MMA Memo 192: The Astronomical Case for Short Integration Times on the Millimeter Array

Michael P. Rupen
National Radio Astronomy Observatory
Socorro, NM 87801
17 November 1997

Abstract

The Millimeter Array will be large, agile, and sensitive enough to warrant integration times much less than a second. While on-the-fly total power mapping and variability studies both demand high time resolution, down to 10μsec, neither requires vast data rates, as only very limited data need be written out. The real push comes from interferometric surveys, since the superb sensitivity implies that the area mapped will be limited by the shortest available integration period, rather than by thermal noise considerations. Dump times of 40 $(\mathrm{D}/8\mathrm{m})^{-2}$ milliseconds would allow most interesting sources to be mapped in reasonable times, although this depends greatly on the observing frequency, and less strongly on (reasonable values for) the sampling of the primary beam. Although these mosaics would result in huge amounts of data, for spectral line experiments well beyond current storage and processing techniques, it still seems worthwhile to aim for such rapid integrations, to allow continuum mapping immediately, and in hopes of clever software or impressive hardware advances over the several-decade lifetime of the instrument.

1 Introduction

The Millimeter Array (MMA) will combine very agile dishes, capable of slew rates of order a degree per second, with a huge collecting area, between 2000 and 10000 square meters in current proposals. This suggests the possibility of very sensitive and rapid observations, using very short integration times; these short integrations in turn have ramifications for the array design, particularly the dump rate of the correlator, the speed and size of the associated data storage systems, and the required capabilities of the mapping and analysis software. There are three main scientific reasons to push for extremely short dump times:

- *To allow on-the-fly total power mapping*: Holdaway, Owen, and Emerson (1995) point out that the MMA may be able to slew fast enough to remove the atmospheric emission from total power measurements without the need for nutating subreflectors at the lower frequencies. Even at shorter wavelengths this on-the-fly (OTF) mapping is more efficient than standard ON/OFF mapping for sources large compared to the primary beam. In either case, the desire to sample the beam several times while moving at a degree per second gives integration times of order 1 millisecond.
- *To track changes in time-variable sources*: Most astronomical sources do not (and are not expected to) vary on very short timescales, but there are a few exceptions. Pulsars

are obvious candidates, together with neutron star/black hole binaries. Closer to home, solar flares and their extrasolar analogues are both bright and extremely variable, with rise times less than a second.

- *To survey large areas on the sky*: Many of the most interesting objects to study at millimeter wavelengths cover a large area on the sky, notably nearby molecular clouds, the Galactic Plane, the Magellenic Clouds, and galaxy clusters. To map such objects at all requires short integrations on each pointing. Given sufficient sensitivity, the shortest available integration will set the sizes both of the largest surveys possible and of the biggest areas routinely mapped with the instrument.

This memorandum expands on and quantifies these *desiderata*, in an attempt to determine the shortest scientifically interesting integration time for the MMA. Mostly this memo is concerned with the scientific gains from short integrations; at the end I also consider the practical implications of these scientific goals. With the collecting area and the maximum dish size somewhat up in the air at the moment, noise levels and various other parameters are often quoted as a range of values, corresponding to the difference between the heterogenous MMA+LSA (40×8m plus 35×15m) and the 'vanilla' MMA alone (40×8m). As a general rule, larger dishes and larger collecting areas lead to shorter integration times, due to smaller primary beam sizes and increased sensitivities.

2 On-the-Fly Total Power Mapping

One of the phase-calibration schemes proposed for the MMA is the fast-switching technique, in which one monitors the atmospheric phase by switching rapidly between the source of interest and a nearby calibrator. Since the atmosphere changes rapidly and the calibrators may not be very close, this demands very rapid slew rates, of order 1 degree/second (Holdaway *et al.* 1995). Holdaway, Owen, and Emerson (1995) pointed out that, with these slew rates, one might be able to use on-the-fly mapping to subtract the atmospheric emission, at least for frequencies up to about 300 GHz. With this slew speed the atmosphere is essentially 'frozen in' at these frequencies, and the errors are dominated by the spatial change in the atmosphere from one end of the slew to the other, rather than by temporal variations. OTF mapping is useful at higher frequencies as well, since it is more efficient than standard ON/OFF techniques (even with a chopper) for mapping large areas (see for instance Mangum 1997). To avoid aliasing, the primary beam should be sampled at the Nyquist rate (λ/2D) or better[1]; the corresponding minimum integration times are given in Table 1.

There are a couple important notes associated with this observing mode. First, the dump time is set not by sensitivity but by the desire to remove the atmospheric emission as well as possible – deeper observations will require several passes across the same patch of the sky, not longer integration times. Presumably most if not all reasonably large (few arcminutes or

[1] OTF mosaics demand oversampling by a factor of at least 4 (i.e., λ/4D) in one dimension, as discussed below.

Table 1. Minimum Integration Times for Nyquist Sampling at 1°/second

	Primary beam			t_{int}		
Freq.	8m	12m	15m	8m	12m	15m
90 GHz	86 asec	57 asec	46 asec	12.0 ms	8.0 ms	6.4 ms
140	55	37	29	7.6	5.2	4.0
230	34	22	18	4.6	3.0	2.6
345	22	15	12	3.0	2.0	1.8
650	12	7.9	6.3	1.8	1.0	1.0
850	9.1	6.1	4.9	1.4	0.8	0.6

The primary beam is $\Theta \approx 77.3 \left(\frac{100\,GHz}{\nu}\right) \left(\frac{8m}{D}\right)$. Integration times are calculated assuming 1 degree/second slews and Nyquist ($\lambda/2D$) sampling. OTF mosaics demand a factor of two shorter integrations, to avoid the loss in short-spacing information resulting from the smearing of the primary beam.

larger) total power observations will be done using OTF mapping. Second, for these total power observations we need record only the autocorrelation spectra, albeit possibly with a large number of channels (however many the correlator can handle – certainly at least 1000). The interferometric modes considered below will be far more demanding. However, if the interferometric data cannot be recorded as fast as the total powers, taking single-dish OTF data may require 'turning off' the interferometer[2]. This loss in observing efficiency would be particularly unfortunate at the higher frequencies, since one will want to take advantage of good weather for both total power and interferometric observations. Further, the potentially great benefits resulting from taking single-dish and interferometric data simultaneously (e.g., identical calibration) would be lost. Depending on one's prejudice, these tradeoffs either argue against OTF mapping even in single-dish mode, or in favor of very short dump times even for cross-correlations. Exactly how the MMA should trade single-dish and interferometric observations off against each other is not yet clear.

- *Shortest integration times:* 0.6–12 (slewrate/1°/sec) msec (Table 1), depending on the observing frequency and dish diameter (set by Nyquist sampling of the primary beam when slewing at the maximum rate).
- *Data needed:* Autocorrelation spectra only. The maximum number of channels the correlator ever produces, for identical single-dish and interferometric frequency resolution/coverage. Full polarization, for polarization experiments and sensitivity.
- *Possible tradeoffs:*
  - *Longer integration times:* requires either slowing down the slew rate, or undersampling the primary beam. The latter may be possible if the data are to be smoothed spatially, but this will cause severe problems when combining single-dish and interferometric data. Slowing down the slew rate results in slower mapping, and makes subtraction of the atmosphere more difficult. The latter may force ON/OFF mapping (presumably using a nutating subreflector) even at relatively low frequencies. Probably one should sample at least as fast as required by 350 GHz ($3.0\left(\frac{8\mathrm{m}}{\mathrm{D}}\right)$ msec), the highest frequncy for which OTF might be used for atmospheric subtraction.
  - *Dual or single polarization:* sufficient for the most demanding spectral line modes (huge numbers of channels); however, most continuum and maser experiments will require full polarization information.
  - *Reduce the number of channels:* Not acceptable in general, as one wishes to obtain data with the same spectral characteristics as produced by the interferometer.

[2] Although one could envision doing the cross-correlations every N integration periods, while recording the autocorrelations continuously.

3 Interferometric Sensitivities

The major scientific (as opposed to practical) factor in determining how fast one might want to record interferometric data is the sensitivity: can the MMA actually see anything in a millisecond? In accordance with MMA Memo 177 (Holdaway 1997) Tables 2 and 3 give the expected sensitivities using the assumptions given by Brown (1997), with a factor two higher receiver temperatures ($4h\nu/k$). While Tables 2 and 3 give sensitivities for all the proposed arrays, Table 4 concentrates on the two extremes (MMA+LSA and "vanilla" MMA alone), showing the dependence of sensitivity on integration time. Note that all of these tables, apart from the first parts of Tables 2a and 3a, give the sensitivity for mosaics made by oversampling the smallest primary beam by a factor of four (λ/4D) in one direction and a factor of two (λ/2D) in the other, and spending 1 msec on each pointing. "Pointed" (as compared to OTF) mosaics could be sampled instead at the Nyquist rate (λ/2D) in both dimensions, which would increase the noise by roughly a factor $\sqrt{2}$, but would cover the same area on the sky a factor 2 faster (given a fixed integration time per pointing).

4 Rapidly Variable Sources

The appropriate noise levels for variability studies are those given for single pointings in Tables 2a and 3a. The continuum seems more likely to vary on short timescales than any spectral lines, and the relevant 1σ noise levels range from 4–20 mJy/beam at 90–140 GHz to 60–320 mJy/beam at 650–850 GHz. Integration times of order a second will be required for many sources, and also to track atmospheric phase fluctuations, so the following concentrates on sources whose variability might require even faster dump rates. Supernovae, active galactic nuclei, and the like are not considered here, simply because they're too large to vary on such short timescales.

