Evaluating the Minimum Baseline Constraints for the MMA D Array

M.A. Holdaway and Scott M. Foster
National Radio Astronomy Observatory
Tucson, AZ 85721

July 9, 1996

Abstract

We quantify the decrease in mosaic image quality when the MMA dishes have a tapered, rather than uniform, illumination. The dynamic range and image fidelity decrease by about 30% for a given minimum antenna separation for maximum entropy mosaicing, worse for maximum emptiness mosaicing. While the decreased image quality is substantial, thermal noise will usually limit the dynamic range of MMA mosaic images so we can probably live with the decreased image quality.

Very small antenna separations are required by homogeneous array mosaicing. We can either design an antenna which allows short enough spacings without the possibility of collision, or we can rely upon some safety mechanism to prevent the antennas from colliding. John Lugten has suggested that a mechanical elevation limit of 30 deg will permit the conventional antenna to have separations as small as 1.30 D, where D is the dish diameter, without the possibility of antenna-antenna collisions. With no elevation limit, the antennas must be 1.48 D apart to completely avoid any antenna collision. (The minimum antenna spacings with and without elevation limits depend upon the details of the antenna design, and the current conventional design does not exactly reproduce the numbers I argue from in this report.) Mosaicing simulations with an 11dB tapered dish illumination indicate that this solution to the minimum separation problem will provide pretty good mosaic image quality over the entire declination range visible from the Chilean MMA site. It is possible to modify the design further to achieve 1.25 D minimum antenna separations. Antenna configurations with a minimum separation of 1.30 D do not generate mosaic images which are significantly worse than configurations with a minimum separation of 1.25 D, so we conclude the design which yields 1.30 D is probably adequate. Configurations with a 1.48 D minimum dish separation perform much worse than the 1.30 D minimum spacing arrays unless they are observing at low elevations and the baselines are significantly foreshortened. With an elevation limit of 30 deg, the slant-axis design has a minimum antenna separation of 1.6 D, which is not acceptable for mosaicing quality or for brightness sensitivity. If the slant-axis antenna is to be used for the MMA, a collision avoidance system must be used.

Armed with the 1.30 D minimum antenna separation, we are able to make rough specifications for four different mosaicing configurations which will cover all elevations down to 10 deg with little shadowing and good short spacings. This can be reduced to three mosaicing configurations by only optimizing down to 15 deg. Due to packing considerations, the 1.30 D minimum spacing will require that the zenith D array be expanded from 70 m to about 80 m. We estimate that a move between adjacent mosaicing configurations requires

moving 10-15 antennas, which will take three transporters between a a few hours and a day, depending upon how many obstructing antennas must be temporarily moved to remove the target antennas. We need to explore the possibility of a grid of antenna foundations rather than discreet antenna pads to provide more flexibility for the D configurations.

1 Introduction

Mosaicing with a homogeneous array (Cornwell, Holdaway, and Uson, 1993) entails measuring total power and interferometric data with the same antennas, but not necessarily at the same time. For homogeneous array mosaicing to work well, the antennas must be close enough together so that the effective (u,v) coverage of the shortest baselines overlaps with the effective (u,v) coverage of the single dishes. Originally, we recommended that the antenna illumination be made as uniform as possible through a shaped subreflector or a lens to increase the amount of overlap in the effective (u,v) coverage of the shortest baselines and the single dishes. However, uniform illumination is unattractive as it seriously degrades the off-axis optics, causing problems for nutating subreflectors and any future focal plane arrays. Welch (MMA Memo 134, 1995) pointed out that the spectral response of a uniformly illuminated dish and a dish with an 11dB illumination taper were very similar at baselines of 0.5 D, (D being the dish diameter), and uniform illumination was eliminated from the antenna design. Emphasis was shifted to finding a way to get the antennas closer together than the nominal safety limit of about 1.5 D.

