MMA Memo 198
Design Concepts for Strawperson Antenna Configurations for the MMA

Tamara T. Helfer & M.A. Holdaway
National Radio Astronomy Observatory
949 N. Cherry Ave.
Tucson, AZ 85721-0655
email: thelfer,mholdawa@nrao.edu

24 February 1998

Abstract

We present concepts that will be used to guide the design of strawperson configurations for the Millimeter Array. The four configurations include 36 $\pm$ 4 element arrays of 10 m antennas. The most compact configuration is a filled array of diameter 95 m; the three other configurations are ringlike arrays of diameters 236 m, 842 m, and 3 km. We describe plans for detailed studies that will be used to refine these concepts and which will be used to produce strawperson configurations for the MMA.

1 Introduction

The detailed design of the array configuration is one of the aspects of the MMA development which depends crucially on the number and diameter of the MMA antennas. However, despite uncertainties in these parameters because of possible collaboration with European and/or Japanese partners, we intend to move forward with the design in two different ways. First, by identifying high level organizing principles and key concepts and by generating optimization algorithms for various parts of the configuration design, we can make generic progress which will help us in any detailed design which we must perform. Second, we can make specific progress on the detailed designs for some of the possible millimeter arrays. Such detailed designs will be needed fairly early on in the Design & Development phase of the MMA for costing purposes; optimization of the arrays for scientific purposes will require considerably more effort, both in identifying the desired goals for observations of different structures as well as in implementing those goals. We recognize that the array configuration development plan will need to react to the changes and refinements in the array's concept.

For the purposes of designing detailed strawperson configurations, we assume that the MMA will comprise N = 36 $\pm$ 4 antennas of 10 m diameter. The geometric collecting area is then 2830 $\pm$ 310 m^2; the "collecting length" nD, the appropriate measure of the mosaicing sensitivity, is 360 $\pm$ 40 m..

2 Array Design

2.1 Limiting Configurations and Resolution Scale Factor

The choice of a compact configuration for the MMA is driven by the desire to maximize surface brightness sensitivity, which is achieved by placing the antennas as close together as is practical. If we assume a filling factor f_{min} of 40% (see § 3.2), then the maximum baseline for the compact array is $b_{compact}$ =

$D_a\sqrt{N_a/f_{min}} = 95 \pm 5$ m. (This array would have the same resolution as a ring array that is about 66 $\pm$ 4 m in diameter.)

The largest configuration is assumed to have a maximum baseline of 3 km. If the sensitivity of the MMA is significantly expanded through a collaboration with the European and/or Japanese groups, then an array of 10 km diameter will be an attractive possibility.

Given the assumed sizes of the minimum and maximum arrays, Holdaway (1998) has performed a cost-benefit analysis for the number of MMA configurations, which showed that the observing efficiency of the MMA would be close to optimal with 4 configurations. We assign these four arrays the letters A (for the largest) through D (for the most compact). Given the described sizes of the D and A arrays, the resolution scale factor between adjacent configurations is about 3.6, and the configuration diameters are 95 m, 236 m, 842 m, and 3000 m.

2.2 Fourier Plane Coverage

It is a difficult problem to determine what the optimal Fourier plane coverage should be for a range of different astronomical observations. The requirements for imaging compact sources are quite different from those for imaging wide-field sources that are confined to within the primary beam or that require mosaics. For the purposes of this study, we assume that many projects will be completed using a single configuration. This assumption needs to be examined more closely; it may especially not be true for A array observations, for high resolution observations of extended sources, or for high frequency observations.

In general, the Fourier plane coverage needs to be optimized for different imaging requirements for the different arrays. The D array must be optimized for high surface brightness sensitivity and for snapshot mosaicing, the C array for snapshot mosaicing. The B and A arrays should be optimized for longer integrations, where the hour angle range of the observations will be determined by the desired sensitivity of the track.

For the D array, since the goal is to maximize surface brightness sensitivity, we require the largest synthesized beam possible; this implies as much coverage at small distances in the *uv* plane as possible. This is best achieved with a filled array, which produces a Fourier plane coverage that to first order is a linearly decreasing function of *uv* distance (e.g. Holdaway 1996).

