MILLIMETER ARRAY

NEWSLETTER

Number 7 February 1989

I. Millimeter Array Newsletter

This is the seventh issue of an occasional newsletter intended to keep the astronomical community up to date on progress toward construction of a U.S. national synthesis array for millimeter wavelengths. The newsletter is edited jointly by P.C. Crane, F.N. Owen, and L.E. Snyder. Comments, requests, and/or contributions should be sent to

P.C. Crane
NRAO
P.O. Box 0
Socorro, New Mexico 87801
BITNET: pcrane@nrao
SPAN: nrao::pcrane.

We invite contributions in the forms of letters or articles. We also invite requests for additions to our mailing list.

II. THE MMA: ORGANIZATION, PROGRESS AND PLANS

The Millimeter Array design concept, which was summarized in volume II of the MMA Design Study* and published a year ago, describes a versatile scientific instrument which emphasizes the following capabilities:

- Sub-arcsecond imaging at 115 GHz and higher frequencies;
- Wide-field imaging, mosaicing;
- Rapid imaging, "snapshots" of high fidelity;
- Sensitive imaging at high frequency (>350 GHz);
- Simultaneous multi-band operation.

Together these capabilities define a unique instrument; astronomers using the MMA will explore scientific areas new to millimeter-wavelength research. Two examples are illustrative. The combination of high sensitivity and sub-arcsecond angular resolution at frequencies of 230

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* The Millimeter Array design is summarized in "The Millimeter Array Design Concept: MMA Design Study Volume II", edited by R. L. Brown and F. R. Schwab. This document was distributed to everyone on the mailing list for the MMA Newsletter and shortly will be circulated more widely in the astronomical community. Copies may be obtained at no charge from Joanne Nance in Charlottesville.

and 350 GHz provided by the MMA will permit the photospheric emission from hundreds of nearby stars to be detected and imaged, the stellar radii to be determined, and the positions established to astrometric precision. The same combination of instrumental parameters will provide images at a resolution superior to that of the Hubble Space Telescope of the redshifted dust emission from galaxies at the epoch of formation (z=5-10). Indeed, these "protogalaxies" will be the dominant source of background confusion at 1mm at levels approaching 1 mJy.

High sensitivity implies that the total collecting area of all the individual elements in the array be made as large as possible, while fast imaging is achieved by distributing that area over many elements. The precise definition of how many elements and the size of the individual antennas is then made by minimizing the total array cost. Sub-arcsecond imaging places a constraint on the array dimension: 0".1 at 230 GHz, for example, requires an array of maximum extent 3 km. Finally, sensitive imaging at high frequency demands that the MMA be located on a high altitude site with excellent atmospheric transparency. Considerations such as these drive the design of the MMA; they are described in some detail in Volume II of the MMA Design Study. A summary of the MMA design parameters is given below:

ARRAY	
Number of Antennas:	30-40
Total Collecting Area:	1750 square meters
Angular Resolution (3 km):	0".07 lambda(mm)
ANTENNAS	
Diameter:	7.5-8.5 m
Precision:	lambda/40 at 1 mm
Pointing:	1/20 beamwidth
Transportable	
CONFIGURATIONS	
Compact:	< 100 m
Intermediate:	300-1000 m
High Resolution:	3 km
FREQUENCIES	
Emphasis on:	200-350 GHz
Capability at:	30-50 GHz, 70-115 GHz
Desirable:	Simultaneous multi-band
SITE	
High altitude--suitable for precision imaging at 1 mm	

In February 1988 this concept was reviewed by the MMA Technical Advisory Committee, the concept was endorsed, and a number of areas were identified as needing further study (see summary below). Working groups were established to investigate the spectrum of issues raised by the Committee. These working groups now define the organizational structure of the MMA project within the NRAO. The committees and their chairpersons are as follows:

Site and Configuration	Frazer Owen
Antennas	Darrel Emerson
Receivers and Telescope Optics	Mike Balister
Central Element, Mosaicing	Tim Cornwell
Correlator	Larry D'Addario

Bob Brown is serving as overall MMA Project Director.