One safe method of reducing the minimum antenna separation, proposed by John Lugten, was to mechanically limit the antenna to some minimum elevation, resulting in a shorter minimum safe separation. Different configurations could have different mechanical elevation limits. Table 1 shows the minimum antenna spacing as a function of the minimum allowed elevation angle for the conventional MMA antenna design. The 1.25 D spacing may not be possible with this antenna design, but the 1.30 D spacing should be possible with the current conventional MMA antenna design. Another competitor for the MMA antenna design is the slant axis mount with an on-axis reflector (Cheng, 1994). The main disadvantage of the slant axis

Elevation Limit	Minimum Safe Antenna Separation
0°	1.48 D
11°	1.46 D
15°	1.44 D
30°	1.30 D
34°	1.25 D

Table 1: Minimum safe antenna spacing as a function of the minimum elevation limit. (Note that since this work was completed, changes in the antenna design have caused the minimum spacing at 0 deg elevation to decrease and the minimum spacing at 30 deg elevation to increase. The minimum spacings will continue to change as the antenna design evolves.)

antenna is that it's close packing performance is very poor. With no elevation limit, the minimum antenna separation is 1.8 D, and when the antenna elevation is mechanically constrained to be above 30 deg, the minimum separation is 1.6 D (Cheng, private communication). With a collision avoidance system which shuts down the antennas when they are not looking in the same direction or when a collision is eminent, the slant axis antennas could have a minimum separation of only 1.2 D.

If the minimum separations of the conventional antenna are not good enough for brightness sensitivity and/or mosaic fidelity, then we are forced to rely upon an active collision avoidance system, which can be used effectively for either the conventional of the slant-axis antenna, and the close packing is no longer a major consideration in choosing the antenna design. However, if the conventional antenna minimum separations are acceptable, the MMA will not require collision avoidance systems. This may be seen to outweight other advantages of the slant-axis antenna, such as its superior pointing and speed.

It has already been recognized that the MMA would required about three different D configurations to ensure that sources at extremely low and high declinations could be observed with a circular beam and without much shadowing. If we achieve very short baselines by a mechanical elevation limit, this elevation limit will also be instrumental in defining the elevation range observable from high elevation optimized and low elevation optimized array configurations. Since significant shadowing will occur at 30 deg elevation in the high elevation D configuration, this is not a significant problem. One possible problem is that the elongated D configuration for observing sources below 30 deg elevation will have a minimum antenna spacing of 1.48 D, which may not be short enough to produce high quality mosaics. Projection will shorten the baselines to less than 1.48 D, predominantly in the N-S direction, but the largely unforeshortened east-west baselines may still present a problem. We address this issue through simulated observations.

In the following sections, we will investigate the effects of a tapered dish illumination on mosaic image quality, determine what minimum baseline is required for mosaicing with a tapered dish illumination, verify that arrays built with the 30 deg elevation limit can produce high quality mosaic images across the observable sky, and paint a high level picture of what the different compact MMA configurations might look like. Most of these investigations are made with the use of numerically simulated observations.

2 Simulation Details

2.1 Configuration Issues

We first had to create test array configurations with some minimum baseline. Some of the crucial issues in laying out the D configuration are

- **Minimum antenna separation.** This will be set by the antenna design and the method used to sneak the antennas closer together.

- **Fitting 40 8 m antennas into a minimum circle.** A hexagonal close packing of 40 8 m antennas separated by 1.30 D takes up the same area as a 69 m diameter circle.

- **Low Sidelobes.** Randomizing the antennas will give a synthesized beam with low sidelobes. Since errors propagate through mosaic images like the sidelobes of the synthesized beam, minimizing the sidelobes will increase the mosaic's dynamic range when the observations have been degraded by pointing errors or primary beam errors. Reduced sidelobes will not necessarily increase the mosaic's fidelity.

- **Shadowing.** With a 1.30 D minimum antenna separation, shadowing begins at an elevation of 50 deg, and approximately half the baselines will be shadowed at an elevation of 40 deg. This quick onset of shadowing indicates that we will need at least three different D configurations to cover all observable declinations.

