# THE USE OF THE MMT FOR INTERFEROMETRIC IMAGING

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## ABSTRACT

We describe recent progress with interferometric imaging using the Multiple Mirror Telescope (MMT). All six telescopes can now be phased over a wide field of view simultaneously resulting in a (u, v) plane coverage corresponding to that of a 686 cm aperture telescope. We describe the open-loop phasing control of the MMT for gravitational changes and we describe a concept of an internal cophasing/coalignment system for MMT type telescopes.

## Introduction

In previous publications [1, 2] we described the use of the Multiple Mirror Telescope (MMT) for interferometry in

*Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

*Proceedings of the IAU Colloquium No. 79: "Very Large Telescopes, their Instrumentation and Programs", Garching, April 9–12, 1984.*

the visible, infrared and sub-millimeter regions of the electromagnetic spectrum. This paper is an update of those papers describing the progress made since then in using the MMT as a phased array in visible wavelengths.

## Fully Phased Operations of all Six MMT Telescopes

We recently completed the construction of a phasable beam combiner for the MMT, consisting of six pairs of identical BK7 glass wedges, one in each of the six MMT telescopes (mode C, in the sketch shown in figure 3, in paper 1). The wedges have an angle of 10°. Each pair of wedges acts effectively as a parallel glass plate whose thickness can be varied by translating one of the wedges thus changing the pathlength of the telescope. The motion of the wedges is controlled by a stepper motor which is interfaced with a computer. Each step of the motor corresponds to a 0.18μm pathlength change and the total range of pathlength adjustment is about 3mm. The pathlengths of each of the telescopes were initially made equal to ±0.5mm by adjusting the height of the tertiary mirrors so that the adjustment range of the wedge pairs suffices.

The combination of the six beams was done in the so called wide field mode described in paper 2. In it, the pathlength equality between a star and the image plane of the MMT is maintained when moving the object star off axis at least over an amount equal to the isoplanatic path. This wide field condition is achieved by matching the exit and entrance pupils of an interferometric array as shown in

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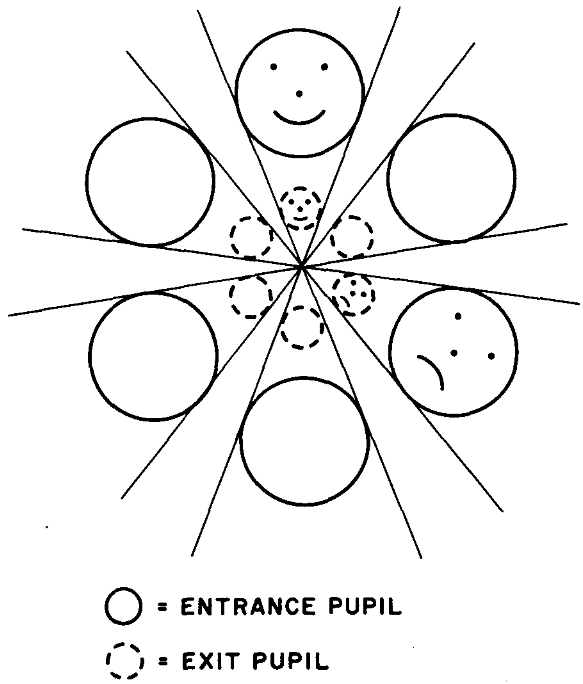



**Figure 1: For wide field interferometry, the entrance and exit pupils should be identical except for a linear scaling factor. Identity is also required for structure within the pupils.**

the cartoon drawing in figure 1. It means that when the diameters of the individual entrance and exit pupils are matched, the distance between the pupils are also matched. Also (as shown by the faces in figure 1), the internal structure of the pupils must be preserved.