For the past year the working groups have been developing plans to incorporate the specific suggestions of the Advisory Committee into the MMA design. Their progress is outlined in the articles that follow. In 1989 we hope to:

- Extend the scope of issues addressed by the working groups especially where prototypes, simulations, and tests can provide critical diagnostics;

- Increase the awareness of the MMA project in the community by distribution of the design study together with the full reports from the working groups;

- Attempt to have a comprehensive draft MMA proposal finished by the end of the year. This will require a great deal of work by people both inside and outside the NRAO.

We welcome your thoughts and participation in any of these areas.

R.L. Brown

III. SUMMARY OF THE MMA ADVISORY COMMITTEE MEETING

The MMA Advisory Committee met in Tucson on 25-26 February 1988. During its discussions the Committee covered a very wide range of issues:

1. Site selection and testing: What is the correlation between opacities measured at 225 GHz and radiosonde data? If reliable, use radiosonde data to study high-altitude sites in the southern hemisphere. Investigate possible correlation between fluctuations of sky brightness and of interferometer phases. Best high-frequency sites are favored.

2. Array configuration: What are the minimum number of configurations needed (one?) and the possible role of outrigger antennas? What constraints may be imposed by topographic limitations of possible sites?

3. Antennas and telescope optics: What is an accurate cost equation for the antennas? What are the costs and limitations of an unblocked aperture? Would operating at 33 GHz limit the antenna and its optics? Other requirements include total-power measurements, under-illumination, and simultaneous observations separated by an octave or more in frequency.

4. Frequency coverage: The widest possible coverage is a primary goal. Will very-broadband quasi-optical SIS receivers be feasible? What are the costs of going to even higher frequencies (460 GHz)? Receivers should be double sideband.

5. Correlator: Flexibility is essential; what are the associated costs? The two sidebands should be simultaneously separable and further divisible into multiple independent windows (as in the BIMA correlator).

6. Mosaicing: Mosaicing places severe constraints on the array, especially on the pointing and sidelobe levels of the individual antennas. Does mosaicing require unblocked apertures?

The Advisory Committee further felt that it was taking on too many roles. One or more technical advisory committees are necessary to study specific design questions. The membership of the Science Workshop should be broadened to include optical and infrared astronomers, theoreticians, and others who will benefit from the MMA. Greater efforts to involve the astronomical community should be undertaken.

R.L. Brown

IV. THE 225-GHz SITE-TESTING RADIOMETERS

The site-testing radiometers underwent a major review and modification during the past summer. The review focused on increasing the stability of the radiometers, especially with respect to changes in the ambient temperature, and on improving the reliability of the operations. A number of changes were made to the circuits and in the box-temperature control system.

The radiometers have been returned to Socorro site where they are now undergoing a series of checks and reviews. They will be run side by side to compare their calibration and stability.

Tests comparing the VLA phase stability at 2cm with the sky temperature fluctuations have shown a correlation near that expected theoretically. Thus we now believe we can use the radiometers to estimate phase stability on remote sites.

Ultimately the plan is to test each of the most promising sites with one of the 225-GHz radiometers. We intend to use a cycle in which we measure the atmospheric transparency for a period of nine hours, followed by a one-hour measurement of the fluctuations of the sky temperature at the zenith. We have begun doing this on the South Baldy site. The data for sky opacity will be analyzed as before (MMA Memorandum No. 45). The fluctuation data will be used to estimate the fraction of the time at each site during which coherence can be maintained with an interferometer over time scales of a few minutes.

D.E. Hogg and F. N. Owen

V. RADIOSONDE STUDIES OF MMA SITES

At the February 1988 MMA meeting in Tucson, R. Martin (Steward Observatory) showed that there was good correspondence between radiosonde measurements made at El Paso and measurements of total precipitable water vapor made with a radiometer at Mt Graham. This is potentially of great importance to the MMA site-testing program, since the radiosonde data base in many instances goes back to 1965. We therefore started our own study of the radiosonde measurements near sites of potential interest for the MMA.