We generated arrays with minimum antenna separation ranging from 1.1 D to 1.9 D. We made 200 different random configurations with 1 D minimum baselines, enforced the desired minimum separation constraint, and then selected the configuration which produced synthesized beams with the lowest rms sidelobes. The requirement of a low sidelobe beam precludes any sort of close pack configuration, and the 1.30 D minimum separation then mandates an array which is closer to 80 m. The 1.48 D separation array was stretched by a factor of 2.0 N-S to produce a more nearly circular beam at low elevations and to provide enough ground to fit the 40 antenna safety spheres.

Note that these simulation configurations would not be economical arrays. A detailed configuration design would maximize the number of shared stations between the most compact and the stretched arrays. This study treats the arrays as being independent, and indicates if the limited elevation concept will work at all.

Also note that configurations with very large minimum antenna separations are probably not acceptable due to their smaller synthesized beams and hence lower surface brightness sensitivity.

2.2 Simulations

We upgraded the SDE mosaicing software to properly treat arbitrary primary beams so that the tapered illumination pattern could be incorporated into these simulations. A single snapshot of each of 49 mosaic pointings at 230 GHz was simulated near transit using the standard M31 HII region source for 9 different declinations ranging from +55 deg to -75 deg. One arcsecond rms pointing errors were added to emphasize the effects of the dip between the total power and the shortest baselines' sensitivity distributions. No thermal noise or other errors were added so that we would be limited primarily by the effects of the short spacing (u,v) coverage and its interaction with the pointing errors. When possible, the (u,v) data were tapered to yield 5 arcsecond resolution in the final mosaics. (The extreme declinations resulted in beams which were larger than 5 arcseconds in the N-S direction, due to our inadequately stretched simulation configurations.) The final images were evaluated using the dynamic range and the image fidelity.

3 Effects of Tapered Illumination

The uniform antenna illumination was eliminated from the MMA design with only a few arguments from the antenna group (see Welch, 1995). In particular, no real investigation of the imaging consequencies of tapered and uniform illumination was performed. Even though the decision has been made, we list some of the relative advantages of tapered and uniform illumination here"

- the off-axis optics is degraded in the case of uniform dish illumination. This affects beam switching and any upgrades to focal plane arrays.
- the point source sensitivity is worse with tapered antenna illumination.
- mosaicing will still require sky sampling at $\lambda/2D$, but the wider tapered illumination primary beam will give a larger sensitivity enhancement than a uniformly illuminated primary beam due to the increased overlap in the primary beams at adjacent mosaic pointings. This approximately offsets the loss in point source sensitivity for tapered illumination in wide field mapping.
- the lower sidelobes in the primary beam will reduce systematic errors and will reduce the number of bright sources which require knowledge of the primary beam beyond the first null in the mosaicing process, thereby speeding up computing.
- the primary affect of tapering the dish illumination will be to degrade the effective Fourier plane coverage, most notably at short baselines, deepening the gap between single dish and the shortest baseline measurements.

Our simulations indicate that mosaic quality with tapered illumination antennas lags behind that of uniformly illuminated antennas. We compared an 11 db illumination taper with uniform illumination (Figure 1). Slices through the resulting primary beams are shown in Figure 2, with the sidelobes blown up in the inset. Figure 3 displays the image dynamic range as a function of the array's minimum antenna separation, which ranges from 1.1 D to 1.9 D, for antennas with uniform illumination and tapered illumination observing a source near the zenith (ie, with minimal baseline foreshorting). Uniformly illuminated antennas result in significantly better images, and they can tolerate a larger minimum antenna separation before degrading to some level.

Figure 4 shows similar results, but for mosaics generated by the maximum emptiness algorithm rather than the maximum entropy algorithm. Maximum emptiness does not have a positivity constraint, so it is better suited to producing images from very low signal-to-noise observations. Without a positivity constraint, we don't have any residual base level in the background blank pixels, resulting in much higher dynamic range images when the Fourier plane coverage is very good. On the other hand, the positivity constraint effectively enables maximum entropy to extrapolate to baselines shorter than those actually measured, providing for improved maximum entropy performance for configurations with rather long shortest baselines. Since maximum emptiness attempts to place flux in the fewest pixels it can get away with, it is not very effective at extrapolating to shorter baselines and performs much worse for configurations with long shortest baselines. In particular, there is a catastrophic drop in maximum emptiness mosaic dynamic range at about 1.5 D.