4.1 Pulsars

(contributed by Dale Frail)

Pulsars are weak, steep spectrum radio sources at centimeter wavelengths, with spectral slopes of -1 to -3. Therefore except in exceptional cases one does not expect to study them in the millimeter or sub-millimeter bands. The most interesting science that can be accomplished would use the interferometer in a non-imaging mode, phasing the individual elements to synthesize the collecting area of a large single dish. In this case one does not require a fast dumping mode in the correlator and can instead collect the data by sampling the phased array output with a modest off-line system, as currently done at the VLA.

Recently, a number of pulsars have been detected at frequencies up to 43 GHz, with a somewhat flatter (or even upturning) spectrum at millimeter wavelengths (e.g., Kramer *et al.* 1997). The detection of this new spectral component in pulsars was unexpected and may enable us to study the inner regions of the pulsar magnetosphere where higher order moments of the magnetic field geometry are likely important. However, even with their flat spectra these

Table 2a. rms Noise for Unresolved Sources in 1 msec: Continuum

*Single pointing:**

Freq.	50 × 12m	60 × 12m	40 × 8m plus 25 × 15m	40 × 8m plus 35 × 15m	40 × 8m	35 × 15m
90 GHz	5.6 mJy/bm	4.7 mJy/bm	4.9 mJy/bm	3.9 mJy/bm	16 mJy/bm	5.1 mJy/bm
140	6.9	5.6	6.1	4.7	19	6.4
230	11	8.8	9.3	7.3	29	9.8
350	20	17	18	14	54	19
650	86	72	74	59	190	86
850	170	140	140	110	320	180

Overlapping pointings:†

Freq.	50 × 12m	60 × 12m	40 × 8m plus 25 × 15m	40 × 8m plus 35 × 15m	40 × 8m	35 × 15m
90 GHz	2.7 mJy/bm	2.2 mJy/bm	1.9 mJy/bm	1.5 mJy/bm	7.6 mJy/bm	2.4 mJy/bm
140	3.3	2.7	2.4	1.8	9.6	3.0
230	5.2	4.2	3.6	3.1	14.	4.7
350	9.8	8.1	6.8	5.8	26.	9.2
650	41.	34.	28.	23.	92.	41.
850	79.	66.	50.	43.	150.	84.

1σ noise calculated assuming 8 GHz bandwidth, dual polarization, and the parameters used in MMA Memo 177.

* Noise level in a single pointing.

† Noise level assuming a large mosaic, taken with OTF sampling (λ/4D in one direction, λ/2D in the other), allowing for the gain in sensitivity due to overlapping beams. The noise levels for Nyquist sampling would be a factor $\sqrt{2}$ higher; those for λ/4D sampling in both directions, $\sqrt{2}$ lower.

Table 2b. rms Surface Brightness Noise in 1 msec: Continuum

*Θ = 3.5 (230 GHz/ν) asec**

Freq.	50×12m	60×12m	40×8m plus 25×15m	40×8m plus 35×15m	40×8m	35×15m
90 GHz	6.4 mK	5.5 mK	4.5 mK	3.6 mK	15. mK	7.3 mK
140	8.0	6.9	5.5	4.3	18.	8.9
230	12.	10.	8.5	7.2	27.	14.
350	24.	20.	16.	14.	48.	27.
650	100.	85.	63.	56.	170.	120.
850	190.	160.	110.	100.	290.	240.

Θ = 7.0 (230 GHz/ν) asec†

Freq.	50×12m	60×12m	40×8m plus 25×15m	40×8m plus 35×15m	40×8m	35×15m
90 GHz	3.0 mK	2.3 mK	2.1 mK	1.6 mK	5.3 mK	2.9 mK
140	3.6	2.9	2.5	1.9	6.7	3.6
230	5.5	4.5	3.9	3.1	10.	5.7
350	11.	8.5	7.3	6.0	18.	11.
650	44.	36.	29.	24.	65.	48.
850	85.	69.	53.	45.	110.	99.

1σ noise calculated assuming 8 GHz bandwidth, dual polarization, and the parameters used in MMA Memo 177.

* Noise level for 50% filled arrays, taking mosaiced observations with $rm\lambda/4D$ in one direction, λ/2D in the other, and tapering to a resolution of 3.5 (230GHz/ν) asec. The noise levels for Nyquist sampling would be a factor $\sqrt{2}$ higher; those for λ/4D sampling in both directions, $\sqrt{2}$ lower.

* To convert to mJy/beam, multiply by 0.530.

* To convert to MJy/sr, multiply by $0.307(\nu/100\,\mathrm{GHz})^2$.

† Noise level for 50% filled arrays, taking mosaiced observations with $rm\lambda/4D$ in one direction, λ/2D in the other, and tapering to a resolution of 7.0 (230GHz/ν) asec. The noise levels for Nyquist sampling would be a factor $\sqrt{2}$ higher; those for λ/4D sampling in both directions, $\sqrt{2}$ lower.

† To convert to mJy/beam, multiply by 2.12.

† To convert to MJy/sr, multiply by $0.307(\nu/100\,\mathrm{GHz})^2$.

Table 3a. rms Noise for Unresolved Sources in 1 msec: Spectral Line

*Single pointing:**

Freq.	50 × 12m	60 × 12m	40 × 8m plus 25 × 15m	40 × 8m plus 35 × 15m	40 × 8m	35 × 15m
90 GHz	0.92 Jy/bm	0.76 Jy/bm	0.80 Jy/bm	0.64 Jy/bm	2.6 Jy/bm	0.84 Jy/bm
140	0.90	0.74	0.80	0.61	2.5	0.83
230	1.1	0.90	0.95	0.75	3.0	1.0
350	1.7	1.4	1.5	1.2	4.4	1.6
650	5.2	4.4	4.5	3.6	12.	5.2
850	8.8	7.3	7.3	6.0	17.	9.3

Overlapping pointings:†

Freq.	50 × 12m	60 × 12m	40 × 8m plus 25 × 15m	40 × 8m plus 35 × 15m	40 × 8m	35 × 15m
90 GHz	0.45 Jy/bm	0.36 Jy/bm	0.31 Jy/bm	0.25 Jy/bm	1.2 Jy/bm	0.40 Jy/bm
140	0.43	0.35	0.31	0.24	1.3	0.39
230	0.53	0.43	0.37	0.32	1.4	0.48
350	0.81	0.67	0.56	0.48	2.1	0.76
650	2.5	2.1	1.7	1.4	5.6	2.5
850	4.2	3.5	2.6	2.3	8.1	4.5

1σ noise for a 1 km/sec channel using dual polarization, based on the parameters used in MMA Memo 177.

* Noise level in a single pointing.

† Noise level assuming a large mosaic, taken with OTF sampling ($\lambda/4$D in one direction, $\lambda/2$D in the other), allowing for the gain in sensitivity due to overlapping beams. The noise levels for Nyquist sampling would be a factor $\sqrt{2}$ higher; those for $\lambda/4$D sampling in both directions, $\sqrt{2}$ lower.

Table 3b. rms Surface Brightness Noise in 1 msec: Spectral Line

$\Theta = 3.5\ (230\ GHz/\nu)\ asec^*$

Freq.	50×12m	60×12m	40×8m plus 25×15m	40×8m plus 35×15m	40×8m	35×15m
90 GHz	1.1 K	0.89 K	0.73 K	0.58 K	2.4 K	1.2 K
140	1.0	0.90	0.72	0.56	2.4	1.2
230	1.3	1.1	0.87	0.74	2.7	1.4
350	2.0	1.7	1.3	1.1	4.0	2.2
650	6.1	5.2	3.8	3.4	11.	7.2
850	10.	8.7	6.1	5.5	15.	13.

$\Theta = 7.0\ (230\ GHz/\nu)\ asec^\dagger$

Freq.	50×12m	60×12m	40×8m plus 25×15m	40×8m plus 35×15m	40×8m	35×15m
90 GHz	0.49 K	0.38 K	0.33 K	0.26 K	0.87 K	0.47 K
140	0.47	0.38	0.33	0.25	0.88	0.47
230	0.56	0.46	0.40	0.32	1.0	0.58
350	0.88	0.70	0.61	0.49	1.5	0.90
650	2.7	2.2	1.8	1.5	4.0	2.9
850	4.5	3.7	2.8	2.4	5.7	5.2

1σ noise for a 1 km/sec channel using dual polarization, based on the parameters used in MMA Memo 177.

* Noise level for 50% filled arrays, taking mosaiced observations with $rm\lambda/4D$ in one direction, λ/2D in the other, and tapering to a resolution of 3.5 (230GHz/ν) asec. The noise levels for Nyquist sampling would be a factor $\sqrt{2}$ higher; those for λ/4D sampling in both directions, $\sqrt{2}$ lower.

* To convert to Jy/beam, multiply by 0.530.

* To convert to MJy/sr, multiply by $307(\nu/100\,GHz)^2$.

† Noise level for 50% filled arrays, taking mosaiced observations with $rm\lambda/4D$ in one direction, λ/2D in the other, and tapering to a resolution of 7.0 (230GHz/ν) asec. The noise levels for Nyquist sampling would be a factor $\sqrt{2}$ higher; those for λ/4D sampling in both directions, $\sqrt{2}$ lower.

† To convert to Jy/beam, multiply by 2.12.

† To convert to MJy/sr, multiply by $307(\nu/100\,\mathrm{GHz})^2$.