We phase the six telescopes with the use of a speckle camera[3]. One of the telescopes is used as a reference. The other 5 telescopes are then phased to the reference telescope, one by one, by searching for the interference fringes in the combined telescope star images, and by centering the white light fringe on the star image. This process takes about 5 minutes after which all six images are combined to give the combined interferometric/speckle

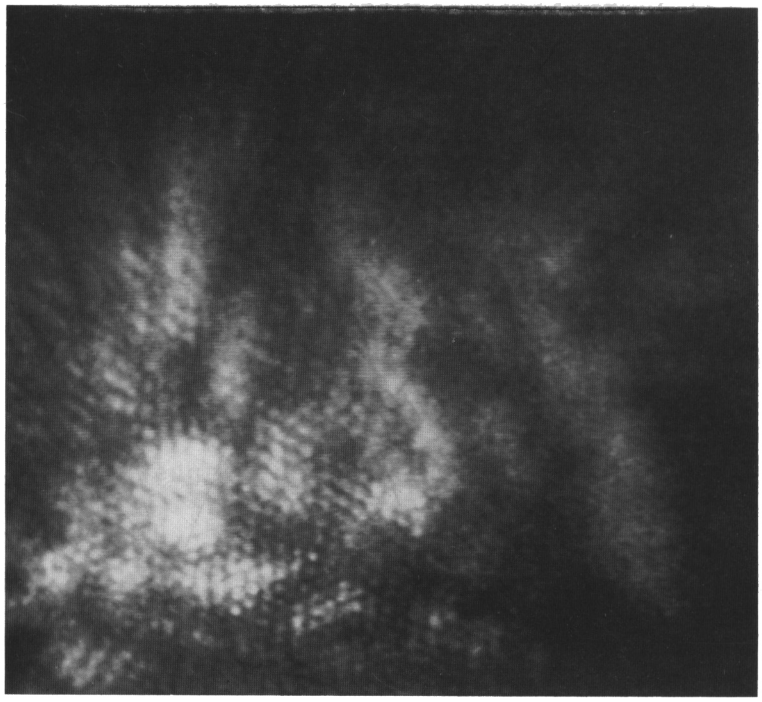
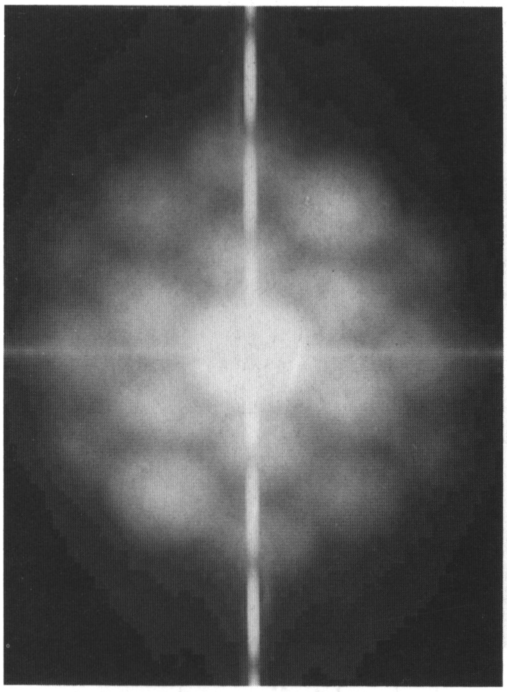


**Figure 2: Speckle image of an unresolved star using the MMT as a fully phased array.**

image. Figure 2 shows the combined image for an unresolved star. In the center of the image the complex fringe/ speckle image is, as expected, showing speckles corresponding in size to the 686 cm telescope aperture. The speckles are, however, clearly of a different character than those of a single aperture telescope because of the predicted preferred spatial frequencies. At the edge of the image where due to seeing, telescope aberrations and image misalignments the six images do not overlap, the full speckle patterns disappear. Figure 3 shows the 2D power spectrum for the unresolved star $\beta$ Tau. The location of the peaks corresponds to those predicted from the (u, v) plane coverage of the six element polygon array (figure 4). The variable amplitudes of the peaks are due to a variety of instrumental effects including image misalign-