As mentioned above, the slant-axis design (with an on-axis parabaloid) (Cheng, 1994) requires a minimum antenna separation of 1.8 D, or 1.6 D with a mechanical elevation limit of 30 deg. Mosaicing will not work well for either minimum separation.

4 Can We Get Good All-Sky Mosaic Imaging Even With Tapered Illumination And Mechanical Elevation Limits?

In this section, we restrict ourselves to array configurations with minimum short baselines of 1.25, 1.30, and 1.48 D, the values corresponding to a 30 deg elevation limit with antenna design modifications, a 30 deg elevation limit without antenna design modifications, and no elevation limit. Can we achieve full sky mosaicing coverage using a number of array configuration which make use of these minimum spacings, with tapered dish illumination?

Dynamic range and image fidelity are plotted against declination for each of the three minimum separation arrays in Figures 5 and 6. The image fidelities are in the low 20's, comparable to the image fidelity from earlier pointing error simulations, but the dynamic ranges are about 2000:1, substantially higher than the earlier simulations. The higher dynamic range can be attributed to the larger synthesized beam size used here, which increases the peak image flux, and to the lower sidelobes in the synthesized beam.

The general trend in the simulations is that the 1.25 D configuration mildly outperforms the 1.30 D configuration, and the 1.48 D configuration lags far behind. This is consistent with our intuition that arrays with smaller minimum antenna separation produce better mosaics. However, at the extreme declinations north and south, the 1.48 D configuration's mosaics greatly improve in image quality so as to be comparable to the more compact arrays' intermediate declination mosaics.

The results with 1.25 D minimum spacing are probably not sufficiently better than the 1.30 D minimum spacing to warrant a major change in the antenna design. While 1.48 D is clearly insufficient for mosaicing sources overhead, configurations with 1.30 D and 1.48 D minimum spacings will permit fairly good mosaic imaging over the entire sky.

5 Configuration Recommendations

If we tried to make a set of D configurations with no shadowing and which always had projected baselines of 1.30 D or less, we would require six configurations to cover down to 12 deg elevation. In order to cover the entire sky with a reasonable number of configurations, we must compromise and have some declinations for which shadowing results, and some for which the shortest N-S projected baselines are somewhat greater than 1.30 D.

The following is a tentative outline for a possible set of four mosaicing arrays to reasonably cover all elevations down to 10 deg:

- The zenith D configuration, or **D1**, should be an 80 m filled circle with minimum antenna separation of about 1.30 D and a hard elevation limit of 30 deg. We do not compromise on the 1.30 D minimum spacing for the D1 configuration because it can observe more sky than all other D arrays combined. Since shadowing results when $D > \sin(\theta) b_{min}$, where θ is the elevation angle and b_{min} is the minimum baseline, shadowing begins at 50 deg elevation, so the 30 deg elevation limit doesn't hurt. The array should be designed to permit southern and northern observing below 50 deg elevation with minimal shadowing and plenty of short usable spacings after the shortest have been shadowed, permitting high quality, high sensitivity mosaicing observations down to 40-45 deg elevation.

- The **D2** array would have a minimum N-S antenna separation of 1.9 D to give 1.3 D in projection at an elevation of 43 deg, and 1.45 D in projection at an elevation of 50 deg. The minimum E-W antenna separation will still be around 1.30 D. This array will be used between 30 deg (set by the elevation safety limit for the 1.30 D antenna separation) and 50 deg.
- The **D3** array would have a minimum N-S antenna separation of 2.8 D to give 1.30 D in projection at an elevation of 28 deg. Since the elevations observed by this array are often below 30 deg, the shortest E-W spacing will have to be 1.48 D. This array would be primarily used between 17 deg and 35 deg elevation.
- Finally, the **D4** array would be used primarily at elevations ranging from 10 deg to 21 deg.

