The VLA Upgrade Project Memo Series

Number 9

Design Studies for the A+ Configuration

Eric Keto

Center for Astrophysics

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Returning the Instrument to the State of the Art

National Radio Astronomy Observatory

VLA Technical Memo

Eric Keto

Smithsonian Astrophysical Observatory

This memo discusses a few configurations for the VLA A+ array chosen to illustrate some of the image quality issues involved in planning the expansion. The memo also shows how eye chart style images and familiar terrestrial scenes can be used to demonstrate the image quality of different arrays. It is often easier to identify defects in images which are recognizable and familiar than in the complex and fascinating images we find in astronomy. This memo is a very preliminary work is meant to help set the scope of the expansion, showing for example approximately how many antennas and what baseline scales are required for good imaging. It is likely that the arrays illustrated in this study can be improved upon.

To motivate this brief study, I list some general imaging objectives without going into any specific scientific objectives. In terms of imaging the goal is to bridge the gap between the capabilities of the VLA and VLBA to enable both instruments to perform very high angular resolution thermal imaging. At the moment, the VLA can image thermal sources, but at lower angular resolution. The VLBA has very high angular resolution, but only for the brightest, usually non-thermal sources. To bridge this gap, the new antennas should expand the VLA outward beyond the A array in order to improve the highest angular resolution imaging, and they should enhance the VLBA inward in terms of the shorter baselines. The expansion should result in a significant improvement, that is to say order of magnitude improvement, in the imaging capabilities of both the VLA and VLBA. These goals have to be achieved with a few new antennas, probably less than the 10 in the current VLBA. The existing Pietown antenna will always be used in the new configuration.

There are two natural size scales for the VLA/VLBA expansion. The larger size scale is set by the smallest baselines of the VLBA. The shortest VLBA baseline is the 52 km separation between Pietown and the VLA, and within a few hundred km there are 5 VLBA antennas, including the VLA. So for the larger scale expansion we would be looking at short spacings of about 50 km and longest spacings of several hundred kilometers. The smaller natural scale for the VLA expansion is set by the largest baseline of the VLA itself. Expanding the VLA by a factor of three continues the matching beams/frequencies capabilities of the VLA scaled arrays. In this case we would have maximum baselines of about 100 km. The number of additional antennas naturally falls between 2 and 10, 2 being quite modest and 10 doubling the present VLBA. More additional antennas will be required in the larger scale expansion than in the small. For this study we can start with two arrays with 4 and 5 expansion antennas.

The first array is a modest expansion with maximum baselines of 90 km requiring 4 additional antennas. The furthest antenna is 71 km from the VLA center. This example is the same pattern as the 6 element SAO Submillimeter Array and uses the VLA center and the Pietown antenna as 2 of the 6 elements. Figure 1 shows the pattern and its autocorrelation function. Figure 2 shows the array based on this pattern, its autocorrelation function or snapshot coverage, and its UV coverage in Earth rotation synthesis for 4 declinations.

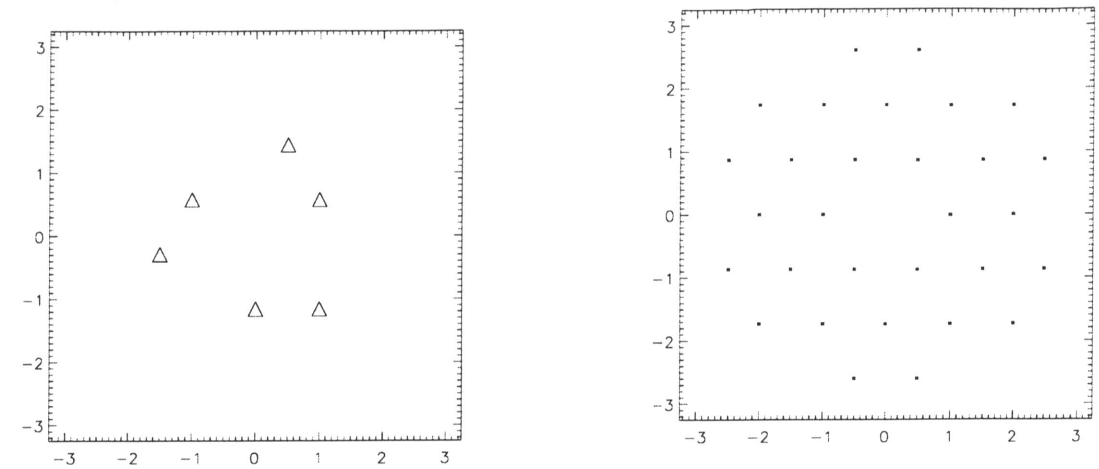


Figure 1. Pattern for a six element array and its autocorrelation function. The triangles represent the antennas and the dots the autocorrelation function. The axes give the coordinates of the antennas and the autocorrelation points.

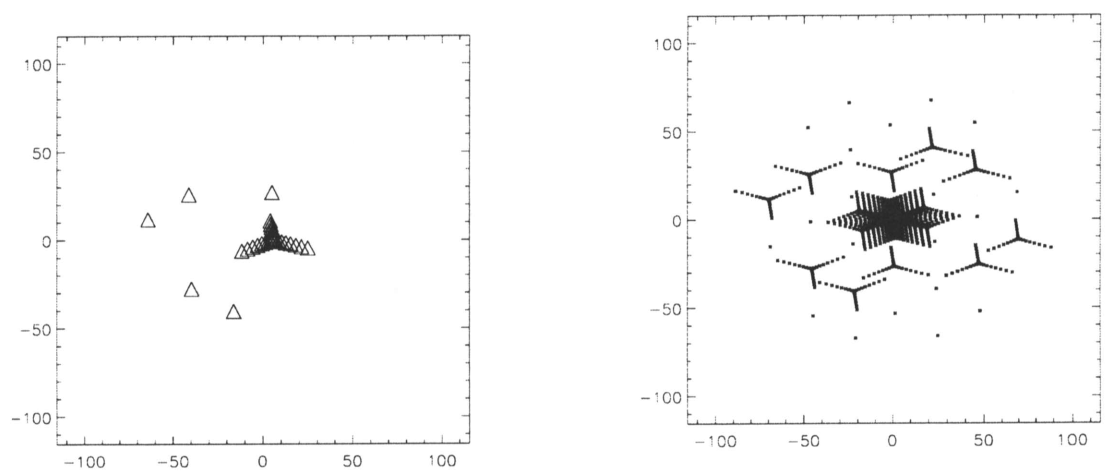


Figure 2a. Antenna locations and snapshot UV coverage for a smaller VLA A+ expansion requiring 4 additional antennas. The triangles represent the antennas and the dots the autocorrelation function. The axes give the coordinates of the antennas and the baseline vectors in km. The VLA appears squashed north-south in this figure because the antenna locations have mistakenly been projected by the sin of the latitude, 34°.

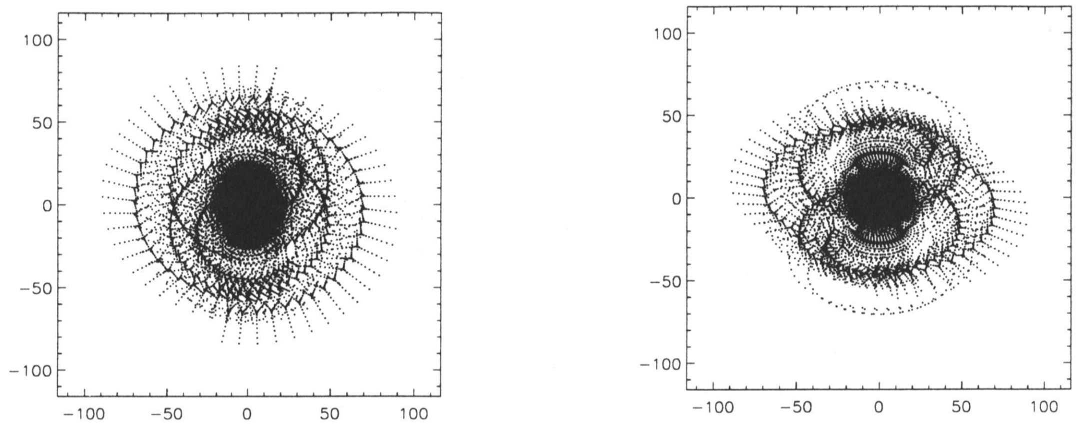


Figure 2b. UV coverage for a source at 60° (left) and 34° (right) for the small VLA A+ array of figure 2a. The UV points are plotted every half hour between elevation limits of 25°.

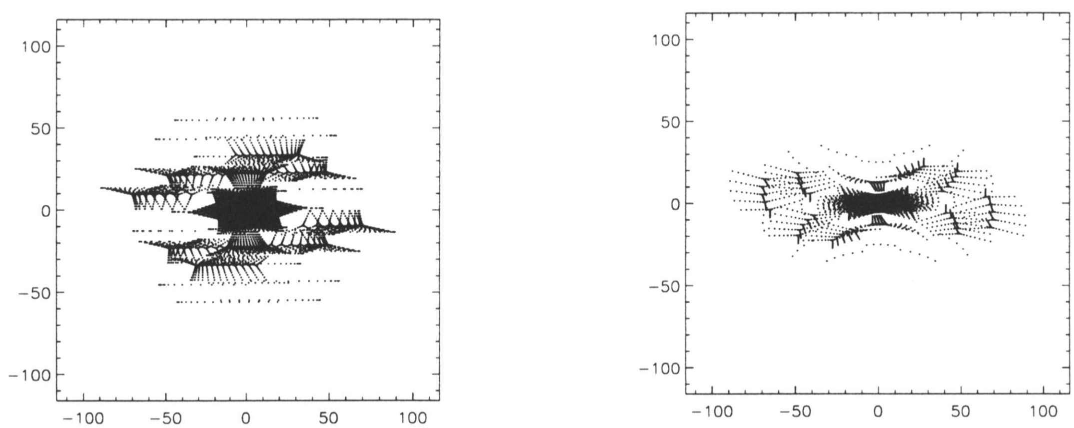


Figure 2c. UV coverage for a source at 0° (left) and -28° (right) for the small VLA A+ array of figure 2a. The UV points are plotted every half hour between elevation limits of 25°.

We can get some appreciation of the imaging quality of this array by examining its performance on a couple of test images. The test images are shown in figure 3. There are many types of images one could use including astronomical images. I find the eye chart useful for locating defects due to missing Fourier modes and the Hudson River scene useful in gaining an appreciation of what it means to be an imaging instrument. The eye chart is one I made up to explore a few simple imaging goals which would be important for an astronomical instrument. The C's at different orientations show how well an array can distinguish between continuous and broken shapes. We need several orientations because most arrays will have different imaging characteristics in different directions. The O's can be compared with the solid disks to see how the array does in distinguishing disks from toroids. The seven disks of different sizes will show how well the array can distinguish single from multiple sources on different scales.

The imaging tests in this study are very simple, and one would want to improve on this procedure in a more formal study. The following is enough to get started. First multiply the Fourier transfer function of the image by the Fourier coverage of the array in Earth rotation synthesis and then deconvolve the dirty image using a Wiener filter. The reason for using the Wiener filter is that the deconvolution can be rapidly done in one step. Noise has not been added because the noise only lessens the effectiveness of this type of deconvolution. I find it better to look at the defects from the Fourier coverage bearing in mind that the noise will reduce the quality of the deconvolution. In a more formal study we would need to add noise of the expected character and use a deconvolution algorithm such as CLEAN or MEM. The results of this experiment on the VLA A+ small scale expansion are shown in figure 4. Figure 4 is not too interesting because the imaging is so good, but it will be useful for comparison.