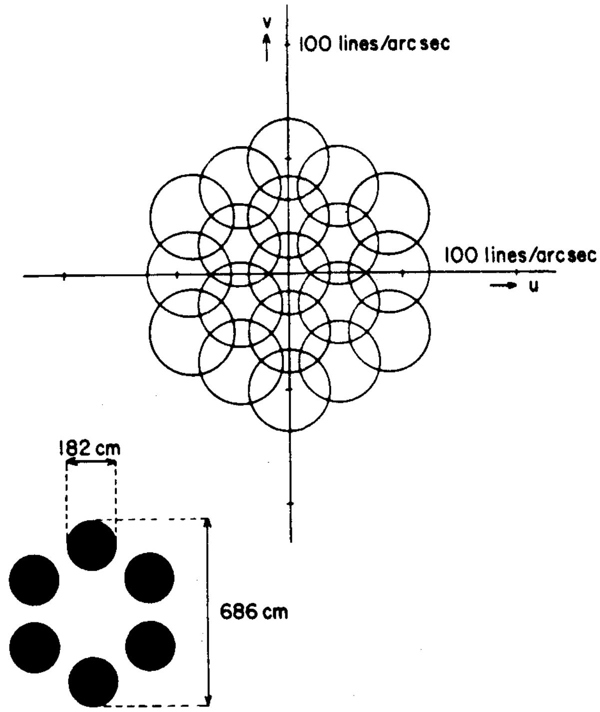



Figure 3: Two dimensional power spectrum of β Tau.

Figure 4: Predicted (u, v) plane coverage of MMT

ments, telescope aberrations, imperfect phasing and the absence of a correction for the off-axis polarization/ retardation effects in the six telescopes. Figure 5 shows the 2D power spectrum for the binary star Capella which at 750nm now shows a full 1.5 cycles of the power spectrum fringe resulting of the binary nature. Because of changing phasing conditions between the observations the ratio of the Capella and β Tau power spectrum (figure 6) show many artifacts (including detector "hot spots"),which makes it dangerous to infer reality for other sets of fringes visible in the ratio spectrum.

These changing phasing and coalignment conditions make it very difficult to do quantitative analysis of the phased

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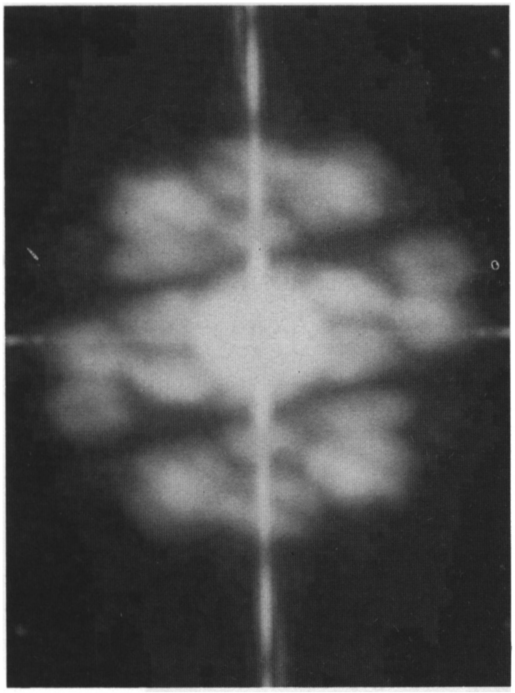