Table 4. rms Surface Brightness Noise: Continuum

*Θ = 3.5 (230 GHz/ν) asec**

	40 × 8m plus 35 × 15m				40 × 8m			
Freq.	1 msec	10 msec	100 msec	1000 msec	1 msec	10 msec	100 msec	1000 msec
90 GHz	3.6 mK	1.1 mK	0.36 mK	0.11 mK	15. mK	4.7 mK	1.5 mK	0.47 mK
140	4.3	1.3	0.43	0.13	18.	5.8	1.8	0.58
230	7.2	2.3	0.72	0.23	27.	8.4	2.7	0.84
350	14.	4.4	1.4	0.43	48.	15.	4.8	1.5
650	56.	18.	5.6	1.8	173.	55.	17.	5.5
850	100.	33.	10.	3.3	290.	91.	29.	9.1

Θ = 7.0 (230 GHz/ν) asec†

	40 × 8m plus 35 × 15m				40 × 8m			
Freq.	1 msec	10 msec	100 msec	1000 msec	1 msec	10 msec	100 msec	1000 msec
90 GHz	1.6 mK	0.50 mK	0.16 mK	0.050 mK	5.3 mK	1.7 mK	0.53 mK	0.17 mK
140	1.9	0.59	0.19	0.059	6.7	2.1	0.67	0.21
230	3.1	0.98	0.31	0.098	10.	3.2	1.0	0.32
350	6.0	1.9	0.59	0.19	18.	5.7	1.8	0.57
650	24.	7.7	2.4	0.77	65.	21.	6.5	2.1
850	45.	14.	4.5	1.4	110.	34.	11.	3.4

1σ noise assuming 8 GHz bandwidth, dual polarization, and the parameters used in MMA Memo 177.

* To convert to mJy/beam, multiply by 0.530.

* To convert to MJy/sr, multiply by $0.307(\nu/100\,\mathrm{GHz})^2$.

† Noise level for 50% filled arrays, taking mosaiced observations with $rm\lambda/4D$ in one direction, λ/2D in the other, and tapering to a resolution of 7.0 (230GHz/ν) asec. The noise levels for Nyquist sampling would be a factor $\sqrt{2}$ higher; those for λ/4D sampling in both directions, $\sqrt{2}$ lower.

† To convert to mJy/beam, multiply by 2.12.

† To convert to MJy/sr, multiply by $0.307(\nu/100\,\mathrm{GHz})^2$.

Table 5. rms Surface Brightness Noise: Spectral Line

*$\Theta = 3.5\ (230\ GHz/\nu)$ asec**

	40 × 8m plus 35 × 15m				40 × 8m			
Freq.	1 msec	10 msec	100 msec	1000 msec	1 msec	10 msec	100 msec	1000 msec
90 GHz	0.58 K	0.18 K	0.058 K	0.018 K	2.4 K	0.77 K	0.24 K	0.077 K
140	0.56	0.18	0.056	0.018	2.4	0.76	0.24	0.076
230	0.74	0.23	0.074	0.023	2.7	0.86	0.27	0.086
350	1.1	0.36	0.11	0.036	4.0	1.3	0.40	0.13
650	3.4	1.1	0.34	0.11	11.	3.3	1.1	0.33
850	5.5	1.7	0.55	0.17	15.	4.8	1.5	0.48

$\Theta = 7.0\ (230\ GHz/\nu)$ asec†

	40 × 8m plus 35 × 15m				40 × 8m			
Freq.	1 msec	10 msec	100 msec	1000 msec	1 msec	10 msec	100 msec	1000 msec
90 GHz	0.26 K	0.082 K	0.026 K	0.008 K	0.87 K	0.27 K	0.087 K	0.028 K
140	0.24	0.077	0.024	0.008	0.88	0.28	0.088	0.028
230	0.32	0.10	0.032	0.010	1.0	0.33	0.10	0.033
350	0.49	0.16	0.049	0.016	1.51	0.48	0.15	0.048
650	1.5	0.47	0.15	0.047	4.0	1.3	0.39	0.13
850	2.4	0.75	0.24	0.076	5.7	1.8	0.57	0.18

1σ noise for a 1 km/sec channel using dual polarization, based on the parameters used in MMA Memo 177.

* Noise level for 50% filled arrays, taking mosaiced observations with $rm\lambda/4D$ in one direction, λ/2D in the other, and tapering to a resolution of 3.5 (230GHz/ν) asec. The noise levels for Nyquist sampling would be a factor $\sqrt{2}$ higher; those for λ/4D sampling in both directions, $\sqrt{2}$ lower.

* To convert to Jy/beam, multiply by 0.530.

* To convert to MJy/sr, multiply by $307(\nu/100\,GHz)^2$.

† Noise level for 50% filled arrays, taking mosaiced observations with $rm\lambda/4D$ in one direction, λ/2D in the other, and tapering to a resolution of 7.0 (230GHz/ν) asec. The noise levels for Nyquist sampling would be a factor $\sqrt{2}$ higher; those for λ/4D sampling in both directions, $\sqrt{2}$ lower.

† To convert to Jy/beam, multiply by 2.12.

† To convert to MJy/sr, multiply by $307(\nu/100\,\mathrm{GHz})^2$.

sources will be weak and require integration times of several minutes to hours be detected. Gating should be used to enhance the final signal-to-noise ratio. This may be accomplished in at least two ways. The simplest is to turn the correlator accumulator ON only during the peak of the pulse profile. If the pulse phase is not known *a priori* then the correlator output could be summed in time bins at the pulsar period, sufficient to phase resolve the pulse profile. For the fastest millisecond pulsars known a dump time of 10 μsec would be sufficient for this purpose. Note that this does not require that the full correlation be read out every dump time, only that the phased array output be binned at this resolution.

Another possible pulsar project is the study of those pulsars which are rendered unobservable at centerimeter wavelengths due to dispersion or scattering by ionized gas along the line of sight. The smearing and broadening effects of dispersion and scattering on a pulsar's pulse vary approximately as ν^{-2} and $\nu^{-4.4}$, respectively. There are an increasing number of pulsars found in orbit around main sequence stars, in particular massive B and Be stars with mass-losing winds (Johnston *et al.* 1992; Kaspi, Tauris & Manchester 1996). This trend is likely to continue due to several diligent searches currently under way at 1.4 GHz. As the pulsar approaches perisatron it becomes obscured by the wind from the companion. Higher frequency observations offer the possibility of observing the pulsar all the way to perisatron and out again, probing the densest part of an OB star's wind in a way impossible with any other technique.

- *Shortest integration times:* 10μsec for the fastest millisecond pulsars known.
- *Data needed:* Raw phased array data only. At most a few hundred channels, to allow for dispersion measures up to 1000 (e.g., Galactic Center) over $\sim$ 10 GHz bands at 30–50 GHz. Full polarization, for polarization experiments and sensitivity.

4.2 The Sun and Nearby Stars

(with thanks to Tim Bastian)

While the Sun is too large to vary rapidly as a whole, it is near and bright enough for small active regions to be detected and mapped. Gamma-ray–millimeter-wave flares are among the most observationally-demanding phenomena probed by the MMA. In these events electrons and protons are accelerated to very high energies, the electrons at 10-100 MeV emitting both millimeter waves and continuum gamma-rays within one or two seconds of flare onset. One would like to image these flares with a time resolution of 0.1 seconds or better, to distinguish between the ion-acoustic and the electron travel time. There are two problems. First, we don't know, to within an arcminute or so, where the flares will occur; and second, once they occur, they may produce emission scattered over an area larger than the primary beam of the antenna elements.

The simplest solution to both problems is to use only the small antennas (if the array is inhomogeneous) to observe solar flares. The flares are quite bright ($10^5 - 10^8$ Jy) so sensitivity is not an issue. At the lowest proposed frequency band, somewhere between 30 and 50 GHz, the field-of-view of an 8m dish is still large enough ($\sim$ 3 arcmin) to monitor the active region;

observations at higher frequencies would require using the 30–50 GHz data to figure out where the flare is occurring in real time, so that the antennas could be pointed there. For larger dishes one would have to do raster scans (and reduce them in real time!), or under-illuminate the reflectors, or use subarrays. Raster scans (OTF mosaics) would be reasonable if the telescopes could turn around after moving only a few arcminutes, without losing too much time to overhead (a spiral pattern on the sky might obviate this requirement). Under-illumination introduces a variety of engineering complexities. Subarrays are probably the simplest option, though there too there would have to be some flag raised to say that subarray X has found a flare. At any rate, once the flare is found and the antennas have moved there, one would like to record the correlations from a reasonable subarray (10s of telescopes) with integration times of 100 msec or less. No polarization information or frequency resolution would be required, and the bandwidths could be fairly small.

Normal solar flares would be about ~ 10 mJy at 5 pc; the γ-ray–mm-wave flares are about 10 times stronger. With the proposed MMA sensitivity at 100 GHz in 100 msec one could detect normal flares at the 10σ level out to distances of 3.5–8 pc, and the stronger flares out to 11–25 pc. Since sensitivity is important one would like all possible baselines and at least dual polarization; however, the stars being unresolved and their positions known, the only essential data would be the phased array sum. Flare stars and RS CVn systems might be detected even further out, but will not require the same time resolutions – characteristic timescales for these events are hours to days.

- *Shortest integration times:* For the Sun, 100 msec for a reasonable array (10s of antennas, set by the uv-coverage); one will probably wish to observe with different frequencies in different subarrays, e.g. 20 dishes each at 30–50, 90, 140, and 230 GHz. For other nearby stars one needs the same time resolution, but only for the summed signal of the phased array.

- *Data needed:* See above. Continuum only. Full polarization, to track the linear/circular polarization behavior during flares.

- *Possible tradeoffs:*

  - *Throw away some baselines:* Fine for solar work, down to a minimum of some 10s of antennas. Since sensitivity is not an issue one would probably toss the larger antennas in an inhomogeneous array, to maximize the size of the primary beam. For stellar work one would want the full array for sensitivity, but only the analogue sum need be recorded.