Figure 3a. Hudson River scene test image for use in assessing the imaging quality of arrays.

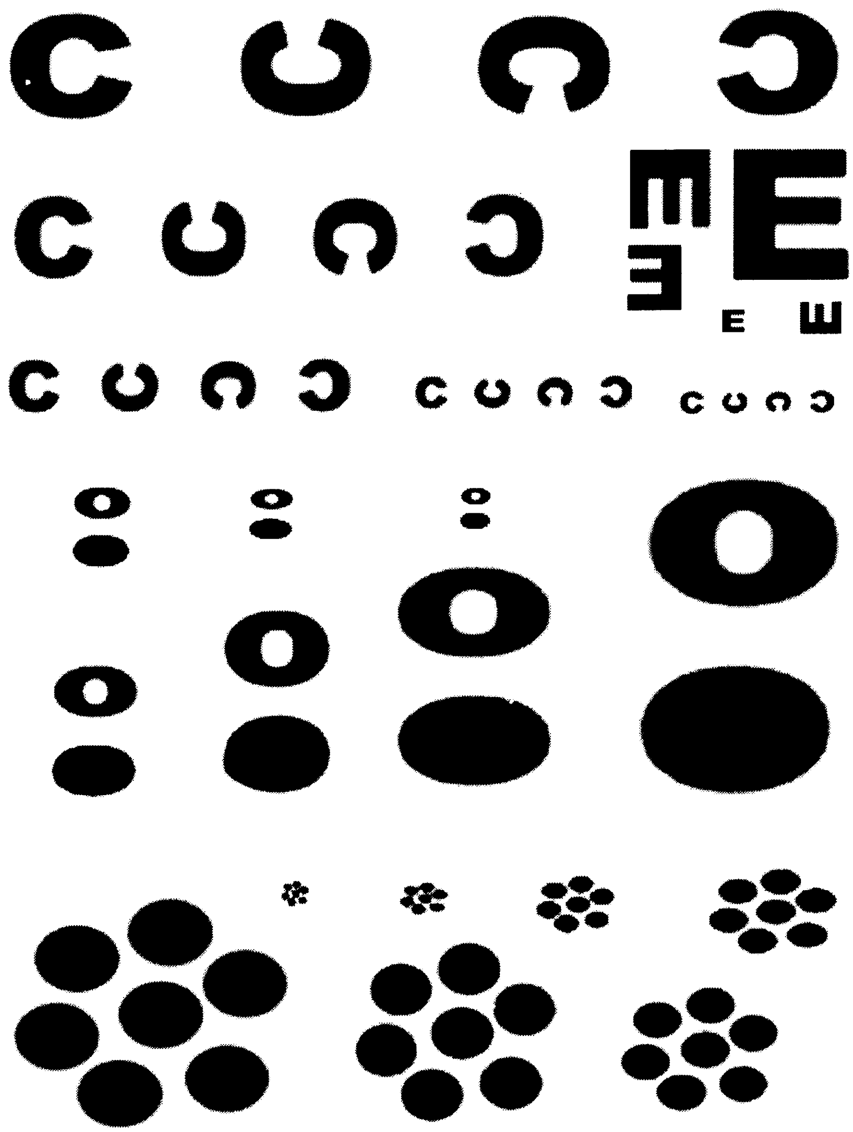


Figure 3b. Eye chart style test image for use in assessing the imaging quality of arrays.

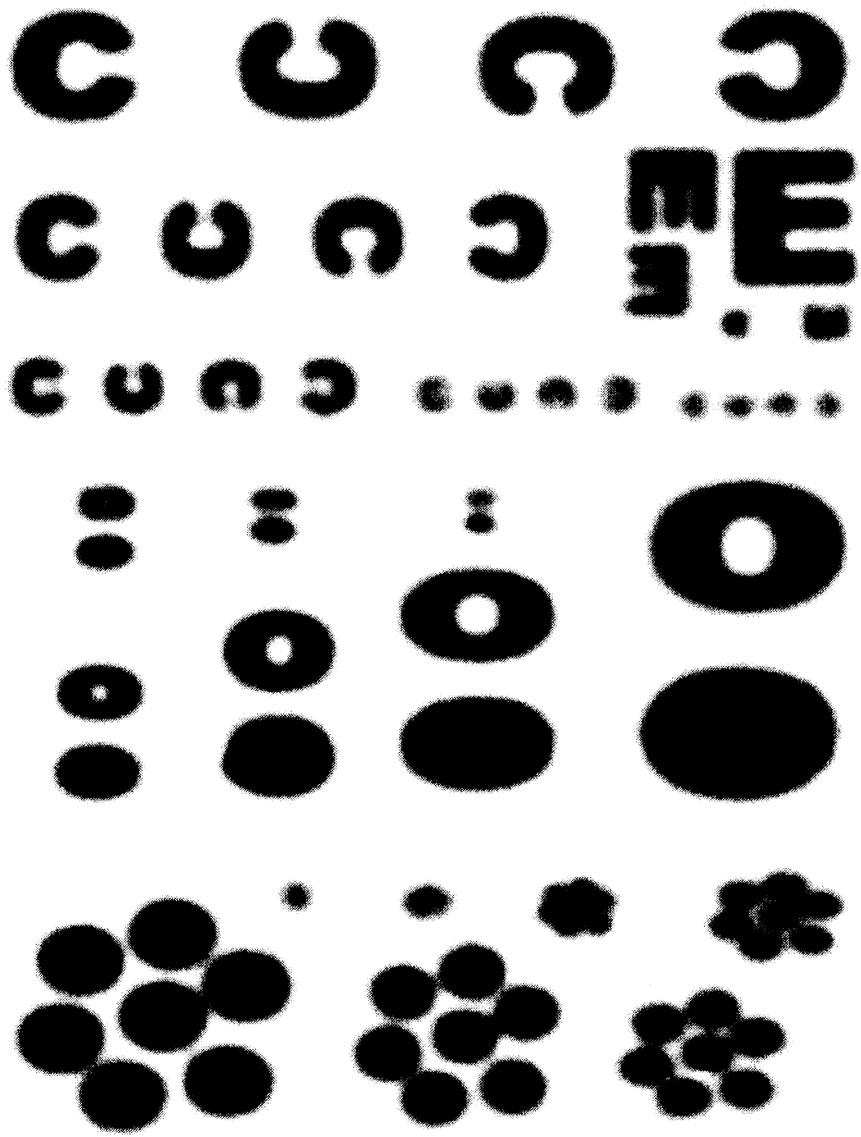


Figure 4. Test image as seen with the small scale VLA A+ expansion of figure 7b(right). The scale of the image for this test 5″ across the whole image.

Now we can examine the coverage of this smaller array when used with the VLBA antennas. Figure 5 shows the antenna locations and the snapshot coverage of the inner 5 stations of the existing VLBA. Figure 6 shows the antenna locations, the snapshot coverage, and the coverage obtained in Earth rotation synthesis for an array made up of the 4 expansion antennas, one VLA antenna, and the existing VLBA antennas at Pietown, Los Alamos, Fort Davis, and Kitt Peak.

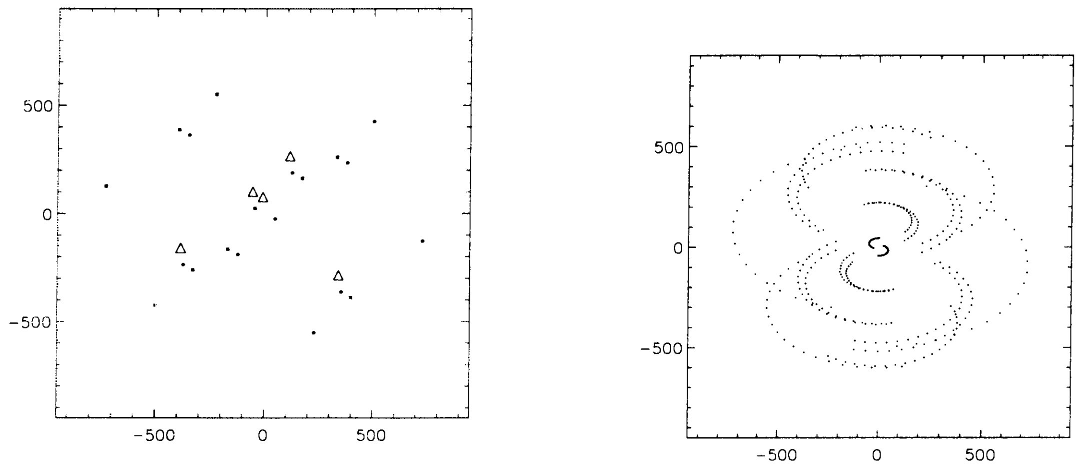


Figure 5. Short spacings of the current VLBA. The left figure shows the antenna locations and the snapshot UV coverage for existing VLBA using one antenna at the VLA, and the antennas at Pietown, Los Alamos, Kitt Peak, and Fort Davis. The triangles represent the antennas and the dots the UV sampling points. The axes in km give the coordinates of the antennas and the baseline vectors of each sampling point. The right panel shows the UV coverage tracking a source at 34° declination between elevation limits of 25°. The UV points are plotted for every half hour.

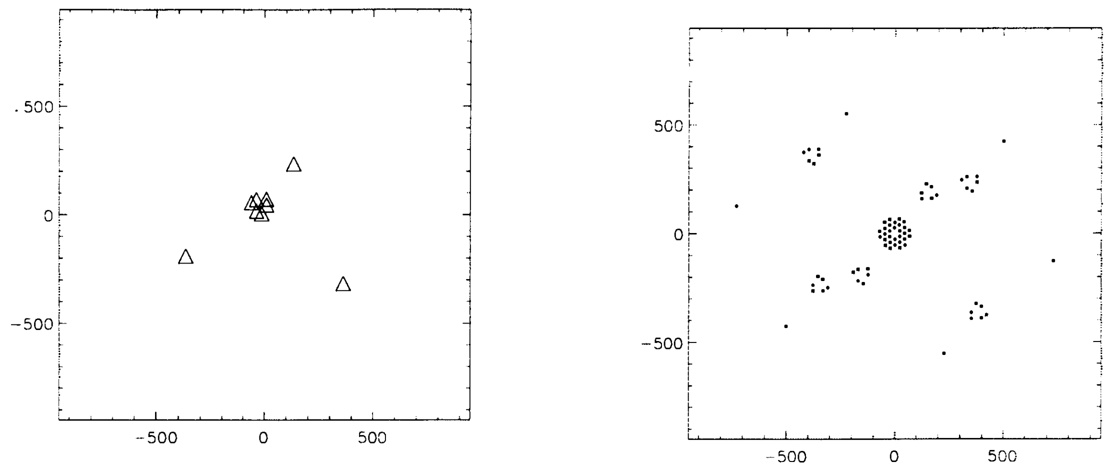


Figure 6a. Antenna locations and snapshot UV coverage for the smaller expansion requiring 4 additional antennas. Plotted here are the 4 expansion antennas, the 4 existing VLBA antennas at Pietown, Los Alamos, Kitt Peak, and Fort Davis, and one of the VLA antennas. The triangles represent the antennas and the dots the sampling function. The axes give the coordinates of the antennas and the baseline vectors in km.

