CHARA TECHNICAL REPORT

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The Need for Additional Array Telescopes

W.G. BAGNUOLO, H.A. MCALISTER AND A.B. KAYE

1. INTRODUCTION

Because of budget constraints, the number of telescopes of the CHARA Array was reduced from seven to five with two telescopes indefinitely deferred. With its present configuration, the Array is capable of performing very high resolution studies of short period binary stars and measuring the diameters of thousands of single stars. These capabilities will enrich our knowledge of the fundamental properties of stars – masses, radii, luminosities, surface temperatures and surface fluxes. However, the Array will be severely limited in its ability to image objects with complex surface structures. Such objects might include stellar photospheres with large spots, surface flux variations stemming from non-radial pulsation effects, and complex morphologies associated with young and pre-main sequence stellar objects. In this report, we explore the ramifications of adding additional telescopes to the Array in terms of improved (U,V)-plane coverage and through simulated imaging performance for several moderately complex objects.

The cost of an additional 1-m aperture telescope, including all optics enclosures and requisite "down-stream" subsystems, is roughly \$1.5M. Thus the restoration of the Array to its originally proposed capability would require approximately \$3M in new funds. An alternative strategy to replicating 1-m telescopes is to emphasize imaging of brighter objects by adding three or more "outrigger telescopes" of half the current telescope diameter. This alternative will also be considered in this report.

2. IMPLICATIONS FOR (U,V)-PLANE SAMPLING

One way to consider the effectiveness of an interferometer in covering the (U,V)-plane is simply to count the number of "snap-shot" points (equal to the number of baseline pairs) sampled in the plane, a quantity given by

$$N(N-1)/2$$

for an N-telescope array. In terms of its imaging capability, the number of closure phase triplets is the more relevant parameter, and that number is given by

$$(N-1)(N-2)/2.$$

[1]Center for High Angular Resolution Astronomy, Georgia State University, Atlanta GA 30303-3083
Tel: (404) 651-2932, FAX: (404) 651-1389, Anonymous ftp: chara.gsu.edu, WWW: http://www.chara.gsu.edu

These quantities are tabulated in Table 1 along with their step-wise percentage improvements. We also include the percentage cost of the project for each additional telescope for comparison and a "cost index" defined as the ratio of the mean percentage improvement in baseline pairs and closure phase triplets to the percentage increase in cost.

TABLE 1. (U,V)-Plane Enhancement

No. of Telescopes N	No. of Baseline Pairs N(N-1)/2	Percent Improvement	No. of Closure Phase Triplets (N-1)(N-2)/2	Percent Improvement	Percent Increase in Cost	Cost Index
5	10	–	6	–	–	–
6	15	50	10	67	13.2	4.4
7	21	40	15	50	11.6	3.9
8	28	33	21	40	10.4	3.5

Table 1 shows that the addition of a sixth telescope represents the most cost-effective improvement in performance of the Array in an expanion program aimed at adding one telescope at a time. If we consider jumping from five telescopes to seven, at a cost of $3M, then the cost index of a seven-telescope array compared with our currently funded project would be 4.9. Jumping straightaway to eight telescopes from five yields a cost index of 5.4, with obviously increasing gains due to the $\sim$N^2 improvements in baseline pairs and triplets while the cost increases linearly. However, the incremental gains decline with increasing N, and we conclude that original goal of a seven-telescope array represents the best choice between balancing costs and enhancing the ability of the CHARA Array to provide actual images of astronomical objects.

3. LOCATING ADDITIONAL TELESCOPES

Our ability to choose potential sites for additional telescopes on Mt. Wilson is a balance between better (U,V)-plane coverage and considerations due to terrain and existing structures. With this in minde, we start with the locations of the five currently planned telescopes and first try to enhance the (U,V)-plane coverage. We then compare target areas with the realities of terrain. We find that, although terrain places tough constraints on where we can realistically locate telescopes, we "luck out" in the sense that the best locations are nearly ideally achievable. As in Technical Report Nos. 11 and 14, the criterion for quality of (U,V)-plane coverage is the weighted coverage in a circle defined by that generated by the original nominal 354 m maximum Array baseline. Figure 1 is a contour plot of (U,V)-plane coverage as a function of the location of a sixth telescope. Note the low points in the figure (about 0.54 coverage) are near the existing telescopes. Adding a telescope close to existing ones of course does not appreciably add to the coverage. The maximum weighted coverage goes up to 0.70 in a number of areas on the mountain.