At present we have acquired radiosonde data for approximately twenty years for two sites in each of New Mexico, Colorado, and Arizona, as well as for Hilo, Hawaii and Antofagasto, Chile. A preliminary analysis of some of these sites has already been made (MMA Memo Number 51). The first results served to identify three questions that must be explored:

1. Is it reasonable to expect that the atmosphere over a site of interest can be studied using a radiosonde measurement from a location many tens of kilometers distant?

2. At what height in the radiosonde measurement should the integration of the atmospheric profile be started, in order to most closely match the actual atmosphere over the site of interest (which is usually much higher than the ground level at the radiosonde launch site)?

3. Is there a layer of water vapor which blankets the ground, leading to a larger amount of water vapor over a high site than might be expected simply from the radiosonde measurements?

We have attempted to address these questions by making a detailed comparison between the radiosonde data from Albuquerque, New Mexico and the 225-GHz radiometer measurements made beginning in January 1987 at South Baldy and at the VLA Site. In the reduction of the radiosonde data we have used Liebe's (1985) model of millimeter-wavelength propagation to infer the opacity. We find good mean seasonal agreement between the radiometric and meteorological observations for the South Baldy site; however,the agreement between simultaneous measurements is less satisfactory, and we also find slight systematic differences. The agreement with radiometric data obtained at the VLA is less satisfactory than with that obtained at South Baldy. The analysis of this material is in progress, and will be completed by the end of March 1989. If the radiosonde data prove to be a useful indicator of site quality, the analysis of such data for all potential sites will be started. Since the radiosonde material is now in hand, this work should be completed by the end of the summer.

D.E. Hogg and F.R. Schwab

VI. STATUS OF POSSIBLE MMA SITES

Over the past year we have completed a process of sifting geographical data on potential MMA sites in the southwest. We have established a list of over fifty sites above 9000 ft and south of latitude 36 degrees. North of 36 degrees the list is less complete because we have concentrated on sites which are clearly at least 3km in extent. South of 36 degrees we have tried to find all potential sites regardless of size.

With this starting list we have then ranked sites in groups depending on elevation, size, access, and environment (e.g., density of trees, distance from the nearest town, etc.) We currently have four sites in the top group:

Springerville, Arizona - Large (10km), high (9200-ft) site in the Apache National Forest about 15 miles from Springerville on a paved road.

South Park, Colorado - High (9300-ft) valley about 60 miles west of Colorado Springs; private land; prime site is about 3km EW by 6km NS; crossed by US 24.

Alpine, Arizona - High (9900-ft) area adjacent to US 666 in Apache National Forest; maybe 3km EW X 5km NS; little else known at this time.

Magdalena Mountains, New Mexico - High (10,500-ft) mountain top occupied by Langumuir Laboratory Scientific Preserve in Cibola National Forest near Socorro; irregularly shaped site for largest configuration (3km EW by 6km NS) but a good 3km scale configuration is possible.

We have not sought permission to use any of these sites yet but we do know no reasons at this time which would rule out any of them. Currently the second group includes, for example, Sacramento Peak, New Mexico (too low, too small, and too many trees), the Aquarius Plateau, Utah (too remote, too much snow, and probably not much better water vapor based on radiosonde data), and the Grand Mesa, Colorado (too far north, heavily used, lots of snow, and not outstanding water vapor based on radiosonde data). In addition, we continue to study Mauna Kea in Hawaii, although it appears to be much too small for the current concept. We hope to have a 225-GHz radiometer on it shortly.

We are following developments in Chile as ESO picks its site for the VLT. Bob Martin (Arizona) is beginning to study water vapor on this site. However, all reports so far suggest that logistics (not to mention politics) may be insurmountable at any site comparable to or better than those in the southwest. Nonetheless, we will continue to collect information on this possibility.