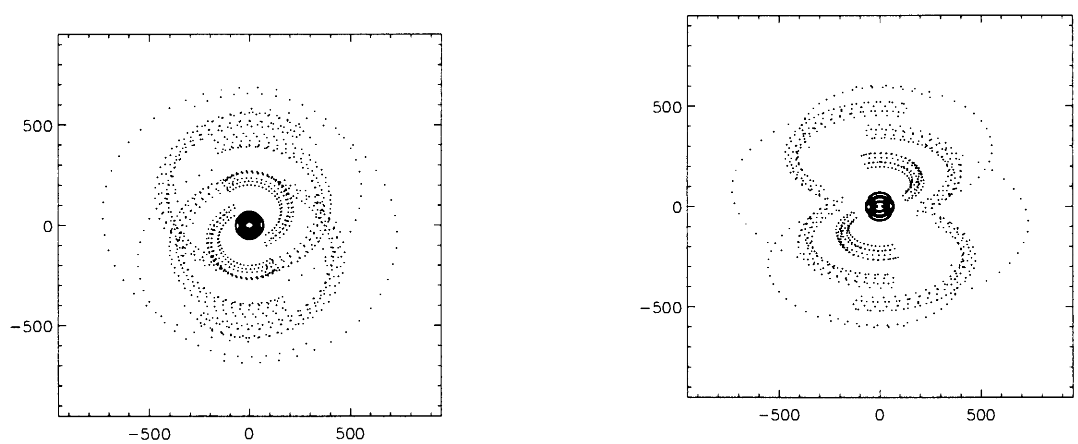


Figure 6b. UV coverage for a source at 60° (left) and 34° (right) using the short spacings of the enhanced VLBA (figure 6a). This array includes the 4 expansion antennas, the 4 existing VLBA antennas at Pietown, Los Alamos, Kitt Peak, and Fort Davis, and one of the VLA antennas. The UV points are plotted every half hour between elevation limits of 25°.

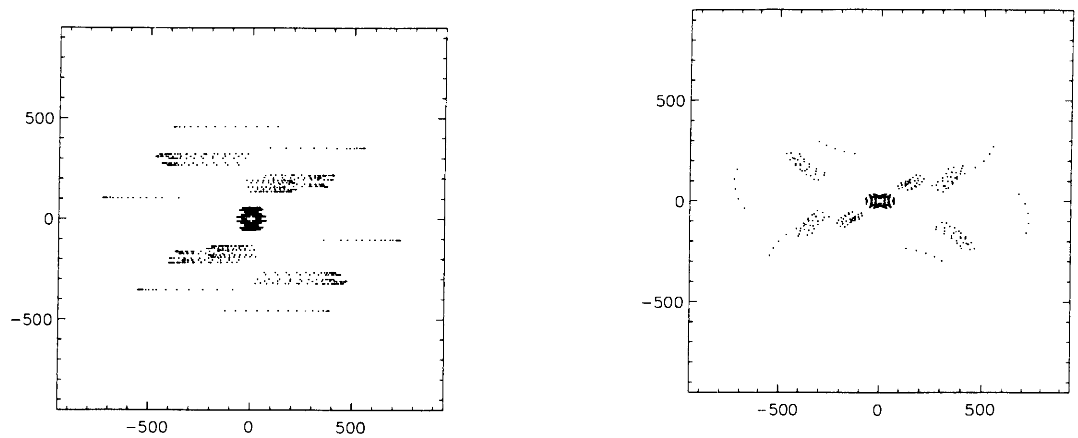


Figure 6c. UV coverage for a source at 0° (left) and -28° (right) using the short spacings of the enhanced VLBA (figure 6a). This array includes the 4 expansion antennas, the 4 existing VLBA antennas at Pietown, Los Alamos, Kitt Peak, and Fort Davis, and one of the VLA antennas. The UV points are plotted every half hour between elevation limits of 25°.

While the small expansion results in dense VLA-like coverage of the VLA A+ out to about 100 km, the VLBA+ coverage remains largely of the same character as the original VLBA as can be seen by comparing figure 5 (right) and 6b (right). In the expansion, there are more UV tracks in the VLBA+ coverage, but they remain tightly grouped around the existing tracks of the VLBA. Figure 7 shows that the VLBA+ in the small expansion improves on the existing VLBA, but the imaging capability is still poor.

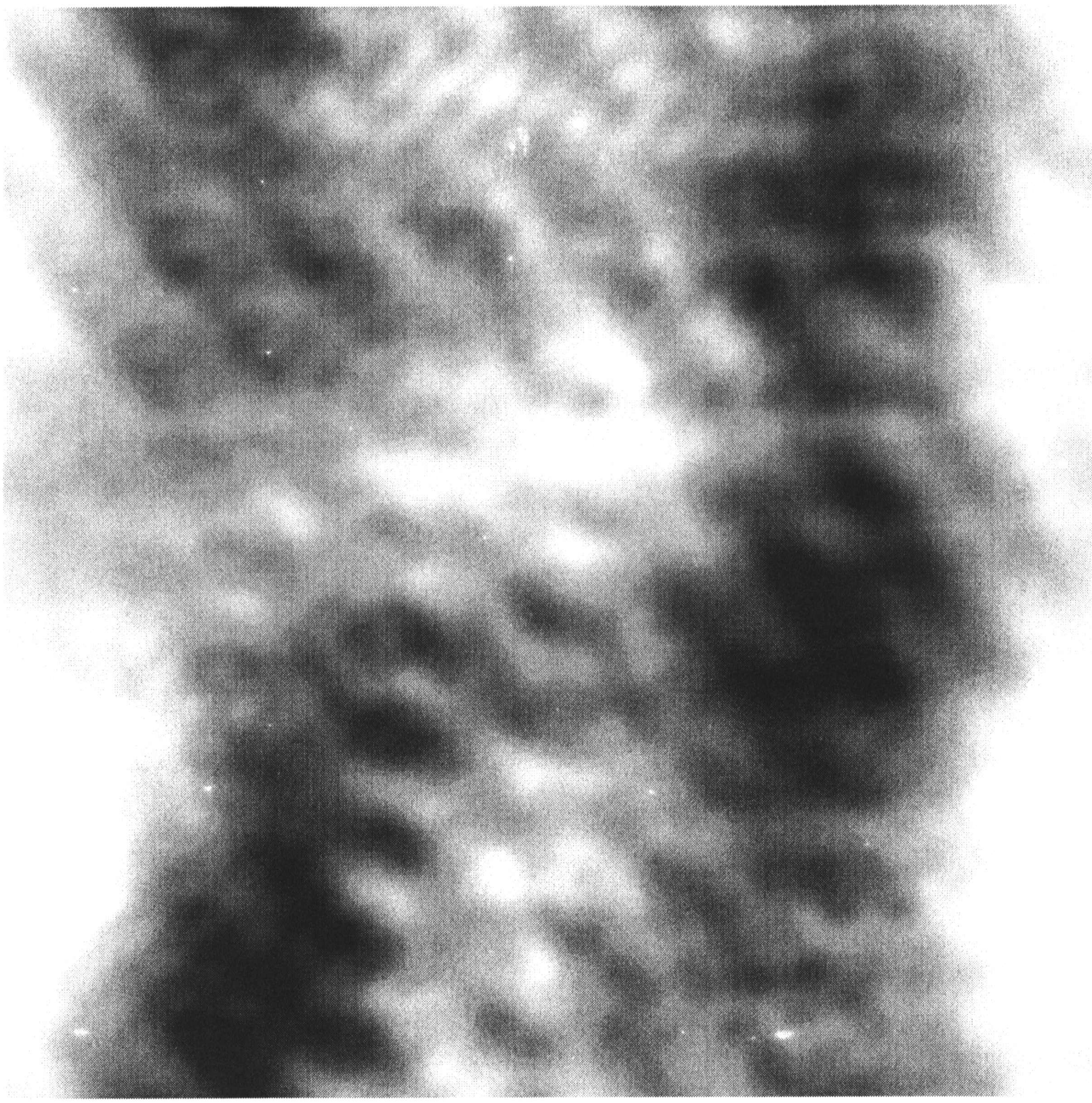


Figure 7a. Image shows the eye chart as seen by the short spacings of the existing VLBA. This includes 5 antennas one at the VLA, Pietown, Los Alamos, Fort Davis and Kitt Peak. The simulation is for the UV coverage of figure 5 (right). In this simulation the whole image is 0.1″ across.

Figure 7b. Eye chart as seen with the VLBA+ including 4 expansion antennas. The image is for the UV coverage of figure 6b (right) In this simulation the whole image is 0.1″ across.

To improve on the VLBA imaging we need to spread the antennas out to longer baselines. The next configuration I have chosen represents a more ambitious expansion in terms of the length of the baselines. The Pietown antenna forms the shortest baseline with the VLA while the furthest antenna is about 170 km away. The configuration is based on the 7 element symmetric pattern in figure 8. This pattern is from an old paper by Golay (1971) which simply lists some patterns with compact autocorrelation functions. The points and the autocorrelation function lie on a regular hexagonal grid. There are no redundant sampling points and the sampling is complete on the hexagonal grid out to about 2/3 of the maximum baseline. The UV coverage then tapers off at the longest baselines which will help reduce the sidelobe level of the beam. Although the array will almost always be used in Earth rotation synthesis, it is always worth looking at the snapshot coverage because this defines the maximum size of the holes in the UV sampling. For example, an array with complete sampling on a regular grid out to some radius has a minimum and uniform maximum hole size within that radius. Any projected array or combination of projected arrays, as in Earth rotation synthesis, will have a smaller maximum hole size. Of course the maximum radius within which the sampling is complete will also be smaller in projection. Obviously one cannot look only at the snapshot coverage because in Earth rotation synthesis, the tracks may overlap. Often better coverage with less redundancy can be obtained with a slight adjustment. This is the case with this 7 element pattern.

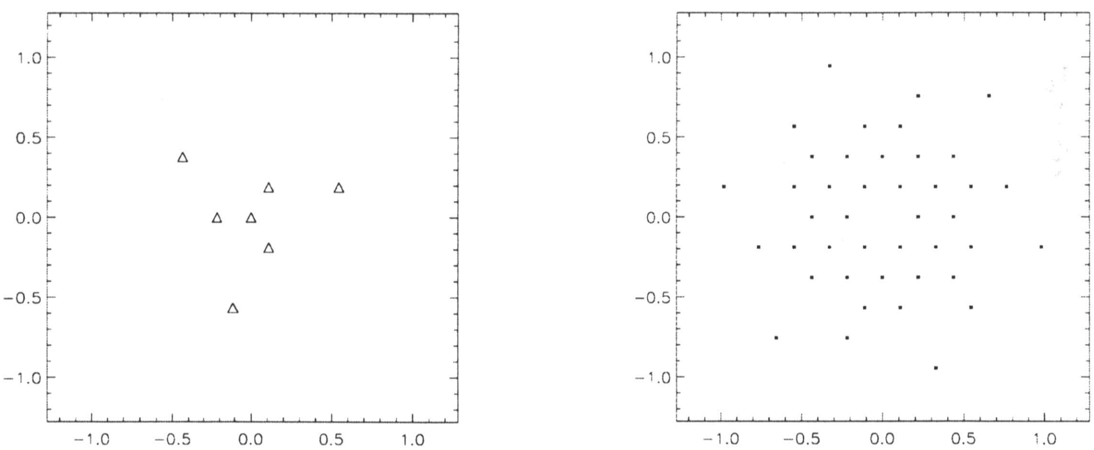


Figure 8. A symmetric configuration of 7 antennas and its autocorrelation function. The triangles represent the antennas and the dots the autocorrelation function. The axes give the coordinates of the antennas and the autocorrelation points.