We find that an excellent choice for locating a sixth telescope is along the western arm of the array at a contour level of approximately 0.67 coverage. This location is immediately behind an existing dwelling but offers otherwise good construction logistics. We therefore adopt this as the best available sixth telescope site. (Note that in Figures 1 and 2, the asterisk marking the confluence of the three arms of the array does not mean to imply that a telescope is located there.)

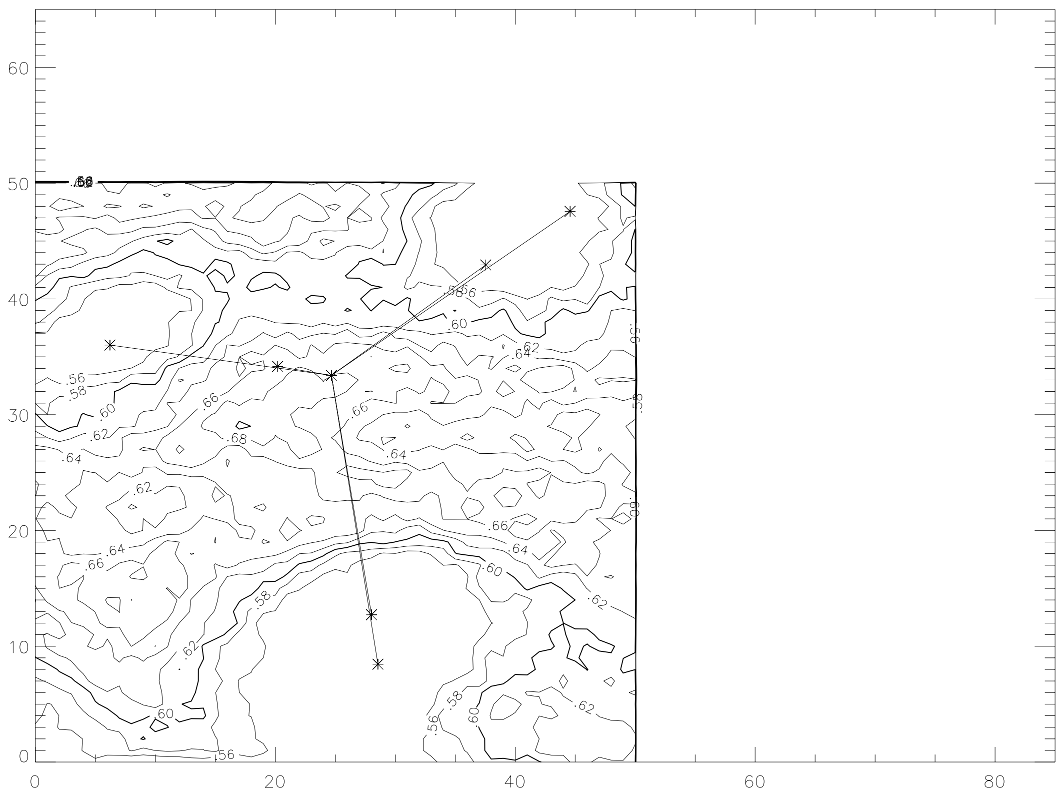

FIGURE 1. (U,V)-plane coverage quality as a function of location of a sixth telescope. Scale: 3.9123 m/pixel

We extend the methodology to find feasible locations for a seventh and eighth telescope. We start with the location found previously for a sixth telescope and look at the contour map of (U,V)-plane coverage as a function of the seventh telescope location. Figure 2 shows this plot. The feasible locations are along the existing lines or in locations off those lines on the southeast side of the array where terrain offer several favorable sites. The coverage is close to maximum at a previously identified site (although not published in a Technical Report) immediately to the west of the Mark III interferometer site and behind our proposed control and office building. We adopt this as the seventh telescope site and again seek to maximize coverage. One of the best eighth sites is relatively close to the Berkeley ISI facility and is shown along with its coverage quality in Figure 2. Note that the coverage index is about 0.84, meaning that most of the 'cells' in the coarse 32×32 pixel weighted coverage map are filled with eight telescopes.

The (U,V)-plane coverages resulting from increasing telescopes from five to eight are shown in Figure 3. The current five-telescope array is limited in its coverage to high and low spatial frequencies, and the addition of telescopes significantly increases the coverage for the midrange of spatial frequencies (corresponding roughly to telescope separations from 70-150 m.) This coverage can play an important role in recovering images of complex objects.