Figure 5: Power spectrum of Capella

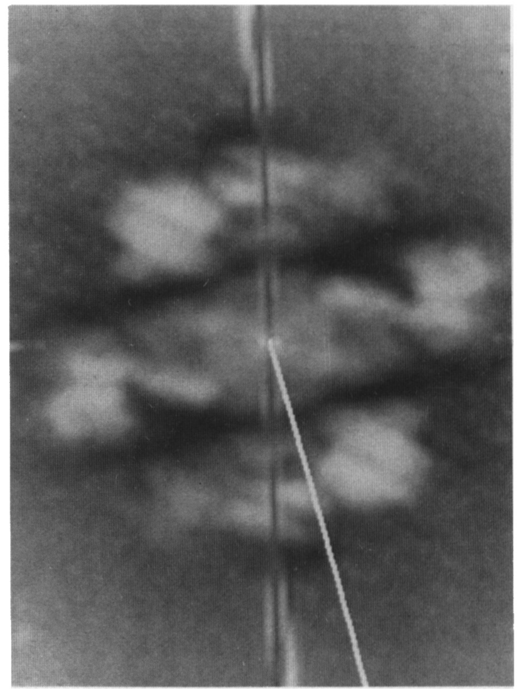

Figure 6: Ratio of Capella and β Tau power spectra

MMT images. We have, therefore, undertaken a development program aimed at maintaining phasing and coaligment of the MMT images. This program includes attempts to correct open-loop for elevation and temperature effects, and plans to construct an internal laser coalignment/cophasing system for the MMT. We will describe these efforts below.

## OPEN-LOOP COPHASING

Most of the variation in the telescope pathlengths results from the gravitational flexure of the telescope structure. We measured the variation of pathlength as a function of the elevation pointing of the MMT on a number of occasions. Figure 7 shows the relative variation in the pathlength for each telescope as made on two nights about one month apart,

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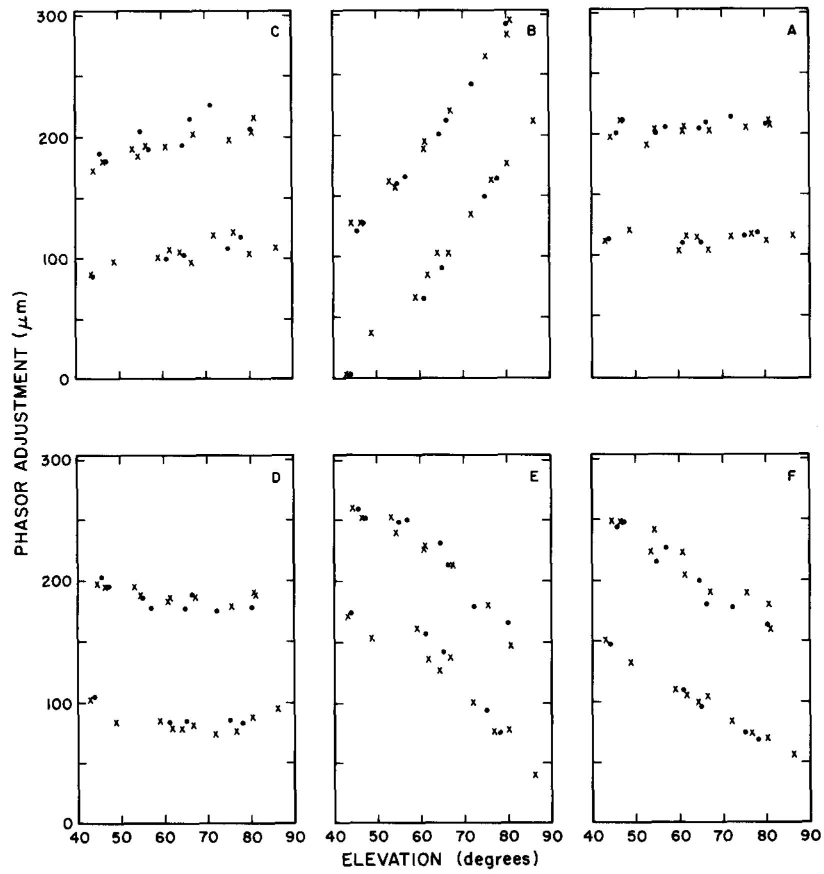