To make an Earth rotation synthesis array out of the 7 element pattern, we replace the central point by the VLA and rotate the array so that the Pietown antenna is on the inner triangle. In addition, to improve the coverage in earth rotation synthesis, we adjust the antenna positions slightly so that the UV tracks overlap less. While the sampling points no longer lie on an exact grid, the important property of this pattern of nearly complete coverage or no large holes in the central region of the UV disk is preserved. Figure 9 shows the VLA A+ UV coverage of this array for 4 declinations. Figure 10 shows the VLBA coverage.

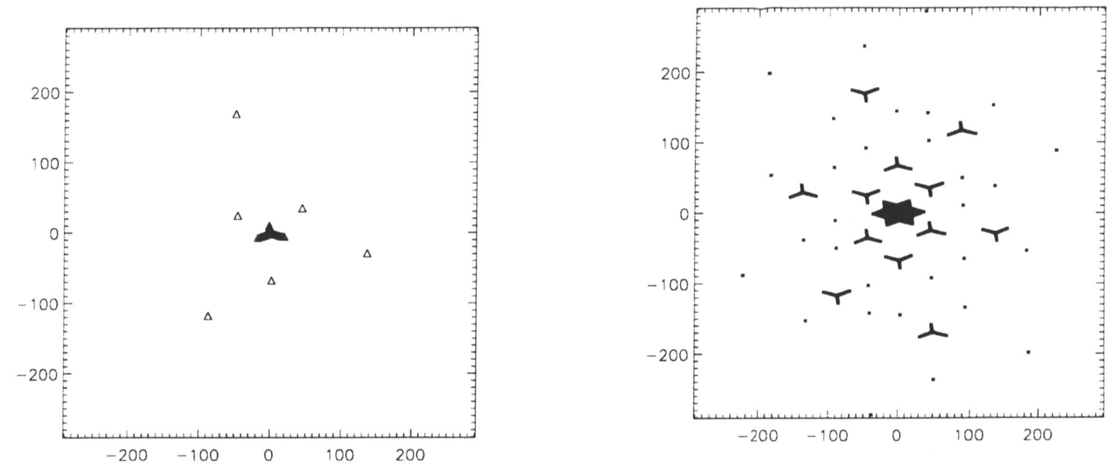


Figure 9a. Antenna locations and snapshot UV coverage for the large VLA A+ array based on figure 8. The axes are labeled in km. The VLA appears squashed north-south in this figure because the antenna locations have mistakenly been projected by the sin of the latitude, 34°.

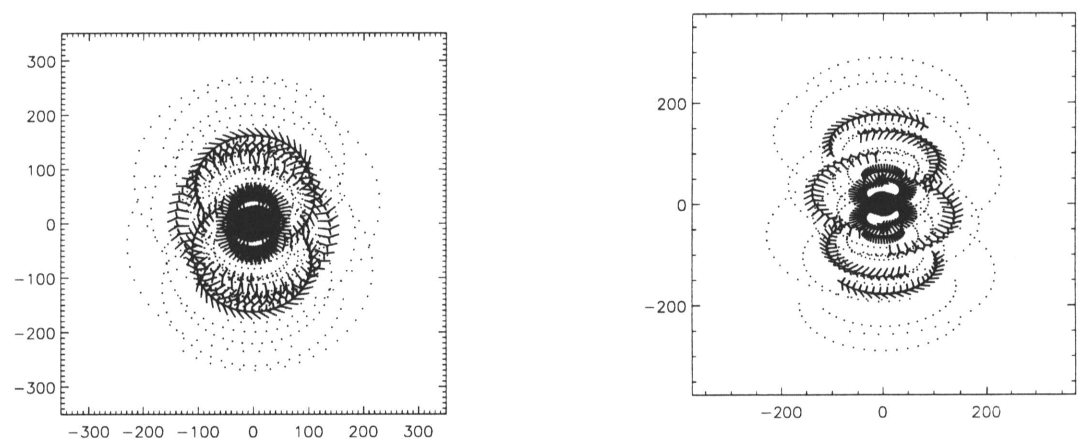


Figure 9b. UV coverage for the large VLA A+ array of figure 9a for a source at 60° (left) and 34° (right) declination. UV points are plotted every half hour between elevation limits of 25°.

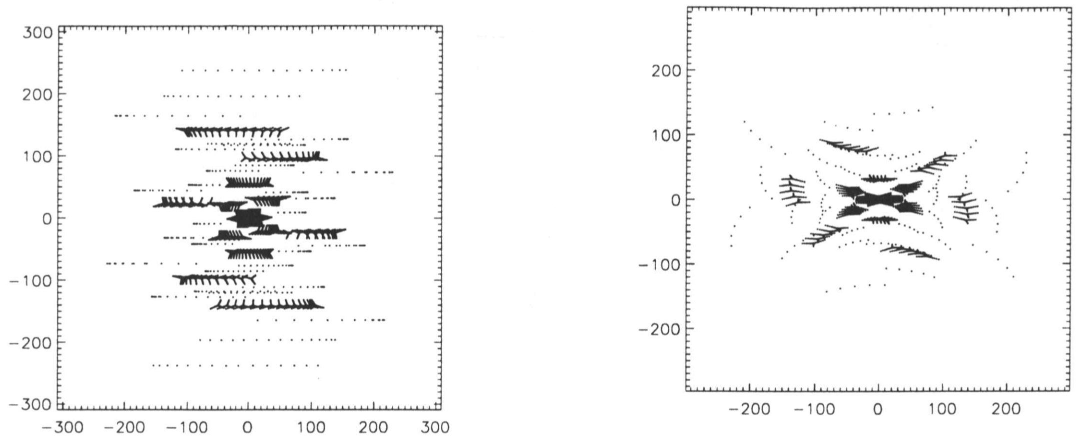


Figure 9c. UV coverage for the large VLA A+ of figure 9a for a source at 0° (left) and -28° (right) declination. UV points are plotted every half hour between elevation limits of 25°.

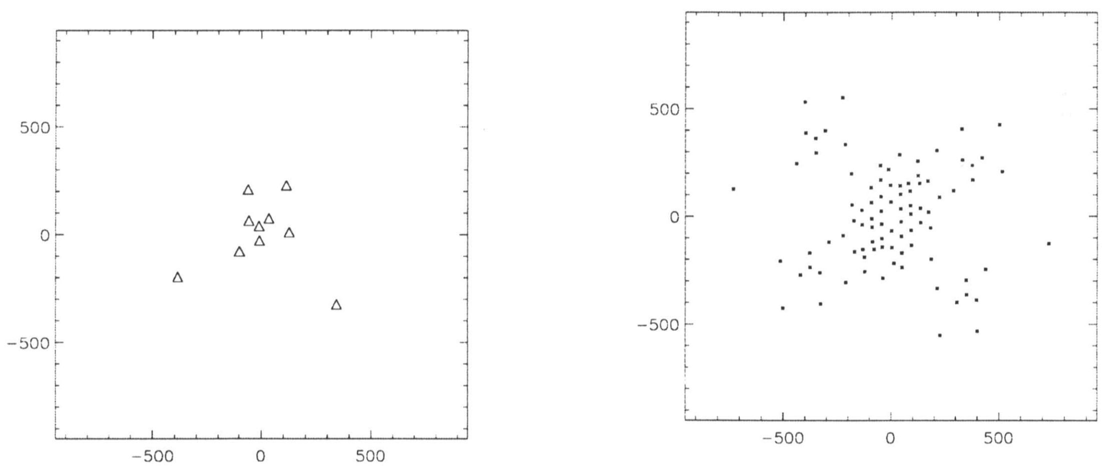


Figure 10a. Snapshot UV coverage for the short spacings of the enhanced VLBA using the antenna locations of figure 9 and the 3 existing VLBA antennas at Los Alamos, Kitt Peak, and Fort Davis. The Pietown antenna is included among the antennas in figure 9a as is one antenna of the VLA. The triangles represent the antennas and the dots the UV sampling points. The axes in km give the coordinates of the antennas and the baseline vectors of each sampling point.

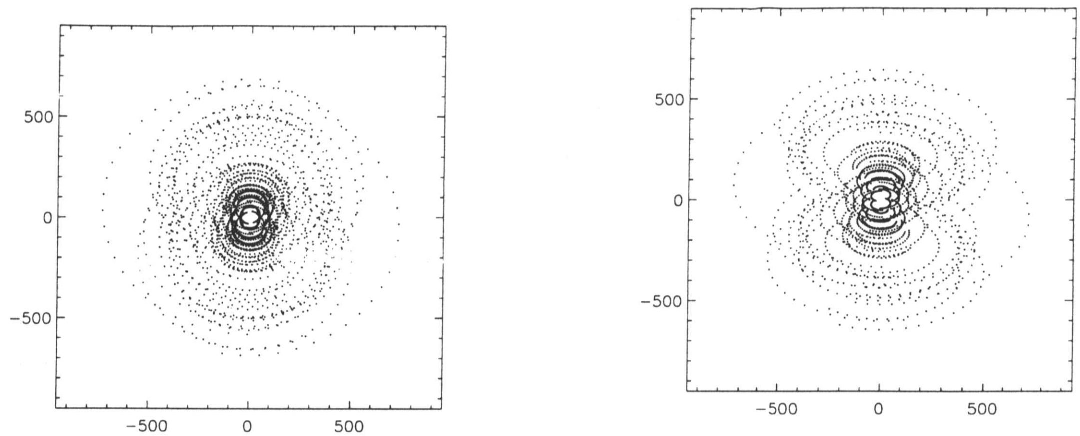


Figure 10b. UV coverage for a source at 60° (left) and 34° (right) using the short spacings of the enhanced VLBA. This array includes the antenna locations of figure 9 and the 3 existing VLBA antennas at Los Alamos, Kitt Peak, and Fort Davis. The Pietown antenna is included among the antennas in figure 9a as is one antenna of the VLA. The UV points are plotted every half hour between elevation limits of 25°.

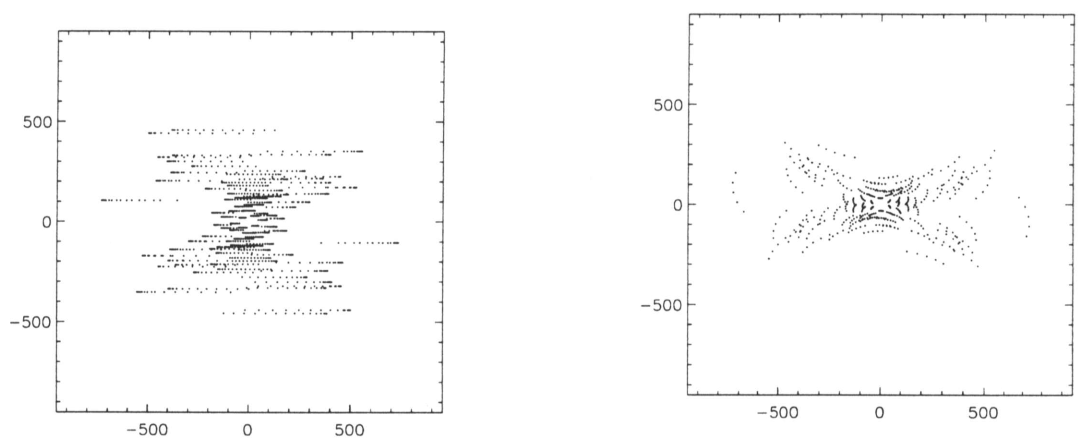


Figure 10c. UV coverage for a source at 0° (left) and -28° (right) using the short spacings of the enhanced VLBA. This array includes the antenna locations of figure 9a and the 3 existing VLBA antennas at Los Alamos, Kitt Peak, and Fort Davis. The Pietown antenna is included among the antennas in figure 2a as is one antenna of the VLA. The UV points are plotted every half hour between elevation limits of 25°.