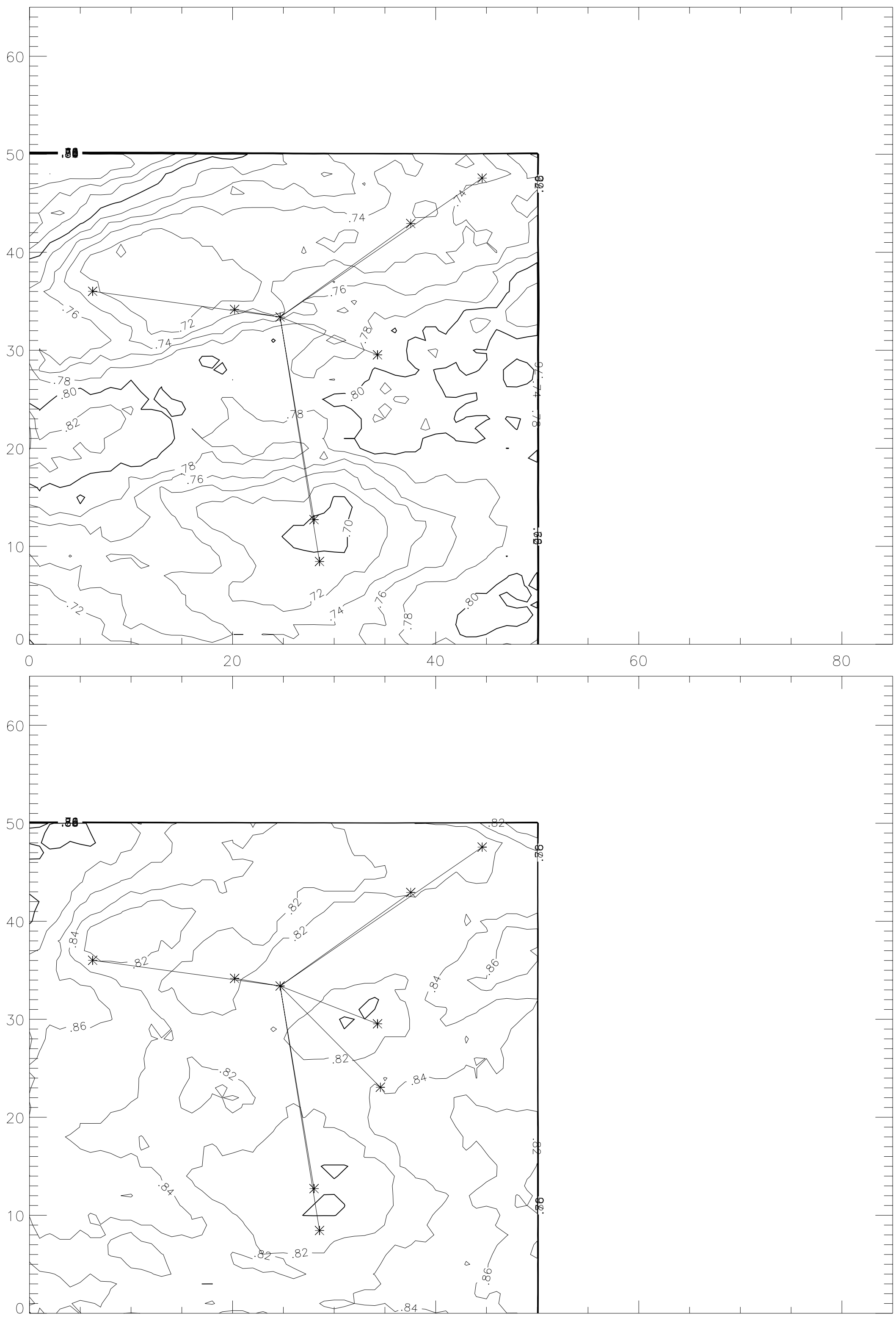

FIGURE 2. (U,V)-plane coverage quality as a function of location of a seventh telescope (above) and an eighth telescope (below).