F.N. Owen

VII. THE CENTRAL ELEMENT

The MMA working group on the Central Element recently released a report (MMA Memorandum No. 50) detailing a strategy for deciding which form of central element to use in the MMA. The three options for collecting short-spacing information are 1) a large single antenna, 2) use of the interferometer elements for total-power measurements, and 3) use of an array of small antennas. Some variant of mosaicing would be used in all three options. Since all three options theoretically allow measurement of the required short-spacing information, a final choice must depend upon practical problems such as pointing problems, aperture-illumination variations, cross-talk between the elements, calibration errors, etc. The working group recommended the design and coding of a computer-based simulation package to address these issues. They also listed a number of critical observational tests which can be performed with existing arrays. Robert Braun and Tim Cornwell have now embarked upon the simulation project. It will accurately simulate mosaicing observations with the MMA in the presence of atmospheric disturbances, pointing errors, and aperture-illumination errors. This package will also be useful for investigating some more general questions about the MMA design - for example, are equatorial mounts for the antennas advantageous? what is the required upper limit on pointing errors? It is planned that the package will be used over the entire design phase of the MMA, although some simple results are already available. These include studies of the effect of incomplete knowledge of the primary beam on the reconstruction of a mosaiced image and of the degradation of such an image by pointing errors in the individual pointings.

In addition to this study, observational tests are being carried out. Juan Uson and Tim Cornwell, together with Mel Wright and Jack Welch, are using the Hatcreek array for various tests of mosaicing which should shed some light on a number of topics including the importance of pointing errors. Robert Braun and Tim Cornwell are planning to test spectral-line mosaicing using VLA HI observations of M33. In spectral-line observations the equivalent of the "zero-spacing" flux is available from the measured auto-correlations, and can be incorporated into the imaging.

Comments or advice about these activities is welcome. Please contact Tim Cornwell or Robert Braun at the VLA.

Tim Cornwell and Robert Braun

VIII. MMA ANTENNA DESIGN

The MMA antenna design group has been reconsidering the basic antenna specifications:

The 345-GHz atmospheric window will undoubtedly be important in the operation of the MMA, so the antennas should have good efficiency at this frequency. The MMA Design Study, Vol. II, specified a surface accuracy of lambda/16 at the shortest wavelength of 850 microns. However, this implies a 46% reduction in gain, relative to the antenna efficiency at lower frequences -i.e., a somewhat marginal performance. Tightening the specifications to a 25-micron rms surface brings the gain reduction down to a little over 10%, which gives the array high performance at 345 GHz. As a by-product, this would also give the array usable performance up to the 500-GHz atmospheric window, but the primary aim is to achieve good performance up to 350 GHz.

Another critical parameter is the telescope pointing accuracy. In order for mosaicing to be successful, the pointing of each element probably needs to be good to (beamwidth)/20, or about 1 arc sec at 1 mm. (The Design Study, Vol. II, had specified 3 arc seconds.) This aspect is being studied in detail by the working group on the Central Element.

We have reviewed existing telescope designs, and performance comparable to these revised specifications already exists in a number of operational telescopes. If these tighter specifications are accepted, then there are several implications. Because of thermal effects, an all-steel antenna design is unlikely to be able to meet the specifications. Incorporating carbon-fibre into the design may be appropriate - a route chosen for other successful high-precision antennas (IRAM, SMT, etc.). At present there is little experience within the U.S. in the use of carbon fibre in antennas. The revised specifications would probably make the antennas more costly, and the dominant component in the overall construction cost of the project. During the lifetime of the array, receivers and computers are likely to be replaced as newer technology becomes available, but the antennas themselves are unlikely to be replaced. This suggests that the basic antenna design may provide the ultimate limitation in performance of the array, and so we do not wish to compromise the ultimate performance with too marginal a design at the start. Experience with the SMT project suggests that the cost equations, used to optimize the size and number of antennas, may in any case need slight revision. However, we do not expect a very dramatic deviation from the current proposal for 40 antennas, each 7.5 m in diameter.

There are various options which could be chosen for the antenna design; e.g., an off-axis feed to reduce sidelobes, a polar mount so that sidelobes do not rotate on the sky. However, as a starting point James Lamb and John Payne (MMA Memorandum No. 52) have sketched a trial antenna concept, which is a symmetric, on-axis alt-azimuth design using a Coude-focus cabin arrangement providing room for a number of independent and/or simultaneous receivers, with good engineering access. This initial design will be used as a starting point in approaching industry for feasibility and cost estimates. We are also establishing contacts with other groups having experience in building antennas of similar performance.