The longest baseline in this VLA A+ array is 290 km. This will produce a beam with almost a factor of 10 improvement in resolution over the VLA A array. One obvious point is the VLA A+ coverage looks a little sparse with this large array. The UV tracks resemble those of a 7 antenna array. This is because the VLA itself is small, 35 km maximum baseline, compared to the expanded array, 290 km. We should expect some imaging defects with coverage this sparse. Figure 11 shows the VLA A+ image of the eye chart. This figure is made with the 27 antenna VLA, Pietown and the 5 expansion antennas. There are some problems.

For example, the lack of coverage on some spacings makes some of the solid disks look like annuli. This might create some interesting interpretations of astronomical sources.

On the other hand, the VLBA+ short coverage is well filled out. The short spacing snapshot coverage in the VLBA+ array is now complete to about 50 km separation out to a baseline of 250 km. That is to say within a radius of 250 km, the furthest separation between sampling points is less than 50 km. Beyond 250 km, the coverage continues, but it is sparser with larger holes. Figure 12 shows the eye chart as seen by the short spacings of the VLBA+ with 5 expansion antennas as shown in figure 10a (left).

An interesting question is what it takes to make the VLBA into an imaging instrument in the sense of being able to discriminate between a thin ring, a thick torus, a disk, and a cluster of point sources. Figure 13 shows the test images as seen by the full 11 antenna VLBA with and without the 5 expansion antennas. Images made with the expanded array show significant improvement from the added Fourier coverage. While the current VLBA has excellent resolution resulting in sharp edges on all the figures, the lack of short and intermediate spacings creates some misleading images.

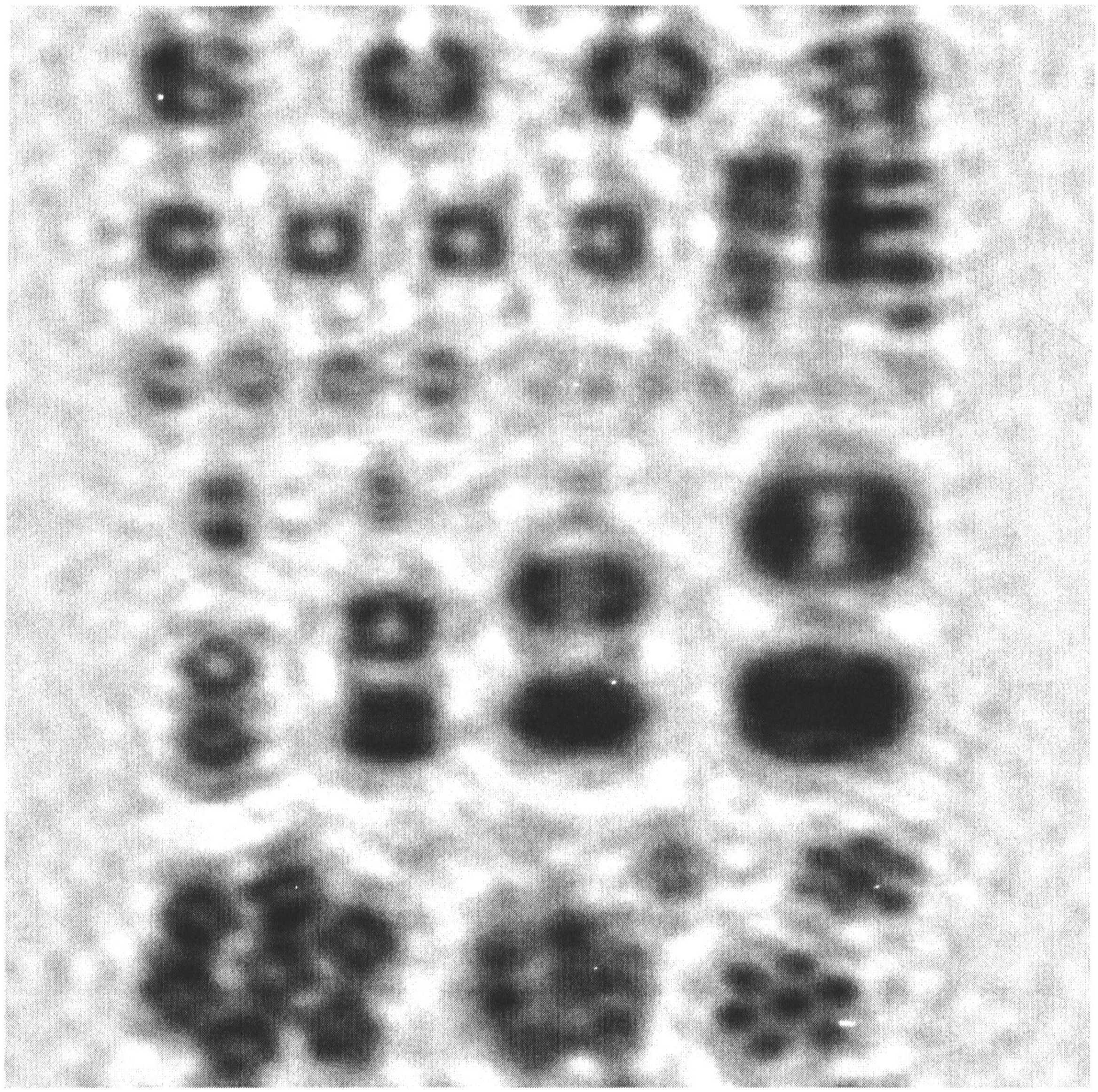


Figure 11. Image of the eye chart with the 5 antenna expansion VLA A+ using the Fourier coverage shown in 9b(right). The scale of the image is 1″ across the full image.

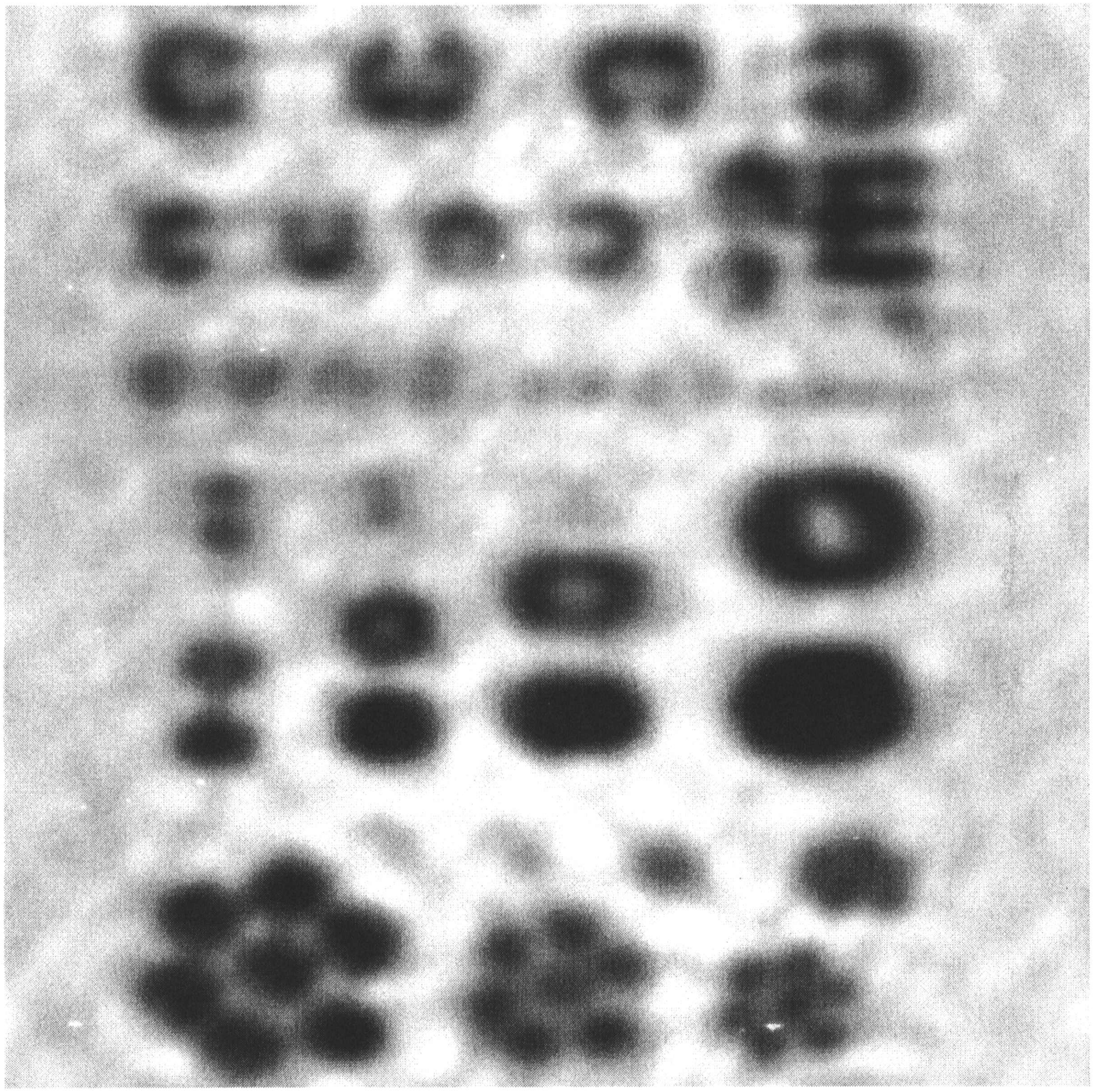


Figure 12. Eye chart as seen by the VLBA+ with 5 expansion antennas with the UV coverage shown in figure 10b(right). The scale of the image is 0.1″ across the full image.