The parameters and observing elevation ranges for these four D configurations are listed in Table 2. The use of these configurations will depend upon the source declination, the hour angle range over which each pointing will be observed, and the strength of the target source. A very bright source which is not sensitivity limited should be observed with the shortest possible baselines present and can tolerate a fair amount of shadowing, so it may be advantageous to observe in the lower elevation range of a higher elevation configuration. A weak source will not be limited by the effects of a larger dip in the Fourier plane at the shortest spacing, but by thermal noise, and therefore can accept shortest projected baselines greater than 1.30 D, but not shadowing, so it may be advantageous to observe in the high elevation range of a lower elevation configuration.

Array Name	Minimum N-S Ant. distance	Elevation of first shadowing	Elevation at which $B_{min} > 1.30D$	Minimum Observing Elevation	Maximum Observing Elevation	N-S Array Elongation
D1	1.30 D	50°	–	$40 - 45°$	90°	1.2
D2	1.91 D	31°	42°	30°	50°+	~1.6
D3	2.60 D	22°	30°	18°	35°+	~2.5
D4	4.30 D	13°	18°	10°	21°+	~3.8

Table 2: Approximate parameters and observing elevation ranges for a possible set of four D configurations.

Administering four separate D configurations will require optimizing the design to minimize the number of antennas that move in each minor reconfiguration, minimizing the geometrical shadowing of antennas, and lots of attention when the configurations are scheduled. Holdaway and Owen (1996) estimate that antenna moves over such short distances could go as quickly as 45 minutes. However, the D array antennas which will need to be moved may well require two or three other antennas to be temporarily moved out of the way. (Perhaps two transporters could pick up and hold the obstructing antennas temporarily until the target antenna was removed from the center of the array.) Reconfiguring from one D configuration to its next neighbor would require moving about 10-15 antennas, plus temporarily moving some obstructing antennas. Depending upon how many obstructing antennas there were (very few in the more extended D arrays), reconfiguration among D arrays with three transporters could take between a few hours and an entire day. We would need on the order of 80 stations to implement all four D arrays, and on the order of 70 stations to implement the D1, D2, and D3 arrays. Since the D3 array will have maximum baselines which are comparable to the C array, we may be able to share stations between the D3 and C arrays, possibly reducing the number of stations unique to the D1, D2, and D3 arrays to 60. In order to provide for more flexible antenna positioning, the discrete antenna pads of the various D arrays might be replaced with a grid of support structures serviced by a single set of power and fiber optics cables with several meters of play.

The elevation coverage of each individual D array is translated into declination coverage in Table 3. A declination is considered observable by a given array configuration (at -23 deg latitude) if it transits within that array's elevation range and stays above that array's minimum elevation for at least 2 hours. The nearly circular D1 array will permit observations of 68% of the sky. As the arrays become more stretched out for low elevation observing, less and less sky is sampled. While pads should be constructed for arrays to observe down to 10 deg elevation, the D4 array, which covers only about 5% of the sky, may not observe regularly, but only when proposal pressure demands it. We expect that the opacity will often be low enough at the Chilean site to permit observations at 10 deg elevation (5.7 airmasses) even at 230 and 345 GHz where the minimum opacities still will be in the range of 0.1-0.2. Observing between $-90° < \delta < 55°$, the MMA will be able to make good quality mosaics of 91% of the sky.

Array Name	Elevation Range	Declination Ranges	Sky Fraction	Fraction Not Covered by higher array
D1	40 to 90°	24 to -72°	0.679	0.679
D2	30 to 50°	17 to 35° -63 to -82°	0.191	0.103
D3	18 to 35°	32 to 47° -78 to -90°	0.112	0.084
D4	10 to 21°	46 to 55°	0.050	0.044

Table 3: Declination ranges observable by each array. A declination must fall within the array's elevation range at transit for at least two hours to be considered observable by that array.

Acknowledgements

The idea of a "grid of antenna foundations" comes from Frazer Owen who initially described it as an "optical bench" for MMA antennas. Thanks to John Lugten for the information of the minimum safe antenna separations as a function of elevation. Thanks to Simon Radford just for being smart. Thanks to Darrel Emerson for being high-minded, and thanks to Peter Napier for being reasonable-minded.