**Figure 7: Pathlength variation in each of the six MMT Telescopes for two different observing runs. Increasing values correspond to increasing pathlength.**

on January 21 and February 13, 1984. The 5 measurements of pathlength difference were adjusted so that the average pathlength was kept constant as one changed elevation. That condition resulted in the six data sets (one for each telescope) shown in figure 7. From this data, one concludes that (i) the systematic changes are very repeatable between the two data set. Between the dates of the two sets, a number of adjustments were made on the MMT like replacing the tertiary, secondary and beam-combiner optics. The repeatabilty is therefore remarkable. Also the pathlength difference between telescopes B and E repeats quite closely the difference between those telescopes measured over half a year before and shown in paper 2 (figure 10), (ii) the hysteresis between up and downward motions is small. The largest amount (for telescope B) is 5µm and (iii) the residual scatter of the observations amounts to ~ 20µm peak to peak. That is substantially more than the measurement errors (± 2-3µm) and is at least, to some extent, due to thermal changes in the optics support structure.[2] The curves shown in figure 7 have been fitted with a second degree polynomial and the wedge position is now open-loop computer controlled to remove the systematic elevation variation.

It should be pointed out that in an array telescope like the MMT, the pointing of the individual telescopes and the phasing of these telescopes are highly interactive. If pointing errors caused by imperfect mount pointing (typically 0.5-1 arc sec) are corrected by tilting the secondary mirrors, the phasing of the telescopes is destroyed (1 arc sec causing as much as a 25µm pathlength difference). It is therefore important not to do so at the MMT, and to point the telescope as a whole using its elevation and azimuth axis. It is equally important to define an algorithum for the differential pointing corrections by the secondary mirrors needed to correct for co-pointing errors between the MMT telescopes. For phasing experiments the algorithum adopted keeps the average position of the six telescope images, in both elevation and azimuth direction, stays the same.

As described in paper 2, we suspect that the residual 20μm PTP variations are due to thermal changes in the MMT optics support structure (OSS), one degree thermal change across the structure causing a ~65μm change in the differential pathlength. A plan to measure the OSS temperatures and to correct open-loop for their change, remains to be implemented. When implemented, it should improve the cophasing. Until implemented, we cannot evaluate the residual variations.

## DESCRIPTION OF AN INTERNAL COALIGNMENT/COPHASING SYSTEM

Ultimately, it is desirable to couple the individual telescopes in MMT configuration systems with a system internal to the MMT, since the open-loop correction systems are not perfect and since coalignment and cophasing on nearby stars will not always be possible. We describe in this section an internal laser coalignment/cophasing system ($LC^2S$) which is aimed at doing simultaneously both internal coalignment and cophasing. As pointed out in the previous section, the coalignment and cophasing of an MMT type telescope are closely related so that an $LC^2S$ system which does both is highly desirable.

A diagram of the $LC^2S$ system is shown in figure 8. It is based on a similar system described by Butts, et al.[5] Figure 8[a] shows the front view of the 4 mirror MMT concept under discussion for the U.S. National New Technology Telescope (NNTT). The dark bars between adjacent

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telescopes are the $LC^2S$ bridges which will coalign and cophase telescopes A to B to C and to D. The fourth bridge between D and A is redundant and can be used as a check and as a spare, in case any of the other bridges fail. A similar scheme with 5 or 6 bridges could be used for the present six mirror MMT. Figure $8^b$ shows the cross section Q through the telescope. It shows how a multiwavelength Argon laser is projected out of the telescope to infinity. Figure $8^c$ shows cross section P through the