For the C, B, and A arrays, the current philosophy has been to achieve as uniform coverage in the Fourier plane as is practical; this philosophy leads to ringlike arrays. True rings or ellipses yield fairly uniform *uv* coverage plus a narrow peak at small spatial frequencies. Keto (1997) showed that the most uniform snapshot Fourier plane coverage could instead be achieved by placing the antennas along the sides of a Releaux triangle. Holdaway, Foster & Morita (1996) extended Keto's work to optimize over longer tracks at arbitrary declination and found that uniform coverage resulted best from some kind of closed figure, not necessarily a triangle, but rather ellipses or other "ringlike" arrays. However, true uniform coverage in the Fourier plane has disadvantages as well: First, the sharp cutoff in *uv* sampling at large spatial frequencies results in large (10-15%) sidelobes close to the central lobe of the synthesized beam (Holdaway 1997), which may complicate an image deconvolution and thereby lower its dynamic range (Holdaway 1996). Second, optimization techniques like the elastic net method used by Keto have so far tended to produce large diameters for the central hole in the Fourier plane coverage. It is probable that this problem can be alleviated to some extent, either by using nested rings or Releaux triangles, or by changing the optimization conditions to include some number of short baselines, but for now this remains an unsolved problem. Third, unpublished simulations by Morita and by Holdaway show that the "extra" coverage provided by the peak at small spatial frequencies in a ring array are responsible for higher dynamic range wide-field images than do more uniform Fourier plane coverages.

An alternative philosophy for Fourier plane coverage has been proposed by Kogan (1997, 1998), who wrote an algorithm which produces antenna configurations which minimize the maximum sidelobe levels of the point spread function. This approach has the advantage of producing PSFs which in general introduce fewer problems in image deconvolution. Kogan has also pointed out that in general, sidelobes that are close to the peak of the PSF can be alleviated using a taper (at the expense of image sensitivity), but that this is not true for sidelobes further out in the image plane. At this writing, Kogan's optimized array looks something like an annulus, where the ratio of the outer and inner radii is about 2, and the antennas are distributed within these boundaries. This configuration deviates enough from a ring to taper the beam naturally, thereby reducing its sidelobes. So far this array has been optimized for a snapshot at one declination only; however, changing the declination should change only the positions and not the amplitudes of the sidelobes for a snapshot observation at transit. The case for longer tracks needs further study. Another attractive feature of Kogan's approach is that it naturally shrinks the hole in the center of the *uv* plane as he optimizes over larger and larger regions in the image plane. This produces good coverage at short baselines in the *uv* plane, which is one of the main shortcomings of the uniform *uv*-coverage optimization described above.

We plan to study the ramifications of these competing philosophies and ultimately to select a design based on imaging simulations of sources of different size and structure.

3 Plans for Detailed Studies

3.1 Optimization for Combined Parameters

In order to produce strawperson configurations, we wish to identify the desired parameters to be coded into some optimization algorithm. We identify the following as key parameters for the A, B, and C arrays: (1) uniform coverage in the Fourier plane, (2) size of the central hole in the *uv* plane, (3) a gradual falloff in sampling at large *uv* distances, characterized by a width and radius of the falloff; this may instead be characterized by maximum allowable sidelobe levels. Note that the first and third points listed here are in conflict with each other. Both have drawbacks: the first produces larger sidelobes, especially close to the central lobe of the PSF; the third requires that the Fourier plane coverage be tapered, and the sensitivity at large spatial frequencies would therefore be reduced.

The key parameters for D array are somewhat different, and are in some cases set by the mosaicing requirements: (1) maximum surface brightness sensitivity, (2) maximum Fourier plane coverage at short baselines, (3) complete snapshot coverage in the Fourier plane (applicable for C array as well), (4) stretched arrays for circular beams and for minimizing the allowable shadowing as a function of elevation (see below), (5) antennas should be accessible with a minimum number of moved antennas, in case of a failure (J. Lugten has shown that this is condition is met with the current working version of the D array), (6) self-similar coverage (i.e., the beams or *uv* coverages rotate into each other for snapshots at different hour angles, applicable for C array as well). Note that the size of the central hole is not a variable parameter for D array; instead, the size of the central hole will be set by the antenna geometry and shadowing considerations.

We propose to use an optimization technique like simulated annealing to solve for configurations with different relative weights for these parameters. In order to evaluate the results, we plan to simulate observations of model sources with different structures.