D. Emerson

IX. STATUS OF THE BERKELEY-ILLINOIS-MARYLAND ARRAY

The Berkeley-Illinois-Maryland Array (BIMA) is now under construction and will be operational before the end of 1990. The BIMA is operated jointly by a consortium of the University of California at Berkeley, the University of Illinois, and the University of Maryland. The array will consist of six 6-m antennas operating at wavelengths of both 3 mm and 1 mm. The construction schedule calls for the new antennas to be delivered and assembled at Hat Creek by the end of 1989. During 1990 the antennas will be equipped with receivers, a new correlator back-end will be installed, and the system will be integrated and tested. Observations should begin in less than two years. In order to operate at 1 mm, one of the three existing antennas at Hat Creek will be completely replaced and the reflector surface of a second will be improved. The goal is that all antennas will have surface errors of about 30 micrometers rms; they will employ lenses such that a nearly uniform aperture illumination will be achieved. An aperture efficiency of approximately 80% is expected. Pointing will be approximately 4" rms in 20-mile-per-hour wind. The 6-m diameter was chosen for the expansion as the most cost-effective size for the maximum speed and information content of mosaiced images. The sensitivity of such images is proportional to the number of antennas times the antenna diameter (not antenna area!). Given that the costs of antennas scale slightly more rapidly than area, a large number of relatively small antennas yields a more powerful system than a smaller number of larger antennas. The receivers will be SIS junctions; local oscillators will be Gunn oscillators, with tuning entirely under computer control. Initially two receivers will be in operation: single-polarization receivers for 75-115 GHz and 210-270 GHz, each operating with an IF bandwidth of 800 MHz. The two sidebands are separated by phase switching of the first LO, so that lines in both sidebands may be observed simultaneously. The dewars are designed to accommodate dual-polarization receivers at four frequency bands. Eventually, the plan is to split the 3-mm band into two parts for lower system temperatures and to add 2-mm receivers. Weather statistics at Hat Creek lead to the expectation that operation at 1 mm will be possible during a large part of the fall, winter, and spring.

The spectrometer will be a very flexible digital correlator which will be based on the architecture of the present Hat Creek correlator. The correlator chip developed by Albert Bos and colleagues at the Netherlands Foundation for Radio Astronomy will be used. The chips will be run at a 50-MHz rate, which with multiplexing will make possible coverage of the entire IF bandpass of 800 MHz (1,000 km/s at CO 2-1). The correlator will have 1024 channels for wide-band work, although it will be possible to use up to 2048 spectral-line channels for galactic work when the full bandwidth is not needed. Up to 4 windows per sideband, which may be located anywhere within the 800-MHz bandpass, will be available; the spectral resolution may be different for different windows. Hence, a total of eight 256-channel spectra may be obtained simultaneously. With a bandwidth more than double that of the present system, it will often be possible to use simultaneously all 8 windows for meaningful spectral-line observations. The maximum resolution can be as fine as 6 kHz. An analogue continuum correlator will also be available to cover the entire 800-MHz bandwidth.

Because of the large number of useful spectrometer channels and the fact that spectroscopic mosaicing will be the dominant observational mode, the data rate and computational requirements of the BIMA will be very large. The BIMA Consortium is working to develop a new software system to handle the data processing and analysis. This software will be optimized to run on the Cray-2 (and later Cray-3) supercomputers of the National Center for Supercomputing Applications at the University of Illinois and on a mini-supercomputer to be acquired by the University of Maryland. The data format has been designed in order to work efficiently with three-dimensional data bases, particularly in the large memories of the Cray-2 (and Cray-3) supercomputers. The new software is designed to be highly modular to allow easy implementation of new algorithms. The logical unit on which a task will operate is a data cube. Visibility and image data will be kept in a tree structure also containing gain, flagging, and history files, so that the entire entity may be referred to by one name. This structure will also allow subsets of the structure to be copied across a network - for example, to allow calibrations derived on a remote node to be applied to a local data set. The current Hat Creek data format will be converted into a more portable data format as part of this structure. Both the Hat Creek telescope format and the FITS format will be acceptable inputs, and the internal UV and image formats can be converted to FITS for porting to other packages, such as AIPS and GIPSY. A window-based user interface has been designed and has been partially implemented. Although currently based on Suntools, the intention is to migrate to X-Windows so the user interface will be hardware-device independent. A VT100 menu offers a similar user interface for terminals. The user interface uses a menu to generate command lines to run tasks. Parameters can either be set directly or called from default files. A help file is accessible for each task and can be displayed for each parameter. Tasks can be run automatically on remote nodes (i.e., on the Cray while the user is signed onto a workstation) simply by specifying the node in the menu. The IDI interface specifications will be used so that graphics software will be device independent.