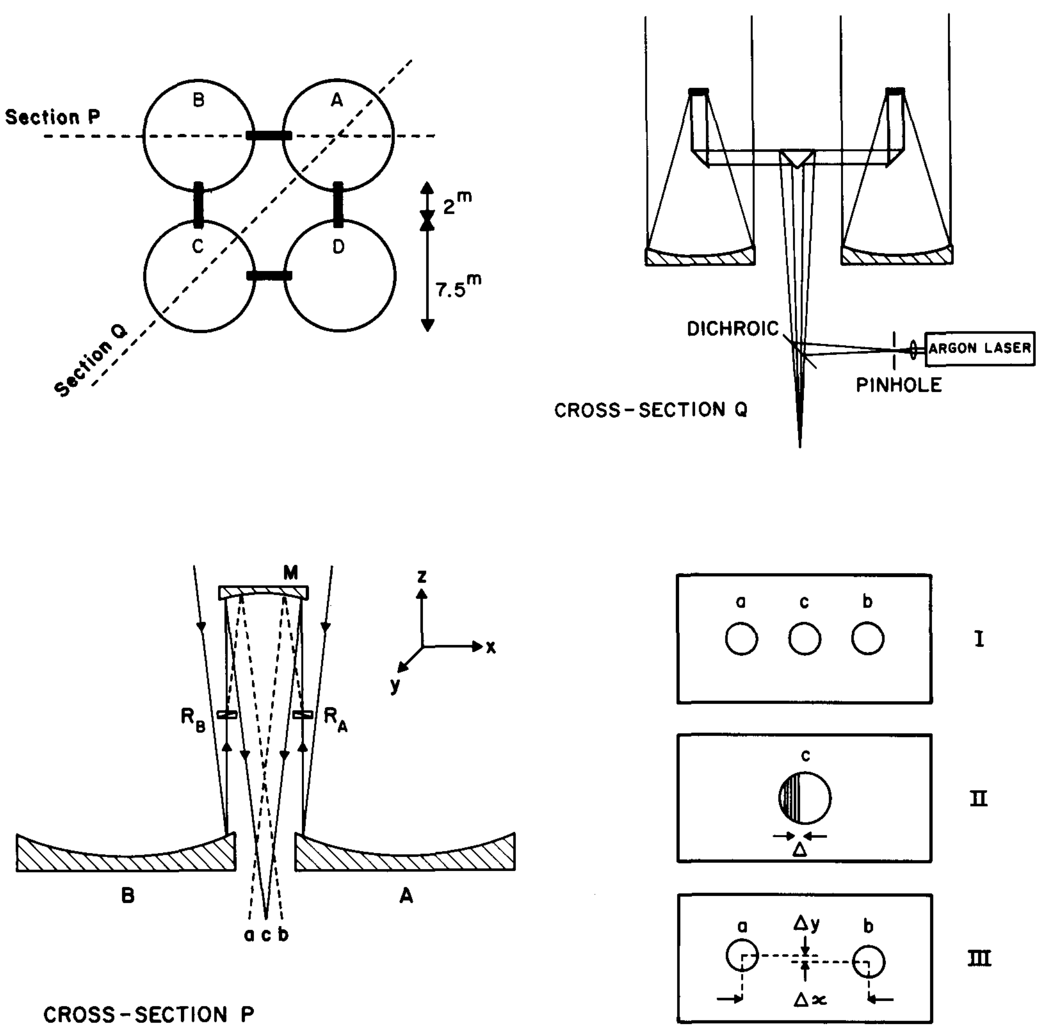


**Figure 8:** Diagram of the laser coalignment/cophasing system for the NNTT-MMT concept. $8^a$, Upper right = $8^b$, etc.

