	119 mas
0.001 K	900 mas	2000 mas	1500 mas	1100 mas

CO thermal emission

We consider here only low redshift or galactic CO emission. The surface brightnesses under consideration are a few Kelvin, and the bandwidths of interest are of order 1 km/s, about 400 kHz. System temperatures are high because the 115 GHz line sits on the edge of the window, just below the second oxygen absorption. The table below gives the beamwidth resulting in tapering to achieve a 1K and a 0.1K brightness RMS in six hours.

	Rings	Power Law	Tree	Conway
1 K	0.27 “	0.62 “	0.51	0.25 “
0.1 K	1.2 “	2.0 “	1.2 “	0.8 “

Lower Frequency Spectral Lines

Here are a couple of spectral line exampes, in the format of the table above. First is a recombination line, H52α. Recombination lines are a little wider and a little hotter than molecular lines. In the table, we show the beam sizes for a 3 K rms and a 3 km/s width.

The second example is ammonia. Here we revert to a 1 km/s line width and 1 K rms.

	Rings	Power Law	Tree	Conway
H52α	0.25 “	0.25 “	0.13 “	0.11 “
Ammonia	7 “	12 “	7 “	3 “

The program used to generate the configurations in this memo may be found at http://www.aoc.nrao.edu/~bclark/config.py. Feel free to use and modify the program to produce thatever configuration interests you, or to calculate other quantities of interest for these configurations.