6 References

Cheng, Jingquan, 1994 "A Slant-Axis Antenna for the MMA: Computer Simulation Results for Fast Switching", MMA Memo 106.

Cornwell, T.J., Holdaway, M.A., and Uson, J., 1993 "Radio-interferometric imaging of very large objects", A&A 143, 77.

Holdaway, M.A., and Owen, F.N., 1996 "How Quickly Can the MMA Reconfigure", MMA Memo 147.

Lugten, John, 1995, *private communication.*

Welch, W.J., 1995, "Comments on Sampling, Antenna Spacings, Uniform Aperture Illumination (BIMA)", MMA Memo 134.

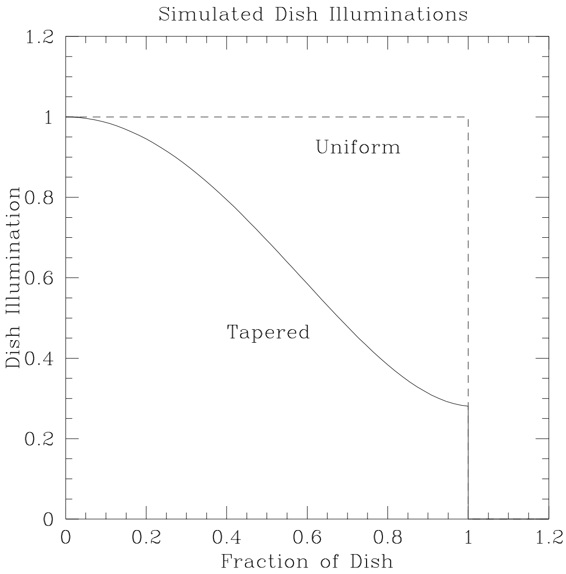

Figure 1: Uniform and 11dB tapered dish illuminations used in our imaging simulations.

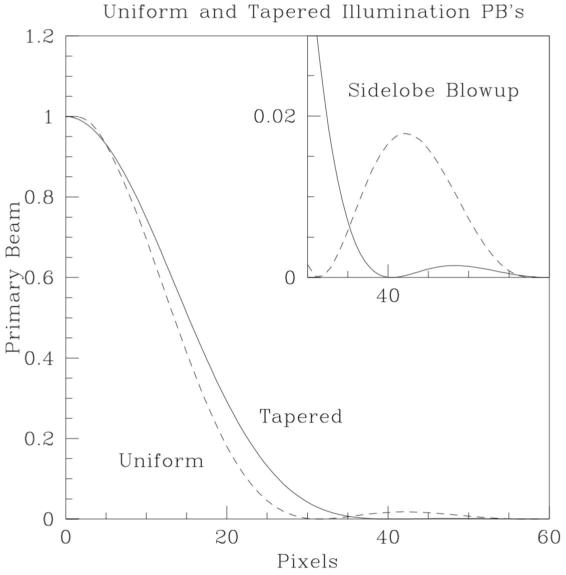

Figure 2: Primary beams which result from uniform and 11dB tapered dish illuminations.

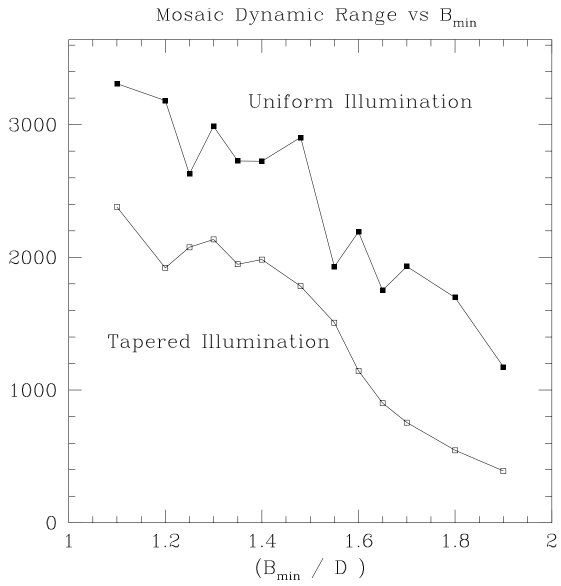

Figure 3: The dynamic range of maximum entropy mosaic images as a function of the minimum antenna separation in the array for both antennas with tapered illumination and with uniform illumination.