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telescopes A and B and through the bridge connecting them. The Argon laser beams at the facing edges of telescopes A and B are intercepted by an inverted telescope M which focuses the laser beam at image c. Two Rochon prisms $R_A$ and $R_B$ split the incoming laser beam in orthogonal linear polarizations. The image c results from the combined undeviated beams whereas the deviated beams from telescopes A and B form two separate images a and b respectively. In figure $8^d$ the three images are shown on a single detector (I) or on two separate detectors (II and III). Image II shows the location of the quasi whitelight fringe with respect to the laser source image. The displacement $\Delta$ between the whitelight fringe and the center of the image c result from a phasing error and can be used as an error signal to adjust the phase of the telescope B with respect to telescope A by means of any of the phase adjustment arrangement described in paper (2). Image III shows the displacements ($\Delta x$, $\Delta y$) of images a and b. Those displacements can be used to coalign telescopes A and B, for example by tilts of their secondary mirrors. Tilts and displacements of the inverse telescope M will displace images a, b and c but will keep the values for $\Delta$, $\Delta x$ and $\Delta y$ quite undisturbed. In paper (4) the sensitivity of the $LC^2S$ scheme to misalignments of the inverse telescope M were discussed. The most critical misalignment is a defocusing of the telescope M which will cause $\Delta x$ to change resulting in a misalignment of the optics. It is important to maintain and/or measure the distance M - c with high precision. The second most critical misalignment is a tilt of M around the y axis which result in a change in $\Delta$.

This $LC^2S$ scheme at the moment is untested, as is a similar scheme by N. Woolf which uses a flat mirror for M. The $\Delta$, $\Delta x$ and $\Delta y$ values will of course be subject to variations due to atmospheric seeing inside the telescope, as was the case for the so called laser coallignment system which was part of the original MMT design. To reduce the effects of seeing, one should measure these quantities every 0.1 second and then average them digitally until the desired coalignment/cophasing precision is reached. An estimate for reasonable internal seeing conditions [4] results in a RMS coalignment and cophasing error of 0.01 arc second and 0.14μm for an integration time of 30 seconds which is much less than any image motion and phasing errors introduced by the atmosphere in front of the telescope.

## NON-REDUNDANT MMT ARRAYS

The present MMT and the proposed MMT concept for the NNTT have a highly redundant aperture configuration from the point of view of interferometry. If one sets as a goal the filling of the maximum area in the (u, v) plane with a polygonal array of telescopes, one would do substantially better with an odd number of telescopes. With 3, 4, 5, 6, 7, 8, 9 and 10 sided polygons, one has 3, 4, 10, 9, 21, 16, 36 and 25 non-redundant baselines respectivey. Figures 9, 10, 11 and 12 show the (u, v) plane coverage with an optimized array of 3, 4, 5 and 6 telescopes, optimized in the sense that gaps in the (u, v) plane coverage are just