3.2 Filling Fraction vs. Sidelobe Levels in D Array

In a compact, filled array, where the goal is to maximize surface brightness sensitivity, it makes sense to push all the antennas as close together as possible and thereby achieve a high filling fraction in the antenna plane. In the extreme example, the antennas would be hexagonally closely packed. However, such a crystalline arrangement of the antennas produces prohibitively large sidelobes in the point spread function. These sidelobes can be alleviated by randomizing the antenna positions in exchange for allowing a reduced filling fraction. In § 2.1, we assumed a filling factor of 40%, which seems like a reasonable compromise based on image simulations. However, we plan to optimize simultaneously for a configuration with maximum filling fraction and minimum sidelobes.

3.3 North-South Stretched D Arrays and Shadowing

Holdaway & Foster (1996) studied the shadowing limitations of a close-packed array and concluded that a set of four compact arrays could reasonably cover all elevations down to 10 degrees with a minimum of shadowing. Since their most stretched D4 configuration is useful for only about 4 percent of the sky, we can probably compromise the other arrays slightly and cover the D array requirements with three compact arrays. The D1 array, with a North-South elongation of 1.2, would cover zenith observations down to somewhat below the shadowing limit of 50°; the D2 and D3 would be progressively more elongated, with elongations of about 2 and 3. These three arrays would cover the range of declinations available from the Chajnantor site, or $-90° < \delta < 55°$.

In addition to the parameters described above, these arrays should be optimized to minimize the number of antennas that move in each D array reconfiguration.

3.4 Optimal Elongation for C, B, and A Arrays

In order to study the optimal North-South elongation for an A array, Foster (1994) looked at gaussian fits to synthesized beams derived from observations of point sources over a variety of declinations and observed with a variety of array elongations. By measuring the deviation of the beam from a circular beam, Foster concluded that the optimal elongation for long tracks was 1.1, though the optimum was a shallow function of the array elongation. For shorter tracks, the optimal elongation increased somewhat, to about 1.3 for an observation between hour angles of −1 hour and +1 hour. For tracks that are not centered on transit, the optimal elongation decreased.

In order to optimize the elongations of all of the arrays, it is important to know the expected source distribution with declination. Holdaway et al. (1996) assumed a model source distribution in order to estimate the pointing errors for the MMA antenna design. We are now in the process of looking at IRAS source distribution with declination in order to get a better estimate of this function.

Finally, we need to examine the issue of hybrid arrays for observing sources at low elevations. For example, for sources at low enough elevation, the required elongation of Holdaway & Foster's (1996) D4 array, ~ 3.8, yields an array that is stretched to a longer North-South extent than the diameter of the C array. Clearly it could be advantageous to combine stations from adjacent arrays to overcome this issue, though for ring arrays the implementation of this idea is considerably more complicated than it is for the case of a "Y" array like the VLA.

3.5 Overlapping Stations for Different Configurations

In addition to astronomical requirements, we wish to optimize the configurations to allow for overlapping stations for the different configurations; this will be especially important for the set of D arrays. The minimization of antenna stations may be key in keeping the cost of building the pads, roads and cables from being prohibitive, though we still need to investigate what these costs are.

3.6 Other issues to be addressed

There are certainly other issues which have not been examined in this document which deserve closer attention. For example, all of the arrays will need to be optimized with respect to the Chajnantor site. The arrays will also need to be optimized for different source declinations, or simultaneously for multiple declinations.

References

Foster, S.M. 1994, "The Optimum Elongation of the MMA A Configuration", MMA Memo #119

Holdaway, M.A., 1998, "Cost-Benefit Analysis for the Number of MMA Configurations", in preparation

Holdaway, M.A., 1997, "Comments on Minimum Sidelobe Configurations", MMA Memo #172

Holdaway, M.A., 1996, "What Fourier Plane Coverage is Right for the MMA?", MMA Memo #156

Holdaway, M.A. & Foster, S.M. 1996, "Evaluating the Minimum Baseline Constraints for the MMA D Array", MMA Memo #155
Holdaway, M.A., Foster, S.M., Emerson, D., Cheng, J., & Schwab, F. 1996, "Wind Velocities at the Chajnantor and Mauna Kea Sites and the Effect on MMA Pointing", MMA Memo # 159
Holdaway, M.A., Foster, S.M., & Morita, K.-I. 1996, "Fitting a 12 km Configuration on the Chajnantor Site", MMA Memo #153
Keto, E. 1997, "The Shape of Cross-correlation Interferometers", ApJ, 475, 843
Kogan, L. 1998, in preparation
Kogan, L. 1997, "Optimization of an Array Configuration Minimizing Side Lobes", MMA Memo # 171