5 Large Surveys: On-the-Fly Mosaics

The MMA's primary beam will be somewhere between modest and miniscule, depending on the frequency and the dish diameter (see Table 1). Mosaicing will therefore be a common if not ubiquitous observing mode. On the other hand, the superb sensitivity of the array means that the amount of time spent on individual pointings can be astonishingly short. The noise levels for oversampled ($\lambda/4D \times \lambda/2D$) mosaics[3] observed for 1 millisecond per pointing are given in Tables 2 and 3. Broadly speaking, we expect noise levels between 1 and 10 mJy/beam (about 2–20 mK) for continuum experiments at the lower frequencies, and a few tenths of a Jy (0.2–2 K) in a 1 km/sec channel for line work. As will be seen below, these are quite sufficient for interesting astronomical surveys.

If the antennas actually stop at each pointing position, one could sample at the Nyquist rate in both dimensions, a factor two slower than required for OTF mosaics. This would give noise levels a factor $\sqrt{2}$ higher than given in the tables, but allow mapping large areas twice as fast. This is very appealing but it seems likely that starting and stopping the telescopes would introduce considerable overhead, not to mention the wear and tear on the antennas themselves. Current thinking has it taking some 100s of milliseconds to stop the antennas, which would argue strongly for OTF mosaics. Clearly this is an important area for future study. For now I assume OTF mosaicing as the standard, commenting on the differences between this and pointed mosaics where appropriate.

Before going into the various experiments which might be done in this short-integration on-the-fly mode, it's interesting to ask how long it would take to map variously-sized regions. Assuming the primary beams are oversampled by a factor of four in one dimension and a factor of two in the other, it would take $N_{\rm ptg} = \left(\frac{3600}{(\Theta_{\rm asec}/2\sqrt{2})}\right)^2$ pointings to cover a square degree; with $\Theta \approx 77.3 \left(\frac{100\,{\rm GHz}}{\nu}\right)\left(\frac{8{\rm m}}{\rm D}\right)$ arcsec (where D is the largest dish diameter in the array), this gives

$$t_{\rm tot} = 17.4 \left(\frac{\nu}{100\,{\rm GHz}}\right)^2 \left(\frac{\rm D}{8{\rm m}}\right)^2 \left(\frac{t_{\rm int}}{1\,{\rm msec}}\right) \text{ seconds/sq. deg.}$$

with $t_{\rm int}$ the integration time per pointing. *Note that this includes no time for overhead or calibration.* Some interesting survey times derive from this:

TMC-1; Virgo spiral: $10' \times 10'$

$$t_{\rm TMC} \sim 2.5 \left(\frac{\nu}{230\,{\rm GHz}}\right)^2 \left(\frac{\rm D}{8{\rm m}}\right)^2 \left(\frac{t_{\rm int}}{1\,{\rm msec}}\right) \text{ seconds}$$

W3 GMC; M31: $1° \times 1°$

$$t_{\rm W3} \sim 1.5 \left(\frac{\nu}{230\,{\rm GHz}}\right)^2 \left(\frac{\rm D}{8{\rm m}}\right)^2 \left(\frac{t_{\rm int}}{1\,{\rm msec}}\right) \text{ minutes}$$

Galactic Center; Coma Cluster: $5° \times 5°$

$$t_{\rm Sgr} \sim 0.64 \left(\frac{\nu}{230\,{\rm GHz}}\right)^2 \left(\frac{\rm D}{8{\rm m}}\right)^2 \left(\frac{t_{\rm int}}{1\,{\rm msec}}\right) \text{ hours}$$

[3]As discussed by Holdaway, Owen, and Emerson (1995), OTF mosaics need to be sampled at better than the Nyquist rate along the slew direction to avoid losing short-spacing information. Since the telescope is moving continuously during an observation, the primary beam is effectively smeared out along the direction of motion; recording the data more frequently minimizes this smearing.

LMC or Virgo Cluster: $\sim 10^\circ \times 10^\circ$

$$\mathrm{t_{LMC}} \sim 2.5 \left(\frac{\nu}{230\,\mathrm{GHz}}\right)^2 \left(\frac{\mathrm{D}}{8\mathrm{m}}\right)^2 \left(\frac{\mathrm{t_{int}}}{1\ \mathrm{msec}}\right) \text{ hours}$$

Galactic plane: $360^\circ \times 10^\circ$

$$\mathrm{t_{Gal}} \sim 3.8 \left(\frac{\nu}{230\,\mathrm{GHz}}\right)^2 \left(\frac{\mathrm{D}}{8\mathrm{m}}\right)^2 \left(\frac{\mathrm{t_{int}}}{1\ \mathrm{msec}}\right) \text{ days}$$

All sky: $4\pi\,\mathrm{sr}$

$$\mathrm{t_{all\,sky}} \sim 44 \left(\frac{\nu}{230\,\mathrm{GHz}}\right)^2 \left(\frac{\mathrm{D}}{8\mathrm{m}}\right)^2 \left(\frac{\mathrm{t_{int}}}{1\ \mathrm{msec}}\right) \text{ days}$$

Clearly if the sensitivity is there this will be a very useful mode for surveys; it is also obvious that fast dumps will be particularly important for larger dish sizes, where the sensitivity is better but the primary beam size is smaller. Note that, even with 1 msec dump times, mapping very large areas takes a substantial commitment of observing time (see Fig. 1) – choosing 1 sec as the shortest possible integration period for instance would probably prevent the MMA from ever surveying the LMC, or even the SMC. Ignoring sensitivity issues for the moment (see below), Figure 1 suggests $40\,(\mathrm{8m/D})^2$ msec as a reasonable integration time for most surveys. Allowing a factor 2 for overhead and calibration, this would allow surveying (at 230 GHz) a square degree in two hours, the Galactic Center region in two days, the LMC and nearby galaxy clusters in a little over a week each, and a two-degree strip around the Galactic Plane in two months. With Nyquist sampling in both directions (requiring pointed observations, starting and stopping the telescopes after each integration), one could match these survey times with a $80\,(\mathrm{8m/D})^2$ msec integration time, assuming no additional overhead. The noise levels in the resulting mosaics would be identical, as the increased time per pointing cancels the lesser overlap between adjacent pointings.

Short integrations also in some sense make the best use of periods of good weather. If as argued below noise is not always the limiting factor, it makes sense to use very short integrations at the high frequencies, to map as large an area as possible when the atmosphere allows it. Of course if the sensitivity is really so wonderful one could argue for doing surveys in *bad* weather, balancing the long integration times mandated by the hardware against the higher system temperatures due to the atmosphere. This sounds like a very dodgy idea, if only because of possible systematic effects, but it might be worth considering. Obviously the total observing time required for mapping a given area would increase significantly, as in Figure 1.

- *Shortest integration times:* $40\,(\mathrm{8m/D})^2$ msec, to allow mapping large areas reasonably quickly. Slower dump rates will eliminate some very interesting observations.
- *Data needed:* Full interferometric/total power correlations, for sensitivity and uv-coverage. Up to 1000 channels (discussed below). Dual polarization for sensitivity, full polarization would be nice for some experiments but could be traded against channels.

- *Possible tradeoffs:*
  - *Use only the smaller antennas:* since the integration time goes as D^{-2} using only the smaller dishes in an inhomogeneous array would speed up mosaicing considerably.
  - *Throw away some baselines:* Could toss some fraction of the correlations if necessary, depending on the sensitivity requirements of the individual experiments. The lower limit on the number of baselines is set by requiring good snapshot imaging, the same requirement that pushed the MMA to ~ 40 antennas.

5.1 Why Use the MMA for Surveys?

As will become obvious, large surveys are one of the strongest scientific drivers towards sub-second integration times at the MMA. It is reasonable then to ask whether these surveys cannot be carried out instead by big single-dish telescopes, either currently existing (e.g., IRAM 30m) or proposed (e.g., LMT 50m). Obviously high-resolution surveys will require the MMA in its larger configurations, but even the most compact 80m configuration offers significant advantages. First, even in this configuration the MMA has twice the resolution of the proposed LMT 50m. Second, as argued in Holdaway and Rupen (1995), an interferometer is significantly faster than a single-dish telescope (even with multi-beam feeds) for mapping large regions. Third, the proposed MMA site in Chile is far superior to that of any other existing or proposed millimeter facility, giving significant improvements in sensitivity, minimizing systematic errors due to the atmosphere, and allowing observations more often, at higher frequencies. Fourth, interferometers are intrinsically less vulnerable than single dishes to a number of systematic errors, e.g. standing waves in the dish. The MMA does indeed have a role in imaging large areas of the sky, and it is important to ensure that this capability is not designed out of the array.

5.2 Continuum Emission

In general thermal will dominate synchrotron emission at millimeter wavelengths, as the former is flat spectrum or even sharply rising as one moves to higher frequencies. Of course some sources like supernova remnants and the brighter quasars will be visible, but the bread-and-butter, large-area mapping experiments will involve thermal dust and bremsstrahlung emission. In brief, MMA surveys will only be sensitive to small, bright Galactic objects, like YSOs and UCHIIs, and to external galaxies not highly resolved by the synthesized beam. Galactic projects require shorter integration times because the sources are bright enough to allow higher noise levels, and large enough to require big mosaics.

5.2.1 Optically-thick Thermal Emission

The flux density emitted by a blackbody at long wavelengths goes as the square of the observing frequency; dust emission goes as ν^{2-4}, depending on the long-wavelength emissivity index.