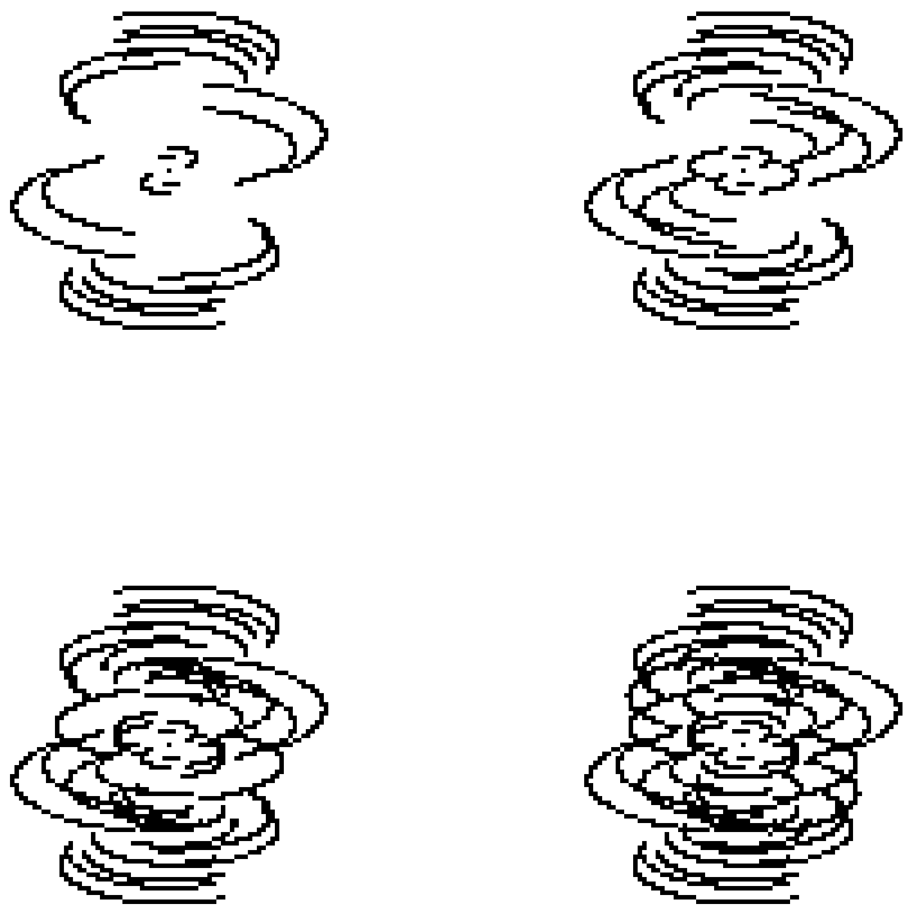

FIGURE 3. (U,V)-plane coverage for star at 20° declination. Upper Left: Coverage with the standard CHARA five-telescope array. Upper Right: (U,V)-plane coverage with best (feasible) six-telescope array. Lower Left and Right: Coverage with best (feasible) seven- and eight-telescope arrays.

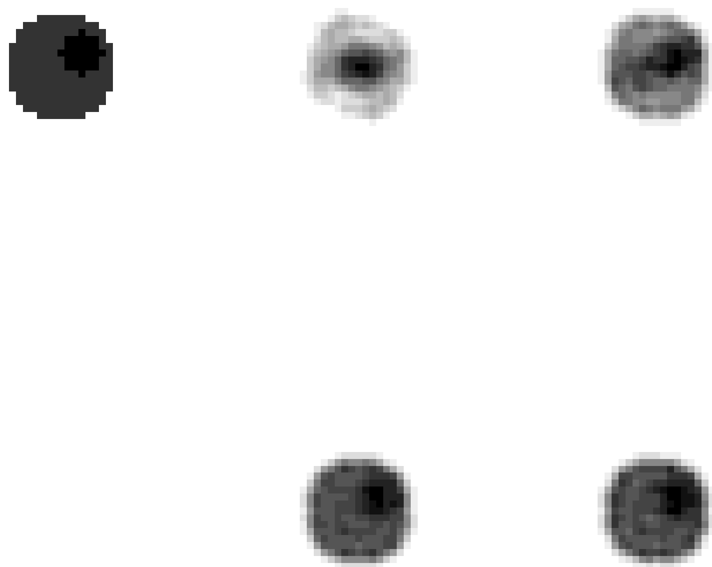

FIGURE 4. Star with spot (30% above background). Upper Left: Original image. Upper Center and Right: Image recovered with CLEAN for five- and six-telescope arrays respectively. Lower Left and Right: Recovered image for seven- and eight-telescope arrays.

4. IMAGING WITH ADDITIONAL TELESCOPE

To evaluate the effectiveness of increasing the number of telescopes in the Array, we have done a series of simulations using several algorithms. The simulation methodology assumes we have a set of observations (including noise) in the complex (U,V)-plane during a night in which a star at declination $20°$ is observable over all zenith angles up to $60°$. By the Van Cittert-Zernike Theorem these observations can be Fourier transformed into an image. This "dirty image" can be improved using the CLEAN algorithm, giving a final image estimate. This methodology is intended to give an initial estimate of how well a given interferometer array configuration can image, for a variety of images.