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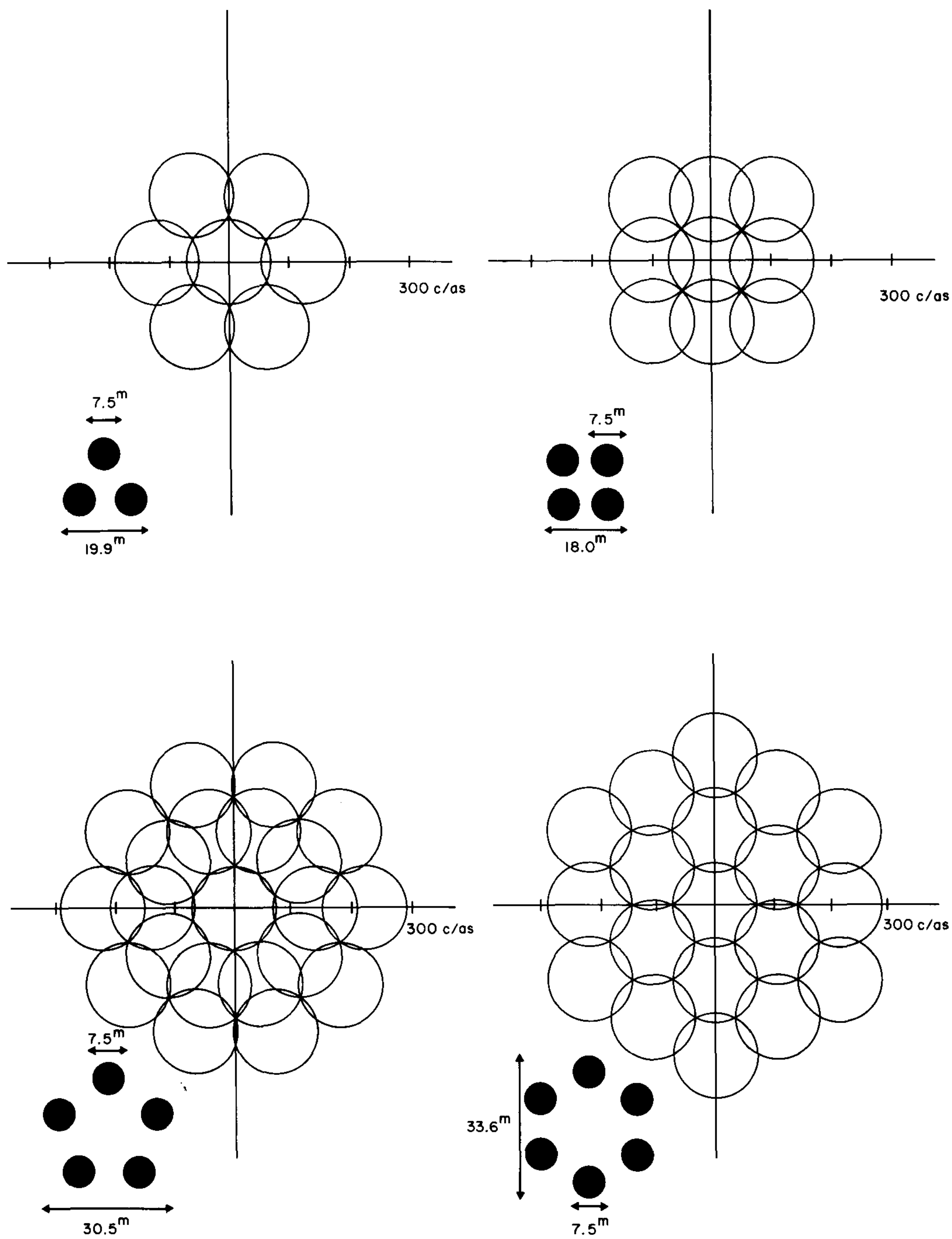


Figure 9: Coverage of the (u, v) plane for 3, 4, 5, and 6 sided polygonal MMT arrays.

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avoided. The (u, v) plane coverage for the (2n-1) telescope is about the same as that for the 2n telescope because of the absence of the redundancy in the former. Structural considerations appear to lead to a preference for even numbered polygons like the MMT and the NNTT-MMT so that the odd numbered non-redundant polygon MMT may be more a curiosity than a realistic proposal.

## CONCLUSION

The MMT has shown itself to be a very powerful interferometric device. When long coherence lengths (small $\Delta\lambda$) are used the MMT, as it is now with the open-loop flexure correction, is very good as a coherent array. For broad bandwidth applications in the visible region of the spectrum, the residual 10-20$\mu$m variations in pathlength are unacceptable. A more refined open-loop control system may not be adequate to cure that and it appears that an optical closed loop control system like the $LC^2S$ will be needed.

## ACKNOWLEDGEMENTS

The MMT interferometry project owes much to the support of the Steward Observatory shops, especially R. Young, and to the help of the engineering and operations staff of the Multiple Mirror Telescope Observatory. This work was supported by NSF grants AST 8113212 and AST 8201092 and USAF Contract F19628-82-K-0025.

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## DISCUSSION

J.E. Noordam: Redundant spacings in the aperture plane are a very powerful calibration-tool in radio aperture synthesis. Since it is possible in optical interferometry to disentangle their contributions and then use them for this same purpose, one should not elimiate them by building non-redundant arrays.

J. Beckers: You are of course correct. Phase closure techniques have not yet been used in optical astronomy. If and when they come about, redundancy may indeed be of help.