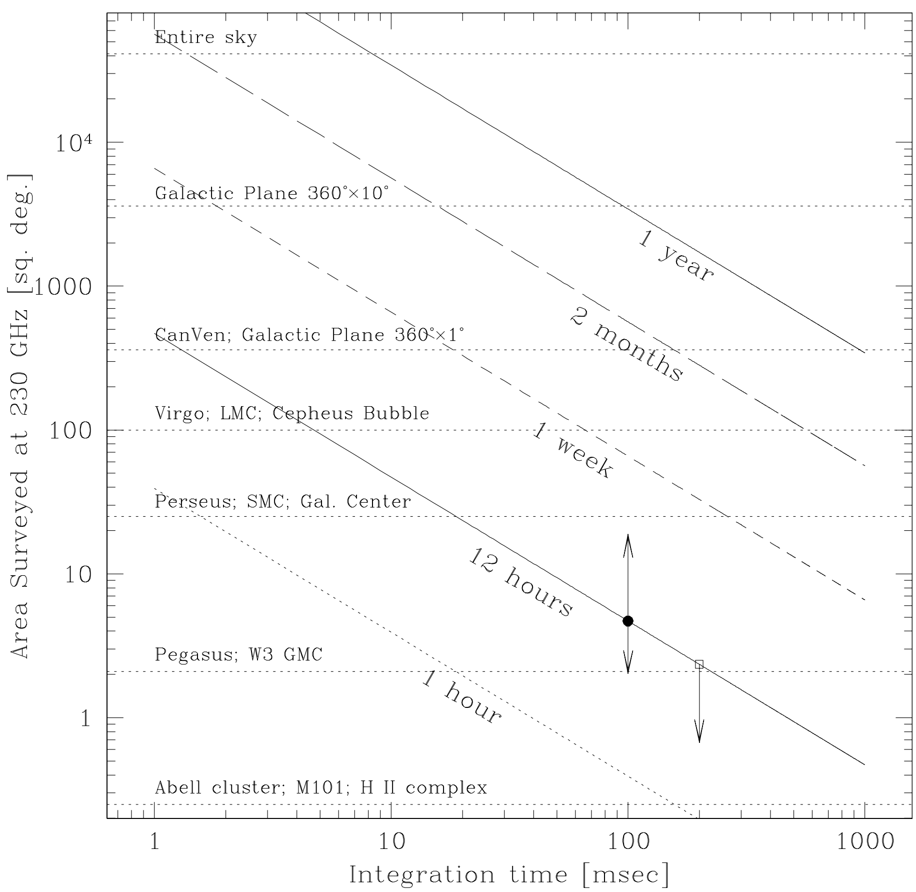

Figure 1: Size of region surveyed in a given observing time **on-source**, as a function of the integration time per pointing. Assumes mosaiced observations using OTF sampling ($\lambda/4D$ in one direction, $\lambda/2D$ in the other) at 230 GHz, **using 8m telescopes.** Diagonal lines represent constant on-source observing time, as indicated; horizontal lines show the sizes of various interesting sources. The vertical arrows attached to the solid circle show the effects of observing at 350 (down arrow) and 115 (up arrow) GHz; the downward arrow attached to the open square shows the decrease in areal coverage when using 15m antennas. Using Nyquist sampling in both dimensions would increase the area surveyed by a factor 1.4.

However, the system temperature goes up with frequency and the primary beam gets smaller. These effects combine to put the optimum frequency for large-scale MMA surveys of unresolved, optically-thick thermal sources around 350 GHz, with an rms noise in 1 msec of 4–18 mJy/beam for mosaiced observations. Two illustrative classes of interesting, optically-thick sources are stars and young stellar objects (YSOs).

Stars without dust will generally be too dim to detect with these fast integration times. The 350 GHz flux density from a stellar surface (assumed to emit as a black body) is $\mathrm{S}_\nu(\mathrm{star}) = 11\left(\frac{\mathrm{T}}{5000\,\mathrm{K}}\right)\left(\frac{\mathrm{R/R_\odot}}{\mathrm{D/pc}}\right)^2$ mJy. With paramaters suitable for a red supergiant, this gives $\mathrm{S}_\nu(\mathrm{star}) = 400\left(\frac{\mathrm{T}}{3000\,\mathrm{K}}\right)\left(\frac{\mathrm{R}/6\times10^{13}\,\mathrm{cm}}{\mathrm{D}/100\,\mathrm{pc}}\right)^2$ mJy. Jupiters will be much colder (~ 100 K), giving $\mathrm{S}_\nu(\mathrm{Jupiter}) = 2.1\left(\frac{\mathrm{r/r_J}}{\mathrm{D/pc}}\right)^2$ μJy. With these low flux densities only red supergiants could be seen readily in integration times below a second, and there are too few of those (a few per million cubic parsecs, Allen 1973) to warrant unpointed surveys.

YSOs and protostars are much more likely targets, emitting strongly at millimeter wavelengths because they are embedded in (or surrounded by) dense dusty envelopes or disks. Mundy *et al.* (1996) show that the emission from HL Tau, a typical Class 1 source[4] with a $\sim 0.065\,M_\odot$ disk at a distance of 140 pc, is well fit by a power law $\mathrm{S}_\nu = (1.5 \pm 0.2)\,\lambda_{\mathrm{mm}}^{-2.5\pm0.2}$ Jy between 0.35 and 3.0mm. A 1 msec-per-pointing 350 GHz survey with the MMA could detect this source (7σ) to a distance of 0.5–1.0 kpc; in the most compact configuration (maximum baseline about 80m) it would be roughly the size of the beam at 100 pc. HL Tau may be atypically bright; Terebey, Chandler, and André (1993) found 1.3mm flux densities ranging from 30 to 300 mJy for ~ 30 IRAS-Dense cores at distances ~ 160 pc. Adopting the millimetric spectral index of HL Tau this corresponds to 0.1–1 Jy at 350 GHz. An MMA OTF mosaic could detect (7σ) even the fainter of such sources out to $120\text{–}250\left(\frac{\mathrm{t_{int}}}{1\,\mathrm{msec}}\right)^{1/4}$ pc, and the bright ones a factor 3.2 further out. This observing mode is therefore perfectly matched to blind searches for the continuum emission of YSOs.

- *Shortest integration times:* As above, set by speed of mapping; probably at least 10 msec integrations would be required for sensitivity. Longer integration times allow either going deeper, or going to lower frequencies (which in turn allows surveying a larger area of the sky in a given time).
- *Data needed:* Full interferometric/total power correlations, for sensitivity and uv-coverage. A few channels for spectral index information and possible multifrequency synthesis. Dual polarization needed for sensitivity; full polarization would be nice for some experiments.

[4]YSOs are classified according to the ratio of the far infrared emission from the dust envelope, to the radiation seen directly from the star: those seen almost 'naked' are called Class 2 sources, those completely enshrouded, Class 0. Class 1s are intermediate.

5.2.2 Optically-thin Bremsstrahlung Emission

Optically-thin bremsstrahlung gives a millimeter spectrum for H II regions which is almost flat with frequency:

$$\mathrm{S}_\nu(\mathrm{H\ II}) = 1.7 \times 10^{-9}\,\mathrm{T_e^{-0.35}}\ (\nu/100\,\mathrm{GHz})^{-0.1}\ \left(\mathrm{E.M./cm^{-6}\,pc}\right)\ (\Theta/\mathrm{arcsec})^2\ \mathrm{Jy},$$

where E.M. is the emission measure, and Θ is the angular size of the source. The well-known, large H II regions like Orion have emission measures of 10^4–$10^6\,\mathrm{cm^{-6}}$ pc, sizes of 1–10 arcmin, and electron temperatures of order 10^4 K (e.g., Table 12 of Lang (1980)). Typical surface brightnesses should then be about

$$\mathrm{S}_\nu(\mathrm{H\ II}) = 6.8\times 10^{-6}\ \left(\frac{\mathrm{T_e}}{10^4\,\mathrm{K}}\right)^{-0.35}\ (\nu/100\,\mathrm{GHz})^{-0.1}\ \left(\mathrm{E.M.}/10^5\,\mathrm{cm^{-6}\,pc}\right)\ (\Theta/\mathrm{arcsec})^2\ \mathrm{Jy/beam},$$

with Θ the size of the synthesized beam. Clearly it will require relatively long (minutes to hours) observations to see the average emission from these objects.

More promising are the much smaller, higher emission measure compact and "ultra-compact" H II regions (UCHIIs) recently mapped with centimeter-wavelength arrays. For example, De Pree, Mehringer, and Goss (1997) found the following (rough, average) parameters for the (U)CHIIs in W49A, at a distance of 11.4 kpc: Θ between < 0.8 and 60 arcsec; electron densities of a few times $10^4\,\mathrm{cm^{-3}}$; E.M. $= 10^7 - 10^8\,\mathrm{cm^{-6}}$ pc; τ (7mm) ~ 0.05; and S_ν(7mm) $\sim$0.1–1 Jy. For such sources the MMA would see

$$\mathrm{S}_\nu = 17\ \left(\frac{\mathrm{T_e}}{10^4\,\mathrm{K}}\right)^{-0.35}\ \left(\frac{\nu}{100\,\mathrm{GHz}}\right)^{-0.1}\ \left(\frac{\mathrm{E.M.}}{10^7\,\mathrm{cm^{-6}\,pc}}\right)\ \left(\frac{\Theta}{1\,\mathrm{arcsec}}\right)^2\ \mathrm{mJy},$$

where Θ here is the apparent source size. Given the flat spectrum, these objects will be easiest to detect at ~ 100 GHz, for which Table 2a gives 1σ =1.5–8 mJy/beam in 1 msec.[5] Requiring the usual 7σ for a detection, this corresponds to a desired 0.4–9.8 msec integration time per pointing. Large-scale MMA surveys could easily see and map these objects anywhere in the Galaxy.