For multiple point source objects, such as binary stars and compact star clusters like R136, our simulations show that even the five-telescope array does very well, and there is no compelling reason to add additional telescopes for such objects. This the case because a "vernier" effect exists (i.e. there are many visibility nulls until the stars themselves are resolved, therefore the baseline coverage is effectively multiplied).

To investigate interesting objects of slightly more complexity we have chosen two targets representing increasing levels of complexity of surface features. The first is a single star of 1.7 milliarcsec (mas) diameter with a single bright spot of 30% above the star background. At this scale, the Array's longest baseline implies approximately 10 resolution elements

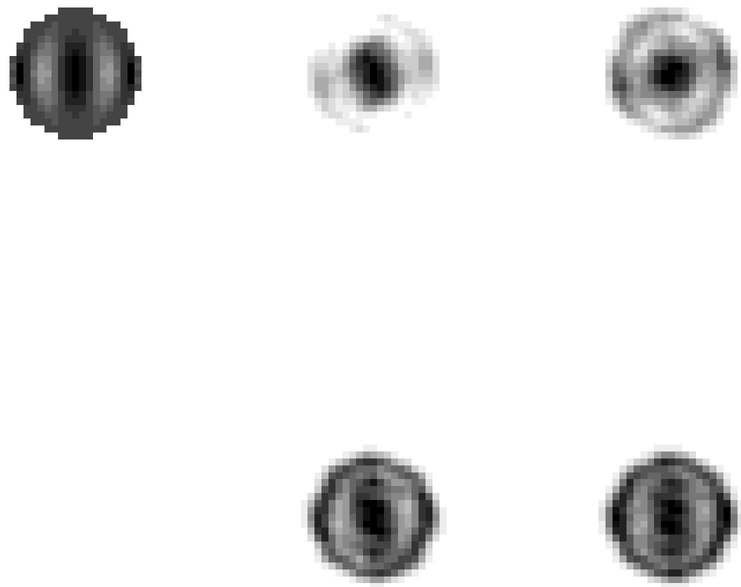

FIGURE 5. Star with NRP pattern. Upper Left: Original image. Upper Center and Right: Image recovered with CLEAN for five- and six-telescope arrays, respectively. Lower Left and Right: Recovered image for seven- and eight-telescope arrays.

across the image of the star. Figure 4 shows the original image, and those recovered with the an increasing number of telescopes in the Array. It is important to note that even for this relatively simple and idealized model image, the five-telescope array completely misses the spot and only marginally provides the means for measuring the diameter of the star. The offset surface feature begins to be imaged with the sixth telescope, and image fidelity improves with additional telescopes.

The failure of the five-telescope array to image the offset spot in Figure 4 is largely attributable to the absense of intermediate baselines now afforded to us. This example clearly shows the importance of adding even a single telescope to improve the uniformity of sampling in the (U,V) plane.

Figure 5 shows another test object, a non-radial pulsating (NRP) star with five equatorial and zero polar modes. Again, the six-telescope array starts to make sense of this object, whereas only a hint is given with the five-telescope array. Seven and eight telescopes improve fidelity even more. Note again that the enhanced details are in the mid to high spatial frequency range which are not well covered by only five telescopes.

5. CONCLUSION

For simple combinations of unresolved point objects, such as binaries or clusters the existing five-telescope Array should produce good images. Angular diameters of resolved single stars with essentially uniform or circularly symmetric photospheres should also be measurable. For moderately complicated objects, such as resolved stars with NRP patterns or spots, there appears to be a definite advantage in adding additional telescopes.

The addition of a sixth telescope to the CHARA Array would be a first step in qualitatively improving the capability of the facility for interferometric imaging. Restoring the project to its original seven telescopes would ensure its viability as an imaging instrument capable of a broader range of scientific programs than is presently available. A seven-telescope CHARA Array would have 2.1 times the baseline pairs and 2.5 times the closure phase triplets than will currently be available to us. This very significant gain comes at an estimated 26% increase in project cost. Although our current program is limited to five telescopes, the central Beam Synthesis Facility has been constructed to simultaneously accomodate up to eight telescopes, a number which we regard as the practical upper limit to expansion, not only because we tend to run out of available sites on Mt. Wilson but also because of the complexity of beam combining systems capable of simultaneously sampling all closure phase triplets.

We close by noting that we have taken advantage of favorable pricing and have optimistically purchased two additional 1-meter Sitall mirror blanks as a head start towards additional telescopes.