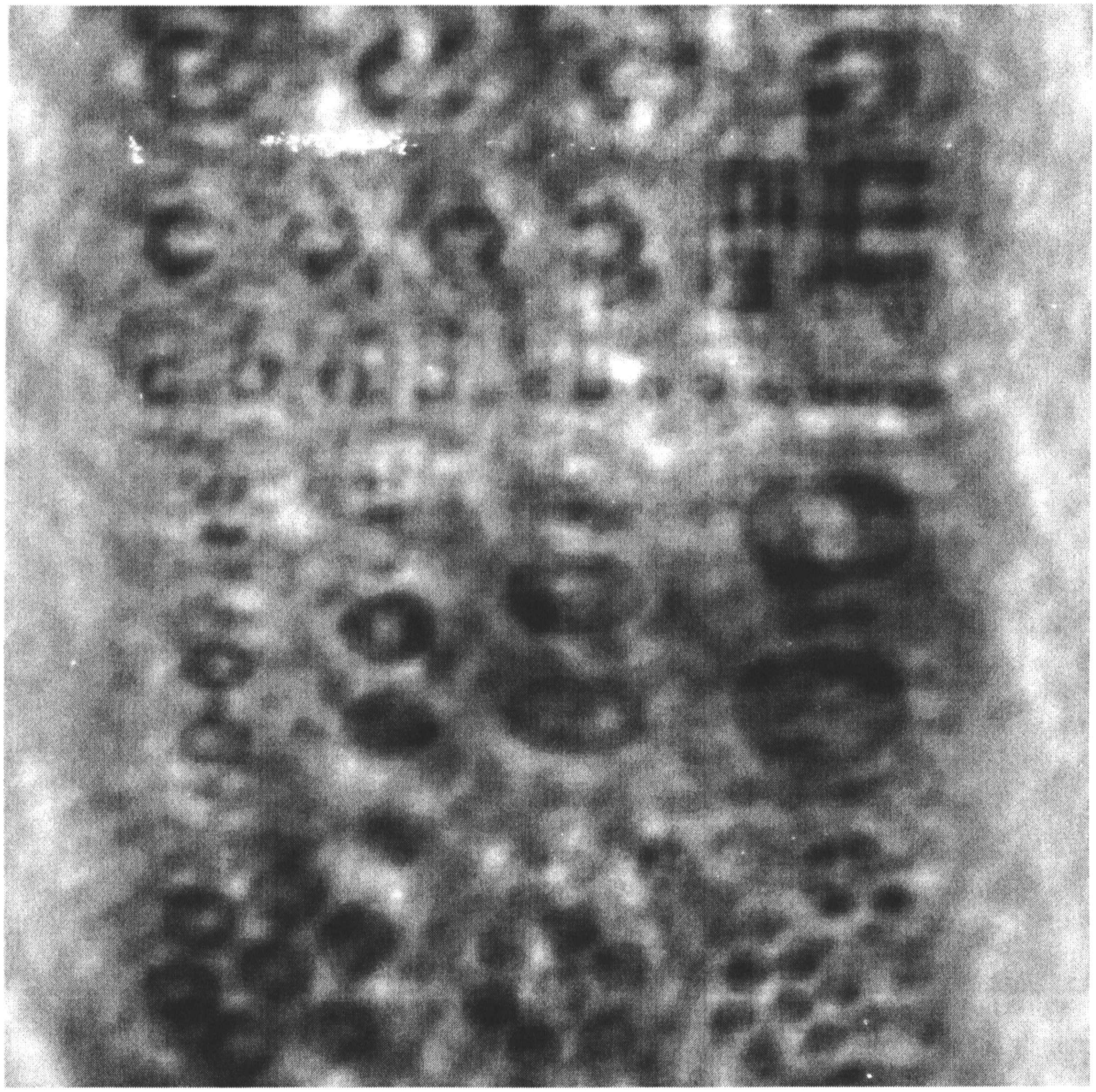


Figure 13a. Test image as seen by the existing 11 station VLBA without the 5 expansion antennas. The simulation assumes a source at 34° declination tracked between elevation limits of 25°. The scale of the image is 0.1″ across the full image.

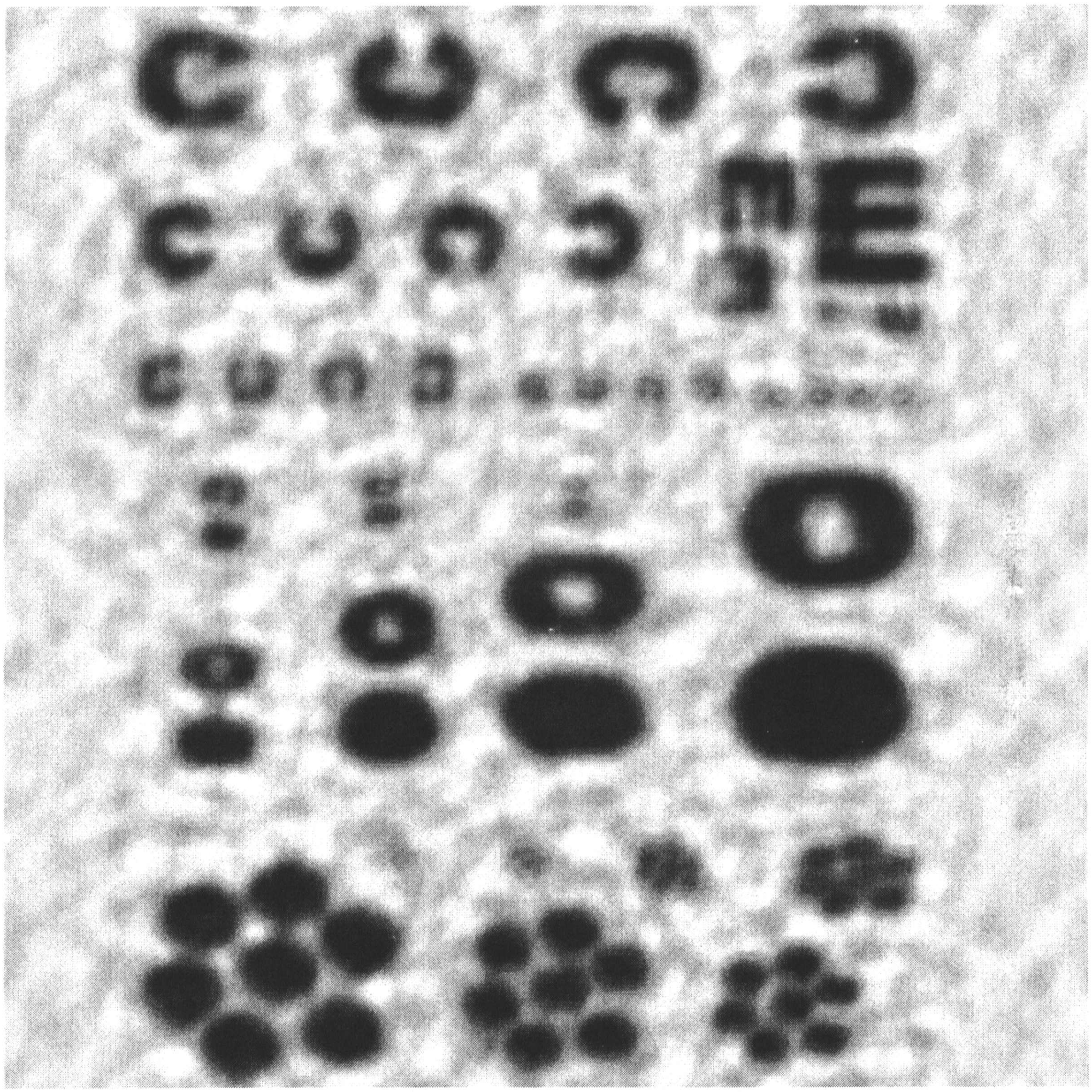


Figure 13b. Test image as seen by the 16 station VLBA+ with the 5 expansion antennas. The simulation assumes a source at 34° declination tracked between elevation limits of 25°. The scale of the image is 0.1″ across the full image.

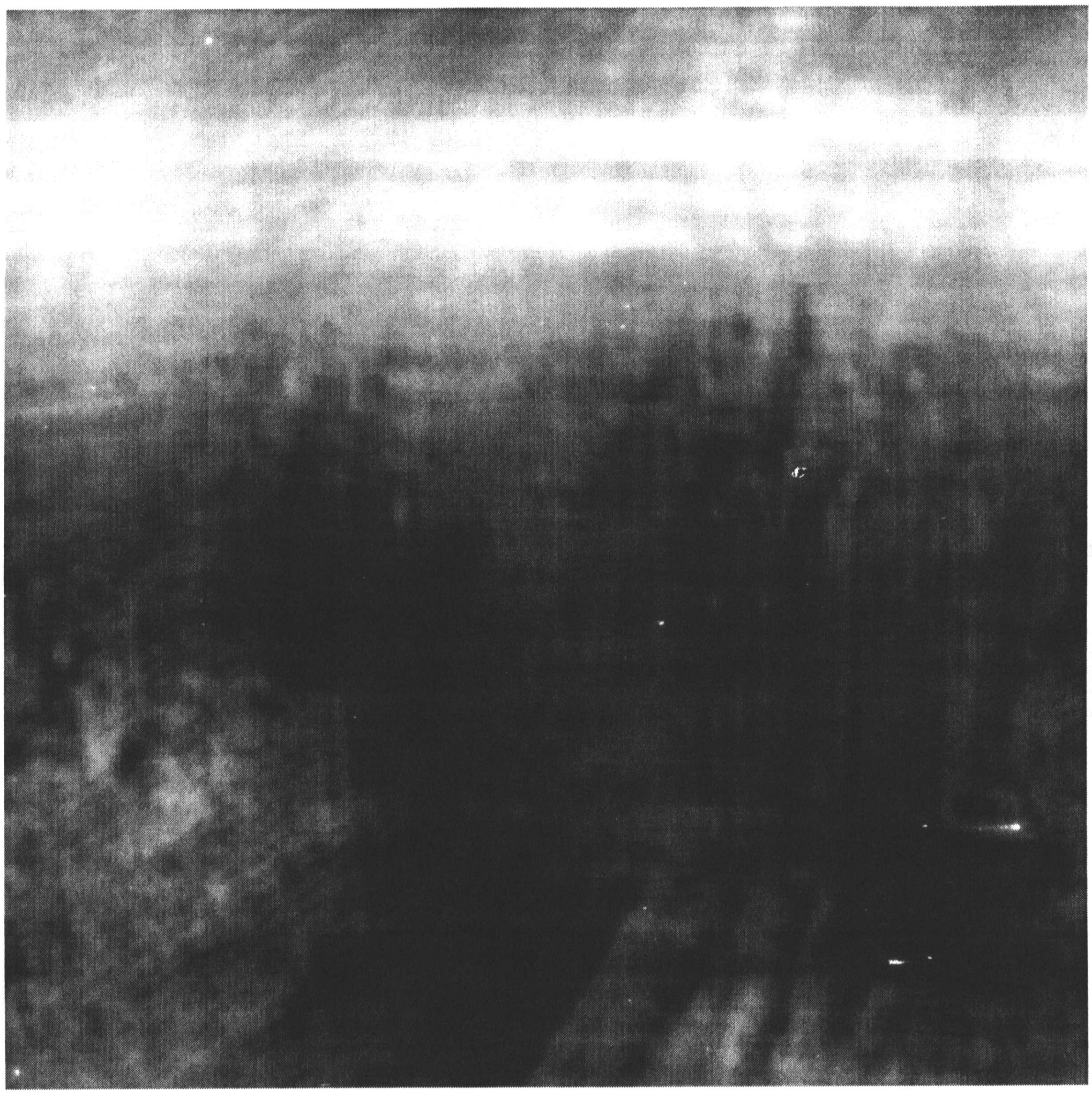


Figure 13c. Test image as seen by the existing 11 station VLBA without the 5 expansion antennas. The simulation assumes a source at 34° declination tracked between elevation limits of 25°. The scale of the image is 0.1″ across the full image.