Similar considerations hold for surveying H II regions in other galaxies. (U)CHIIs in the Magellenic Clouds would be about 1 mJy, as would the larger (no longer resolved) 'standard' H II regions; those in more distant galaxies will be correspondingly fainter. Survey work is therefore impractical for all but the Local Group galaxies, and even there will require relatively long integrations (0.11–2.8 seconds, for a 7σ detection of a 1 mJy source). Although observing more distant galaxies would 'stack' all the resident H II regions in one beam, thus improving the signal, dust emission masks that from ionized gas above about 45 GHz (Condon 1992). Of course this means that the dust emission is much stronger and more readily observed; this is discussed in the next section.

[5] I have avoided discussing 45 GHz observations in this memo, as that system is somewhat controversial at the moment, and besides will have a sufficiently large primary beam that surveys can be done with longer integration times than at the higher frequencies.

- *Shortest integration times:* As above for mapping large areas; sensitivity requires 0.4–10 msec for typical Galactic (U)CHIIs, 100–2800 msec for the Magellenic Clouds (set by thermal noise).

- *Data needed:* All cross-correlations, for sensitivity and uv-coverage. A few channels for spectral index information and possible multi-frequency synthesis. Dual polarization for sensitivity.

5.2.3 Galactic Cirrus: Distributed Dust Emission

IRAS discovered the existence of very cold dust clouds extending throughout the Galactic disk, and dominating the 60–100 μm emission from our own and most other galaxies. Will the MMA be able to see this dust? Typical 100 μm surface brightnesses (with a $\sim$ 200 arcsec beam) are 1–100 MJy/sr. Assuming 30 K dust with a dust emissivity index $n = 1$ the corresponding 230 GHz emission will be a factor $\sim$ 120 fainter, $\sim$0.01–1 MJy/sr. To achieve a noise level (1σ) of 1 MJy/sr would take some 25–260 msec at 7 arcsec resolution, a factor of $\sim$ 800 in beam area. Whether this is useful depends on the clumpiness of the IRAS emission; the surface brightness of CO does *not* seem to increase drastically from 480 arcsec (Cohen *et al.* 1986) to 45 arcsec (Sanders *et al.* 1986) resolutions, which suggests that cold dust will not be readily detectable with sub-second MMA integrations.

External galaxies should prove easier targets, because the flux is more concentrated. In 1 msec a mosaiced 230 GHz MMA observation will have a noise level of 4–14 mJy/beam, corresponding to 0.5–1.7 Jy/beam at 100μm. A typical Virgo spiral has a $100 \mu m$ flux density of several Jansky (e.g., Knapp, Helou, and Stark 1987), so a noise level of a few tenths of a Jansky would be appropriate for surveying the cluster; this would require an integration time of 9–80 msec per pointing. A 100 msec integration time would give reasonable sensitivity out to a redshift of 1340–4000 km/sec. Note that the dust is expected to dominate the synchrotron emission from normal galaxies at these wavelengths (e.g., Condon 1992).

- *Shortest integration times:* 10–100 msec, for sensitivity to external galaxies.

- *Data needed:* All cross-correlations, for sensitivity. Dual polarization for sensitivity.

5.2.4 Finding Calibrators

Current thinking has the MMA finding its own calibrators before each experiment using total power data. If the instrument could do OTF mosaics as well, one could consider using the interferometric data instead. The main advantage is that any source so found will obviously be a good calibrator, with no difficulties due to over-resolution or confusion. However, this would require accurate mosaics (or at least clever self-calibrations) to be done in real time, the data being processed and mapped as fast as the total power data. Also, it's not clear how many potential calibrators found by using total power data would really be resolved out; most arguments point to bright millimeter sources being fairly small, particularly if chosen with reference to a survey of known 'steady' emission. At the moment using interferometric data to find calibrators seems more trouble than it would likely be worth.

- *Shortest integration times:* set by area mosaiced – see above.
- *Data needed:* Full interferometric/total power correlations, for sensitivity and uv-coverage. A few channels for spectral index information. Dual polarization for sensitivity.

5.3 Spectral Lines

The MMA will probably spend a great deal of its time observing spectral lines, taking advantage of the plethora of species emitting at millimeter wavelengths. Of these, the strongest common lines will be the rotational transitions of CO, a very common molecule with strong lines. The MMA will probably be most sensitive to the J =2–1 transition at 230 GHz, as that is expected to be sufficiently stronger than the J =1–0 line under ordinary molecular cloud conditions that the higher amplitude will outweight the lost sensitivity.

The large Galactic CO surveys currently available have rms noise levels of 0.1–0.5 K at 1.3 km/sec resolution, with beam sizes ranging from 44 arcsec to 30 arcmin (see Combes 1991). A mosaicing survey using the MMA, with 1 msec integration times, would reach a comparable sensitivity (0.3–0.9 K) for the same velocity resolution, with a much smaller beam (7 arcsec), and would take only a week to a month to cover a 10° strip around the entire Galactic Plane. Maps of much smaller areas made with the existing interferometers have shown that such brightness temperature limits are useful even at these resolutions, revealing dense clumps of molecular gas within the more diffuse structures. Surveys of molecules which trace much denser gas, SiO or CH_3CN for instance, would probably have to go deeper to be successful, say 0.1 K rms at 1 km/sec resolution. This would require somewhat longer integrations (10–80 msec); even then, if a total power survey were being done simultaneously, it would make sense to use integrations of a few milliseconds (to allow slewing fast enough to remove atmospheric emission) and scan each field several times to reach the desired sensitivity. Surveys like this are probably among the most important uses of the OTF mosaicing mode.

In the extragalactic context, the first volume of the MMA Design Study (*Science with a Millimeter Array*) gives an interesting table of CO J =1–0 parameters for various size objects. This is reproduced here as Table 6, together with the distance to which the MMA could detect such a source in a 1 msec mosaic. The 1 msec mosaicing mode would be ideal for unbiased surveys of CO in galaxy clusters, blind searches for CO-rich galaxies out to half a Gpc or more ($z \sim 0.1$), and looking for spiral-rich clusters out to the edge of the Universe.

- *Shortest integration times:* As in §5, 40 $(8\mathrm{m/D})^2$ msec, set by mapping times. Sensitivity will be an issue for the less common species observed by the 'vanilla' MMA; in this case a factor two longer integrations are desirable. May still want 1 msec integrations to allow simultaneously taking total power data.
- *Data needed:* Full interferometric/total power correlations, for sensitivity and uv-coverage. 1000 channels to cover the Galaxy at 1 km/sec resolution – could get away with perhaps

Table 6. J =2–1 CO Parameters

Type	Peak $\langle$T$\rangle$ [K]	ΔV [km/sec]	Scale Size	Max. Detection Distance in 1 msec*
Orion Core	100	10	0.5 pc	0.1– 0.3 Mpc
GMC (local)	2.5	5	50 pc	1. – 3. Mpc
GMC (inner galaxy)	5	10	50 pc	3. – 5. Mpc
Galactic Center (Milky Way)	5	250	150 pc	15. – 35. Mpc
Central Molecular Annuli (e.g., NGC 1068)	0.5	50	1 kpc	15. – 40. Mpc
Global integrated (Milky Way)	0.5	50	20 kpc	0.3– 0.8 Gpc
Global integrated (Virgo Cluster)	0.2	250	5 Mpc	80. –250. Gpc

Typical CO emission line strengths, assuming J =2–1 to be the same strength as J =1–0.

* Maximum distance to which such an object could be detected (7σ in a single channel of width ΔV km/sec) in a mosaiced experiment with 1 msec integrations on each pointing, assuming $\frac{\lambda}{4\mathrm{D}} \times \frac{\lambda}{2\mathrm{D}}$ sampling. This takes account of the apparent source size at the maximum detectable distance, which is about 7 arcsec for 40×8m antennas (3.5 arcsec for the maximal MMA+LSA array) for the local GMC, central molecular annuli, integrated galaxy and cluster sources. The smaller distances correspond to 40×8 m dishes, the larger to the most sensitive of the proposed MMA+LSA arrays (40×8m plus 35×15m). The other combined arrays achieve noise levels roughly half again as high as this most sensitive combination (see Table 3a), and would give distance limits a factor $\sqrt{1.5} = 1.2$ closer. Nyquist sampling in both dimensions would reduce the detection distance by a factor 1.2.

a factor 2 lower resolution but more than that would lose the cloud linewidths and hence signficantly lower the SNR. Dual polarization for sensitivity.

- *Possible tradeoffs:*
  - *Longer integration times:* Up to $100\,(8\mathrm{m/D})^2$ msec would still allow a 230 GHz Galactic Plane survey to be done in a few months, with $\lambda/4\mathrm{D} \times \lambda/2\mathrm{D}$ sampling.
  - *Fewer channels:* see above

6 Weather and Observing Efficiency

This point has been made in passing above, but it seems important enough to repeat by itself: if sensitivity is less of an issue than observing time, the most efficient use of good weather will be to use the minimum possible integration time on each pointing. While many projects will demand long integrations, many others will be aimed not at single-pointing detections but at mapping some area larger than the primary beam, which is less than half an arcminute across, even at 350 GHz. This point is especially important for the larger antennas and the more sensitive arrays. Note also that $3.0\left(\frac{8\mathrm{m}}{\mathrm{D}}\right)$ msec integration times are required for OTF total power observations – simultaneous interferometric observations would require the same short integrations, or clever observing schemes.

7 Practicalities

This memorandum has so far focused on how fast a scientist would like to write data out, if she didn't have to worry about storing or reducing it. This is not the place to address what can or cannot be done, but it is clearly important to state what sort of data rates and total data volumes we're talking about.