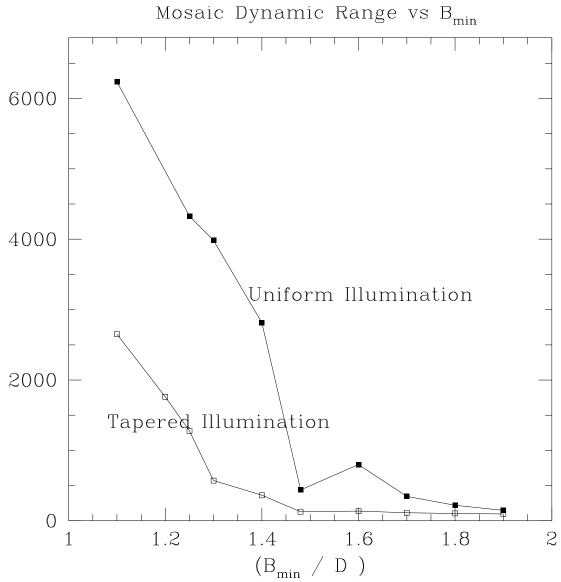

Figure 4: The dynamic range of *maximum emptiness* mosaic images as a function of the minimum antenna separation in the array for both antennas with tapered illumination and with uniform illumination.

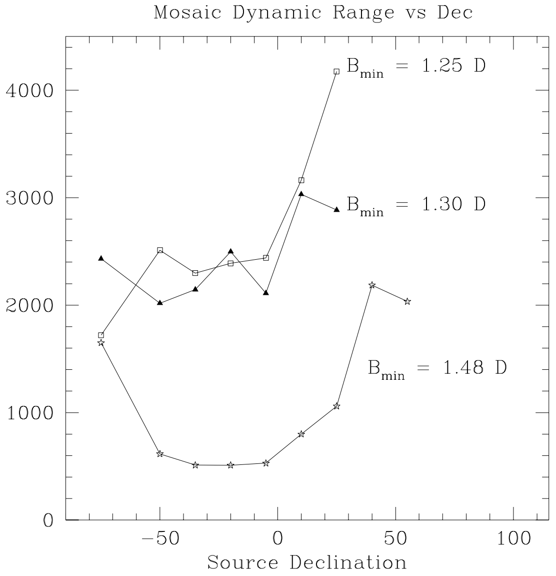

Figure 5: The dynamic range of mosaic images as a function of declination (which affects the minimum projected spacing and antenna shadowing) for the 1.25, 1.30, and 1.48 D minimum spacing arrays.

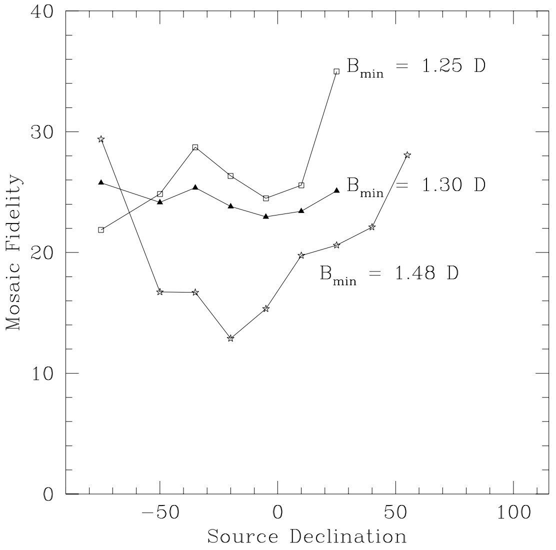

Figure 6: The fidelity of mosaic images as a function of declination (which affects the minimum projected spacing and antenna shadowing) for the 1.25, 1.30, and 1.48 D minimum spacing arrays.