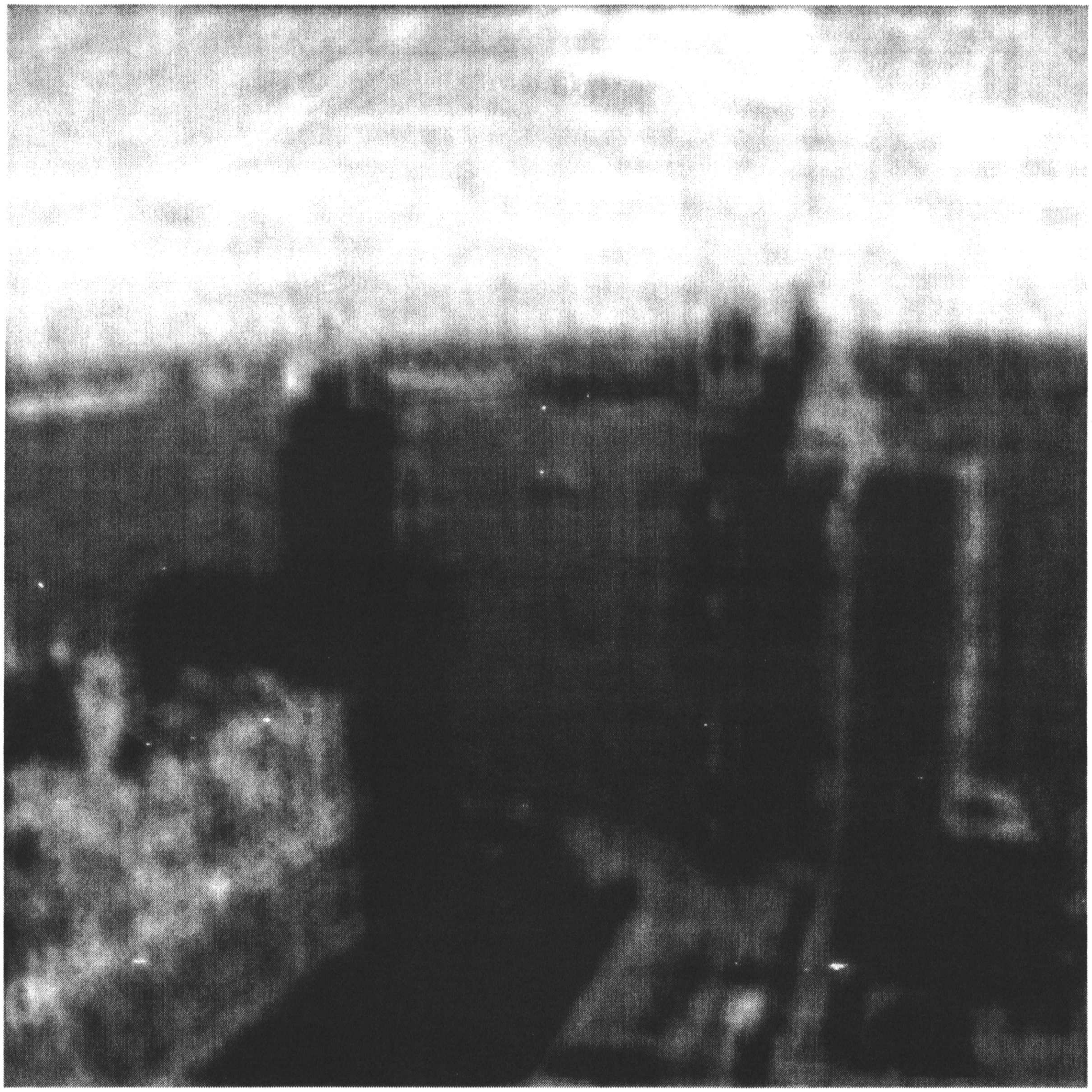


Figure 13d. Test image as seen by the 16 station VLBA+ with the 5 expansion antennas. The simulation assumes a source at 34° declination tracked between elevation limits of 25°. The scale of each image is 0.1″ across the full image.

With these two different expansion arrays of 4 and 5 antennas, it seems that we although we improve the imaging of both the VLA A+ and the VLBA+, we still leave imaging defects in one or the other. This suggests that a few more antennas are needed to fully bridge the gap allowing both the VLA A+ and the VLBA+ to make good images on all scales from 35 km baselines to 730 km.

The next two configurations with more antennas show how the coverage can be improved. The first example is based on the 12 element pattern shown in figure 14. The array and the snapshot coverage are shown in figure 15.

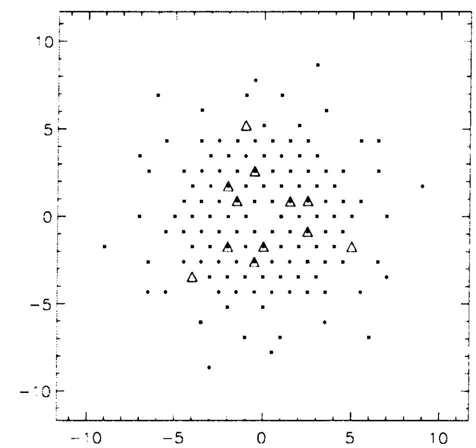


Figure 14. Pattern for a 12 element array and its autocorrelation function. The triangles represent the antennas and the dots the autocorrelation function. The axes give the coordinates of the antennas and the autocorrelation points.

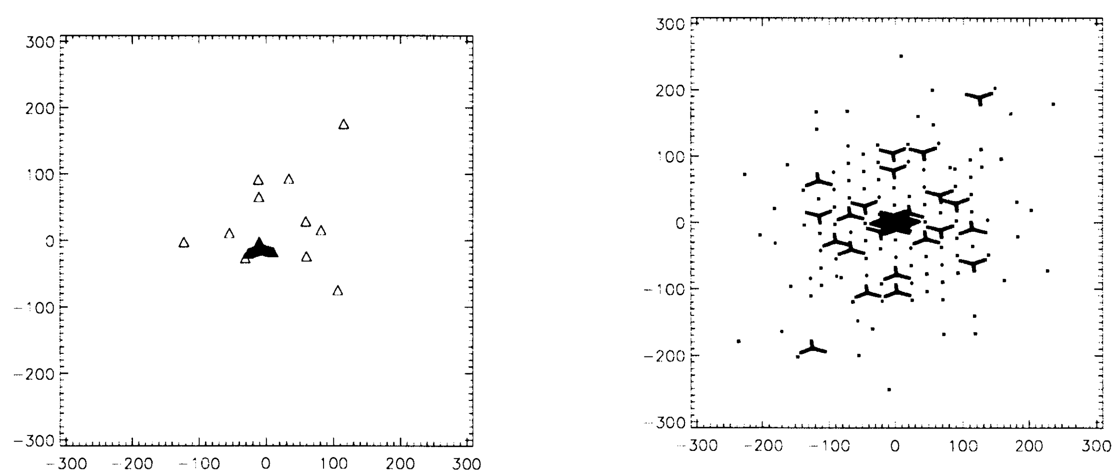
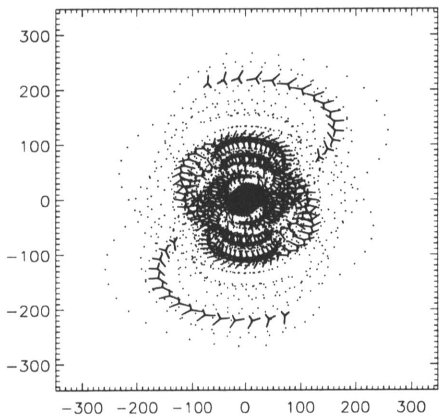


Figure 15. Antenna locations and snapshot UV coverage for an 8 antenna expansion based on the pattern in figure 14. The triangles represent the antennas and the dots the autocorrelation function. The axes give the coordinates of the antennas and the baseline vectors in km. The VLA appears squashed north-south in this figure because the antenna locations have mistakenly been projected by the sin of the latitude, 34°.

The array shown in figure 15 uses the VLA center, Pietown, Los Alamos, and the last antenna on the southwest arm of the VLA as 4 of the 12 elements. All 27 elements of the VLA are used in the VLA A+, and 2 VLA antennas would be required for the VLBA+ if used without the VLA. Using the existing Los Alamos antenna for one of the 12 elements results in a couple of 70 km holes in the snapshot coverage (figure 15 right) because it is not possible to fit both Los Alamos and Pietown exactly on the pattern. Aside from these holes, the snapshot coverage is complete on a 35 km grid out to 150 km. Figure 16 shows the tracked coverage for the VLA+ and the VLBA+ with these expansion antennas. Although this array does an excellent job on the smaller and intermediate scales, there is a gap in coverage evident in figure 16b, the short spacings of the VLBA. This array needs a few more longer spacings.



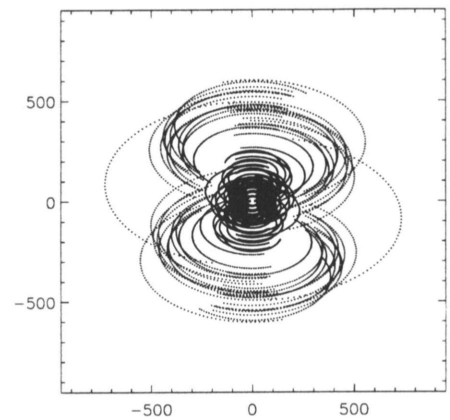


Figure 16. UV coverage for the 8 antenna expansion (figure 15) with the VLA antennas, VLA A+ (left), and with the VLBA antennas, VLBA+ (right). The source is at 34° declination. UV points are plotted every half hour (left) and every six minutes (right) between elevation limits of 25°.

Figure 17 shows test images at 5″ and 1″ scales, the intermediate scales between the existing VLA and VLBA (remember that this is 5″ and 1″ across the entire image). These images are made with the 27 antenna VLA, Pietown, and Los Alamos, but not Fort Davis and Kitt Peak. The 5″ image can be made without the Los Alamos antenna because the baselines to this antenna are all longer than 100 km.

The 5″ image (figure 17a) compares favorably with the imaging of the 4 antenna small scale expansion (figure 4) and the 1″ image (figure 17b) is better than with the previous 5 antenna expansion (figure 12) which had some defects due to missing intermediate scales. But some defects are still evident.