7.1 Data Rates

The number of visibilities written per integration period is

$$\mathrm{N_{vis}} = \left\{ \left(\frac{\mathrm{N\,(N-1)}}{2} \right) + \mathrm{N} \right\} \mathrm{N_{chan}\,N_{pol}},$$

with N the number of antennas, $\mathrm{N_{chan}}$ the number of channels, and $\mathrm{N_{pol}}$ the number of polarization products. This gives $1640\,\mathrm{N_{chan}}$ and $4970\,\mathrm{N_{chan}}$ visibilities per integration period for 40 and 70 antennas, respectively, assuming two polarization products are recorded (e.g., RR and LL). Figure 2 shows the corresponding data rates (assuming 8 bytes per visibility[6]) as a function of integration time, assuming continuous dumps. The continuum data rate is achievable now, albeit with some difficulty; spectral line observations will probably initially be limited by the ability to store the data.

7.2 Data Volume

The total amount of data one must store for a given mosaic is set not by the integration time, but by the total number of pointings required to cover the required area on the sky. The minimum number of visibilities stored per pointing (assuming one integration per pointing)

[6] As in the VLBA correlator. The VLA correlator gets by with 4 bytes per visibility, at the expense of some fancy compression/uncompression. Such tricks slow down the software sufficiently that they're unlikely to be possible at the highest data rates considered here.

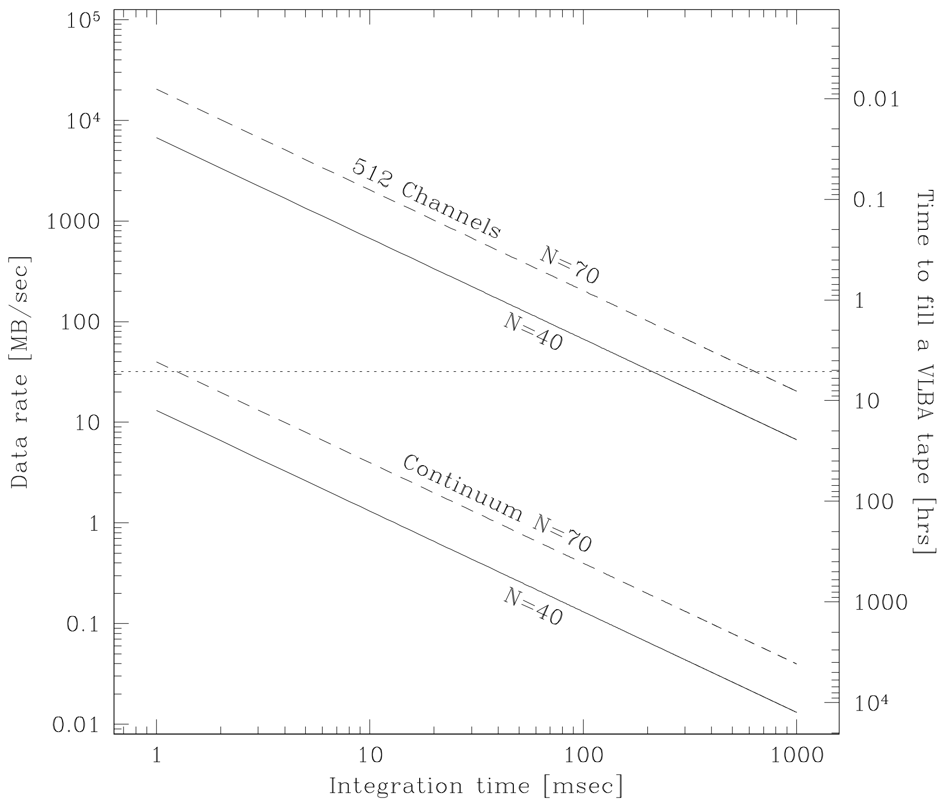

Figure 2: Rate at which data would be produced by the correlator, for N antennas and either one (continuum) or 512 channels, as a function of integration time. I assume 8 bytes per visibility. The left axis shows the data rate in MB/second, the right axis the time it would take to fill a VLBA thin tape (591.36 GB) at that rate. The horizontal line shows the maximum recording speed of a VLBA thin tape (32 MB/sec, at which rate it takes a little over 5 hours to fill a tape). An Exabyte written at high density can store roughly 1/100th as much as a VLBA tape, 4.585 GB.

was given in the last subsection. The total number of pointings, assuming $\frac{\lambda}{4D} \times \frac{\lambda}{2D}$ sampling, is

$$N_{ptg} = 17,351 \left(\frac{A}{\mathrm{sq.\,deg.}}\right) \left(\frac{\nu}{100\,\mathrm{GHz}}\right)^2 \left(\frac{D}{8\mathrm{m}}\right)^2,$$

with A the total sky coverage. Taking N_{vis} from §7.1 and again assuming 8 bytes per visibility, this implies a total data volume of

$$V \approx 227\, N_{chan} \left(\frac{N}{40}\right)^2 \left(\frac{A}{\mathrm{sq.\,deg.}}\right) \left(\frac{\nu}{100\,\mathrm{GHz}}\right)^2 \left(\frac{D}{8\mathrm{m}}\right)^2 \mathrm{Mbytes}.$$

Table 7 summarizes the sizes of some interesting data sets, together with the time required to obtain them. At the moment a handful of places in the country can handle 100 GB-ish data sets (NCSA, Fermilab, Caltech), and Subaru has a 256 terabyte disk farm at the telescope. With improvements in computer storage this may become more common, but in any case the MMA will clearly require a similar or even larger disk farm. As usual, going to Nyquist sampling in both dimensions will reduce the volume by a factor of four.

8 Discussion

The above discussion may be summarized as follows.

1. On-the-fly total power mapping requires dump times of a few milliseconds for the autocorrelation spectra. This limit is set by requiring Nyquist sampling of the primary beam when slewing at a degree per second. Longer dump times require slower slew rates, which may not suffice to remove the atmospheric emission without using ON/OFF switching. In any case full polarization information and the maximum number of channels should be recorded.

2. Rapidly-variable sources require time resolutions as short as 10μsec (for the fastest pulsars), but only the phased array (analogue sum) data need be sampled this fast. A few hundred channels would suffice for even the highest dispersion measures. Observations of solar flares would require the full cross-correlation of several subarrays, each containing some 10s of antennas, with full polarization information; but only one (possibly narrow) channel would be needed, and only on timescales of 100 msec. Stellar flares would require similar time resolution and the full array, but only the phased array data would be needed.

3. By far the most difficult problem is that of surveying large areas on the sky. Sensitivity is less of an issue than the total time required for such surveys (see Figure 1 and Table 7); Table 8 lists some of the projects possible for various minimum integration times. Here a natural cutoff (but a fairly woofly one; see below) would be somewhere between 10 and 100 msec for the fastest integration period, set by the desire to at least eventually allow mapping of the full LMC and the Virgo Cluster.

Table 7. MMA 230 GHz Surveys

Type		Min. Data Volume cont. [GB]	512 chan. [GB]	Total time on source	Det. limit $(7\sigma)^*$
$10' \times 10'$	*TMC-1; spiral at 10 Mpc*	0.033	17	1 hour	0.02–0.07
$1^\circ \times 1^\circ$	*W3 GMC; M31*	1.2	615	1 hour	0.12–0.43
$5^\circ \times 5^\circ$	*Gal. Ctr.; Coma Cluster*	30.	15,000	26 hours	0.12–0.43
$10^\circ \times 10^\circ$	*LMC; Virgo Cluster*	120.	60,000	100 hours	0.12–0.43
$360^\circ \times 1^\circ$	*Galactic Plane*	430.	220,000	15 days	0.12–0.43
4π sr	*entire sky*	9,500.	4,800,000	4.8 years	0.12–0.43

Size of data produced, time required, and detection limits of some possible 230 GHz MMA surveys, assuming

- $\frac{\lambda}{4\mathrm{D}} \times \frac{\lambda}{2\mathrm{D}}$ sampling. Nyquist sampling in both dimensions reduces the data size by a factor two, and increases the detection limit by a factor $\sqrt{2}$, assuming the dump time is kept constant. If the dump time is increased to match the sampling the data volumes and detection limits will be the same as listed in the table.
- **8m antennas**: both the total time and the data volume go as $\nu^2\,\mathrm{D}^2$.
- 40 msec integration times in all cases except the smallest $(10' \times 10')$ survey, where the integration time is 1400 msec.

"Total time" refers to time **on-source only**. Data volume is the *minimum*, assuming one dump per pointing; this is probably an underestimate.

* Detection limits are 7σ surface brightness sensitivities for a 3.5 arcsec beam at 230 GHz. the smaller number refers to the maximal, MMA+LSA $(40 \times 8\mathrm{m} + 35 \times 15\mathrm{m})$ array, while the larger refers to the MMA alone $(40 \times 8\mathrm{m})$.

- Spectral line: detection limits are in K (multiply by 0.53 to get Jy/beam), assuming dual polarization and 1 km/s channels.
- Continuum: multiply detection limits by 10 to get mK, or by 5.3 to get mJy/beam, assuming 8 GHz bandwidth and dual polarization.

Table 8. **The Effect of t_{int} on Big Surveys**

Observation	Area Covered	Examples
1 msec integrations:		
Routine (8 hrs on-source)	$18^\circ \times 18^\circ$	Taurus cloud; CanVen Cluster
Big project (100 hrs on-source)	$360^\circ \times 10^\circ$	Galactic Plane
Large survey (1 month on-source)	8.6 sr	2/3 of the sky
10 msec integrations:		
Routine (8 hrs on-source)	$5^\circ.7 \times 5^\circ.7$	Galactic Center; Perseus Cloud; Coma Cluster
Big project (100 hrs on-source)	$20^\circ \times 20^\circ$	Taurus cloud; CanVen Cluster
Large survey (1 month on-source)	$360^\circ \times 8^\circ$	Galactic Plane
100 msec integrations:		
Routine (8 hrs on-source)	$1^\circ.8 \times 1^\circ.8$	W3 GMC; M31
Big project (100 hrs on-source)	$5^\circ.7 \times 5^\circ.7$	Galactic Center; Perseus Cloud; Coma Cluster
Large survey (1 month on-source)	$17^\circ \times 17^\circ$	Taurus cloud; CanVen Cluster
1000 msec integrations:		
Routine (8 hrs on-source)	$34' \times 34'$	Cepheus A; M81
Big project (100 hrs on-source)	$2^\circ \times 2^\circ$	W3 GMC; M31
Large survey (1 month on-source)	$5^\circ.2 \times 5^\circ.2$	Galactic Center; Perseus Cloud; Coma Cluster

How much sky can be covered in a given amount of **on-source** time, assuming an integration time as indicated, one integration per pointing, and OTF sampling ($\lambda/4$D in one direction, $\lambda/2$D in the other). This assumes **8m antennas** and 230 GHz; the area covered scales as $\nu^{-2}\,\mathrm{D}^{-2}$.