The code development is well underway. A test was run in January 1989 with the window-based user interface running on a Sun workstation in Berkeley connected via NSFnet to the Cray-2 in Illinois. A multi-channel data set was computed and cleaned on the Cray, and a 1024x1024-pixel image was displayed remotely on the Sun, all within a couple of minutes; the effective baud rate was 120 kilobaud. This test convincingly demonstrated the feasibility of running aperture-synthesis code on a remote host.

The cost (approximately $4 million) of expanding the present three-antenna Hat Creek array into the improved six-antenna BIMA is being borne entirely by the three universities. In addition, approximately $1 million/year in operating funds will be supplied by the three universities. Additional funds for operating expenses and for scientific research will be required from the National Science Foundation. The BIMA will have 30% (equivalent to 150% of a three-antenna array) of its observing time available to scientists outside the three universities in the BIMA Consortium.

Although the BIMA will be the most powerful millimeter-wavelength array in the world when it becomes operational, a six-antenna array is still very small. The BIMA Consortium has proposed to the National Science Foundation that the array be expanded to nine antennas and that additional receivers be added, at a cost of approximately $3 million, with 50% of the time on the expanded array available to visitors.

R.M. Crutcher and M.C.H. Wright

X. MILLIMETER ARRAY SCIENTIFIC MEMORANDUM SERIES

No new Scientific Memoranda have been received since the last newsletter - certainly not because of a lack of issues. We encourage the radio-astronomy community to contribute to the Millimeter Array Scientific Memorandum series. Contributions should address specific scientific issues and their relation to the design of the array. Please send contributions to:

A. Wootten
NRAO
Edgemont Road
Charlottesville, VA 22903-2475
BITNET: awootten@nrao
SPAN: nrao::awootten.

We invite requests for additions to our mailing list, which is identical to that for the this newsletter.

XI. MILLIMETER ARRAY MEMORANDUM SERIES

Fourteen Millimeter Array Memoranda have been released since the last newsletter:

39	Comparison Study of Astronomical Site Quality of Mount Graham. 870410	K.M. Merrill F.F. Forbes
40	Measurement of Atmospheric Opacity Due to Water Vapor at 225 GHz. 870911	M. McKinnon
41	225 GHz Atmospheric Receiver - User's Manual. 871028	Zhong-Yi Liu
42	Analysis of the Ekers and Rots Method of Short-Spacing Estimation. 871120	T.J. Cornwell
43	A Comparison of a Mosaiced VLA Image and a Conventional Penticton Image. 871120	T.J. Cornwell
44	The Size of the Central Element: Pointing Considerations. 880131	T.J. Cornwell
45	First Results from the Site Testing Program of the Millimeter-Wave Array. 880201	D. Hogg F. Owen M. McKinnon

46	Mosaicing with High Dynamic Range. 880201	R. Braun
47	High Site Millimeter Array Configurations. 880221	R. M. Hjellming G. Hoyer
48	List of Millimeter-Array Memoranda. 880314	
49	Measurement of Atmospheric Phase Stability with a 225GHz Radiometer. 880519	M.M. McKinnon
50	Report of the Central Element Working Group 880630	T.J. Cornwell R. Braun D. Emerson J.M. Uson
51	Millimeter-Wave Seeing Inferred from Radiosonde Observations - Preliminary Results. 880831	F.R. Schwab D.E. Hogg
52	Preliminary Optics Design for the Millimeter Array Antennas. 881202	J. Lamb J. Payne

Copies of individual memoranda may be obtained by writing to:

Sandra Montoya
NRAO
P.O. Box O
Socorro, New Mexico 87801