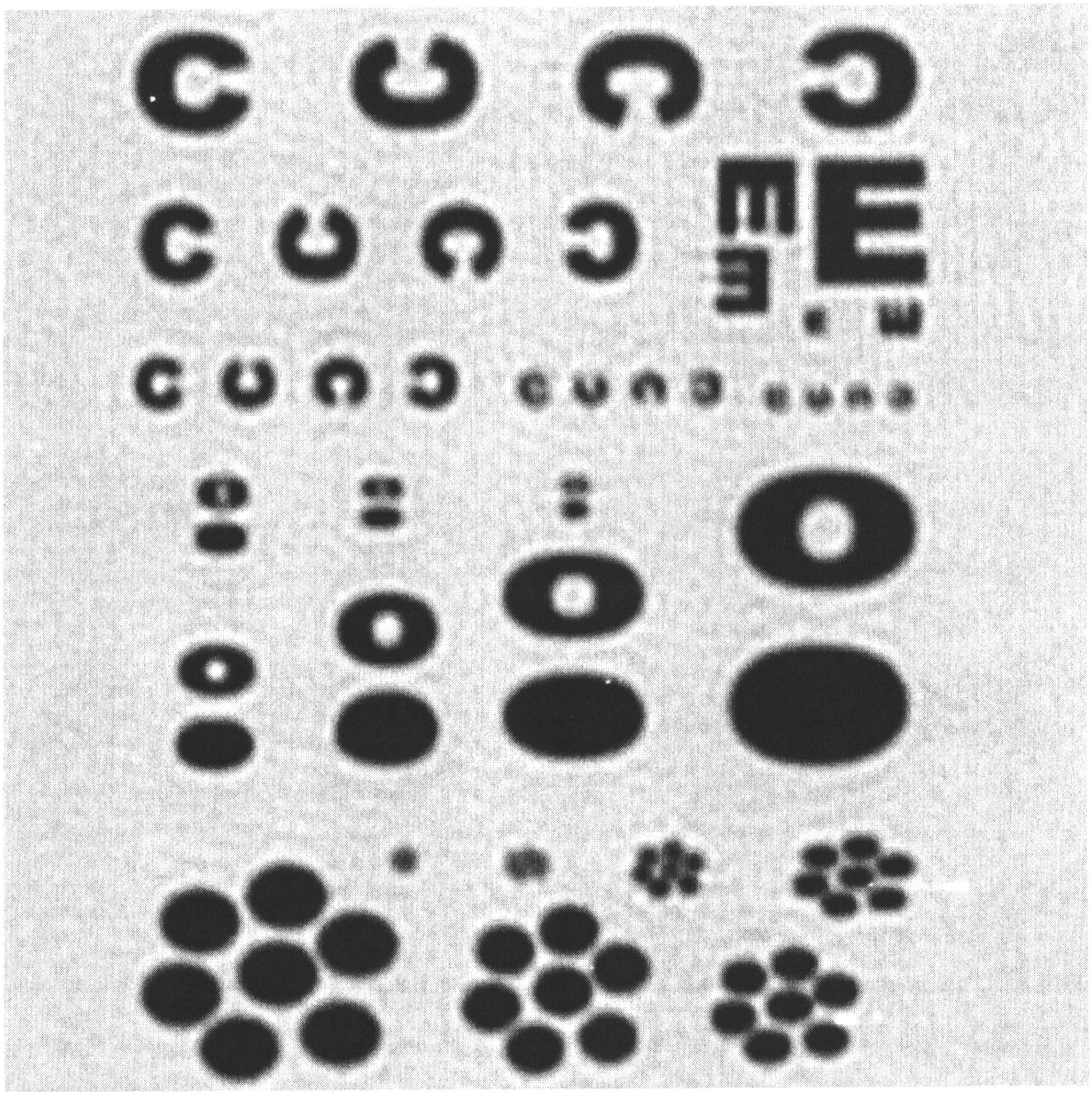


Figure 17a. Test image as seen by the VLA+ with 8 expansion antennas. The simulation assumes a source at 34° declination tracked between elevation limits of 25°. The scale of the image is 5″ across the full image.

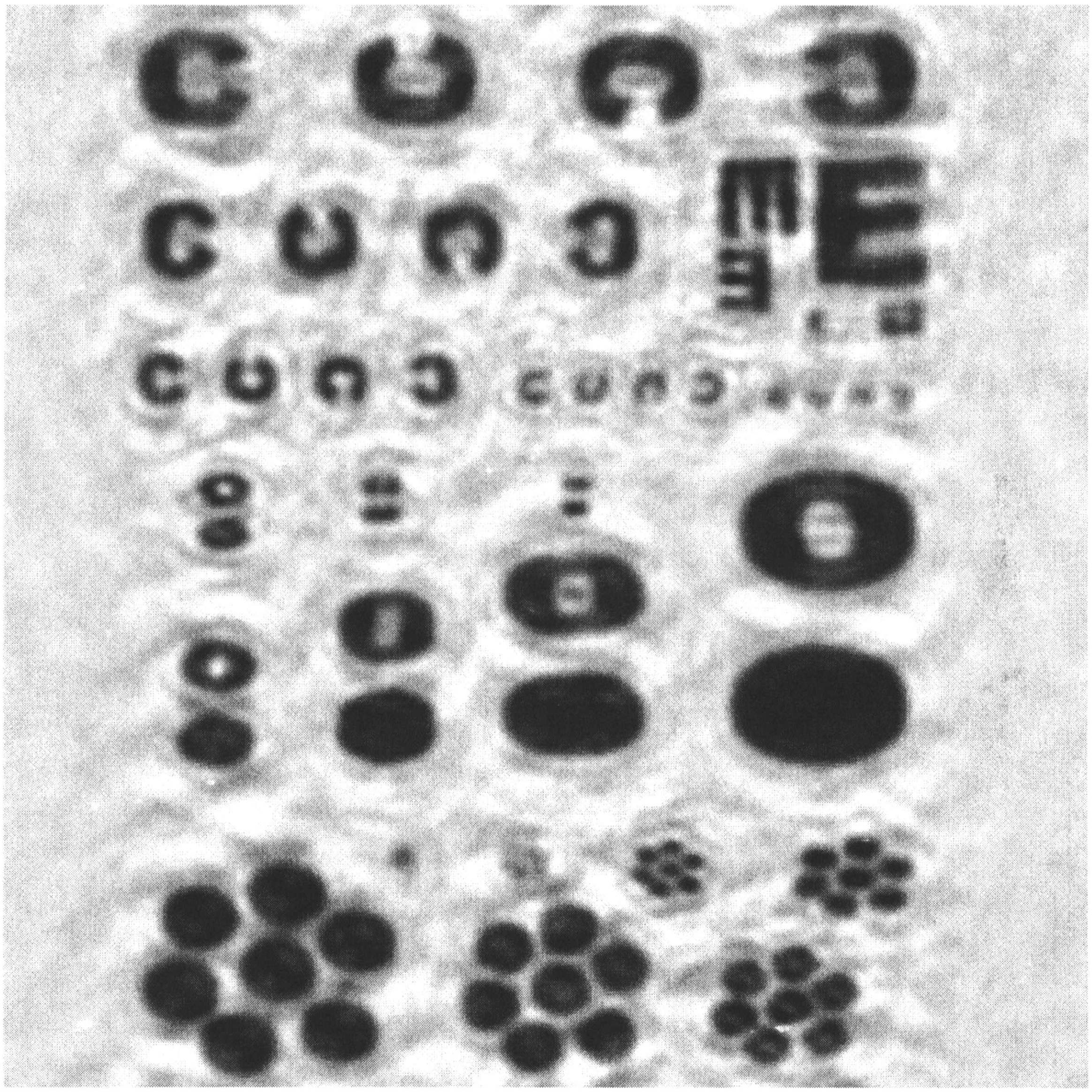


Figure 17b. Test image as seen by the VLA+ with 8 expansion antennas. The simulation assumes a source at 34° declination tracked between elevation limits of 25°. The scale of the image is 1″ across the full image.

The last example adds three antennas to the previous 5 antenna expansion to make a different 8 antenna expansion. The expansion antennas and the VLA are shown in figure 18a. The Pietown antenna is one of the antennas in this pattern. Figure 18b shows the snapshot coverage and figure 19a and 19b show the tracked coverage in the VLA+ and VLBA+ arrays. This is probably a better pattern than the previous one because there are fewer gaps in the Fourier plane coverage.

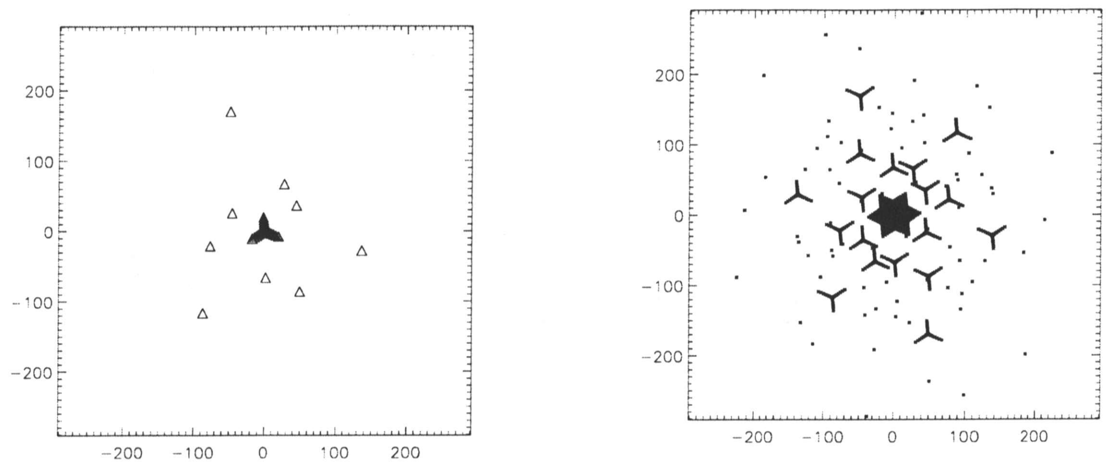


Figure 18. Antenna locations and snapshot UV coverage for the an 8 antenna expansion which adds 3 antennas to the 5 antenna expansion of figure 9. Plotted here are the 8 expansion antennas, and the existing antennas at Pietown and the VLA. The triangles represent the antennas and the dots the sampling function. The axes give the coordinates of the antennas and the baseline vectors in km. The VLA does not appear squashed in this figure because the antennas are in local rather than celestial coordinates.

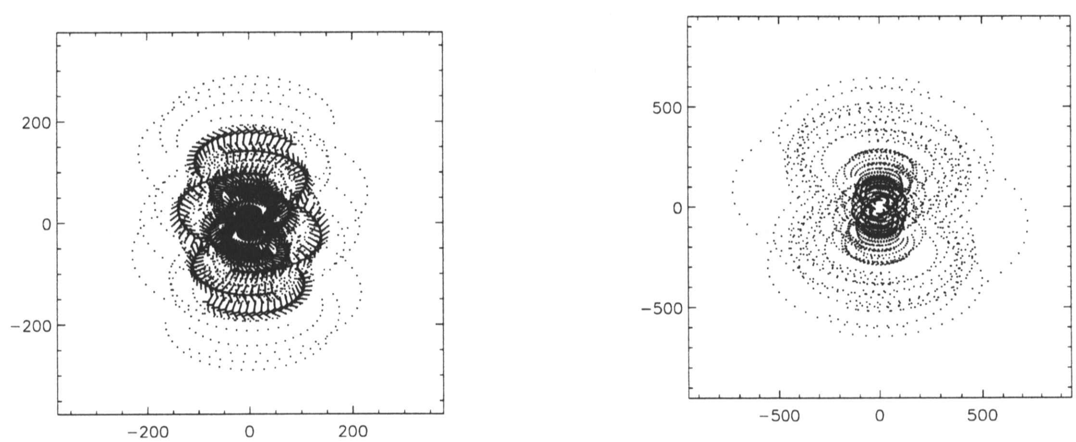


Figure 19. UV coverage for the 8 antenna expansion (figure 18) with the VLA antennas, VLA A+ (left), and with the VLBA antennas, VLBA+ (right). The source is at 34° (left) declination. UV points are plotted every half hour between elevation limits of 25°.

From this brief study one would suppose that about 8 antennas are required to bridge the gap between the VLA and the VLBA. Even so there are a few holes in the coverage resulting in noticeable imaging defects on a 1″ image. Expansions of 4 or 5 antennas seem capable of significantly improving the imaging of both the VLA or the VLBA but with this few antennas the expansions will leave some imaging defects in one of the scales. To have good imaging the expansion array will need several baselines as short as to Pietown and several baselines at least as long as to Los Alamos.