Interferometric mosaicing is the most demanding project, both in terms of the fastest sampling rate (apart from pulsar observations) and the most information saved per sample (cross-correlations of a large number of antennas, and hundreds of channels, with dual polarization). There are several important points here. First is the importance of antenna size: 15m antennas will make large-area mosaics take four times as long compared to 8m dishes, or equivalently cut the area surveyed by the same factor. This suggests that an inhomogeneous array would usually observe in 'survey mode' with only the smaller dishes, which could also cut the data rate significantly. A related issue is the observing frequency, which also changes the primary beam size. I have taken 230 GHz as the standard throughout this document, because this is the most sensitive CO band, because it sits roughly in the middle of the MMA's frequency range, and because the atmosphere should be quite good there most of the time (and is much less subject to the vaguaries of current atmospheric modeling). The larger beam size at 115 GHz is obviously a strong argument for using this lower frequency for survey work, if not for the most sensitive experiments. On the other hand, it's likely that one will want to image e.g. W3 in a number of different transitions, covering a range of frequencies, and this will become prohibitive if the minimum integration time is not much less than a second.

Another source of ambivalence in all these numbers is the oversampling rate. Throughout this document I have taken $\frac{\lambda}{4\mathrm{D}} \times \frac{\lambda}{2D}$ sampling as the standard, as required for accurate OTF mosaics. If the telescopes can settle rapidly enough that standard pointed mosaicing is feasible, or if one is willing to live with less-than-optimal short-spacing information in OTF mosaics, one could Nyquist sample in both dimensions, doubling the required minimum integration time, and increasing the noise by $\sqrt{2}$. Further study is needed to determine quantitatively how much difference this would make to the resulting mosaics. Since the purpose of these big mosaics would presumably be to map large structures, and since the noise levels derived for even these short integrations are generally excellent, it would be unwise simply to assume that Nyquist (or even worse) sampling is good enough – this might easily set the limit on the quality of the maps.

All of the discussion so far has assumed perfect data, allowing one to get away with a single integration per pointing. This seems rather unlikely, certainly without continuous scanning (OTF mosaicing), although intelligent online flagging might take care of most problems (e.g. antennas not being on source at the beginning of the supposed integration). With continuous scanning this is probably less of an issue.

Both the data rates and the total data volumes are staggering, especially for spectral line work. Presumably this means that initial surveys will be limited to continuum work or to spectral imaging of very small regions. I feel however that it would be unwise to let our current computing/storage limitations set the parameters for an observatory that will be used for many decades after first light. The VLA correlator's capabilities are only now matched by off-line facilities, but we are already chafing under the limitations imposed by such 'ancient' technology, and there is little prospect of improvement until after the MMA is built. A similar situation can be expected for the MMA. It would be a pity to limit the possibilities of the array by requiring that we be able to reduce all the data it could produce using today's computers, or even those available when the MMA first begins to observe.

Having said that, it is worth asking what trade-offs are possible to limit at least initially the data volumes that come out. The integration time has been discussed *ad nauseum*, but while it will greatly affect the rate at which the data are produced, it will matter not at all in the final reckoning of total bits spewed to disk. The great sensitivity of the instrument, and the huge number of elements available, make subarrays very attractive, much more so than in the VLA. As mentioned above, splitting the array by telescope size makes particular sense for large surveys, and for the most rapid mapping further subarraying is plausible. The number of subarrays will be limited by the snapshot uv-coverage, probably requiring ~ 30 antennas in each subarray, and requiring some thought in the placement of the individual antennas. A special case is that of solar monitoring, where one might want to observe some 10 square arcminutes simultaneously using subarrays of a few (10?) antennas each. The data rate and volume of data produced would both go down by a factor equal to the number of subarrays (assuming all contain the same number of antennas). Something similar might be done when searching for nearby calibrators. In the same vein, one could record only some fraction of the baselines. One could even imagine using different integration periods for the different baselines, recording the short ones frequently to preserve the benefits of overlapping primary beams, but allowing the rest to be smeared out. Whether this would work, how much it would help, and whether the pain involved in allowing it would be worth the gains, is very much open to question. On first glance it seems too complicated to implement on the fast timescales here discussed, but this should be looked into.

An easier task would be to use a “burst mode” to obtain the required time resolution: store, say, a millisecond’s worth of data, then allow it to drip through the correlator over the next second. Unfortunately this would completely discard the benefits of rapid integration for surveys, though a mode where the total-power data were being recorded continuously while the interferometric data were taken only occasionally might at least allow simultaneous single-dish and interferometric work during exceptionally good weather.

A more obvious economy involves cutting the number of channels significantly. For individual regions this may be possible, but one will often want several hundred channels, not only to give good spectral resolution over a wide bandwidth (e.g. for extragalactic experiments), but also to allow mapping several transitions at once. The ~ 500 channels discussed here is probably a reasonable minimum, though there are doubtless experiments which would benefit from more channels (e.g. for simultaneous surveys of several CO isotopes, or to cover a big cluster at a few km/sec resolution). This will be addressed in a future memorandum.

As to the maximum bandwidth one would wish to correlate, the full 8–16 GHz would be desirable, since continuum surveys will be partly limited by thermal noise. Certainly going to less than 1 GHz would be unacceptable, and even that is probably pushing it. Most continuum experiments would demand at least dual polarization for sensitivity; many spectral line surveys could get by with a single polarization, though of course the lower noise level would be nice if it were possible.

9 Conclusions

Sub-second integration times on the MMA would be very useful, certainly for total power and phased-array variability experiments, but also for line and continuum surveys. On-the-fly total power observations require writing autocorrelation spectra every few milliseconds; a good hard limit is $3.0\left(\frac{8\mathrm{m}}{\mathrm{D}}\right)$ msec, to allow good atmospheric subtraction up to 350 GHz. Pulsar observations need time resolution as good as 10μsec, but only for the phased array (vector sum) output. The ability to survey large regions in finite time necessitates dumping a substantial fraction of the total array's correlations every few 10s of milliseconds, with the shortest available integration time directly proportional to the biggest area that can be mapped. Dump times of more than perhaps 100msec will make mapping such interesting objects as the Magellenic Clouds, the Cepheus Bubble, and the Virgo and Coma Clusters, virtually impossible; a good compromise would be around $40\left(\frac{8\mathrm{m}}{\mathrm{D}}\right)^2$ msec. Despite the large data rates and huge data volumes such surveys would produce, it is important not to design them out of the Millimeter Array from the beginning, since the initial correlator will probably not be replaced for several decades after first light.

10 Acknowledgements

Tim Bastian and Dale Frail provided the bulk of the useful information in the sections on solar and pulsar astronomy, respectively. Debra Shepherd and Stan Kurtz cast wary eyes over the mosaicing and spectral line discussions, pointing out several important oversights. As always, Mark Holdaway and Frazer Owen combined invaluable advice with accessible lore, as well as the occasional hard fact. Barry Clark pointed out a few harsh realities about data processing and storage, dimming my enthusiasm only briefly. Finally, Tim Cornwell very patiently avoided harassing me in the hallways about AIPS++ testing.

11 References

Allen, C.W. 1973, *Astrophysical Quantities* (University of London, London: Athlone Press).

Combes, F. 1991, ARAA 29, 195.

Brown, R.L. 1997. "Uniform Assumptions for the Atacama Array Workshop," email, 19 February 1997.

Bridle, A.H. and Schwab, F.R. 1991, in *Synthesis Imaging in Radio Astronomy*, eds. R.A. Perley, F.R. Schwab, and A.H. Bridle (ASP Conf. Series, vol. 6), p. 247.

Condon, J.J. 1992, ARAA 30, 575.

De Pree, C.G., Mehringer, D.M., and Goss, W.M. 1997, ApJ, 482, 307-333.

Foster, S.M. 1994, *MMA Memo No. 124: Distances to MMA Calibrators Based on 90 GHz Source Counts.*

Holdaway, M.A., Owen, F.N., and Emerson, D.T. 1995, *MMA Memo No. 122: On-the-Fly Mosaicing.*

Holdaway, M.A., Radford, S.J.E., Owen, F.N., and Foster, S.M. 1995, *MMA Memo No. 139: Fast Switching Phase Calibration: Effectiveness at Mauna Kea and Chajnantor.*

Johnston, S. et al. 1992, ApJ, 387, L37

Kaspi, V. M., Tauris, T. M., & Manchester, R. N. 1996, ApJ 459, 717.

Knapp, G.R., Helou, G., & Stark, A.A. 1987, AJ 94, 54.

Kramer, N., Jessner, A., Doroshenko, O., and Wielebinski, R. 1997, ApJ, *in press.*

Mangum, J. 1997, *On The Fly Observing at the 12m* (NRAO 12m document for observers).

Mundy, L.G. *et al.* 1996, ApJL, 464, L169.

Terebey, S., Chandler, C.J., and André, P. 1993, ApJ 414, 759.